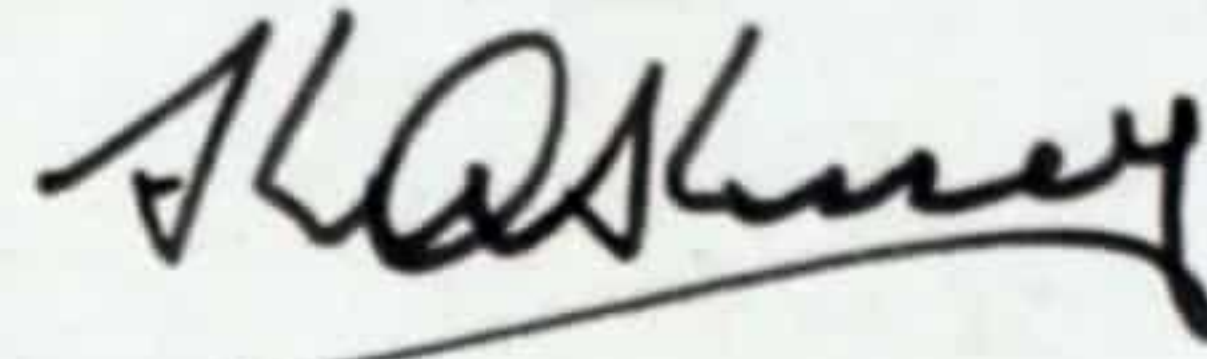


DECLARATION

This Thesis is my original research work undertaken at the Department of Mechanical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi, Ghana, under the supervision of the undersigned.

All works consulted have been acknowledged as reflected in the references.

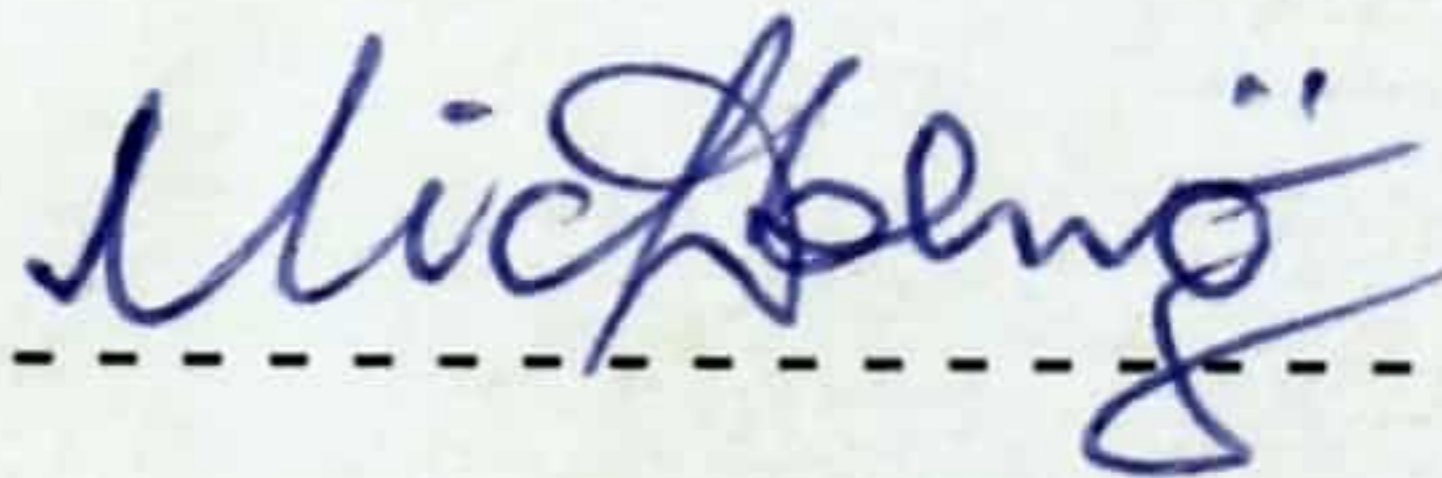


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Project Supervisor

CERTIFICATION

I certify that this Thesis has been assessed and all corrections have been made in accordance with the comments made by my Examiners.



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**DESIGN OF A CHARCOAL/METHANOL
SOLAR REFRIGERATOR**

**A Thesis presented to the School of Engineering, Kwame Nkrumah University of
Science and Technology, Kumasi, in partial fulfilment of the requirement for a
Master of Science Degree
in
Mechanical Engineering**

By

FRANCIS EKU QUAGRINE

February, 2000

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Francis Eku Quagraine

February, 2000

ABSTRACT

The research deals with the application of solar energy in refrigeration, specifically the design of a charcoal/methanol adsorption solar refrigerator.

Equations for the design of the collector, the condenser and the evaporator box of the charcoal/methanol solar refrigerator are developed. A collector simulation computer programme is written to simulate the performance of the solar collector and to determine the performance of the condenser and the COP of the refrigerator. A computer programme is also written to determine the performance of the evaporator box.

The collector simulation programme is used to simulate the performance of the solar collector of a charcoal/methanol solar refrigerator, which has been built and tested at the Asian Institute of Technology, Bangkok. The simulation is carried out for two typical days, ie 17th and 29th October 1987. A comparison of the simulation and experimental results indicates a very good agreement, validating the simulation programme.

Numerical results are produced with the simulation and the evaporator box design computer programmes using Kumasi meteorological data and 1 m² collector surface area. The numerical results indicate that charcoal/methanol solar refrigeration is feasible in Ghana, specifically Kumasi. A charcoal/methanol solar refrigerator is designed, and economic analysis is done. The analysis shows that the refrigerator will be economically viable when it is produced and used for commercial purposes.

It is recommended that the designed charcoal/methanol solar refrigerator be constructed, tested and developed. The collector simulation computer programme is also recommended for development.

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CHAPTER 1

INTRODUCTION

1.1 Background

Conventional energy is becoming more expensive especially in the developing countries where the demand for energy has increased due to the high growth in population. In addition the increasing use of conventional energy especially fossil fuels has contributed greatly to the degradation of the environment. In the developing countries, poverty and the increased demand for energy have also led to the over-exploitation of the forests for firewood, and this has caused a lot of damage to the forests. It has become inevitable to use renewable energy, which does not degrade the environment, to meet more of the energy needs so as to conserve conventional energy and limit the use of firewood and thus contribute to the attempts being made to protect the environment and forests from damage.

A major form of renewable energy is solar energy and its use is widespread. Maximum use should be made of solar energy especially in the developing countries, where it is abundant. Solar energy shows promise. There have been significant developments in solar science and technology. Today solar radiation is being harnessed for various use, such as crop drying, refrigeration, electricity generation, water distillation, etc. Generally solar-powered systems have low operating and maintenance costs, though high initial costs.

This project deals with the application of solar energy in refrigeration, specifically charcoal/methanol adsorption refrigeration. Previous research work by others has shown that absorption and adsorption solar refrigeration systems are feasible. Photovoltaic cells are also being used to convert solar radiation to electricity to power conventional refrigerators. Compared with these refrigerators using PV cells, absorption and adsorption

solar refrigeration systems are lower in cost, more maintenance free and can be produced locally.

In Ghana and other tropical areas much of the fish caught during bumper harvest and much of the farm produce especially fruits and vegetables go bad because of lack of cold storage facilities and other forms of preservation. The food spoilage reduces the amount of food produced and this constitutes a loss to the farmers and the people. Provision of cold storage and other storage facilities for the preservation of farm produce and fish will reduce spoilage. It will also extend the time that the farm produce and fish can be sold before they become unwholesome. This will lead to the control of their supply to the market and the consequent reduction in the instability in their prices.

Cold storage facilities could be provided in the rural areas for short-term storage and preservation of fruits and vegetables, after harvesting, before marketing or processing. The storage temperatures, for fruits and vegetables, required for short-term preservation are above freezing, between 0°C and 8°C . The lowering of the temperatures of the fruits and vegetables remove metabolic heat and retard biochemical deteriorative processes and microbial spoilage. Dried or roasted fish and meat could also be stored in these facilities for short periods.

Small cold storage units employing freezing temperatures (evaporating temperatures), say between -2°C and -10°C , could be sited at fishing communities and used for the temporary storage of fresh fish (especially for the night after catch in the afternoon) before the selling or processing of the fish. Such cold storage units could also be employed for ice production in both rural and urban areas.

Charcoal/methanol adsorption solar refrigerators can be used to provide the above cold storage facilities. They can also be used for the preservation of certain vaccines eg DPT, Tetanus Toxoid, DT and BCG which need storage temperatures (Exell et al, 1993) between 0°C and 8°C. Such refrigerators could be used at health posts in the rural areas. Since they are powered by solar energy, charcoal/methanol solar refrigerators can be used in areas where there is no electricity. They do not contain compounds that are harmful to the environment unlike ammonia/water solar refrigerators and some conventional refrigerators whose refrigerants (ammonia and chlorofluorocarbons) when released harm the environment.

1.2 Objectives of Research

The research seeks to determine the feasibility of a solar powered charcoal/methanol adsorption refrigerator using Kumasi solar insolation values and other meteorological data.

The research aims at:

- (i) Establishing the equations for the design of charcoal/methanol solar refrigerator consisting of a solar collector, a condenser/water tank and an evaporator box containing the evaporator.
- (ii) Developing a computer simulation programme to simulate the performance of the solar collector and determine the COP of the solar refrigerator.
- (iii) Developing computer design programmes to design the condenser/water tank and the evaporator box.
- (iii) Designing the solar collector, the condenser/water tank and the evaporator box (ie the whole solar refrigerator).

1.3 Limitation of Research

The average condenser and evaporator pressures are used in the simulation of the charcoal/methanol solar collector performance. Simulation (which is numerical experiment) is used to determine whether charcoal/methanol solar refrigeration is feasible in an area in Ghana. The construction and test of a charcoal/methanol solar refrigerator do not form part of the project.

1.4 Solar Thermal Refrigeration

In solar thermal refrigeration, solar radiation is converted to heat in a solar collector and the heat is used to power the refrigeration system. The absorption and the adsorption solar refrigeration systems are the main solar thermal refrigeration systems. In the absorption solar refrigeration system, an absorbent is used and part or all of it is contained in the solar collector; whilst in the adsorption solar refrigeration system an adsorbent is used and all of it is contained in the solar collector. The solar collector together with the absorbent or the adsorbent replaces the compressor of a conventional refrigeration system.

1.4.1 Liquid Absorption Solar Refrigeration

An absorbent, a liquid or liquid solution, is used to absorb refrigerant vapour from the evaporator by exposing it (the absorbent) to the evaporator pressure and by cooling it to remove the heat released from absorption. When the absorbent with the absorbed refrigerant is heated and exposed to the condenser pressure, absorbed refrigerant gets released, in vapour form, from the absorbent and moves to the condenser.

The solar collector provides the heat energy, which is used to heat up the absorbent/refrigerant liquid solution, which is in the solar collector, and to generate the refrigerant vapour at the condenser pressure.

Figs. 1.1, 1.2 and 1.3 illustrate an absorption solar refrigeration system (ie the ammonia-water system). Fig. 1.2 describes the absorption cycle and fig. 1.3 the refrigeration cycle.

The absorbent/refrigerant solution initially with the highest refrigerant concentration is heated in the solar collector from state A to B (see fig.1.2) before the generation of refrigerant vapour. Valves J and K (see fig.1.1) are closed. The temperature and pressure of the solution increase whilst the refrigerant concentration remains the same.

At state B, valve J is opened (valve K remains closed). The vapour pressure of the solution has reached the condenser pressure and since the solar collector is still providing heat to the solution, refrigerant vapourizes from solution until state C is reached where the temperature reaches maximum and begins to fall. From B to C, the pressure (condenser pressure) remains constant whilst the refrigerant concentration in the solution falls, reaching the minimum at state C. The refrigerant vapour generated moves from the solar collector to the condenser where it is condensed to liquid. The condensation process is represented by state 1' to 3' in fig.1.3. The liquid refrigerant flows to the receiver and then the evaporator, where it is further cooled to state 4'.

From state C to D, valve J is closed (K remains closed) and the weak solution in the collector cools. The heat supply from the solar collector has decreased (latter part of the afternoon when solar radiation has fallen significantly) to the extent that the temperature of

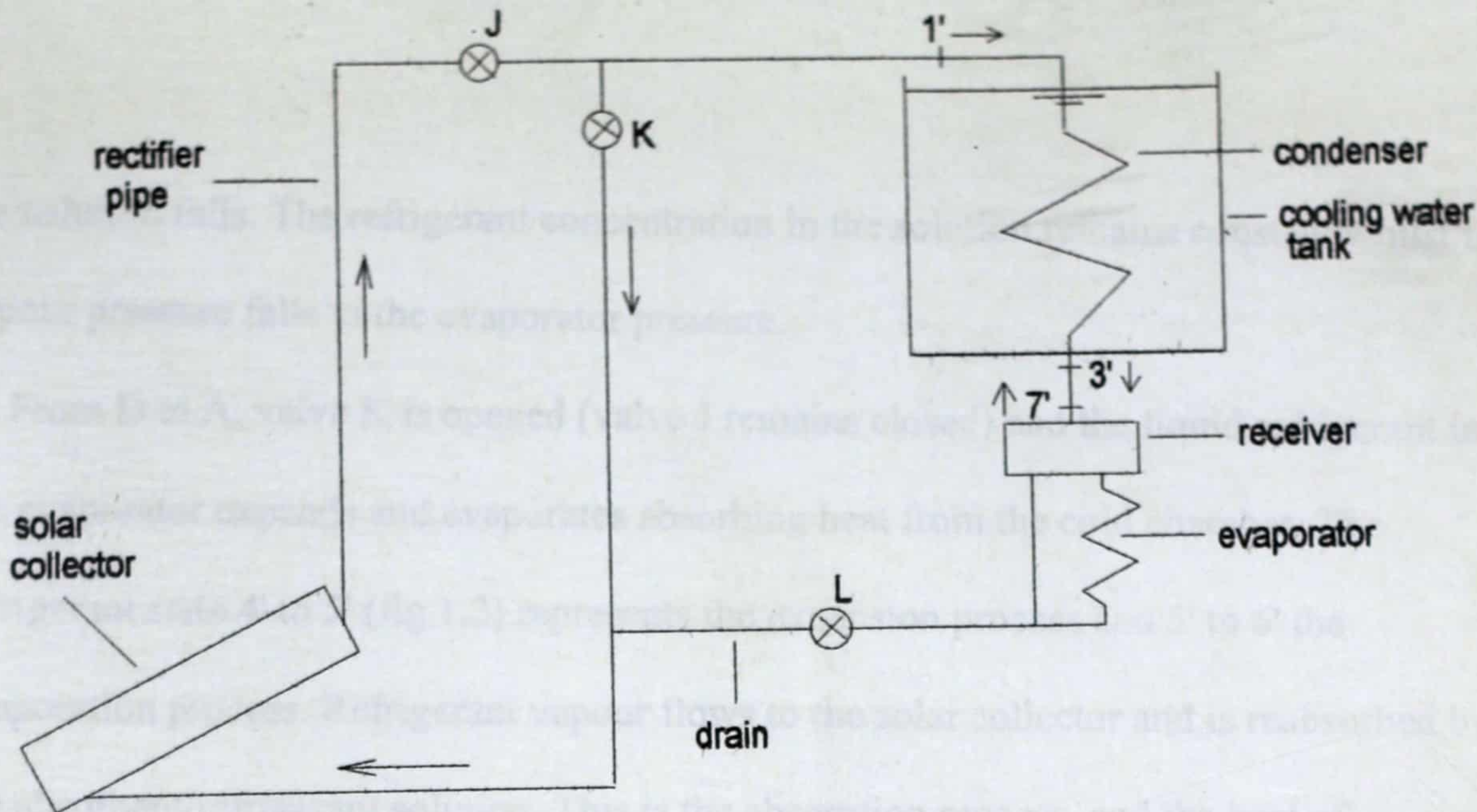


Fig. 1.1 Scheme For Ammonia / Water Absorption Solar Refrigerator

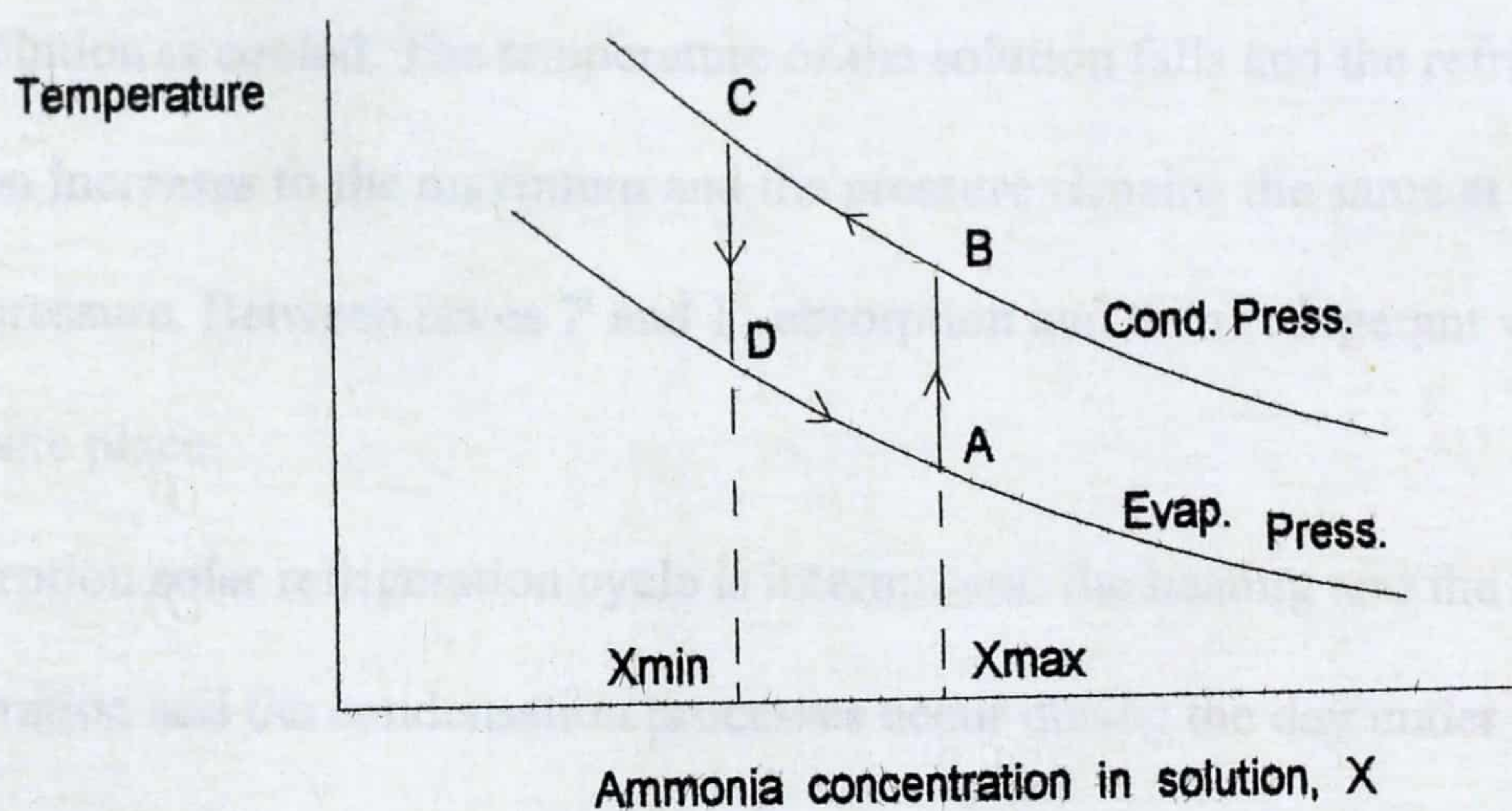


Fig. 1.2 Ideal absorption cycle

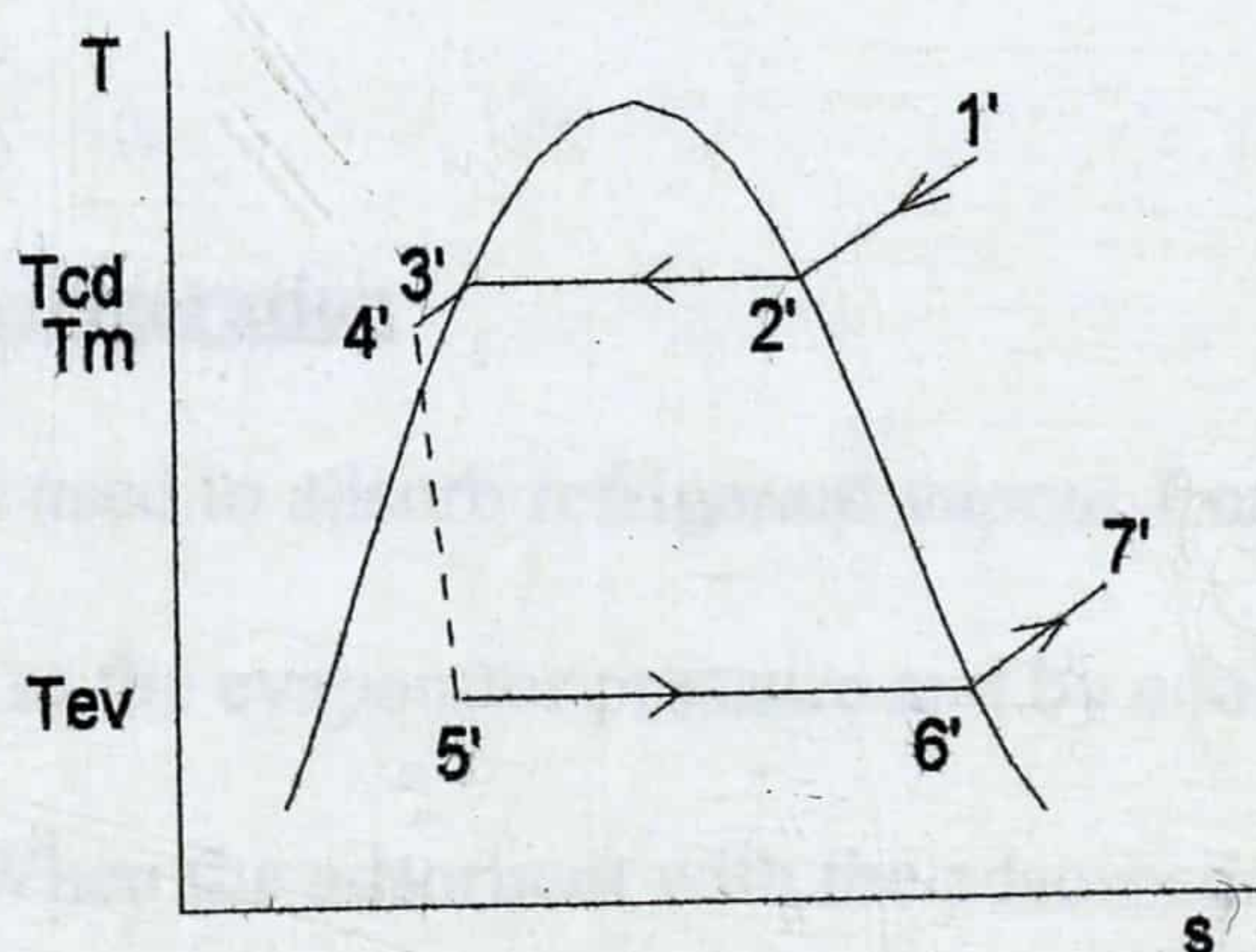


Fig. 1.3 T-s diagram of the refrigeration cycle

the solution falls. The refrigerant concentration in the solution remains constant whilst the vapour pressure falls to the evaporator pressure.

From D to A, valve K is opened (valve J remains closed) and the liquid refrigerant in the evaporator expands and evaporates absorbing heat from the cold chamber. The refrigerant state 4' to 5' (fig.1.3) represents the expansion process and 5' to 6' the evaporation process. Refrigerant vapour flows to the solar collector and is reabsorbed by the absorbent/refrigerant solution. This is the absorption process, and the heat of absorption is dissipated to the ambient air. Heat dissipation is facilitated by lowering/removing the bottom insulation of the collector, or an absorber is employed where the solution is cooled. The temperature of the solution falls and the refrigerant concentration increases to the maximum and the pressure remains the same at the evaporator pressure. Between states 7' and 1', absorption and then refrigerant vapour generation take place.

The absorption solar refrigeration cycle is intermittent: the heating and the refrigerant vapour generation and the condensation processes occur during the day under the sun, and the cooling and the evaporation/absorption processes occur at the latter part of the day and at night. The cycle ABCDA (Fig.1.2) is the ideal absorption cycle, and the cycle 1'3'4'5'7'1' (fig. 1.3) the ideal refrigeration cycle.

1.4.2 Adsorption Solar Refrigeration

An adsorbent, a solid, is used to adsorb refrigerant vapour from the evaporator by exposing it (the adsorbent) to the evaporator pressure and by cooling it to remove the heat released from adsorption. When the adsorbent with the adsorbed refrigerant is heated and

exposed to the condenser pressure, adsorbed refrigerant gets released in vapour form (ie desorbed) from the adsorbent and moves to the condenser.

The adsorbent is placed in the solar collector. The adsorbent initially with the highest concentration of the refrigerant is heated by the solar collector from state A to B, (see fig.1.5), before refrigerant vapour is generated. Valves J and K (see fig.1.4) are closed. The temperature of the adsorbent/adsorbed refrigerant and the equilibrium pressure increase whilst the concentration of the adsorbed refrigerant remains the same. The equilibrium pressure is the pressure of the vapour refrigerant at equilibrium with the adsorbed (liquid) refrigerant.

At state B, valve J is opened and K remains closed. The equilibrium pressure has reached the condenser pressure P_2 and since the solar collector is still supplying heat, refrigerant desorbs from the adsorbent and moves to the condenser. Desorption takes place from state B to C and stops at state C where the temperature reaches maximum and begins to fall. The equilibrium pressure remains constant at the condenser pressure whilst the concentration of adsorbed refrigerant falls, reaching the minimum at state C. The desorbed refrigerant which is in the vapour form is condensed to liquid in the condenser. The condensation process is represented by state 1' to 3' in fig.1.3.

From state C to D, valve J is closed and K is opened. The adsorbent cools dissipating heat to the ambient air. Heat supply from the solar collector has decreased (latter part of the afternoon) to the extent the adsorbent temperature falls. The equilibrium pressure falls whilst the adsorbed refrigerant concentration remains the same at the minimum. Liquid refrigerant flows to the evaporator, where it is further cooled to state 4' (fig 1.3).

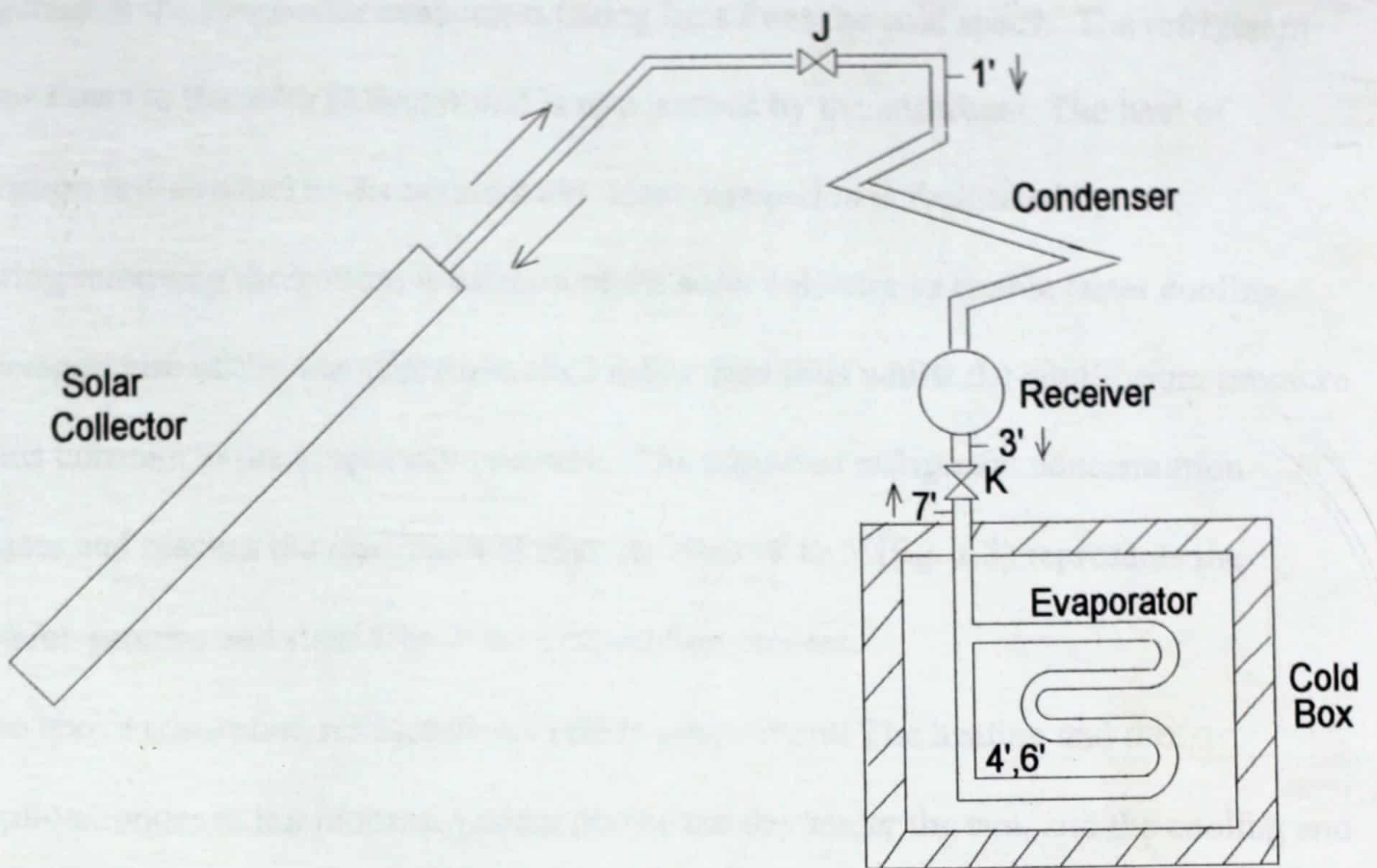


Fig. 1.4 Schematic diagram of an adsorption solar refrigerator

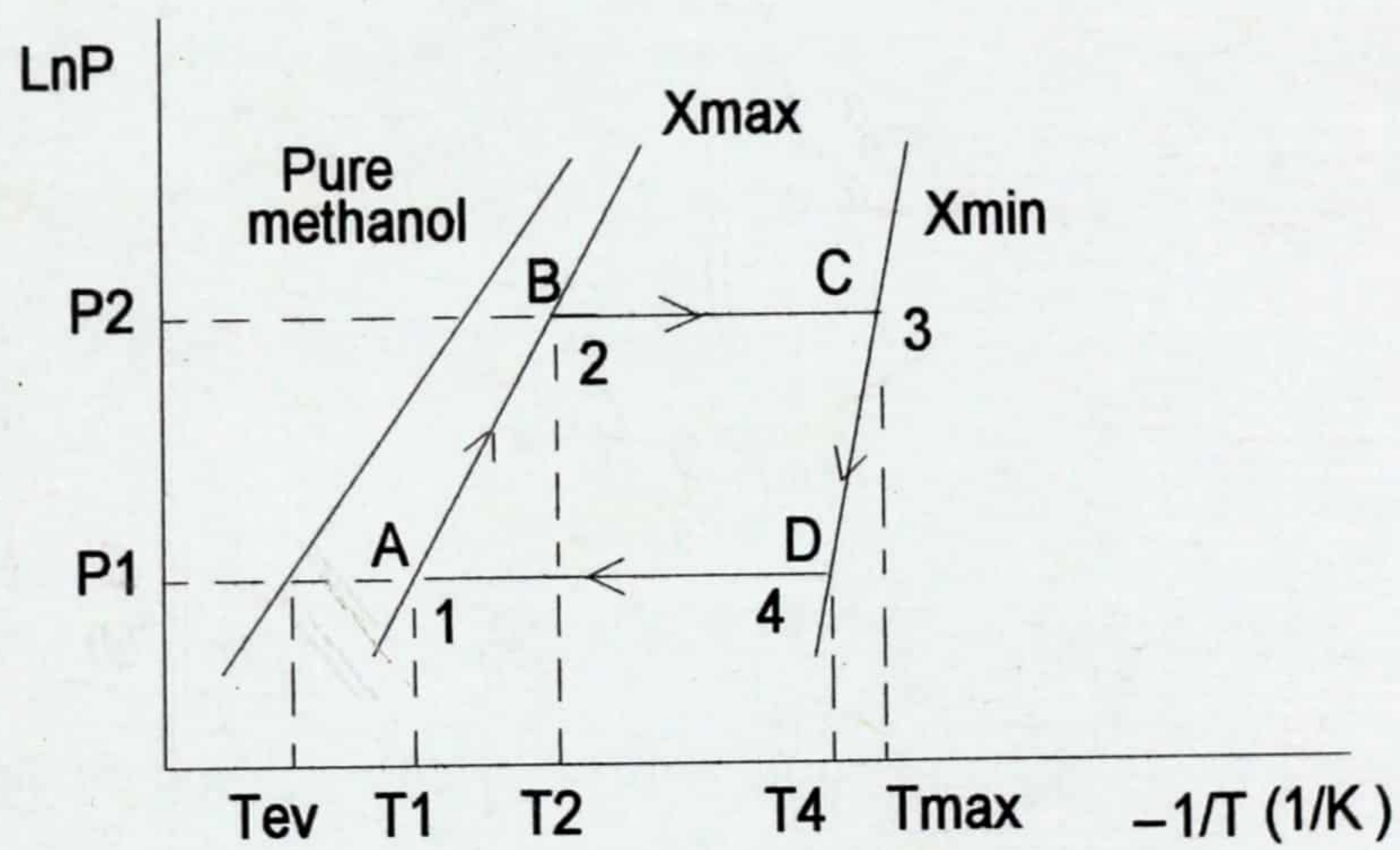


Fig. 1.5 P-T-X diagram of ideal adsorption cycle

From state D to A (fig.1.5), valve J is opened (valve K remains opened) and the liquid refrigerant in the evaporator evaporates taking heat from the cold space. The refrigerant vapour flows to the solar collector and is re-adsorbed by the adsorbent. The heat of adsorption is dissipated to the ambient air. Heat dissipation is facilitated by lowering/removing the bottom insulation of the solar collector to enable faster cooling. The temperature of the adsorbent/adsorbed refrigerant falls whilst the equilibrium pressure remains constant at the evaporator pressure. The adsorbed refrigerant concentration increases and reaches the maximum at state A. State 4' to 5' (fig. 1.3) represents the expansion process and state 5' to 7' the evaporation process.

The above adsorption refrigeration cycle is intermittent: The heating and the desorption/condensation processes occur during the day under the sun, and the cooling and the evaporation/adsorption processes occur at the latter part of the day and at night. The cycle ABCDA (fig.1.5) is the ideal adsorption cycle, and the cycle 1' 2' 3' 4' 5' 6' 7' 1' (fig.1.3) the ideal refrigeration cycle.

CHAPTER 2

LITERATURE REVIEW OF SOLAR THERMAL REFRIGERATION

2.1 Absorption Refrigeration

2.1.1 Ammonia/Water Absorption System

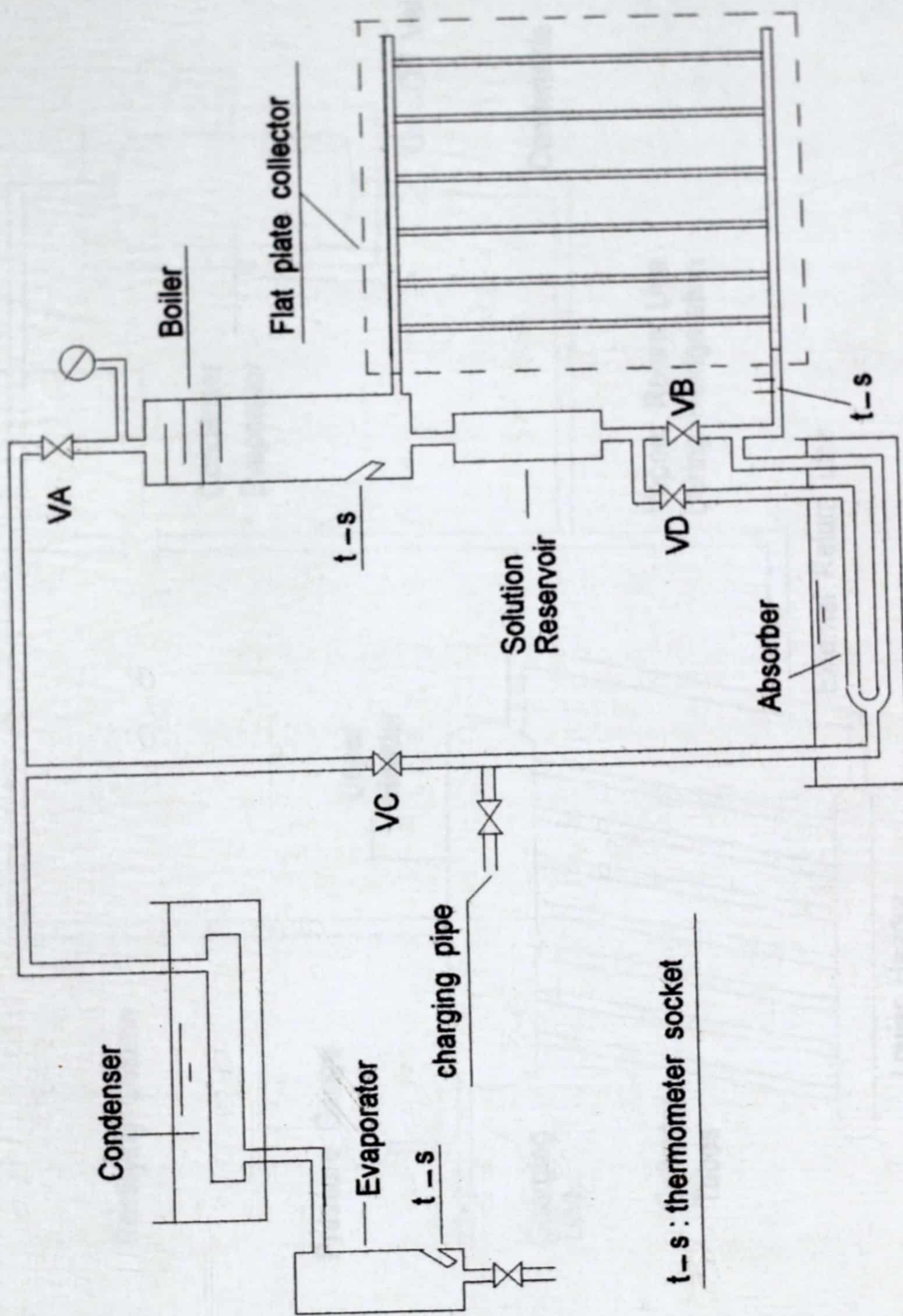
Williams et al (1958) reported an experimental study of an intermittent Ammonia/Water cooler using concentrating collector for regeneration.

Chinnappa (1962) did the pioneering work in intermittent ammonia/water absorption refrigeration that uses flat-plate solar collectors. A diagram of his plant is shown in fig.

2.1. The generation system consisted of solar collector, a boiler and a solution reservoir.

The collector plate was a copper sheet, 1.52 m x 1.07 m x 0.76 mm, painted dull black. Six steel pipes each of diameter 6 mm were soldered to the plate at intervals of 152 mm and were welded to headers. The collector had three glass covers. After evacuation the generating system was charged with 9 kg of ammonia-water solution of concentration 0.46 ammonia by weight. A water-cooled absorber was used. Test results showed that about 1.2 kg of ammonia could be distilled from the solution on a clear day, and minimum evaporator temperatures of -12°C were obtained and the overall coefficient of performance of the plant was about 0.06. About 1.4 kg of ice could be produced per square metre of collector area.

A similar intermittent ammonia/water absorption refrigeration unit (fig. 2.2) was built and tested by Swartman and Swaminathan (1970). Their unit differed from that of Chinnappa in two ways. Their collector had as integral part a large upper header, of diameter of 152 mm, which provided the required capacity for the solution and a large surface for the evaporation of ammonia, instead of a boiler and a solution reservoir outside



t - s : thermometer socket

Fig. 2.1 Schematic Diagram of Solar Refrigerator by Chinnappa

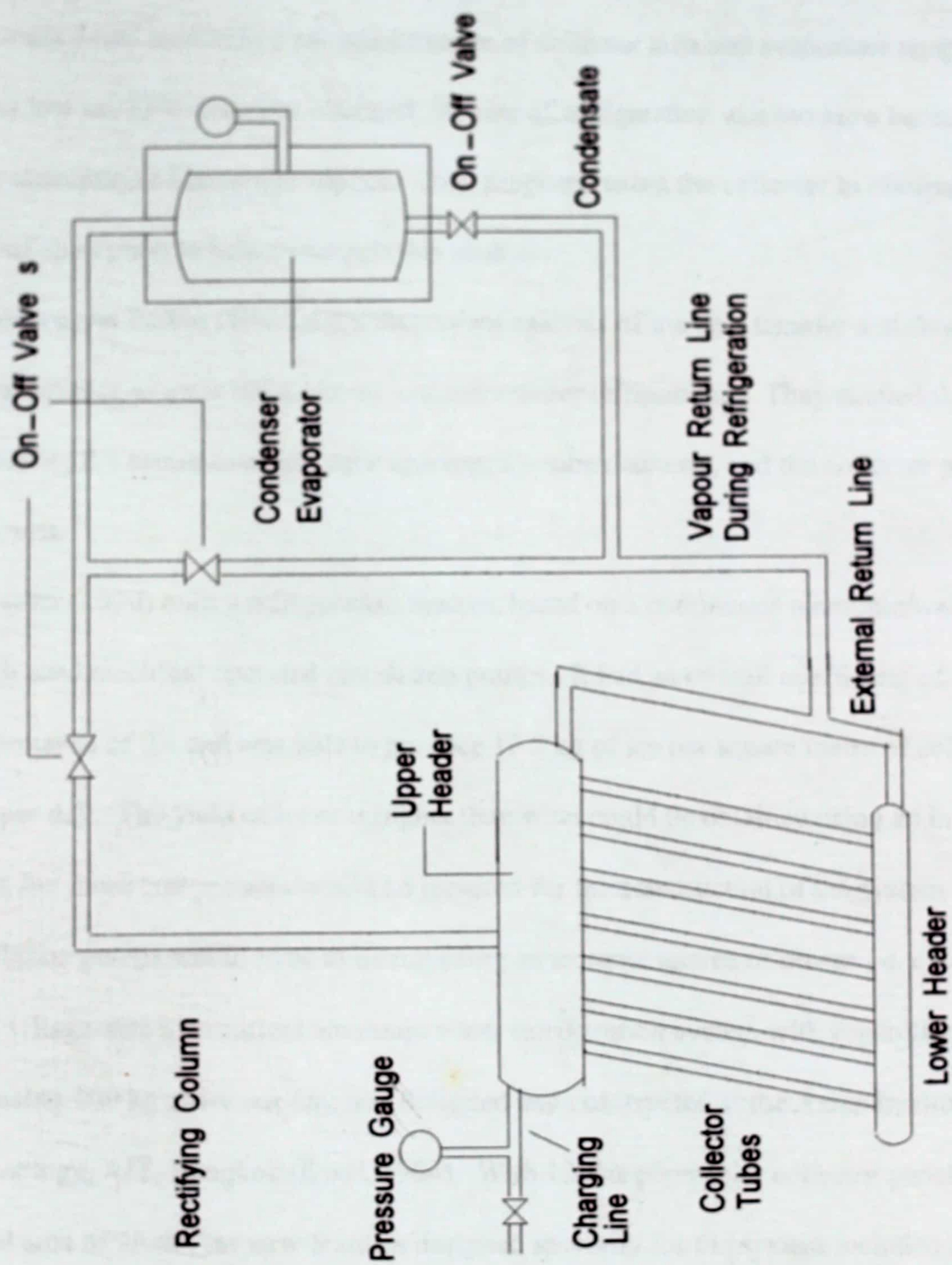


Fig. 2.2 Schematic Diagram of Solar Refrigerator by Swartman and Swaminathan

the collector. They also connected the evaporator with a tube to the lower and upper headers of the collector instead of to a water-cooled absorber. The glass cover of the collector was opened to facilitate cooling during absorption. Although about 1.9 kg of ammonia could be distilled per square metre of collector area and evaporator temperatures are as low as -12°C could be obtained, the rate of refrigeration was too slow because of poor absorption of ammonia vapour. They proposed using the collector to dissipate the heat of absorption to help overcome this problem.

Moore and Farber (1967) did a theoretical analysis of the heat transfer and flow characteristics of solar collectors of ammonia/water refrigerators. They studied the effects of varying the centre-to-centre tube spacing, the tube diameter, and the collector plate thickness.

Farber (1970) built a refrigeration system, based on a continuous ammonia/water cycle, which used electrical operated circulation pumps. It had an overall coefficient of performance of 0.1 and was able to produce 12.5 kg of ice per square metre of collector area per day. The yield of ice was higher than what could be obtained using an intermittent cycle, but more components would be required for the construction of the system and the circulation pumps would have to be run using an external source of power i.e. electricity.

A village-size intermittent ammonia/water refrigeration system with capability of producing 100 kg of ice per day was designed and constructed at the Asian Institute of Technology, AIT, Bangkok (Exell, 1984). With 12 flat-plate solar collector panels having a total area of 25 m^2 , the new features designed specially for the system included a liquid seal to control the flow of ammonia vapour, and a distributor to ensure the even absorption of ammonia in the collectors. Tests showed that 65 kg of ice could be obtained every day.

The economic evaluation showed that if such a system were used in a village in a developing country, the payback time should be from two to six years depending on interest rates and the price of ice.

A detailed numerical model to study the performance of an intermittent ammonia/water absorption icemaker having flat plate solar collectors was developed by Exell (1983). The model has been verified by experimental tests.

Harvey (1988) developed an intermittent regenerative cycle with ammonia/water for solar cooling. In Harvey's system, a counter-flow solution heat exchanger (SHE) was arranged between the rich solution from the upper part of the reservoir and the returning weak solution to the lower part, which allowed the reclaim of liquid sensible heat. The efficiency of generation was substantially greater which would allow smaller collector areas and thus cost reduction (collectors make up half of the cost of an ammonia/water system, Exell 1984). The sensible heat loading was less, allowing quicker response in periods of intermittent sunshine. A computer simulation programme using steady state conditions for the heat exchanger and the generator was written by Harvey (1985). An improved simulation programme taking into account transient conditions and varying specific heat capacities was later developed (Harvey, 1988).

To increase the COP of continuous ammonia/water refrigeration systems, the double effect generation cycle was developed. In the double effect generation cycle, one more generator ie a second generator was used. The second generator was introduced between the first generator and the condenser. Kaushik (1985) carried out the performance comparison for different working pairs between single and double effect generation cycles

by means of numerical computer model. The results showed that the COP values of double effect generation absorption cycles approached twice that of single effect ones.

Ammonia/water refrigeration system has these practical disadvantages:

1. The pressures are high.
2. Aqua-ammonia is corrosive and toxic. Ammonia is unpleasant and potentially dangerous chemical when released.
3. The system needs a rectifier to prevent water vapour from entering the condenser.

2.1.2 Calcium Chloride/Ammonia System

Nielsen et al (1977) built an indoor test rig for calcium chloride/ammonia pair to study the heat and mass transfer processes during absorption and desorption. Worsoe-Schmidt (1978) built a demonstration unit with a 4m^2 flat plate solar collector containing a porous solid made of calcium chloride and Portland cement. Test results showed that the process COP was 0.34 and the overall solar COP was 0.096. On a clear day 6kg of ice could be produced per square metre of collector area. The experiments showed that there was a problem of making the adsorbent continue to function effectively after a large number of cycles. It was also found necessary to design the collector so that all the insulation could be removed from the back to release the heat of absorption of ammonia during the refrigeration process.

Iloeje (1985) tested a calcium chloride/ammonia solar refrigerator over the annual climatic variations at Nsukka, Nigeria. He charged the system with different pressures, 900, 500 and 200 kPa, to determine the effect of the charging pressure on COP. He concluded that the maximum useful cooling per day in the dry season was 1.65 kg of ice

per square metre of collector area. The best charging pressure was found to lie between the condensing and the absorption pressures and depended on the system volume and the evaporator design. He developed a simple model and a computer programme for the system and carried out parametric study with a view to optimizing the design.

2.1.3 Other Absorption Refrigeration Pairs

Muradov and Shadiev (1971) built an intermittent refrigerator using ammonia/sodium chloride. The generator consisted of 2 m² double-glazed flat plate collector. The refrigerator could produce 2 kg of ice.

Swartman, Ha and Swaminathan (1975) compared ammonia/water and ammonia/sodium thiocyanate refrigeration systems. They obtained overall COP of 0.05 to 0.14 for ammonia/water and 0.11 to 0.27 for ammonia/sodium thiocyanate. They also commented that because of the low volatility of sodium thiocyanate a rectifying column was not needed unlike in the ammonia/water system.

Uncertainties about the technology of these systems, such as the problems of corrosion, crystallization of the absorbent, and the maintenance of a uniform concentration in the solution, still exist.

2.2 Adsorption Refrigeration

2.2.1 Silica Gel/Water System

Sakoda and Suzuki (1986) built a small adsorption cooling experimental unit, using silica gel/water as the adsorbent/refrigerant pair, to study the heat and mass transfers during desorption and adsorption. They developed a simple theoretical model, which could

interpret the experimental results well. Their study showed that the heat transfer area between the adsorbent and the adsorbent container had a considerable effect on COP.

2.2.2 Zeolite/Water Refrigeration System

The disadvantages associated with the ammonia/water refrigeration system could be avoided by using zeolite/water or charcoal/methanol refrigeration systems.

Meunier and Mischer (1979) developed zeolite 13X/water refrigeration system in France. They presented a study on the use of microporous adsorbents for solar cooling. The zeolite 13X/water pair could only produce an evaporation temperature of 0°C when heat sink temperatures were 50°C , typical of the air-cooled condensers in tropical climate. For ice making, the pair was reported to be suitable, and it was possible to achieve an overall COP of 0.13.

Bechec et al (1981) reported the design of a system using zeolite 13X/water pair, but a later study by Guilleminot et al (1981) found the pair chemically unstable due to a catalytic reaction, in which dimethyl ether was formed.

Synthetic zeolites, such as zeolite 13X (zeolites are aluminosilicates), have ordered crystalline structure, uniform pore size, and can be tailor-made to suit a particular use. For solar refrigeration, natural zeolites are preferred, as the heat of adsorption of water in natural zeolites is about 2791 kJ/kg compared with a value of about 4187 kJ/kg for synthetic zeolites. Natural zeolites are also reported to be much less expensive than synthetic zeolites (Tchernev, 1978).

Grenier and Pons (1985) built at Montpellier (France) a zeolite/water solar cold storage.

They designed a theoretical model and compared the predictions with the experimental results. In 1988 they reported the development of an improved model (Grenier et al 1988).

The daily overall solar COP of zeolite-water pair has been experimentally found by Tchernev (1984) to be in the range 0.12 to 0.15 with a peak at 0.30.

Zeopower company, U.S.A., produced a natural zeolite/water adsorption solar refrigerator (Tchernev, 1979) with a glass evaporator calibrated in thousands of BTU's. It was reported the refrigerator could produce 9.8 kg of ice per day per square metre of collector area for a total solar insolation of 20 MJ/m²-day, under typical climatic condition of Boston, Massachusetts. One such unit was shipped to AIT, Bangkok, and tested (Zhu, 1987). The testing results showed that the lowest temperature of the evaporator attained was about 4°C; no ice could be produced in the evaporator and the overall solar COP was between 0.05 and 0.06. The attempts made to improve the performance of the refrigerator were unsuccessful.

2.2.3 Charcoal/Methanol Refrigeration System

Critoph and Vogel (1986) compared the performance of synthetic zeolites 5A, 13X and activated charcoal for solar cooling using different refrigerants, R11, R12, R22 and R114. The activated charcoal proved to be the better adsorbent. The study done by Grenier and Pons (1983) and Meunier et al (1986) on synthetic zeolite/water and charcoal/methanol pairs showed that the charcoal/methanol pair gave a better COP generally. The study also showed that when the nighttime ambient temperature and the evaporating temperature were particularly high then the zeolite/water pair was better.

Other advantages of activated charcoal are:

1. Activated charcoals can be made with properties to suit particular applications by varying the activation time and temperature, etc.
2. Activated charcoals (particularly coconut shell charcoal) can be manufactured in the country where they are to be used.

Critoph (1988) has studied theoretically adsorption cycles of activated charcoal with different refrigerants. He concluded that methanol, acetonitrile, methyl amine and nitrogen dioxide were suitable for producing ice and that methanol would give the best COP.

Advantages of methanol:

1. Low evaporating temperatures
2. Small size of molecule
3. Significant latent heat of vaporization (1100kJ/kg)
4. Non-corrosiveness

Pons and Guillemint (1986) built a prototype activated charcoal/methanol solar icemaker in Orsay, France. The system had 6 m² flat plate solar collectors made with copper, which contained 130 kg of activated charcoal. Air-cooled condenser was used. The system could produce 30-35 kg ice after a sunny day. The overall COP was between 0.10 and 0.12.

Guillemint and Meunier (1987) developed a uniform pressure model to describe the heat and mass transfers in a fixed bed of solid adsorbent (activated charcoal) in a finned reactor heated on the upper surface by means of an electrical element. They neglected resistance to mass diffusion in their model.

Passos and Escobedo (1989) established a similar uniform pressure model for the reactor based on the work of Guilleminot and Meunier. He introduced a linear driving force (LDF) equation to account for the resistance to mass transfer in the pellet.

Exell designed and built an activated charcoal/methanol ice maker of collector area 0.97m^2 in 1987 at the Asian Institute of Technology (AIT), Bangkok (Exell, 1993). The collector plate (flat plate) was made with copper tubes, which contained 18 kg of activated charcoal. The system could produce 2.5 kg of ice at -1°C to -3°C after a sunny day. After lying idle for half a year, the system was tested again by Yuan (1988) and its performance was found to have deteriorated. This was attributed to the formation of formaldehyde and dimethyl ether, which also increased the system pressure. Formaldehyde and dimethyl ether were formed in the collector due to the decomposition of methanol in the presence of copper which acted as catalyst at the higher collector temperatures.

Boubakri et al (1992) reported their experimental study of activated charcoal/methanol icemakers. The flat plate solar collector, 1m^2 area, and the condenser of each icemaker were assembled together to form one unique component called the collecto-condenser. Three such icemakers (manufactured by BLM, a French company) were tested in actual conditions in Agadir, Morocco. The units produced more than 4 kg of ice per square metre of collector area for more than 60% of the days investigated.

Jing (1992) designed a computer simulation programme at AIT for activated charcoal/methanol icemaker. Simulation results were compared with data obtained from experimental tests, and the agreement was quite good. The programme was used to determine the sensitivity of the system performance to variations in the design parameters and methods of operating the system.

CHAPTER 3

CHARCOAL/METHANOL ADSORPTION RELATIONS

3.1 D-A Equation

The state equation for adsorption originally proposed by Dubinin and Radushkevich is expressed as (as cited by Smisek and Cerny, 1970),

$$W = W_o \cdot \exp[-k(T \cdot \ln(P_s/P))^2] \dots\dots\dots 3.1$$

The above equation is called the D-R equation. Dubinin and Astakhov (1970) modified the equation to fit experimental data better by introducing another parameter n . The modified D-R equation is called the D-A equation, which is given as,

$$W = W_o \cdot \exp[-D(T \cdot \ln(P_s/P))^n] \dots\dots\dots 3.2$$

Multiplying the D-A equation by the density of the adsorbate (here methanol) gives (Jing, 1992),

$$X = \rho_m \cdot W_o \cdot \exp[-D(T \cdot \ln(P_s/P))^n] \dots\dots\dots 3.3$$

Rearranging the above equation, we have,

$$P = \frac{P_s}{\exp\left[\frac{1}{T} \left(-\frac{1}{D} \ln\left(\frac{X}{\rho_m W_o} \right) \right)^{\frac{1}{n}} \right]} \dots\dots\dots 3.4$$

Finding the natural log of equation 3.2 gives,

$$\ln W = \ln W_o - D(T \cdot \ln(P_s/P))^n \dots\dots\dots 3.5$$

Graph of $\ln W$ against $(T \cdot \ln(P_s/P))^n$ is a straight line. D is the gradient and $\ln W_o$ is the constant of the equation or the intercept on the $\ln W$ axis and n is the quantity that gives the best linear correlation between $\ln W$ and $(T \cdot \ln(P_s/P))^n$ for the experimental data. W_o , D , and n can therefore be determined from experimental data.

3.2 Clausius-Clapeyron Equation

The Clausius-Clapeyron equation can be used to describe the equilibrium states of adsorption. Assuming vapour to be an ideal gas and neglecting the specific volume of saturated liquid in comparison with the specific volume of saturated vapour, the Clausius-Clapeyron equation can be expressed as (Jing, 1992):

$$\frac{\partial(\ln P)}{\partial T} \Big|_{X=const.} = \frac{H_{des}}{R.T^2} \dots\dots\dots 3.6$$

Integrating, we have,

$$\ln P = -\frac{H_{des}}{R.T} + G \dots\dots\dots 3.7$$

where G is integration constant and R is given by,

$$R = Ru / M$$

Graph of lnP against -1/T is a straight line. H_{des}/R is the gradient of the graph and since R is known, H_{des} can be determined. H_{des} is a function of the adsorbate (methanol) concentration, X, and it changes as X changes. G also changes with X.

3.3 Graphs and Parameters of Charcoal/Methanol Equations

The parameters Wo, D and n (Equation 3.2) have been determined for various activated charcoals with methanol as the adsorbate at the Asian Institute of Technology (AIT), Bangkok (Jing, 1992). The graphs of lnP against -1 /T were also determined for various methanol concentrations, X, for each activated charcoal.

Table 3.1 gives the experimentally determined values of the parameters W_o , n and D for the various charcoals tested at AIT. The descriptions of the charcoals are listed in Table 3.2.

Fig. 3.1 shows graph of $\ln W$ against $(T.\ln P_s/P)^n$ for activated charcoal 207E4. Fig. 3.2 also shows graphs of $\ln P$ against $-1/T$ for the same charcoal. Charcoal 207E4, which was made in U.K, was one of the activated charcoals tested at AIT, Bangkok. The properties of this charcoal have been used in the design of the solar refrigerator in this project.

The gradients H_{des}/R (or $H_{des}.M/R_u$) of the graphs $\ln P$ vs $-1/T$ for charcoal 207E4 are given by Jing (1992),

$0.02 \leq X < 0.06,$
 $H_{des}/R = 6027.159 - 9935.65X$

$0.06 \leq X < 0.14,$
 $H_{des}/R = 5681.649 - 4144.85X$

.....3.9

$0.14 \leq X < 0.20,$
 $H_{des}/R = 5547.501 - 3104.39X$

Table 3.1 Values of the parameters of Equation 3.2 for different charcoals

Charcoal	W_o (l/kg)	N	$D \times 10^5$ (K^{-n})	Temperature Range ($^{\circ}C$)
207E4	0.365	1.34	14.962	30 – 110
LSZ 40	0.384	1.28	28.814	30 – 110
LSZ 30	0.405	1.16	31.972	30 – 110
MD 6070	0.989	1.12	88.982	30 – 120
MD 5060	0.535	1.50	4.5895	30 – 120
Normal	0.1569	2.0	0.1982	30 – 110

Table 3.2 Charcoal samples (activated)

Charcoal sample	Country	Description
207E4	U.K	Coconut shell based, extruded
LSZ40	China	Coal based CCL ₄ >55%, extruded
LSZ30	China	Coal based CCL ₄ >65%, extruded
MD6070	Thailand	Coconut shell based, granular, mesh size = 4x8
MD5060	Thailand	Coconut shell based, granular, Mesh size = 8x30
Normal charcoal	Thailand	Coal based, not activated.

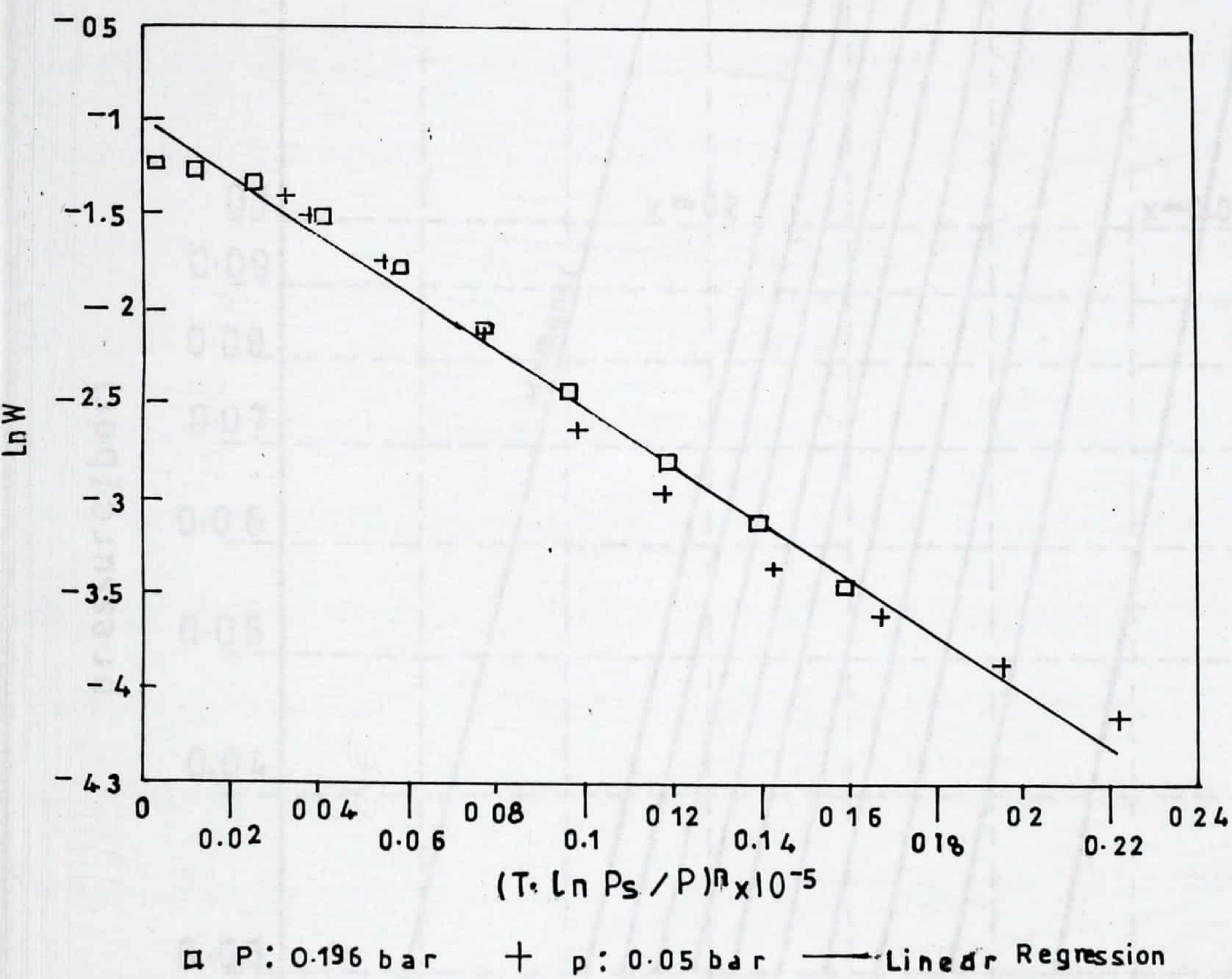


Fig 3.1 D-A Representation of 207 E4 (n = 1.34)
(AIT)

3.4 Charcoal/Methanol Adsorption Cycle

The charcoal/methanol adsorption cycle is an adsorption cycle with charcoal as the adsorbent.

The ideal adsorption cycle is described in section 3.1. The cycle is shown in fig. 3.3.

pressure and the evaporating pressure are not too low, say 0.03 bar and 0.02 bar respectively (or the average vapour pressure in the collector is not too low, say 0.03 bar).

respectively. The adsorption cycle is shown in fig. 3.4. The cycle is shown in fig. 3.4.

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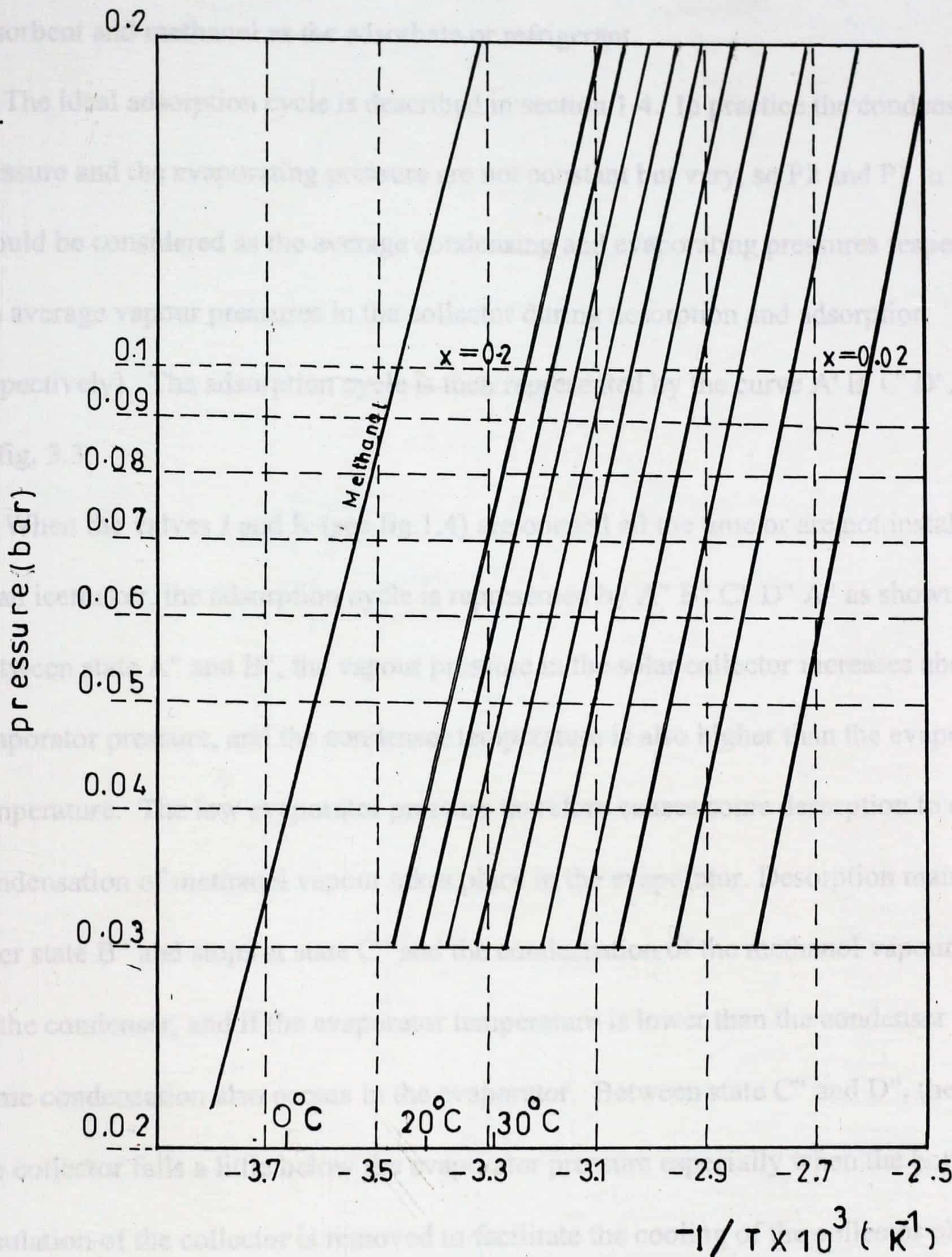


Fig 3.2. Experimental isosters on a $\ln p$ vs. $-1/T$ plot for charcoal 207E4(AIT)

3.4 Charcoal/Methanol Adsorption Cycle

The charcoal/methanol adsorption cycle is an adsorption cycle with charcoal as the adsorbent and methanol as the adsorbate or refrigerant.

The ideal adsorption cycle is described in section 1.4. In practice the condensing pressure and the evaporating pressure are not constant but vary, so P_2 and P_1 in fig. 3.3 should be considered as the average condensing and evaporating pressures respectively (or the average vapour pressures in the collector during desorption and adsorption respectively). The adsorption cycle is then represented by the curve $A' B' C' D' A'$, shown in fig. 3.3.

When the valves J and K (see fig.1.4) are opened all the time or are not installed eg as in an icemaker, the adsorption cycle is represented by $A'' B'' C'' D'' A''$ as shown in fig.3.4. Between state A'' and B'' , the vapour pressure in the solar collector increases above the evaporator pressure, and the condenser temperature is also higher than the evaporator temperature. The low evaporator pressure therefore causes some desorption to occur, and condensation of methanol vapour takes place in the evaporator. Desorption mainly occurs after state B'' and stops at state C'' and the condensation of the methanol vapour takes place in the condenser, and if the evaporator temperature is lower than the condenser temperature some condensation also occurs in the evaporator. Between state C'' and D'' , the pressure in the collector falls a little below the evaporator pressure especially when the bottom insulation of the collector is removed to facilitate the cooling of the collector plate. A small amount of methanol thus evaporates from the liquid methanol in the evaporator and flows to the collector and adsorption occurs. Methanol evaporation (in the evaporator) and adsorption (in the collector) occur mainly after state D'' and stop at state A'' .

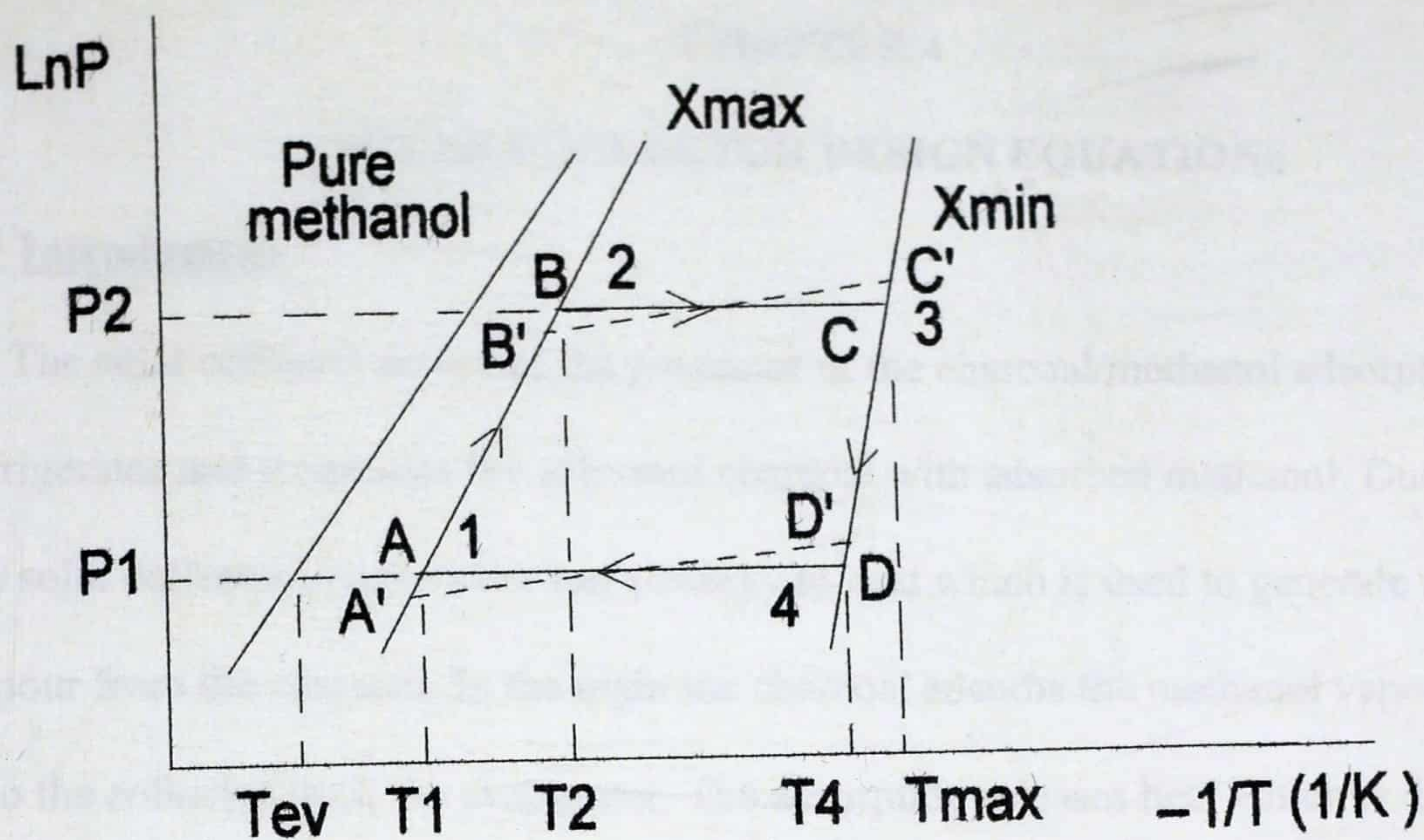


Fig. 3.3 P-T-X diagrams of an adsorption cycle of a solar refrigerator with one valve (K) operated, and the ideal adsorption cycle

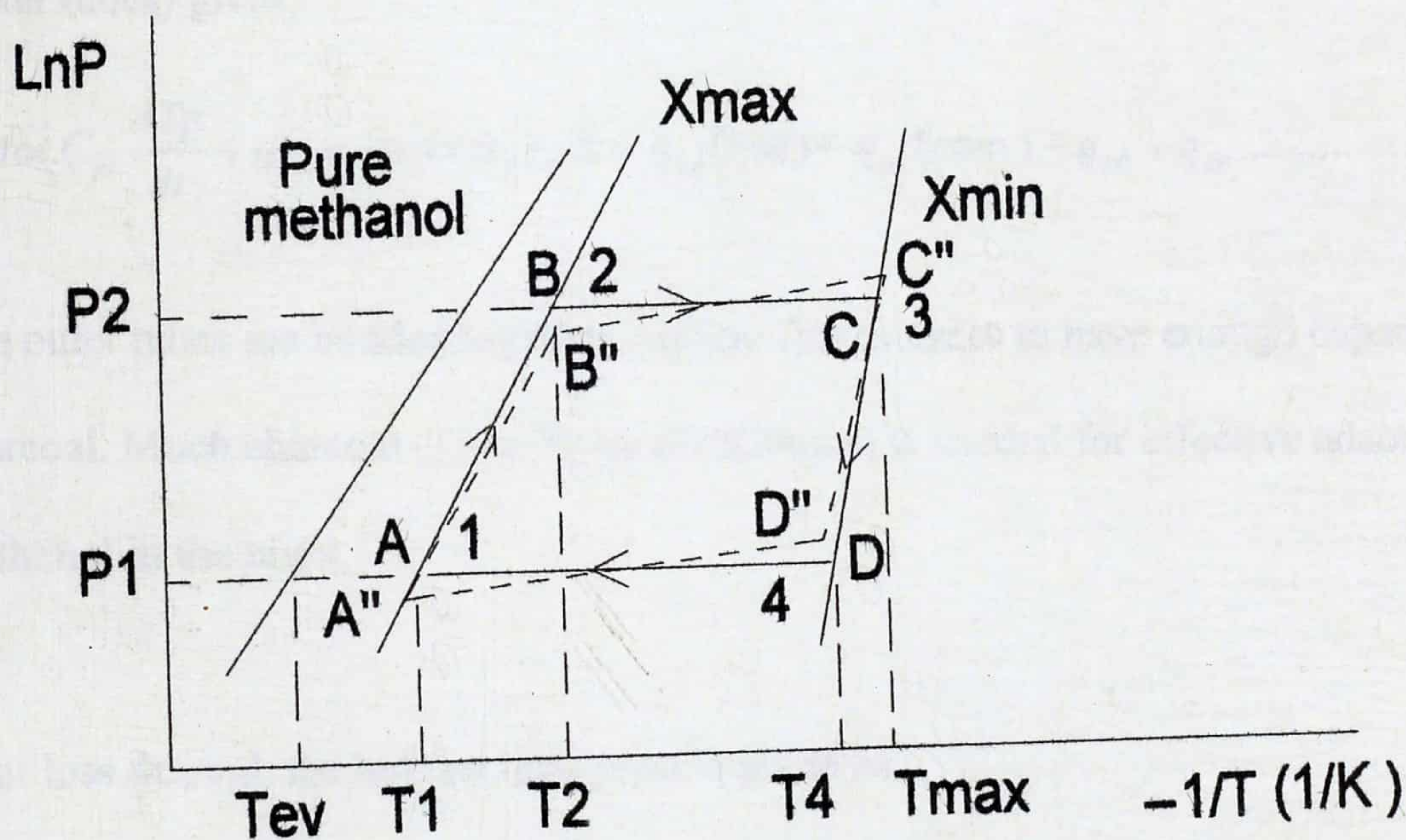


Fig. 3.4 P-T-X diagrams of an adsorption cycle of a solar refrigerator with no valves, and the ideal adsorption cycle

CHAPTER 4

SOLAR COLLECTOR DESIGN EQUATIONS

4.1 Introduction

The solar collector serves as the generator of the charcoal/methanol adsorption solar refrigerator and it contains the activated charcoal with adsorbed methanol. During daytime the solar collector converts the sun's energy to heat which is used to generate methanol vapour from the charcoal. In the night the charcoal adsorbs the methanol vapour flowing into the collector from the evaporator. The adsorption releases heat which is dissipated to the atmosphere.

4.2 Energy Balance on the Collector Plate Outer Tubes

Fig. 4.1 shows the energy flows in the solar collector. Energy balance on the collector plate (outer tubes) gives,

$$Mot.C_{pt} \frac{dT_p}{dt} + q_{pc} = Ac.(\tau.\alpha_p)_{av} I_t - q_{pg}(rad) - q_{pg}(conv) - q_{pb} - q_{pe} \dots\dots\dots 4.1$$

The outer tubes are bonded together with no fins in order to have enough capacity for charcoal. Much charcoal (15 to 30 kg for Kumasi) is needed for effective adsorption of methanol in the night.

Heat loss through the bottom insulation is given as,

$$q_{pb} = Ac \frac{k_b}{L_b} (T_p - T_b) \dots\dots\dots 4.2$$

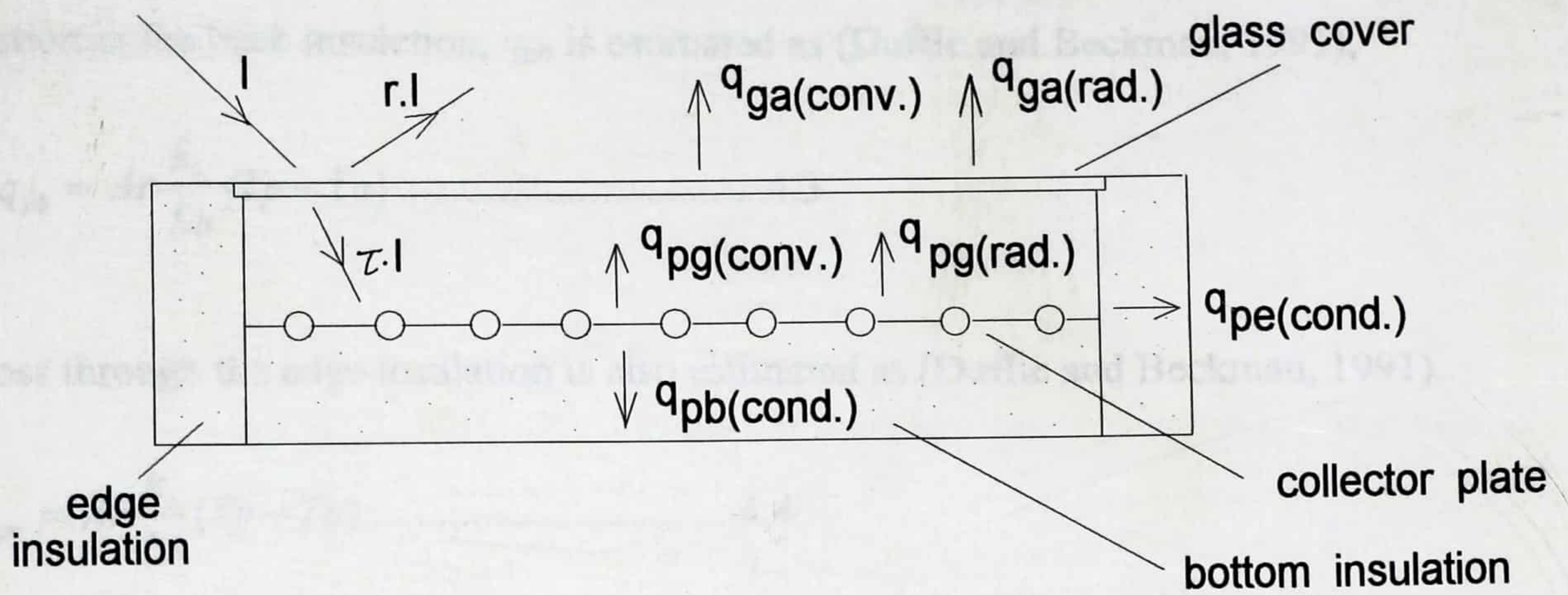


Fig. 4.1 Energy flows in flat plate solar collector

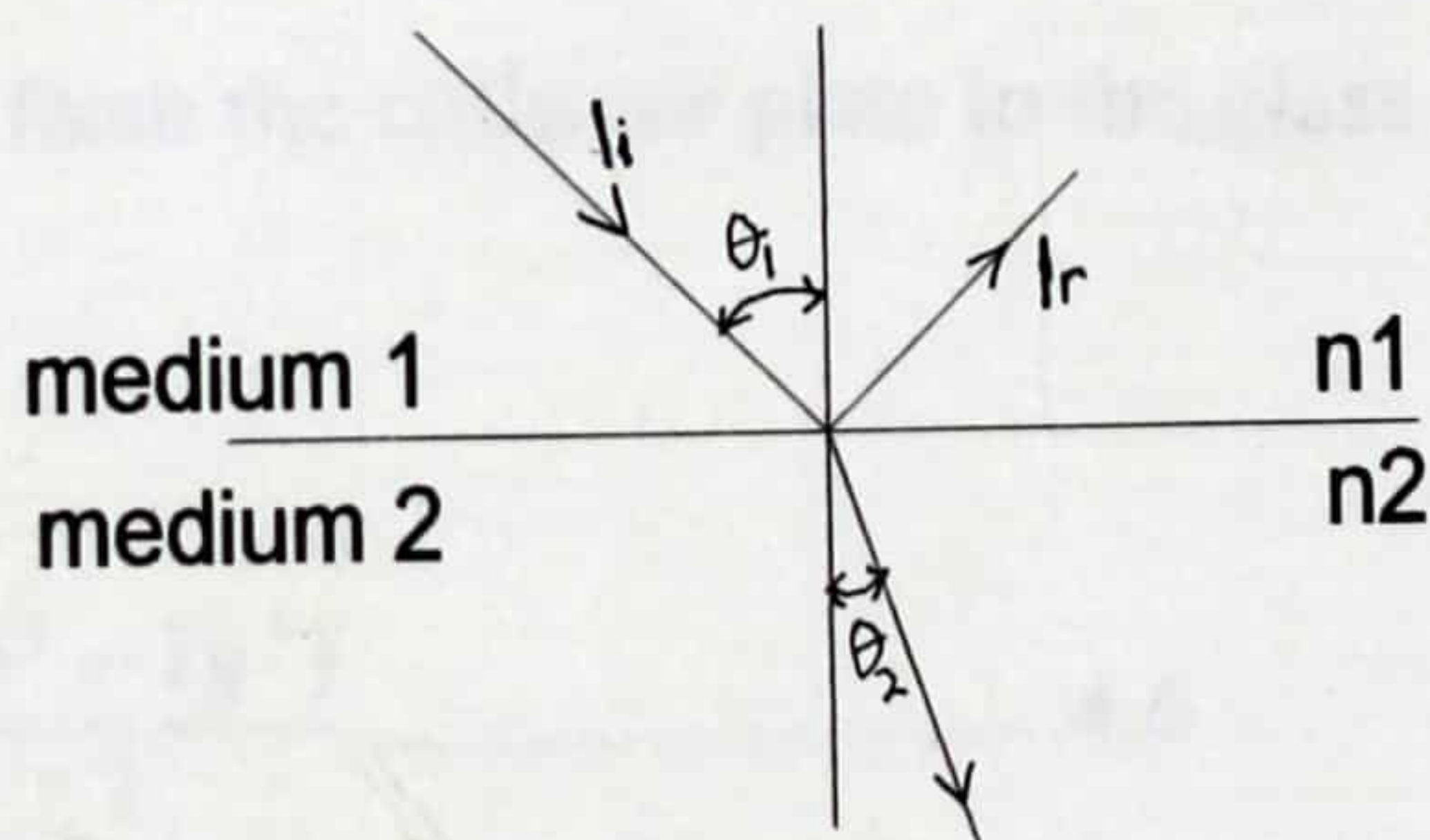


Fig. 4.2 Solar radiation passing from one medium to another

Neglecting the resistance to heat loss by convection and radiation from the bottom of the back insulation to the surroundings as it is very small compared with the resistance to conduction in the back insulation, q_{pb} is estimated as (Duffie and Beckman, 1991),

$$q_{pb} = Ac \frac{k_b}{L_b} (T_p - T_a) \dots\dots\dots 4.3$$

Heat loss through the edge insulation is also estimated as (Duffie and Beckman, 1991),

$$q_{pe} = Ae \frac{k_e}{Le} (T_p - T_a) \dots\dots\dots 4.4$$

where $Ae = Pe.he$

And,

$$q_{pe} = Ac.A \frac{k_e}{Le} (T_p - T_a) \dots\dots\dots 4.5$$

where, $A = Ae/Ac$

Heat transfer by radiation from the collector plate to the glass cover is expressed as (Duffie and Beckman, 1991),

$$q_{pg}(rad) = Ac \frac{\sigma(T_p^4 - T_g^4)}{\frac{1}{E_p} + \frac{1}{E_g} - 1} \dots\dots\dots 4.6$$

Heat loss by convection from the collector plate to the glass cover is given by,

$$q_{pg}(conv) = Ac.Nu \frac{k_1}{L_s} (T_p - T_g) \dots\dots\dots 4.7$$

In an experimental study using air, Hollands et al (1976) gave the relationship between the Nusselt number and the Rayleigh number for convective heat transfer between flat parallel plates tilted at $0-75^\circ$ to the horizontal as,

$$Nu = 1 + 1.44 \left[1 - \frac{1708(\sin 1.8\beta)^{1.6}}{Ra \cdot \cos \beta} \right] \left[1 - \frac{1708}{Ra \cdot \cos \beta} \right]^+ + \left[\left(\frac{Ra \cdot \cos \beta}{5830} \right)^{1/3} - 1 \right]^+ \dots\dots\dots 4.8$$

Where the + exponent means that only positive values of the terms in the square brackets are to be used (ie use zero if the term is negative).

$$Ra = \frac{g\beta'(Tp - Tg)Ls^3}{\nu\alpha} \dots\dots\dots 4.9$$

Properties are determined at the film temperature,

$$Tf = (Tp + Tg) / 2$$

And the volumetric thermal expansion coefficient of air is (Incropera and DeWitt, 1990),

$$\beta' = 1 / Tf$$

In the night the bottom insulation is removed and heat is dissipated through radiation and convection from the bottom of the collector plate to the ambient air.

The heat flow by radiation (from bottom of collector plate to ambient air) is estimated as,

$$q_{pa}(\text{rad}) = Et.Ac.\sigma(Tp^4 - Ta^4) \dots\dots\dots 4.10$$

The heat flow by convection (natural) is,

$$q_{pa}(\text{conv}) = Ac.h_b(Tp - Ta) \dots\dots\dots 4.11$$

If the collector plate is horizontal, h_b in Equation 4.11 is given as (Incropera and DeWitt, 1990):

$$h_b = Nu_b \frac{k}{Lpa} \dots\dots\dots 4.12$$

where,

$$Lpa = Ac/Pe$$

$$Nu_b = 0.27Ra^{1/4} \dots\dots\dots 4.13$$

$$Ra = \frac{g\beta'(Tp - Ta)Lpa^3}{\nu\alpha} \dots\dots\dots 4.14$$

Properties are determined at the film temperature,

$$Tf = \frac{Tp + Ta}{2}$$

If the collector plate is tilted at an angle β to the horizontal, h_b in Equation 4.11 is given as (Exell et al, 1993):

$$h_b = Nu_{bt} \frac{k}{L} \dots\dots\dots 4.15$$

where,

$$Nu_{bt} = 0.56(Gr Pr \cos\theta)^{1/4} \dots\dots\dots 4.16$$

$$Pr = \frac{\nu}{\alpha} \dots\dots\dots 4.17$$

$$Gr = g\beta' \frac{(Tp - Ta)L^3}{\nu^2} \dots\dots\dots 4.18$$

$$\theta = 90^\circ - \beta$$

$$\beta' = \frac{1}{Ta + 0.25(Tp - Ta)}$$

L is the length of the collector plate

Properties are determined at the film temperature given as (Exell et al, 1993),

$$T_f = T_p - 0.25(T_p - T_a)$$

If wind (forced convection) is taken into consideration h_b is given as (Duffie and Beckman, 1991),

$$h_b = Nu_{bw} \frac{k}{L_{pw}} \dots\dots\dots 4.19$$

where,

$$Nu_{bw} = 0.86 Re^{1/2} Pr^{1/3} \dots\dots\dots 4.20$$

$$Re = \frac{V.L_{pw}}{\nu} \dots\dots\dots 4.21$$

$$L_{pw} = \frac{4Ac}{Pe}$$

Properties are determined at the film temperature,

$$T_f = \frac{T_p + T_a}{2}$$

If forced convection is considered, the bigger of the forced and natural convective heat transfer coefficients should be used.

Solar radiation absorbed by the collector plate per unit area is given as (Duffie and Beckman, 1991),

$$S_p = (\tau.\alpha_p)_{av} I_t \dots\dots\dots 4.22$$

and,

$$I_t = I_b.R_b + \frac{I_d.(1 + \cos \beta)}{2} + \frac{I.\rho_g.(1 - \cos \beta)}{2} \dots\dots\dots 4.23$$

$$I = I_b + I_d \dots\dots\dots 4.24$$

$$R_b = \frac{\sin(\lambda - \beta) \sin \delta + \cos(\lambda - \beta) \cos \delta \cosh}{\sin \lambda \sin \delta + \cos \lambda \cos \delta \cosh} \dots\dots\dots 4.25$$

R_b for the hourly period is evaluated at the mid-point of the hour. Solar irradiance can be averaged for the hour and the average considered constant over the hour and assigned to the mid-point of the hour.

Equation 4.22 can be written as (Duffie and Beckman, 1991),

$$(\tau.\alpha_p)_{av}.It = I_b.R_b.(\tau.\alpha_p)_b + I_d.(\tau.\alpha_p)_d \frac{(1 + \cos \beta)}{2} + I.\rho_g.(\tau.\alpha_p)_g \frac{(1 - \cos \beta)}{2} \dots\dots\dots 4.26$$

For It data available, the average transmittance-absorptance product is approximated as (Duffie and Beckman, 1991),

$$(\tau.\alpha_p)_{av} \approx 0.96(\tau.\alpha_p)_b \dots\dots\dots 4.27$$

And for most practical solar collectors $(\tau.\alpha_p)_b$ is approximated as,

$$(\tau.\alpha_p)_b = 1.01\tau.\alpha_p \dots\dots\dots 4.28$$

The transmittance of the glass cover for solar beam radiation is given by (see Duffie and Beckman, 1991),

$$\tau = \frac{\tau_a}{2} \left[\frac{1 - rr}{1 + rr} \left(\frac{1 - rr^2}{1 - (rr.\tau_a)^2} \right) + \frac{1 - rl}{1 + rl} \left(\frac{1 - rl^2}{1 - (rl.\tau_a)^2} \right) \right] \dots\dots\dots 4.29$$

$$\tau_a = \exp \left(\frac{-K.Lg}{\cos \theta_2} \right) \dots\dots\dots 4.30$$

(K varies from 4m^{-1} for “water white” glass to approximately 32m^{-1} for poor glass)

For smooth surfaces Fresnel derived expressions for the reflection of unpolarized radiation (incident solar radiation is unpolarized or only slightly polarized) on passing from medium 1 with a refractive index n_1 to medium 2 (fig. 4.2) with a refractive index n_2 (see Duffie and Beckman, 1991):

$$rr = \frac{\sin^2(\theta_2 - \theta_1)}{\sin^2(\theta_2 + \theta_1)} \dots\dots\dots 4.31$$

$$rl = \frac{\tan^2(\theta_2 - \theta_1)}{\tan^2(\theta_2 + \theta_1)} \dots\dots\dots 4.32$$

$$r = \frac{Ir}{Ii} = \frac{1}{2}(rr + rl) \dots\dots\dots 4.33$$

Snell’s law is given as (Duffie and Beckman, 1991),

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1} \dots\dots\dots 4.34$$

For solar radiation at normal incidence both θ_1 and θ_2 are zero and r , rr , and rl are given as (Duffie and Beckman, 1991),

$$rr = rl = r(0) = \left(\frac{n_1 - n_2}{n_1 + n_2} \right)^2 \dots\dots\dots 4.35$$

If one medium is air,

$$n_1 \approx 1$$

Equation 4.35 becomes,

$$r(0) = \left(\frac{n - 1}{n + 1} \right)^2 \dots\dots\dots 4.36$$

where, $n = n_2$

For glass cover,

$$n = 1.526$$

q_{pc} (in equation 4.1) is given by Equation 4.92,

$$q_{pc} = 2\pi Ro.L.Ns.h_{pc}(Tp_f - Tc_{f6}) + 4\pi Ro.Ld.Ns.k_d \left(\frac{1 - \delta x / 2Ro}{\delta x} \right) (Tp_f - Td_{f5})$$

$\frac{dT_p}{dt}$ (in equation 4.1) is taken as,

$$\frac{dT_p}{dt} \approx \frac{\Delta T_p}{\Delta t} = \frac{T_{p_f} - T_{p_i}}{\Delta t}$$

Equation 4.1 can be written as,

$$\begin{aligned} Mot.C_{pt} \frac{(T_{p_f} - T_{p_i})}{\Delta t} = & Ac(\tau.\alpha_p)_{av} It - Ac \frac{\sigma(T_{p_f}^4 - T_{g_f}^4)}{\frac{1}{Ep} + \frac{1}{Eg} - 1} \\ & - Ac.Nu \frac{k_1}{Ls} (T_{p_f} - T_{g_f}) - Ac \frac{k_b}{Lb} (T_{p_f} - Ta) Day \\ & - Ac.A. \frac{k_e}{Le} (T_{p_f} - Ta) - [Et.Ac.\sigma(T_{p_f}^4 - Ta^4) + Ac.h_b(T_{p_f} - Ta)] Nite \\ & - 2\pi Ro.L.Ns.h_{pc}(Tp_f - Tc_{f6}) - 4\pi Ro.Ld.Ns.k_d \left(\frac{1 - \delta x / 2Ro}{\delta x} \right) (Tp_f - Td_{f5}) \end{aligned}$$

.....4.37

If the bottom insulation is removed during the night, and once it has been removed then let,

$$Day = 0, Nite = 1$$

Once the bottom insulation is in place (eg during daytime) then let,

$$Day = 1, Nite = 0$$

Let,

$$h_{pgr} = \frac{\sigma(Tp_f^2 + Tg_f^2)(Tp_f + Tg_f)}{\frac{1}{Ep} + \frac{1}{Eg} - 1}$$

$$h_{par} = \sigma(Tp_f^2 + Ta^2)(Tp_f + Ta)$$

$$P_d = -4\pi Ro.Ld.Ns.k_d \frac{(1 - \delta x / 2Ro)}{\delta x}$$

$$P_c = -2\pi Ro.L.Ns.h_{pc}$$

$$P_g = -\left(h_{pgr} + Nu \frac{k_1}{Ls}\right)Ac$$

$$PP = \left(\frac{k_b}{Lb} Day + A \frac{k_e}{Le}\right)Ac.Ta + (Et.h_{par} + h_b)Ta.Ac.Nite + Ac.Sp + Mot.C_{pt} \frac{Tl}{\Delta}$$

$$P_p = Mot \frac{C_{pt}}{\Delta t} + \left(h_{pgr} + Nu \frac{k_1}{Ls}\right)Ac + \left(\frac{k_b}{Lb} Day + A \frac{k_e}{Le}\right)Ac \\ + 2\pi Ro.Ns.\left(L.h_{pc} + 2Ld.k_d \frac{(1 - \delta x / 2Ro)}{\delta x}\right) + (Et.h_{par} + h_b)Ac.Nite$$

Then,

$$P_d.Td_{f5} + P_c.Tc_{f6} + P_p.Tp_f + P_g.Tg_f = PP \dots\dots\dots 4.38$$

4.3 Energy Balance on the Glass Cover

Energy balance on the glass cover (using Fig. 4.1) gives,

$$Mg.C_g \frac{dTg}{dt} = Ac.Sg + q_{pg}(rad) + q_{pg}(conv) - q_{ga}(rad) - q_{ga}(conv) \dots\dots\dots 4.39$$

Let,

$$\frac{dTg}{dt} \approx \frac{\Delta Tg}{\Delta t} = \frac{Tg_f - Tg_i}{\Delta t}$$

Heat loss by convection from the glass cover to the open air is,

$$q_{ga}(conv) = Ac.Nu_g \frac{k_2}{Lga} (Tg - Ta) \dots\dots\dots 4.40$$

For forced convection (laminar flow), the Nusselt number is given as (Equation 4.20),

$$Nu_g = Nu_{gw} = 0.86 Re^{1/2} Pr^{1/3} \dots\dots\dots 4.41$$

And,

$$Re = \frac{V.Lgw}{\nu}$$

$$Lga = Lgw = \frac{4Ac}{Pe}$$

For free convection, the Nusselt number is expressed as (Incropera and DeWitt 1990),

$$Nu_g = 0.54 Ra^{1/4} \quad \text{for } 10^4 \leq Ra \leq 10^7 \dots\dots\dots 4.42$$

$$Nu_g = 0.15 Ra^{1/3} \quad \text{for } 10^7 \leq Ra \leq 10^{11} \dots\dots\dots 4.43$$

$$Ra = g\beta' \frac{(Tg - Ta)Lga^3}{\nu.\alpha}$$

$$Lga = \frac{Ac}{Pe}$$

Properties are determined at the film temperature.

Radiation heat loss from glass cover to the ambient air is,

$$q_{ga}(rad) = Eg.Ac.\sigma(Tg^4 - Ts^4) \dots\dots\dots 4.44$$

The equivalent blackbody sky temperature is given as (Duffie and Beckman, 1991),

$$Ts = Ta[0.711 + 0.0056Tdp + 0.000073Tdp^2 + 0.013\cos(15t)]^{1/4} \dots\dots\dots 4.45$$

Total solar energy falling on the glass cover in an hour per unit surface area is calculated using Equation 4.23. The most common measurement of solar radiation is the hourly global radiation, I , ie the hourly total radiation falling on a horizontal surface. The hourly diffuse radiation falling on a horizontal surface, I_d , and the hourly total radiation falling on an inclined surface, I_t , if measurements are not available, are estimated using the Erbs et al correlation and Equation 4.23 respectively.

Erbs et al correlation (see Duffie and Beckman, 1991):

$$\frac{I_d}{I} = \begin{cases} 1.0 - 0.09k_T & \text{for } k_T \leq 0.22 \\ 0.9511 - 0.1604k_T + 4.388k_T^2 - 16.638k_T^3 + 12.336k_T^4 & \text{for } 0.22 < k_T \leq 0.80 \\ 0.165 & \text{for } k_T > 0.80 \end{cases} \dots\dots\dots 4.46$$

$$k_T = \frac{I}{I_o} \dots\dots\dots 4.47$$

$$I = I_b + I_d$$

$$I_o = \frac{12}{\pi} 1367 \left(1 + 0.033 \cos \left(\frac{360N}{365} \right) \right) \left[\cos \lambda \cos \delta (\sin(h_2) - \sin(h_1)) + \frac{\pi(h_2 - h_1)}{180} \sin \lambda \sin \delta \right] \dots\dots\dots 4.48$$

Solar energy absorbed by the glass cover per unit area is given by (see Duffie and Beckman, 1991),

$$S_g = I_b.R_b.\alpha_{gb} + I_d.\alpha_{gd} \left(\frac{1 + \cos \beta}{2} \right) + \rho_g.I.\alpha_{gr} \left(\frac{1 - \cos \beta}{2} \right) \dots\dots\dots 4.49$$

Absorptance of glass cover for solar beam radiation is given by (see Duffie and Beckman, 1991),

$$\alpha_{gb} = \left(\frac{1 - \tau a}{2} \right) \left\{ \frac{1 - rr}{1 - rr \cdot \tau a} + \frac{1 - rl}{1 - rl \cdot \tau a} \right\} \dots\dots\dots 4.50$$

Absorptance of glass cover for diffuse radiation and ground-reflected radiation, ie α_{gd} and α_{gr} respectively, are calculated with Equation 4.50 using the equivalent incidence angles θ_{ed} and θ_{er} (in place of θ_1) respectively which are given by (Duffie and Beckman, 1991),

$$\theta_{ed} = 59.7 - 0.1388\beta + 0.001497\beta^2 \dots\dots\dots 4.51$$

$$\theta_{er} = 90 - 0.5788 \beta + 0.002693 \beta^2 \dots\dots\dots 4.52$$

Using finite-difference approximation, Equation 4.39 can be written in the implicit finite-difference form:

$$\begin{aligned} Mg.C_g \frac{Tg_f - Tg_i}{\Delta t} = & Ac.Sg + Ac.\sigma \frac{(Tp_f^4 - Tg_f^4)}{\frac{1}{Ep} + \frac{1}{Eg} - 1} + Ac.Nu \frac{k_1}{Ls} (Tp_f - Tg_f) \\ & - Ac.Eg.\sigma(Tg_f^4 - Ts^4) - Ac.Nu_g \frac{k_2}{Lga} (Tg_f - Ta) \dots\dots\dots 4.53 \end{aligned}$$

Let,

$$h_{gar} = \sigma(Tg_f^2 + Ts^2)(Tg_f + Ts)$$

$$G_g = Mg \frac{C_g}{\Delta t} + \left(h_{pgr} + Nu \frac{k_1}{Ls} \right) Ac + \left(Eg.h_{gar} + Nu_g \frac{k_2}{Lga} \right) Ac$$

$$G_p = - \left(h_{pgr} + Nu \frac{k_1}{Ls} \right) Ac$$

$$GG = Mg.C_g \frac{Tg_i}{\Delta t} + Ac.Sg + Eg.h_{gar}.Ac.Ts + Nu_g \frac{k_2}{Lga} Ac.Ta$$

Then

$$G_p.Tp_f + G_g.Tg_f = GG \dots\dots\dots 4.54$$

4.4 Finite-Difference Solution to the Heat Equation

4.4.1 Heat Flow in the Charcoal

Heat flows in the activated charcoal, placed between the inner and outer tubes of the solar collector, fig. 4.3, are estimated by using the implicit finite-difference technique to solve the heat conduction equation (Equation 4.55).

The charcoal is divided into six finite-difference regions for the purpose of solving the heat conduction equation. The two regions adjacent to the inner tube and the outer tube have thickness $\delta x/2$ each. The rest of the five regions have thickness δx each as shown in fig. 4.4 [$\delta x < R_i$; as seen in $R_i = 6.86$ mm, $R_o = 28.5$ mm (table 8.7)].

Assumptions to simplify the heat flows in the charcoal:

1. The collector plate outer tubes have uniform temperature
2. There are no temperature gradients in the circumferential and axial directions
3. The charcoal and methanol are in local thermodynamic equilibrium
4. The vapour pressure is uniform in the charcoal
5. The heterogeneous charcoal/methanol is treated as a continuous medium
6. The specific heat of adsorbed methanol is equal to that of liquid methanol
7. Convective heat transfer in the vapour phase is neglected
8. Mass diffusion resistance in the vapour phase is neglected
9. The outer tube-inner tube-charcoal assemblies are identical

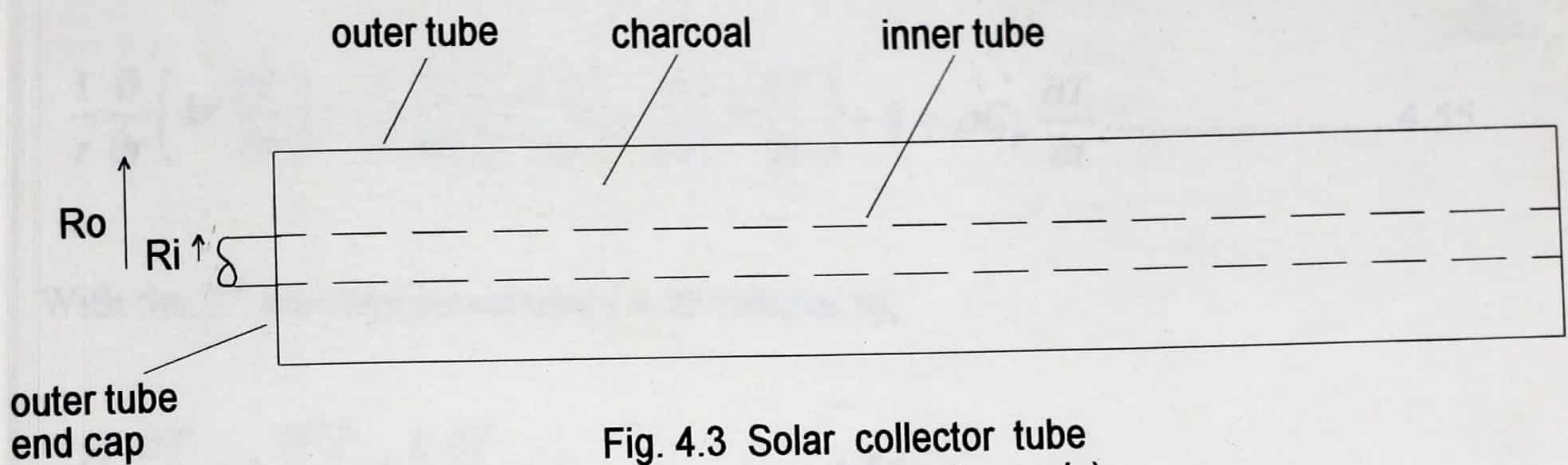


Fig. 4.3 Solar collector tube
(not drawn to scale)

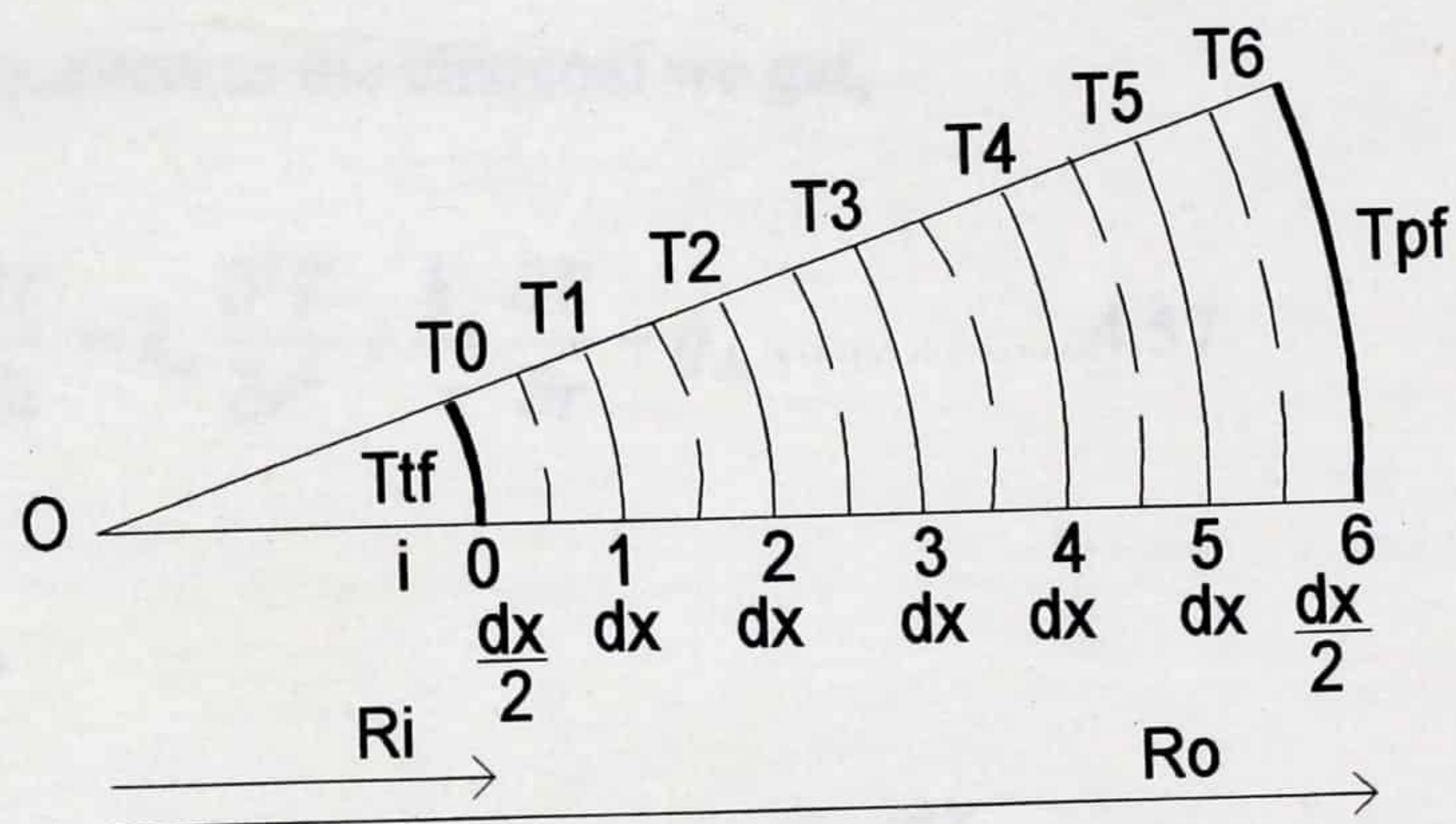


Fig. 4.4 Finite difference representation
for charcoal between two tubes

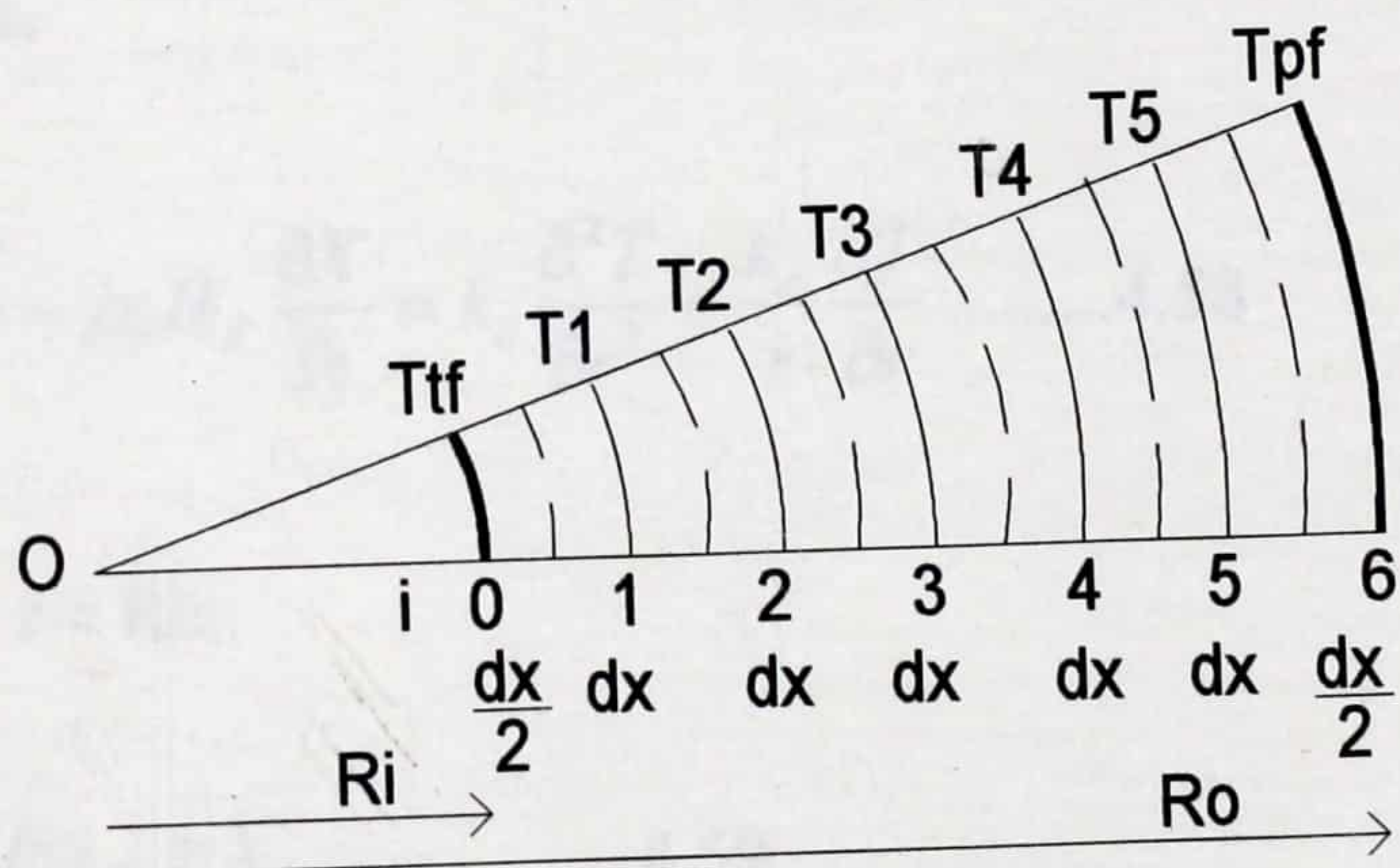


Fig. 4.5 Finite difference representation
for outer tube end cap

General heat conduction equation in cylindrical coordinates (Ozisik, 1992):

$$\frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) + \frac{1}{r^2} \frac{\partial}{\partial \phi} \left(k \frac{\partial T}{\partial \phi} \right) + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) + \dot{q} = \rho C_p \frac{\partial T}{\partial t} \dots\dots\dots 4.55$$

With the 2nd assumption equation 4.55 reduces to,

$$\rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial r^2} + \frac{k}{r} \frac{\partial T}{\partial r} + \dot{q} \dots\dots\dots 4.56$$

Applying the above equation to the charcoal we get,

$$(\rho_c C_c + \rho_c X C_m) \frac{\partial T}{\partial t} = k_c \frac{\partial^2 T}{\partial r^2} + \frac{k_c}{r} \frac{\partial T}{\partial r} + \dot{q}_{ds} \dots\dots\dots 4.57$$

where (Jing, 1992),

$$\rho C_p = \rho_c C_c + \rho_c X C_m, \quad \dot{q} = \dot{q}_{ds} = \rho_c H_d \frac{\partial X}{\partial t}$$

Equation 4.57 becomes,

$$(\rho_c C_c + \rho_c X C_m) \frac{\partial T}{\partial t} - \rho_c H_d \frac{\partial X}{\partial t} = k_c \frac{\partial^2 T}{\partial r^2} + \frac{k_c}{r} \frac{\partial T}{\partial r} \dots\dots\dots 4.58$$

Boundary condition at r = Ri:

$$-k_c \frac{dT}{dr} = h_{pc} (T_t - T_0) \dots\dots\dots 4.59$$

Boundary condition at r = Ro:

$$k_c \frac{dT}{dr} = h_{pc} (T_p - T_M) \dots\dots\dots 4.60$$

Using the finite-difference approximation the left and the right hand sides of Equation 4.58 become,

$$\begin{aligned}
 LHS &: \rho_c C_c \frac{T_i^{h+1} - T_i^h}{\Delta t} + \rho_c X_{av} C_{mi} \frac{T_i^{h+1} - T_i^h}{\Delta t} - \rho_c H_{di} \frac{X_i^{h+1} - X_i^h}{\Delta t} \\
 RHS &: k_c \frac{T_{i-1}^{h+1} - 2T_i^{h+1} + T_{i+1}^{h+1}}{\delta x^2} + \frac{k_c}{Ri + i\delta x} \frac{T_{i+1}^{h+1} - T_{i-1}^{h+1}}{2\delta x} \\
 X_{av} &= \frac{X_i^{h+1} + X_i^h}{2}
 \end{aligned}$$

Equation 4.58 becomes,

$$\begin{aligned}
 &\left(\rho_c C_c + \rho_c C_{mi} \frac{X_i^{h+1} + X_i^h}{2} \right) \frac{T_i^{h+1} - T_i^h}{\Delta t} - \rho_c H_{di} \frac{X_i^{h+1} - X_i^h}{\Delta t} \\
 &= k_c \frac{T_{i-1}^{h+1} - 2T_i^{h+1} + T_{i+1}^{h+1}}{\delta x^2} + \frac{k_c}{Ri + i\delta x} \frac{T_{i+1}^{h+1} - T_{i-1}^{h+1}}{2\delta x} \dots\dots\dots 4.61
 \end{aligned}$$

Collecting like terms, this becomes,

$$\begin{aligned}
 &-\frac{\rho_c}{2\Delta t} \left(2C_c + C_{mi} (X_i^{h+1} + X_i^h) \right) T_i^h - \frac{\rho_c H_{di}}{\Delta t} (X_i^{h+1} - X_i^h) \\
 &= k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x (Ri + i\delta x)} \right) T_{i-1}^{h+1} - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} \left(2C_c + C_{mi} (X_i^{h+1} + X_i^h) \right) \right] T_i^{h+1} \\
 &\quad + k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x (Ri + i\delta x)} \right) T_{i+1}^{h+1} \dots\dots\dots 4.62
 \end{aligned}$$

The above equation can be written as,

$$A_i T_{i-1}^{h+1} + B_i T_i^{h+1} + C_i T_{i+1}^{h+1} = Z_i \dots\dots\dots 4.63$$

where,

$$A_i = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + i\delta x)} \right)$$

$$B_i = - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{mi} (X_i^{h+1} + X_i^h)) \right]$$

$$C_i = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + i\delta x)} \right)$$

$$Z_i = - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{mi} (X_i^{h+1} + X_i^h)) T_i^h + 2H_{di} (X_i^{h+1} - X_i^h) \right]$$

for i = 1, 2, 3,, M-1

For i = 1, Equation 4.63 becomes,

$$A_1 T_0^{h+1} + B_1 T_1^{h+1} + C_1 T_2^{h+1} = Z_1 \dots\dots\dots 4.64$$

And substituting T_{c0} , T_{c1} , T_{c2} , X_{c1} and X_{c2} for T_0^{h+1} , T_1^{h+1} , T_2^{h+1} , X_1^{h+1} and X_1^h respectively and also C_{m1} , H_{d1} and $Ri + \delta x$ for C_{mi} , H_{di} and $Ri + i\delta x$ respectively,

Equations 4.64 becomes,

$$A_1 T_{c0} + B_1 T_{c1} + C_1 T_{c2} = Z_1 \dots\dots\dots 4.65$$

where,

$$A_1 = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + \delta x)} \right), \quad B_1 = - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m1} (X_{c1} + X_{c2})) \right]$$

$$C_1 = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + \delta x)} \right), \quad Z_1 = - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m1} (X_{c1} + X_{c2})) T_{c1} + 2H_{d1} (X_{c1} - X_{c2}) \right]$$

Similarly for $i = 2$, we have,

$$A_2 T_{c_{f1}} + B_2 T_{c_{f2}} + C_2 T_{c_{f3}} = Z_2 \dots\dots\dots 4.66$$

where,

$$A_2 = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + 2\delta x)} \right), \quad B_2 = - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m2}(X_{c_{f2}} + X_{c_{i2}})) \right]$$

$$C_2 = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + 2\delta x)} \right), \quad Z_2 = - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m2}(X_{c_{f2}} + X_{c_{i2}})) T_{c_{i2}} + 2H_{d2}(X_{c_{f2}} - X_{c_{i2}}) \right]$$

For $i = 3$, we have,

$$A_3 T_{c_{f2}} + B_3 T_{c_{f3}} + C_3 T_{c_{f4}} = Z_3 \dots\dots\dots 4.67$$

where,

$$A_3 = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + 3\delta x)} \right), \quad B_3 = - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m3}(X_{c_{f3}} + X_{c_{i3}})) \right]$$

$$C_3 = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + 3\delta x)} \right), \quad Z_3 = - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m3}(X_{c_{f3}} + X_{c_{i3}})) T_{c_{i3}} + 2H_{d3}(X_{c_{f3}} - X_{c_{i3}}) \right]$$

For $i = 4$, we have,

$$A_4 T_{c_{f3}} + B_4 T_{c_{f4}} + C_4 T_{c_{f5}} = Z_4 \dots\dots\dots 4.68$$

where,

$$A_4 = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + 4\delta x)} \right), \quad B_4 = - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m4}(X_{c_{f4}} + X_{c_{i4}})) \right]$$

$$C_4 = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + 4\delta x)} \right), \quad Z_4 = - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m4}(X_{c_{f4}} + X_{c_{i4}})) T_{c_{i4}} + 2H_{d4}(X_{c_{f4}} - X_{c_{i4}}) \right]$$

For $i = 5$, we have,

$$A_5 T_{c_{f4}} + B_5 T_{c_{f5}} + C_5 T_{c_{f6}} = Z_5 \dots\dots\dots 4.69$$

where,

$$\begin{aligned}
 A_5 &= k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x(Ri + 5\delta x)} \right), & B_5 &= - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m5}(X_{c_{f5}} + X_{c_{i5}})) \right] \\
 C_5 &= k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x(Ri + 5\delta x)} \right), & Z_5 &= - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m5}(X_{c_{f5}} + X_{c_{i5}}))T_{c_{i5}} + 2H_{d5}(X_{c_{f5}} - X_{c_{i5}}) \right]
 \end{aligned}$$

For i = 0, Equation 4.63 becomes,

$$A_0T_{-1}^{h+1} + B_0T_0^{h+1} + C_0T_1^{h+1} = Z_0 \dots\dots\dots4.70$$

where,

$$\begin{aligned}
 A_0 &= k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x.Ri} \right), & B_0 &= - \left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{m0}(X_0^{h+1} + X_0^h)) \right] \\
 C_0 &= k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x.Ri} \right), & Z_0 &= - \frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m0}(X_0^{h+1} + X_0^h))T_0^h + 2H_{d0}(X_0^{h+1} - X_0^h) \right]
 \end{aligned}$$

Applying finite-difference approximation to Equation 4.59 (boundary condition at r = Ri), we have,

$$k_c \frac{T_{-1}^{h+1} - T_1^{h+1}}{2\delta x} = h_{pc} (T_t^{h+1} - T_0^{h+1}) \dots\dots\dots4.71$$

T₋₁^{h+1} is considered a fictitious temperature of a fictitious node i = -1 located at a distance δx to the left of the node i = 0

Eliminating T₋₁^{h+1} from Equation 4.70 using Equation 4.71, we get,

$$A'_0T_0^{h+1} + B'_0T_0^{h+1} + C'_0T_1^{h+1} = Z'_0 \dots\dots\dots4.72$$

where,

$$\begin{aligned}
 A'_0 &= h_{pc} \left(\frac{2}{\delta x} - \frac{1}{Ri} \right), & B'_0 &= - \left[\frac{2k_c}{\delta x^2} + h_{pc} \left(\frac{2}{\delta x} - \frac{1}{Ri} \right) + \frac{\rho_c}{2\Delta t} (2C_c + C_{m0}(X_0^{h+1} + X_0^h)) \right] \\
 C'_0 &= \frac{2k_c}{\delta x^2}, & Z'_0 &= Z_0
 \end{aligned}$$

Substituting $T_{c_{f0}}$, $T_{c_{i0}}$, $T_{c_{f1}}$, T_{t_f} , $X_{c_{f0}}$ and $X_{c_{i0}}$ for T_0^{h+1} , T_0^h , T_1^{h+1} , T_1^h , X_0^{h+1} and X_0^h respectively, Equation 4.72 becomes,

$$A''_0 T_{t_f} + B''_0 T_{c_{f0}} + C''_0 T_{c_{f1}} = Z''_0 \dots\dots\dots 4.73$$

where,

$$A''_0 = A'_0, \quad B''_0 = -\left[\frac{2k_c}{\delta x^2} + h_{pc} \left(\frac{2}{\delta x} - \frac{1}{Ri} \right) + \frac{\rho_c}{2\Delta t} (2C_c + C_{m0} (X_{c_{f0}} + X_{c_{i0}})) \right]$$

$$C''_0 = C'_0, \quad Z''_0 = -\frac{\rho_c}{2\Delta t} \left[(2C_c + C_{m0} (X_{c_{f0}} + X_{c_{i0}})) T_{c_{i0}} + 2H_{d0} (X_{c_{f0}} - X_{c_{i0}}) \right]$$

For $i = M$ where $r = R_0$, ie $R_0 = Ri + M\delta x$, Equation 4.63 becomes,

$$A_M T_{M-1}^{h+1} + B_M T_M^{h+1} + C_M T_{M+1}^{h+1} = Z_M \dots\dots\dots 4.74$$

where,

$$A_M = k_c \left(\frac{1}{\delta x^2} - \frac{1}{2\delta x \cdot R_0} \right), \quad B_M = -\left[\frac{2k_c}{\delta x^2} + \frac{\rho_c}{2\Delta t} (2C_c + C_{mM} (X_M^{h+1} + X_M^h)) \right]$$

$$C_M = k_c \left(\frac{1}{\delta x^2} + \frac{1}{2\delta x \cdot R_0} \right), \quad Z_M = -\frac{\rho_c}{2\Delta t} \left[(2C_c + C_{mM} (X_M^{h+1} + X_M^h)) T_M^h + 2H_{dM} (X_M^{h+1} - X_M^h) \right]$$

Applying finite-difference approximation to Equation 4.60 (boundary condition at $r = R_0$), we have,

$$k_c \frac{T_{M+1}^{h+1} - T_{M-1}^{h+1}}{2\delta x} = h_{pc} (T_p^{h+1} - T_M^{h+1}) \dots\dots\dots 4.75$$

T_{M+1}^{h+1} is considered a fictitious temperature of a fictitious node $i = M+1$ located at a distance δx to the right of the node $i = M$

Eliminating T_{M+1}^{h+1} from Equation 4.74 using Equation 4.75, we get,

$$A'_M T_{M-1}^{h+1} + B'_M T_M^{h+1} + C'_M T_p^{h+1} = Z'_M \dots\dots\dots 4.76$$

where,

$$A'_M = \frac{2k_c}{\delta x^2}, \quad B'_M = -\left[\frac{2k_c}{\delta x^2} + h_{pc} \left(\frac{2}{\delta x} + \frac{1}{Ro} \right) + \frac{\rho_c}{2\Delta t} (2C_c + C_{mM} (X_M^{h+1} + X_M^h)) \right]$$

$$C'_M = h_{pc} \left(\frac{2}{\delta x} + \frac{1}{Ro} \right), \quad Z'_M = Z_M$$

For M = 6 and substituting Tc_{f6}, Tc_{i6}, Tc_{f5}, Tp_f, Xc_{f6} and Xc_{i6} for T_M^{h+1}, T_M^h, T_{M-1}^{h+1}, Tp^{h+1}, X_M^{h+1} and X_M^h respectively, Equation 4.76 becomes,

$$A_6 Tc_{f5} + B_6 Tc_{f6} + C_6 Tp_f = Z_6 \dots\dots\dots 4.77$$

where,

$$A_6 = \frac{2k_c}{\delta x^2}, \quad B_6 = -\left[\frac{2k_c}{\delta x^2} + h_{pc} \left(\frac{2}{\delta x} + \frac{1}{Ro} \right) + \frac{\rho_c}{2\Delta t} (2C_c + C_{m6} (Xc_{f6} + Xc_{i6})) \right]$$

$$C_6 = h_{pc} \left(\frac{2}{\delta x} + \frac{1}{Ro} \right), \quad Z_6 = -\frac{\rho_c}{2\Delta t} [(2C_c + C_{m6} (Xc_{f6} + Xc_{i6})) Tc_{i6} + 2H_{d6} (Xc_{f6} - Xc_{i6})]$$

C_{m0}, C_{m1}, C_{m2}, C_{m3}, C_{m4}, C_{m5} and C_{m6} are calculated with equation 5.1 using the average temperatures Tc_{v0}, Tc_{v1}, Tc_{v2}, Tc_{v3}, Tc_{v4}, Tc_{v5} and Tc_{v6} respectively for the period Δt. Xc_{f0}, Xc_{f1}, Xc_{f2}, Xc_{f3}, Xc_{f4}, Xc_{f5} and Xc_{f6} are calculated using equation 3.3. H_{d0}, H_{d1}, H_{d2}, H_{d3}, H_{d4}, H_{d5} and H_{d6} are the average heats of adsorption for the period Δt.

4.4.2 Heat Flow in the Outer Tube End Caps

The finite-difference representation is shown in fig. 4.5.
 For the outer tube end caps, equation 4.56 and the finite-difference form become,

$$\begin{aligned}
 k_d \frac{\partial^2 T}{\partial r^2} + \frac{k_d}{r} \frac{\partial T}{\partial r} &= \rho_d C_d \frac{\partial T}{\partial t} \\
 \rho_d C_d \frac{T_i^{h+1} - T_i^h}{\Delta t} &= k_d \frac{T_{i-1}^{h+1} - 2T_i^{h+1} + T_{i+1}^{h+1}}{\delta x^2} + \frac{k_d}{Ri + i\delta x} \frac{T_{i+1}^{h+1} - T_{i-1}^{h+1}}{2\delta x} \dots\dots\dots 4.78
 \end{aligned}$$

for i = 1, 2, 3,, N-1

Boundary conditions: At r = Ri, T₀^{h+1} = T_{t_f} , and at r = Ro, T_N^{h+1} = T_{p_f}

For i = 1 and substituting T_{d_{f1}}, T_{d_{i1}}, T_{d_{f0}} and T_{d_{f2}} for T₁^{h+1}, T₁^h, T₀^{h+1} and T₂^{h+1} respectively, Equation 4.78 becomes,

$$\rho_d C_d \frac{Td_{f1} - Td_{i1}}{\Delta t} = k_d \frac{Td_{f0} - 2Td_{f1} + Td_{f2}}{\delta x^2} + \frac{k_d}{Ri + \delta x} \frac{Td_{f2} - Td_{f0}}{2\delta x} \dots\dots\dots 4.79$$

But T_{d_{f0}} = T_{t_f} and substituting T_{t_f} for T_{d_{f0}} in Equation 4.79 we get,

$$\begin{aligned}
 &\left(\frac{k_d}{2\delta x(Ri + \delta x)} - \frac{k_d}{\delta x^2} \right) Tt_f + Z_7 Td_{f1} - \left(\frac{k_d}{2\delta x(Ri + \delta x)} + \frac{k_d}{\delta x^2} \right) Td_{f2} \\
 &= \rho_d C_d \frac{Td_{i1}}{\Delta t} \dots\dots\dots 4.80
 \end{aligned}$$

where,

$$Z_7 = \rho_d \frac{C_d}{\Delta t} + \frac{2k_d}{\delta x^2}$$

For i=2,

$$\begin{aligned}
 &\left(\frac{k_d}{2\delta x(Ri + 2\delta x)} - \frac{k_d}{\delta x^2} \right) Td_{f1} + Z_7 Td_{f2} - \left(\frac{k_d}{2\delta x(Ri + 2\delta x)} + \frac{k_d}{\delta x^2} \right) Td_{f3} \\
 &= \rho_d C_d \frac{Td_{i2}}{\Delta t} \dots\dots\dots 4.81
 \end{aligned}$$

For i=3,

$$\left(\frac{k_d}{2\delta x(Ri + 3\delta x)} - \frac{k_d}{\delta x^2} \right) Td_{f2} + Z_7 Td_{f3} - \left(\frac{k_d}{2\delta x(Ri + 3\delta x)} + \frac{k_d}{\delta x^2} \right) Td_{f4} \\ = \rho_d C_d \frac{Td_{i3}}{\Delta t} \dots\dots\dots 4.82$$

For i=4,

$$\left(\frac{k_d}{2\delta x(Ri + 4\delta x)} - \frac{k_d}{\delta x^2} \right) Td_{f3} + Z_7 Td_{f4} - \left(\frac{k_d}{2\delta x(Ri + 4\delta x)} + \frac{k_d}{\delta x^2} \right) Td_{f5} \\ = \rho_d C_d \frac{Td_{i4}}{\Delta t} \dots\dots\dots 4.83$$

For i=5, where N = 6 and $T_N^{h+1} = T_6^{h+1} = T_{pf}$,

$$Td_{f6} = T_{pf}$$

And,

$$\left(\frac{k_d}{2\delta x(Ri + 5\delta x)} - \frac{k_d}{\delta x^2} \right) Td_{f4} + Z_7 Td_{f5} - \left(\frac{k_d}{2\delta x(Ri + 5\delta x)} + \frac{k_d}{\delta x^2} \right) T_{pf} \\ = \rho_d C_d \frac{Td_{i5}}{\Delta t} \dots\dots\dots 4.84$$

4.4.3 Heat Flow from the Outer Tubes or Inner Tubes to the Charcoal and the

End Caps

Let,

$$\rho_d = \frac{m_i}{2\pi r.Ld.\delta x} \dots\dots\dots 4.85$$

where m_i is the mass of the finite-difference region of node i.

Substituting Equation 4.85 into 4.78 gives,

$$\frac{mi}{2\pi r.Ld.\delta x} C_d \frac{T_i^{h+1} - T_i^h}{\Delta t} = k_d \frac{T_{i-1}^{h+1} - 2T_i^{h+1} + T_{i+1}^{h+1}}{\delta x^2} + \frac{k_d}{Ri + i\delta x} \frac{T_{i+1}^{h+1} - T_{i-1}^{h+1}}{2\delta x}$$

..... 4.86

$$\frac{T_i^{h+1} - T_i^h}{\Delta t} = \frac{\Delta T_i}{\Delta t}$$

$$r = Ri + i\delta x$$

Equation 4.86 becomes:

$$miC_d \frac{\Delta T_i}{\Delta t} = 2\pi.r(1 + \delta x / 2r).Ld.k_d \frac{T_{i+1}^{h+1} - T_i^{h+1}}{\delta x}$$

$$+ 2\pi.r(1 - \delta x / 2r).Ld.k_d \frac{T_{i-1}^{h+1} - T_i^{h+1}}{\delta x} \dots\dots\dots 4.87$$

$$\Rightarrow -k_d \frac{dT}{dr} \Big|_{radius=r-\delta x/2} = k_d \frac{T_{i-1}^{h+1} - T_i^{h+1}}{\delta x} \dots\dots\dots 4.88$$

$$\Rightarrow k_d \frac{dT}{dr} \Big|_{radius=r+\delta x/2} = k_d \frac{T_{i+1}^{h+1} - T_i^{h+1}}{\delta x} \dots\dots\dots 4.89$$

$r(1+\delta x/2r) = r+\delta x/2$ is the effective radius at the boundary between the regions of nodes i and $i+1$

$r(1-\delta x/2r) = r -\delta x/2$ is the effective radius at the boundary between the regions of nodes i and $i-1$

Heat flow (conduction) from the region of node $i+1$ to the region of node i is then,

$$q_a = 2\pi(r + \delta x / 2).Ld.k_d \frac{T_{i+1}^{h+1} - T_i^{h+1}}{\delta x} \dots\dots\dots 4.90$$

Heat flow (conduction) from the region of node $i-1$ to the region of node i is also,

$$q_b = 2\pi(r - \delta x / 2).Ld.k_d \frac{T_{i-1}^{h+1} - T_i^{h+1}}{\delta x} \dots\dots\dots 4.91$$

Using Equations 4.60 (M=6) and 4.90, and noting that each collector outer tube has two end caps, heat flow from the outer tubes to the charcoal and the outer tube end caps is,

$$q_{pc} = 2\pi Ro.L.Ns.h_{pc}(Tp_f - Tc_{f6}) + 4\pi Ro.Ld.Ns.k_d \left(1 - \frac{\delta x}{2Ro}\right) \frac{(Tp_f - Td_{f5})}{\delta x}$$

.....4.92

Similarly, using Equations 4.59 and 4.91, heat flow from the inner tubes to the charcoal and the outer tube end caps is,

$$q_{ub} = 2\pi Ri.L.Ns.h_{pc}(Tt_f - Tc_{f0}) + 4\pi Ri.Ld.Ns.k_d \left(1 + \frac{\delta x}{2Ri}\right) \frac{(Tt_f - Td_{f1})}{\delta x}$$

.....4.93

4.5 Energy Balance on the Inner Tubes of the Collector Plate

Energy balance on the inner tubes:

$$MitC_t \frac{(Tt_f - Tt_i)}{\Delta t} = -q_{ub}$$
$$MitC_t \frac{(Tt_f - Tt_i)}{\Delta t} = 2\pi Ri.L.Ns.h_{pc}(Tc_{f0} - Tt_f) + 4\pi Ri.Ld.Ns.k_d \left(\frac{1 + \delta x / 2Ri}{\delta x}\right) (Td_{f1} - Tt_f) \dots\dots\dots 4.94$$

Let,

$$ZZ_3 = Mit \frac{C_t}{\Delta t} + 2\pi Ri.L.Ns.h_{pc} + 4\pi Ri.Ld.Ns.k_d \frac{(1 + \delta x / 2Ri)}{\delta x}$$

Then,

$$ZZ_3 Tt_f - 2\pi Ri.L.Ns.h_{pc} Tc_{f0} - 4\pi Ri.Ld.Ns.k_d \frac{(1 + \delta x / 2Ri)}{\delta x} Td_{f1} = Mit.C_t \frac{Tt_i}{\Delta t}$$

.....4.95

4.6 Solution to the Solar Collector Equations

Given the system of equations in n unknowns (Y₁,Y₂, ,Y_n):

$$\begin{aligned} a_{11}Y_1 + a_{12}Y_2 +.....+ a_{1n}Y_n &= b_1 \\ a_{21}Y_1 + a_{22}Y_2 +.....+ a_{2n}Y_n &= b_2 \\ \\ \\ a_{n1}Y_1 + a_{n2}Y_2 +.....+ a_{nn}Y_n &= b_n \end{aligned}$$

And assuming that a_{ii} ≠ 0 for all i, the above equations can be solved for Y₁, Y₂, ,Y_n numerically by using the Successive Over-Relaxation (SOR) iterative method (see Ozisik, 1992).

The SOR method is,

$$Y_i^{(k+1)} = (1 - w)Y_i^{(k)} + \frac{w}{a_{ii}} \left(b_i - \sum_{j=1}^{i-1} a_{ij}Y_j^{(k+1)} - \sum_{j=i+1}^n a_{ij}Y_j^{(k)} \right)4.96$$

where,

$$\begin{aligned} 1 < w < 2 \\ i &= 1, 2, 3,.....,n \\ k &= 0, 1, 2, 3,..... \end{aligned}$$

w is scalar and is called the relaxation parameter. When 0 < w < 1, the method is described as “under-relaxation”.

The starting point or values Y⁽⁰⁾ is arbitrary.

$$Y^{(0)} = \left(Y_1^{(0)}, Y_2^{(0)}, Y_3^{(0)},....., Y_n^{(0)} \right)^T$$

The Gauss-Seidel method is the case where w = 1, ie

$$Y_i^{(k+1)} = \frac{1}{a_{ii}} \left(b_i - \sum_{j=1}^{i-1} a_{ij}Y_j^{(k+1)} - \sum_{j=i+1}^n a_{ij}Y_j^{(k)} \right)4.97$$

Equations 4.95, 4.73, 4.65, 4.66, 4.67, 4.68, 4.69, 4.77, 4.80, 4.81, 4.82, 4.83, 4.84, 4.38 and 4.54 are solved for T_{tf} , T_{cf0} , T_{cf1} , T_{cf2} , T_{cf3} , T_{cf4} , T_{cf5} , T_{cf6} , T_{df1} , T_{df2} , T_{df3} , T_{df4} , T_{df5} , T_{pf} and T_{gf} by using the SOR iterative method. For each of the iterations, recent values of X_{cf0} , X_{cf1} ,, X_{cf5} and X_{cf6} are computed with Equation 3.3 using the recent computed values of T_{cf0} , T_{cf1} ,, T_{cf5} and T_{cf6} respectively. The starting values (initial guess values) of T_{tf} , T_{cf0} , T_{cf1} ,, T_{cf6} , T_{df1} , T_{df2} ,, T_{df5} , T_{pf} and T_{gf} and also of X_{cf0} , X_{cf1} ,, X_{cf5} and X_{cf6} for the SOR computations are taken to be the values of T_{ti} , T_{ci0} , T_{ci1} ,, T_{ci6} , T_{di1} , T_{di2} ,, T_{di5} , T_{pi} , T_{gi} , X_{ci0} , X_{ci1} ,, X_{ci5} and X_{ci6} respectively, which are known.

4.7 Solar Collector Efficiency

Let:

$$T_{mf} = 2\pi\delta x[(Ri + \delta x)T_{cf1} + (Ri + 2\delta x)T_{cf2} + (Ri + 3\delta x)T_{cf3} + (Ri + 4\delta x)T_{cf4} + (Ri + 5\delta x)T_{cf5} + 0.5(Ro - 0.25\delta x)T_{cf6} + 0.5(Ri + 0.25\delta x)T_{cf0}] / \pi(Ro^2 - Ri^2) \dots 4.98$$

$$T_{mi} = 2\pi\delta x[(Ri + \delta x)T_{ci1} + (Ri + 2\delta x)T_{ci2} + (Ri + 3\delta x)T_{ci3} + (Ri + 4\delta x)T_{ci4} + (Ri + 5\delta x)T_{ci5} + 0.5(Ro - 0.25\delta x)T_{ci6} + 0.5(Ri + 0.25\delta x)T_{ci0}] / \pi(Ro^2 - Ri^2) \dots 4.99$$

$$T_{dmf} = 2\pi\delta x[(Ri + \delta x)T_{df1} + (Ri + 2\delta x)T_{df2} + (Ri + 3\delta x)T_{df3} + (Ri + 4\delta x)T_{df4} + (Ri + 5\delta x)T_{df5} + 0.5(Ro - 0.25\delta x)T_{pf} + 0.5(Ri + 0.25\delta x)T_{tf}] / \pi(Ro^2 - Ri^2) \dots 4.100$$

$$T_{dmi} = 2\pi\delta x[(Ri + \delta x)T_{di1} + (Ri + 2\delta x)T_{di2} + (Ri + 3\delta x)T_{di3} + (Ri + 4\delta x)T_{di4} + (Ri + 5\delta x)T_{di5} + 0.5(Ro - 0.25\delta x)T_{pi} + 0.5(Ri + 0.25\delta x)T_{ti}] / \pi(Ro^2 - Ri^2) \dots 4.101$$

$$X_{mff} = 2\pi\delta x[(Ri + \delta x)X_{cf1} + (Ri + 2\delta x)X_{cf2} + (Ri + 3\delta x)X_{cf3} + (Ri + 4\delta x)X_{cf4} + (Ri + 5\delta x)X_{cf5} + 0.5(Ro - 0.25\delta x)X_{cf6} + 0.5(Ri + 0.25\delta x)X_{cf0}] / \pi(Ro^2 - Ri^2) \dots 4.102$$

$$X_{mi} = 2\pi\delta x[(Ri + \delta x)X_{c_{i1}} + (Ri + 2\delta x)X_{c_{i2}} + (Ri + 3\delta x)X_{c_{i3}} + (Ri + 4\delta x)X_{c_{i4}} + (Ri + 5\delta x)X_{c_{i5}} + 0.5(Ro - 0.25\delta x)X_{c_{i6}} + 0.5(Ri + 0.25\delta x)X_{c_{i0}}] / \pi(Ro^2 - Ri^2) \dots 4.103$$

And using Equation 3.4,

$$PO = \frac{Ps}{\exp\left[\frac{1}{T_{mf}}\left(-\frac{1}{D}\ln\left(\frac{X_{mi}}{\rho_m W_o}\right)\right)\right]^{1/n}} \dots\dots\dots 4.104$$

Ps and ρ_m are determined at temperature Tmf

Let,

$$DE1 = Mc.C_c(T_{mf} - T_{mi}) / \Delta t + Mc.C_{mm}(X_{mff} + X_{mi})(T_{mf} - T_{mi}) / 2\Delta t + Mot.C_{pt}(T_{pf} - T_{pi}) / \Delta t$$

$$DE2 = Mc.H_{dm}(X_{mi} - X_{mff}) / \Delta t + Mit.C_t(T_{tf} - T_{ti}) / \Delta t + Mdt.C_d(T_{dmf} - T_{dmi}) / \Delta t$$

Then the efficiency of the solar collector during the period Δt for $It \neq 0$ is,

$$Eff = \frac{DE1 + DE2}{It.Ac} \dots\dots\dots 4.10$$

for $Eff \geq 0$

The overall solar collector efficiency is,

$$Effcy = \frac{\sum Eff . It . Ac}{\sum It . Ac} = \frac{\sum Eff . It}{\sum It} \dots\dots\dots 4.106$$

C_m is determined at temperature $T_{mv} = (T_{mf} + T_{mi}) / 2$

H_{dm} is the average heat of adsorption for the period Δt

CHAPTER 5

CONDENSER DESIGN EQUATIONS

5.1 Introduction

The methanol (refrigerant) vapour generated in the charcoal/methanol solar collector flows to the condenser, which condenses the vapour to liquid. The heat released from the condensation is absorbed by the cooling medium around the condenser. The liquid methanol flows to or is introduced at a particular time into the evaporator.

5.2 Properties of Methanol

The following are properties of methanol given in equation form (see Jing, 1992; Reid et al, 1987):

$$C_{pl} = 3992.4 - 15.8T + 0.0364T^2 \quad \dots\dots\dots 5.1$$

$$\rho_l = 937.911 - 0.058267T - 0.001495T^2 \quad \dots\dots\dots 5.2$$

$$k_l = 0.3225 - 4.785(10^{-4})T + 1.168(10^{-7})T^2 \quad \dots\dots\dots 5.3$$

$$\ln(\mu_l) = -39.35 + 4826/T + 0.1091T - 1.127(10^{-4})T^2 \quad \dots\dots\dots 5.4$$

$$h_{fg} = 1038139.5 + 2432.9T - 6.665T^2 \quad \dots\dots\dots 5.5$$

$$k_v = -7.797(10^{-3}) + 4.167(10^{-5})T + 1.214(10^{-7})T^2 - 5.184(10^{-11})T^3 \quad \dots\dots\dots 5.6$$

$$h_v = 1134.9 + 3.295397T - 0.0038872T^2 \quad \dots\dots\dots 5.7$$

$$h_l = 95.8734 + 0.86247T + 0.0027778T^2 \quad \dots\dots\dots 5.8$$

Vapour pressure of methanol can be expressed as (Reid et al, 1987),

$$\ln(P_s/PC) = (1-x)^{-1}[-8.54796x + 0.76982x^{1.5} - 3.10850x^3 + 1.54481x^6] \quad \dots\dots\dots 5.9$$

$$x = 1 - T/T_c$$

The non-ideality of a gas (or vapour) is conveniently expressed by the compressibility factor, Z, which is given as (see Reid et al, 1987),

$$Z = \frac{P_{s.v}}{R_u.T} \dots\dots\dots 5.10$$

Cubic equation of state (Reid et al, 1987):

$$Z^3 - (1 + B - U.B).Z^2 + (A + W.B^2 - U.B - U.B^2).Z - A.B - W.B^2 - W.B^3 = 0 \dots\dots\dots 5.11$$

To get the Soave (SRK) equation from the cubic equation, we have,

$$U = 1, \quad W = 0$$

Equation 5.11 becomes,

$$Z^3 - Z^2 + (A - B - B^2).Z - A.B = 0 \dots\dots\dots 5.12$$

where,

$$A = \frac{a.P_s}{R_u^2.T^2}$$

$$B = \frac{b.P_s}{R_u.T}$$

$$a = \frac{0.42748 R_u^2 .TC^2}{PC} (1 + fw(1 - Tr^{1/2}))^2$$

$$fw = 0.48 + 1.574w - 0.176w^2$$

$$Tr = T/TC$$

$$b = \frac{0.08664 R_u .TC}{PC}$$

For methanol,

$$w = 0.556$$

$$\bar{h}D = 0.555 \left[\frac{g \cdot \rho_l \cdot (\rho_l - \rho_v) \cdot k_l^3 \cdot hfg'}{\mu_l \cdot (T_{sat} - T_I) D} \right]^{1/4} \dots\dots\dots 5.16$$

where the Reynold's number of the vapour at tube inlet is less than 35,000:

$$Re = \left(\frac{\rho_v \cdot V \cdot D}{\mu_v} \right)_i < 35000 \dots\dots\dots 5.17$$

The modified latent heat is given by (see Incropera and DeWitt, 1990),

$$hfg' = hfg + \frac{3}{8} Cpl \cdot (T_{sat} - T_I) \dots\dots\dots 5.18$$

The condensate (liquid) properties are evaluated at the film temperature,

$$T_f = T_{fm} = (T_{sat} + T_I) / 2$$

hfg is evaluated at $T = T_{sat}$

The rate of heat transfer from the condensing vapour to the condenser tube wall is,

$$q_s = \bar{h}D \cdot A_s \cdot (T_{sat} - T_I) \dots\dots\dots 5.19$$

Also,

$$q_s = \dot{m}_o \cdot hfg' \dots\dots\dots 5.20$$

And,

$$\dot{m}_o = \frac{Mc \cdot (X_{max} - X_{min})}{3600hr} \dots\dots\dots 5.21$$

$$A_s = \pi DC \cdot L_f$$

And from Equations 5.19 and 5.20 the length of the tube required for condensation is,

$$L_f = \frac{\dot{m} o . h_{fg}'}{\pi D C . \bar{h} D . (T_{sat} - T_I)} \dots\dots\dots 5.22$$

5.4 Heat Transfer from Condenser to Water Tank Walls

The condenser is immersed in a tank full of water. The heat transfer from the condenser tubes to the walls of the tank is mainly by convection, and it is approximated to that between a cylindrical body and its enclosure.

For a cylindrical body in a cubical enclosure, Warrington and Powe (1985) have given the following correlation for the Nusselt number for the heat transfer by convection, at steady state, from the cylindrical body (at a higher temperature) to the enclosure:

$$\overline{Nu}_L = 0.418 Ra^{0.239} (Lo / Ric)^{0.687} Pr^{0.00403} \dots\dots\dots 5.23$$

$$Ra = \rho^2 g \beta' (T_I - T_E) Lo^3 Cp / (\mu . k) \dots\dots\dots 5.24$$

The properties of water (ρ , β' , Cp , μ , k , and Pr above) are evaluated at the film temperature,

$$T_f = (T_I + T_E) / 2$$

The above correlation for the Nusselt number was determined by taking the inner cylindrical body and the cubical enclosure to be concentric spheres (with fluid, here water, between them) having the same volumes as that of the cylindrical body and the cubical enclosure.

$$Lo = Roc - Ric$$

And,

$$Lo > Ric$$

For concentric spheres the heat flow rate, q , and the Nusselt number are related by the expression (given by Kakac et al, 1987):

$$q = Nu.k.\pi.Do.Di \frac{TI - TE}{Roc - Ric} \dots\dots\dots 5.25$$

$$Do = 2Roc, \quad Di = 2Ric$$

Thus heat transfer by convection at steady state from the condenser tube walls to the walls of the water tank (cubical) is,

$$q_{ct} = \overline{Nu}_L.k_w.\pi Do Di \frac{TI - TE}{Roc - Ric} \dots\dots\dots 5.26$$

Let,

$$UI = \frac{\overline{Nu}_L.k_w}{Roc - Ric} \dots\dots\dots 5.27$$

5.5 Heat Transfer from Water Tank to Ambient Air

Heat is transferred from the sides, top and bottom of the water tank to the ambient air.

The tank is cubical (or nearly so) and the surfaces are assumed to have the same temperature, TE .

For free convection on a vertical surface (vertical surface of tank), Churchill and Chu have recommended the following correlation that may be applied over the entire range of Rayleigh number (see Incropera and DeWitt, 1990):

$$\overline{Nu} = \left\{ 0.825 + \frac{0.387 Ra^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{8/27}} \right\}^2 \dots\dots\dots 5.28$$

An improvement for the laminar range is given as,

$$\overline{Nu} = 0.68 + \frac{0.670 Ra^{1/4}}{[1 + (0.492 / Pr)^{9/16}]^{4/9}} \quad \text{for } 0 < Ra < 10^9$$

.....5.29

Characteristic length is,

$$L_c = s$$

And,

$$Ra = \frac{g \beta' (T_E - T_A) s^3}{\nu \alpha} \quad \text{.....5.30}$$

The convective heat transfer coefficient for the vertical surface is,

$$h_{vc} = \overline{Nu} \frac{k}{s} \quad \text{.....5.31}$$

For free convection from the bottom of a hot horizontal surface (bottom surface of tank),

McAdams suggested the correlation (see Incropera and DeWitt, 1990),

$$\overline{Nu} = 0.27 Ra^{1/4} \quad \text{for } 10^5 \leq Ra \leq 10^{10} \quad \text{.....5.32}$$

Characteristic length is,

$$L_c = A/Pe = s/4$$

And,

$$Ra = \frac{g \beta' (T_E - T_A) \left(\frac{s}{4}\right)^3}{\nu \alpha} \quad \text{.....5.33}$$

The convective heat transfer coefficient for the bottom surface is,

$$hbc = 4\overline{Nu} \frac{k}{s}5.34$$

For free convection from the top of a hot horizontal surface (top surface of tank), McAdams also suggested the following correlations:

$$\overline{Nu} = 0.54Ra^{1/4} \quad \text{for } 10^4 \leq Ra \leq 10^75.35$$

$$\overline{Nu} = 0.15Ra^{1/3} \quad \text{for } 10^7 \leq Ra \leq 10^{11}5.36$$

The characteristic length and Rayleigh number of the top horizontal surface are the same as that of the bottom horizontal surface.

The convective heat transfer coefficient for the top surface is then,

$$htc = 4\overline{Nu} \frac{k}{s}5.37$$

The properties of air are evaluated at the film temperature,

$$Tf = \frac{TE + TA}{2}$$

And the volumetric thermal expansion coefficient is given by,

$$\beta' = \frac{1}{Tf} = \frac{2}{TE + TA}$$

Heat flow by radiation from the water tank (top is covered) to the surroundings is,

$$q_{rad} = 6s^2.Etc.\sigma(TE^4 - TA^4)5.38$$

Heat flow from the water tank to the ambient air neglecting forced convection is,

$$q_{ta} = (4hvc + hbc + htc)(TE - TA)s^2 + 6s^2.Etc.\sigma(TE^4 - TA^4)5.39$$

The water tank should be shielded from the sun's rays to prevent it from being heated up. The size of the tank should be such that TE is very close to TA.

5.6 Energy Balance on Condenser Tube Walls and Water Tank Walls

Methanol vapour velocity in the condenser tube is low and the flow is assumed to be laminar.

Average temperature of methanol vapour at entry to the condenser is,

$$T_{vi} = (TC2+TC3)/2$$

The corresponding enthalpy is,

$$h_{vi} = (1134.9 + 3.295397T_{vi} - 0.0038872T_{vi}^2)10^35.40$$

Enthalpy of the methanol vapour just before condensation starts is,

$$h_{vf} = (1134.9 + 3.295397T_{sat} - 0.0038872T_{sat}^2)10^35.41$$

Heat lost by methanol vapour in the condenser tube before condensation is,

$$q = \dot{m}o(h_{vi} - h_{vf})5.42$$

For laminar flow in a circular tube of constant surface temperature, the Nusselt number for heat flow through the surface is (Incropera and DeWitt, 1990),

$$Nu_D = \frac{h}{k/D} = 3.665.4$$

The initial length of condenser tube, from entry, that will cool the methanol vapour from the initial entry temperature T_{vi} to the condensation temperature T_{sat} is given by the expression,

$$\dot{m}o(h_{vi} - h_{vf}) = \frac{3.66k_v}{DC} \pi DC \cdot L_t \cdot (TV - TI)$$

$$L_t = \frac{\dot{m}o(h_{vi} - h_{vf})}{3.66\pi k_v (TV - TI)} \dots\dots\dots 5.44$$

where,

$$TV = \frac{T_{vi} + T_{sat}}{2}$$

and,

$$k_v = -7.797(10^{-3}) + 4.167(10^{-5})TV + 1.214(10^{-7})TV^2 - 5.184(10^{-11})TV^3 \dots\dots\dots 5.45$$

The total length of condenser tube L_{ct} is related to the hypothetical sphere radius R_{ic} by,

$$\frac{\pi DC^2}{4} L_{ct} = \frac{4}{3} \pi R_{ic}^3$$

$$L_{ct} = \frac{16R_{ic}^3}{3DC^2} \quad \text{or} \quad R_{ic} = \left(\frac{3L_{ct} \cdot DC^2}{16} \right)^{1/3} \dots\dots\dots 5.46$$

For design, let,

$$L_{ct} \geq L_t + L_f \dots\dots\dots 5.47$$

The energy balance on the walls of the condenser tubes (heat storage in the walls of the condenser tubes is neglected), taking into consideration the heat storage in the water medium, is expressed by the equation,

$$\overline{Nu}_L.k_w.\pi DoDi \frac{TI - TE}{Roc - Ric} = \dot{m}o.hfg + \frac{3}{8}\dot{m}o.Cpl(Tsat - TI) + \dot{m}o(hvi - hvf) - \frac{4190(10^3)Vo}{3600HR} 2\left(\frac{TI + TE}{2} - Twi\right) \dots\dots\dots 5.48$$

Energy balance on the walls of the water tank, neglecting heat storage in the walls of the tank, is given by,

$$\overline{Nu}_L.k_w.\pi DoDi \frac{TI - TE}{Roc - Ric} = (4hvc + hbc + htc)(TE - TA)s^2 + 6s^2.Etc.\sigma(TE^4 - TA^4) \dots\dots\dots 5.49$$

With TC2 and TC3 estimated, the inequality 5.47 (noting equations 5.22, 5.44 and 5.46) and equations 5.48 and 5.49 can be solved numerically for Tsat, TI and TE. The computed values of Tsat, TI and TE are the average values for the period of the condensation. TA in equation 5.49 is taken as TAFN, ie the average atmospheric temperature during the period of the condensation.

CHAPTER 6

EVAPORATOR BOX DESIGN EQUATIONS

6.1 Introduction

A schematic diagram of the charcoal/methanol solar refrigerator is shown in fig. 6.1. Valve J is opened all the time, but if required it can be closed to isolate the solar collector from the condenser or the evaporator. Valve K is closed about sunrise, or between 6am and 7am, and opened when desorption is near completion, ie when the collector plate temperature is near maximum (2pm- 3pm for Kumasi).

Valve K is closed to prevent desorbed methanol vapour from entering the evaporator. If desorbed methanol vapour enters the evaporator it will condense and release latent heat which will add up to the heat flow to the cold chamber and thus contribute to the rise in cold chamber temperature. Condensation of methanol vapour in the evaporator, during desorption, should therefore be prevented or checked, especially if the refrigerator is being used for the storage and preservation of food.

Valve K is opened for condensed methanol (liquid methanol) to flow to the evaporator, and will remain opened in the evening and in the night for evaporated methanol (methanol vapour) to flow from the evaporator to the solar collector for adsorption to take place.

6.2 Extraction of Heat from Cold Chamber

Fig. 6.2 shows the T-s diagram of the refrigeration cycle of the charcoal/methanol solar refrigerator. The condensing temperature T_{cd} and the evaporating temperature T_{ev} are the average condensing and evaporating temperatures.

Enthalpies of liquid methanol at the temperatures T_{cd} , T_m and T_{ev} are estimated using Equation 5.8 and are given by,

$$hf_{cd} = 95,873.4 + 862.47T_{cd} + 2.7778T_{cd}^2 \dots\dots\dots 6.1$$

$$hf_m = 95,873.4 + 862.47T_m + 2.7778T_m^2 \dots\dots\dots 6.2$$

$$hf_{ev} = 95,873.4 + 862.47T_{ev} + 2.7778T_{ev}^2 \dots\dots\dots 6.3$$

Latent heat of vaporisation of methanol at temperature T_{ev} is also estimated with Equation 5.5 and is given by,

$$hf_{gev} = 1038139.5 + 2432.9T_{ev} - 6.665T_{ev}^2 \dots\dots\dots 6.4$$

Heat released by the methanol liquid in the cold chamber before evaporation starts is,

$$Q_t = m(hf_{cd} - hf_m) \dots\dots\dots 6.5$$

$$m = M_c.(X_{max} - X_{min}) \dots\dots\dots 6.6$$

If the temperature of the cold chamber is atmospheric when the condensed methanol enters the evaporator, T_m is taken as equal to T_{cd} for the calculation of hf_m (ie $hf_m = hf_{cd}$ in this case).

Refrigeration effect or net heat extracted from the cold chamber by the methanol (refrigerant) is estimated as,

$$Q_e = m.(1-y).hf_{gev} \dots\dots\dots 6.7$$

where y is given by,

$$y = \frac{hf_{cd} - hf_{ev}}{hf_{gev}} \dots\dots\dots 6.8$$

Also,

$$Q_E = m.(1-x).hf_{gev} \dots\dots\dots 6.9$$

where,

$$x = \frac{h_{fm} - h_{fev}}{h_{fgev}} \dots\dots\dots 6.10$$

Coefficient of performance is given by,

$$COP = \frac{Q_e}{3600.A_c.ITT} \dots\dots\dots 6.11$$

6.3 Heat Transfer in Evaporator Box

From the First Law of Thermodynamics we have the expression,

$$Q = dH - V.dP$$

and,

$$H = M.h$$

Applying the above equations to the control volume in fig. 6.3 we have,

$$\begin{aligned} \dot{Q}a.t + Q_t - Q_E = & \int [M_{er}.d(h_{er}) + h_{er}.d(M_{er}) + M_{cw}.d(h_{cw}) + h_{cw}.d(M_{cw}) \\ & + M_{gt}.d(h_{gt}) + h_{gt}.d(M_{gt}) + M_{gz}.d(h_{gz}) + h_{gz}.d(M_{gz}) \\ & + M_w.d(h_w) + h_w.d(M_w) + M_{ce}.d(h_{ce}) + h_{ce}.d(M_{ce}) \\ & + M_{fs}.d(h_{fs}) + h_{fs}.d(M_{fs}) + M_{fz}.d(h_{fz}) + h_{fz}.d(M_{fz}) \\ & + M_i.d(h_i) + h_i.d(M_i) + M_{eb}.d(h_{eb}) + h_{eb}.d(M_{eb}) - V.d(p)] \dots\dots\dots 6.12 \end{aligned}$$

But,

$$d(p)=0, \quad d(M_i)=0, \quad d(M_{er})=0$$

$$d(M_{eb})=0, \quad d(M_{cw})=0$$

Let,

$$M_{we} = M_w + M_{ce} \dots\dots\dots 6.13$$

$$M_{we} = \text{const.} \dots\dots\dots 6.14$$

$$\Rightarrow d(M_{we}) = d(M_w) + d(M_{ce})$$

$$\Rightarrow d(M_{we}) = 0$$

$$\therefore d(M_w) = -d(M_{ce}) \dots\dots\dots 6.15$$

Similarly,

$$d(M_{gt}) = -d(M_{gz}) \dots\dots\dots 6.16$$

$$d(M_{fs}) = -d(M_{fz}) \dots\dots\dots 6.17$$

Equation 6.12 becomes,

$$\begin{aligned} \dot{Q}_{a.t} + Q_t - Q_E = & \int [M_{er}.d(h_{er}) + M_{cw}.d(h_{cw}) + M_{gt}.d(h_{gt}) + (h_{gz} - h_{gt}).d(M_{gz}) \\ & + M_{gz}.d(h_{gz}) + M_w.d(h_w) + (h_{ce} - h_w).d(M_{ce}) \\ & + M_{ce}.d(h_{ce}) + M_{fs}.d(h_{fs}) + (h_{fz} - h_{fs}).d(M_{fz}) \\ & + M_{fz}.d(h_{fz}) + M_i.d(h_i) + M_{eb}.d(h_{eb})] \dots\dots\dots 6.18 \end{aligned}$$

For the heat transfer between the outside walls of the evaporator box and the ambient air, the

Rayleigh number is given by,

$$Ra = \frac{g\beta'(T_a - T_b)L_c^3}{\nu\alpha} \dots\dots\dots 6.19$$

The film temperature and the expansion coefficient are given by,

$$T_f = (T_a + T_b)/2$$

$$\beta' = 1/T_f$$

The characteristic length of the vertical surface of the evaporator box is,

$$Lc(vert.) = Lh$$

The characteristic length of the top or bottom horizontal surface of the evaporator box is given by,

$$Lc(hor.) = \frac{Ll.Lb}{2(Ll + Lb)}$$

The heat transfer coefficients by natural convection for the vertical, bottom horizontal, and top horizontal surfaces (outside walls) of the evaporator box are given by,

$$hvc = \overline{Nu} \frac{k}{Lh} \dots\dots\dots 6.20$$

$$hbc = \frac{2(Ll + Lb)k}{Ll.Lb} \overline{Nu} \dots\dots\dots 6.21$$

$$htc = \frac{2(Ll + Lb)k}{Ll.Lb} \overline{Nu} \dots\dots\dots 6.22$$

The average Nusselt numbers in the above equations 6.20, 6.21 and 6.22 are not the same but are given by the equations 5.28 or 5.29, 5.32, and 5.35 or 5.36 respectively.

Heat flow from the ambient air to the evaporator box is by convection and radiation and is estimated by,

$$\begin{aligned} \dot{Q}a = & [2hvc.(Ll.Lh + Lb.Lh) + hbc.Ll.Lb + htc.Ll.Lb](Ta - Tb) \\ & + Etb.\sigma(2Ll.Lh + 2Lb.Lh + 2Ll.Lb)(Ta^4 - Tb^4) \dots\dots\dots 6.23 \end{aligned}$$

For the heat balance on the outside walls of the evaporator box, we have,

$$\dot{Q}a - k.A.\frac{\partial(Ti)}{\partial s} \Big|_{ins.surf.} = Meb.Cpb.\frac{d(Tb)}{dt} \dots\dots\dots 6.24$$

where s is distance, with the positive direction in the outward direction.

$-k.A.\frac{\partial(T_i)}{\partial s}\Big|_{ins.surf.}$ is the heat flow from the outer surface of the insulation to the outside.

walls of the evaporator box

The equations of the evaporator box are simplified by assuming the following:

- 1. Heat storage by the evaporator box outside walls is neglected.
- 2. Heat storage by the insulation is neglected.
- 3. The inner surface of the evaporator box outside walls and the outer surface of the insulation, which are in contact, have the same temperature.
- 4. The outer surface of the evaporator box inside walls and the inner surface of the insulation, which are in contact, have the same temperature.
- 5. Heat flow through the evaporator box insulation is estimated by taking the outside and inside walls of the evaporator box to be concentric spheres (with the insulation between them) having the same volumes as the volumes enclosed by the outside and inside walls of the evaporator box.

Equation 6.24 becomes,

$$\dot{Q}_a = k.A.\frac{dT_i}{ds}6.25$$

And, using equation 5.25,

$$\dot{Q}_a = k.A.\frac{dT_i}{ds} = \pi.ki.Dov.Div.\frac{(T_b - T_{ch})}{Rov - Riv} \dots\dots\dots 6.26$$

$$Rov = \left(\frac{3}{4\pi} . Ll.Lb.Lh \right)^{1/3}$$

$$Riv = \left(\frac{3}{4\pi} . Lli.Lbi.Lhi \right)^{1/3}$$

where,

$$Dov = 2Rov$$

$$Div = 2Riv$$

Equation 6.18 also becomes,

$$\begin{aligned} \dot{Q}_a.t + Q_t - Q_E = & \int [Mer.d(her) + Mcw.d(hcw) + Mgt.d(hgt) + (hgz - hgt).d(Mgz) \\ & + Mgz.d(hgz) + Mw.d(hw) + (hce - hw).d(Mce) + Mce.d(hce) \\ & + Mfs.d(hfs) + (hfz - hfs).d(Mfz) + Mfz.d(hfz)] \dots\dots\dots 6.27 \end{aligned}$$

Equations 6.27 and 6.26 can be written as,

$$\begin{aligned} & t.\pi.ki.Dov.Div.\frac{(T_b - T_{ch})}{Rov - Riv} + m(hfcd - hfm) - m(1 - x).hfgev \\ = & \int [Mer.d(her) + Mcw.d(hcw) + Mgt.d(hgt) + (hgz - hgt).d(Mgz) \\ & + Mgz.d(hgz) + Mw.d(hw) + (hce - hw).d(Mce) + Mce.d(hce) \\ & + Mfs.d(hfs) + (hfz - hfs).d(Mfz) + Mfz.d(hfz)] \dots\dots\dots 6.28 \end{aligned}$$

And,

$$\begin{aligned} & \pi.ki.Dov.Div.\frac{(T_b - T_{ch})}{Rov - Riv} \\ = & [2hvc.(Ll.Lh + Lb.Lh) + hbc.Ll.Lb + htc.Ll.Lb](Ta - Tb) \\ & + Etb.\sigma(2Ll.Lh + 2Lb.Lh + 2Ll.Lb)(Ta^4 - Tb^4) \dots\dots\dots 6.29 \end{aligned}$$

6.4 Short-term Storage of Vegetables or Fruits

The evaporation process occurs during the night. It is assumed that fresh vegetables or fruits are introduced into the cold chamber at about the time the main evaporation process starts, ie about 6pm in Kumasi.

In the first day of operation of the refrigerator, or whenever the cold chamber temperature is atmospheric when the condensed methanol enters the evaporator, T_m is taken as equal to T_{cd} .

During the evaporation process and for vegetables or fruits storage, Equation 6.28 becomes,

$$t.\pi.ki.Dov.Div.\frac{(Tb - Tch)}{Rov - Riv} - m(1 - x).hfgev$$
$$= \int [Mer.d(her) + Mcw.d(hcw) + Mgt.d(hgt) + (hgz - hgt).d(Mgz) + Mgz.d(hgz)] \dots\dots 6.30$$

where,

$$Qt = 0$$

$$Mw = Mce = Mfs = Mfz = 0$$

For the period of the evaporation process, let,

$$Ta = Tan$$

$$Tb = Tbn$$

$$Tch = Tchn$$

$$t = t_1$$

And for short-term storage of vegetables or fruits, the storage temperatures are above freezing.

Thus,

$$Mgz = 0$$

Also, from thermodynamics,

$$dh = Cp.dT$$

Equation 6.30 becomes,

$$t_1.\pi.ki.Dov.Div.\frac{(Tbn - Tchn)}{Rov - Riv} - m(1 - x).hfgev$$

$$= \int_{Te1}^{Te2} Mer.Cper.dT + \int_{Tc1}^{Tc2} Mcw.Cpw.dT + \int_{Tg1}^{Tg2} Mgt.Cpgt.dT$$

$$t_1.\pi.ki.Dov.Div.\frac{(Tbn - Tchn)}{Rov - Riv} - m(1 - x).hfgev$$

$$= Mer.Cper.(Te2 - Te1) + Mcw.Cpcw.(Tc2 - Tc1) + Mgt.Cpgt.(Tg2 - Tg1)6.31$$

$$Te2 \leq Tc2$$

Let,

$$Te1 = Tc1 = Tm1$$

If the temperature of the cold chamber is atmospheric when condensed methanol enters the evaporator, then let,

$$Te1 = Tc1 = Tai \quad (\text{here } Tm1 = Tai)$$

For the final temperatures, let,

$$Te2 = Tg2 = Tc2 = Tm2$$

For fresh supply of vegetables or fruits placed in the cold chamber, let,

$$T_{g1} = T_{ai}$$

For vegetables or fruits already in the cold chamber and cooled the previous night,

let,

$$T_{g1} = T_{m1} = T_{m4}$$

(For T_{m4} see Equations 6.37 and 6.38; for $T_{m1} = T_{m4}$, see end of the section)

Equation 6.31 can be written in the form,

$$\begin{aligned} & t_1 \cdot \pi \cdot k_i \cdot D_{ov} \cdot Div. \frac{(T_{bn} - T_{chn})}{R_{ov} - R_{iv}} - m(1 - x) \cdot h_{fgev} \\ &= Mer \cdot C_{per} \cdot (T_{e2} - T_{e1}) + M_{cw} \cdot C_{pcw} \cdot (T_{c2} - T_{c1}) \\ &+ M_{gtf} \cdot C_{pgt} \cdot (T_{g2} - T_{ai}) + M_{gtc} \cdot C_{pgt} \cdot (T_{g2} - T_{m1}) \dots\dots\dots 6.32 \end{aligned}$$

where,

$$M_{gt} = M_{gtf} + M_{gtc}$$

Letting,

$$T_{chn} = \frac{T_{c2} + T_{c1}}{2}$$

Equation 6.29 becomes,

$$\begin{aligned} & \pi \cdot k_i \cdot D_{ov} \cdot Div. \frac{(T_{bn} - T_{chn})}{R_{ov} - R_{iv}} \\ &= [2h_{vc} \cdot (L_l \cdot L_h + L_b \cdot L_h) + h_{bc} \cdot L_l \cdot L_b + h_{tc} \cdot L_l \cdot L_b] (T_{an} - T_{bn}) \\ &+ E_{tb} \cdot \sigma (2L_l \cdot L_h + 2L_b \cdot L_h + 2L_l \cdot L_b) (T_{an}^4 - T_{bn}^4) \dots\dots\dots 6.33 \end{aligned}$$

The mass of the evaporator, Mer , and that of the walls of the cold chamber, M_{cw} , are to be estimated.

With T_{m2} chosen, eg $T_{m2} = 0^\circ \text{C}$, and T_{m1} ($T_{m1} = T_{ai}$ or $T_{m1} = T_{m4}$) and T_{g1} known,

Equation 6.31 (or Equation 6.32) and Equation 6.33 can be solved for T_{bn} and M_{gt} or M_{gtf} (M_{gtc} known).

T_{cd} , T_{ev} and X_{min} (computed from the computer simulation programme), m , T_m ($T_m = T_{cd}$ or $T_m = T_{m4}$) and hence Q_E (Equation 6.9) are known or can be calculated.

For the period, during the day, after the evaporation process and before the condensed methanol enters or is introduced into the evaporator, Equations 6.28 and 6.29 become simplified as follows:

Equation 6.28 becomes,

$$t_2 \cdot \pi \cdot k_i \cdot D_{ov} \cdot Div. \frac{(T_{bd1} - T_{ch1})}{R_{ov} - R_{iv}} = \int_{T_{m2}}^{T_{e3}} M_{er} \cdot C_{per} \cdot dT + \int_{T_{m2}}^{T_{c3}} M_{cw} \cdot C_{pcw} \cdot dT + \int_{T_{m2}}^{T_{g3}} M_{gt} \cdot C_{pgt} \cdot dT \dots\dots\dots 6.34$$

Letting,

$$T_{e3} = T_{c3} = T_{g3} = T_{m3}$$

Equation 6.34 becomes,

$$t_2 \cdot \pi \cdot k_i \cdot D_{ov} \cdot Div. \frac{(T_{bd1} - T_{ch1})}{R_{ov} - R_{iv}} = (M_{er} \cdot C_{per} + M_{cw} \cdot C_{pcw} + M_{gt} \cdot C_{pgt})(T_{m3} - T_{m2}) \dots\dots\dots 6.35$$

Equation 6.29 also becomes,

$$\pi \cdot k_i \cdot D_{ov} \cdot Div. \frac{(T_{bd1} - T_{ch1})}{R_{ov} - R_{iv}} = [2h_{vc} \cdot (L_l \cdot L_h + L_b \cdot L_h) + h_{bc} \cdot L_l \cdot L_b + h_{tc} \cdot L_l \cdot L_b](T_{ad1} - T_{bd1}) + E_{tb} \cdot \sigma (2L_l \cdot L_h + 2L_b \cdot L_h + 2L_l \cdot L_b)(T_{ad1}^4 - T_{bd1}^4) \dots\dots\dots 6.36$$

where,

$$T_a = T_{ad1}, \quad T_b = T_{bd1}, \quad T_{ch} = T_{ch1}, \quad t = t_2$$

Let,

$$T_{ch1} = \frac{T_{m3} + T_{c2}}{2} = \frac{T_{m3} + T_{m2}}{2}$$

The above Equations 6.35 and 6.36, with Mgt and the initial temperature Tm2 known, can be solved for Tbd1 and Tm3.

For the period when the condensed methanol is introduced into the evaporator and just before evaporation begins, Equations 6.28 and 6.29 become simplified as follows:

Equation 6.28 becomes,

$$\begin{aligned} & t_3 \cdot \pi \cdot ki \cdot Dov \cdot Div \cdot \frac{(T_{bd2} - T_{ch2})}{R_{ov} - R_{iv}} + m(h_{fcd} - h_{fm}) \\ &= \int_{T_{m3}}^{T_{e4}} Mer \cdot C_{per} \cdot dT + \int_{T_{m3}}^{T_{c4}} Mcw \cdot C_{pcw} \cdot dT + \int_{T_{m3}}^{T_{g4}} Mgt \cdot C_{pgt} \cdot dT \dots\dots\dots 6.37 \end{aligned}$$

Letting,

$$T_{e4} = T_{c4} = T_{g4} = T_{m4}$$

the above equation becomes,

$$\begin{aligned} & t_3 \cdot \pi \cdot ki \cdot Dov \cdot Div \cdot \frac{(T_{bd2} - T_{ch2})}{R_{ov} - R_{iv}} + m(h_{fcd} - h_{fm}) \\ &= (Mer \cdot C_{per} + Mcw \cdot C_{pcw} + Mgt \cdot C_{pgt})(T_{m4} - T_{m3}) \dots\dots\dots 6.38 \end{aligned}$$

Equation 6.29 also becomes,

$$\pi.ki.Dov.Div.\frac{(Tbd2 - Tch2)}{Rov - Riv}$$

$$= [2hvc.(Ll.Lh + Lb.Lh) + hbc.Ll.Lb + htc.Ll.Lb](Tad2 - Tbd2)$$

$$+ Etb.\sigma(2Ll.Lh + 2Lb.Lh + 2Ll.Lb)(Tad2^4 - Tbd2^4)6.39$$

where,

$$Ta = Tad2, \quad Tch = Tch2, \quad Tb = Tbd2, \quad t = t_3$$

Also let,

$$Tch2 = \frac{Tm4 + Tm3}{2}, \quad Tm = Tm4, \quad Tm1 = Tm4$$

Equations 6.38 and 6.39 can be solved for Tbd2 and Tm4, with Mgt and the initial temperature Tm3 known.

[t₁ is estimated from the results obtained when the simulation programme is run; and t₂ and t₃ are estimated from the same results and how valve K is operated].

6.5 Ice Production

When water is placed in the cold chamber at about 6pm or sunset, ice can be produced from the water in the night during the evaporation process. The ice is to be removed from the cold chamber in the morning at about sunrise.

For ice production Equation 6.28 becomes simplified as,

$$t.\pi.ki.Dov.Div.\frac{(Tb - Tch)}{Rov - Riv} - m(1 - y).hfgev$$

$$= Mer.Cper(Te2 - Te1) + Mcw.Cpcw(Tc2 - Tc1) + Mw.Cpw(Tw2 - Tw1)$$

$$+ Mce.(hce1 - hw2) + Mce.(hce2 - hce1)6.40$$

where,

$$M_{gt} = M_{gz} = 0$$

$$M_{fs} = M_{fz} = 0$$

Also,

$$T_{w1} = T_{ai}$$

$$T_{w2} \equiv 0^{\circ}\text{C} \equiv 273.15\text{ K}$$

$$h_{ce1} - h_{w2} = -333500$$

(333.5 kJ/kg is the latent heat of fusion of water at 0°C)

Let,

$$T_{e1} = T_{c1} = T_{ai}$$

and,

$$t = t_1, \quad T_a = T_{an}, \quad T_b = T_{bn}, \quad T_{ch} = T_{chn}$$

For maximum amount of ice to be produced, ie for water to be changed to ice which at sunrise after the evaporation process is to have a temperature of 0°C, Equation 6.40 becomes,

$$\begin{aligned} & t_1 \cdot \pi \cdot k_i \cdot \text{Dov} \cdot \text{Div} \cdot \frac{(T_{bn} - T_{chn})}{R_{ov} - R_{iv}} - m(1 - y) \cdot h_{fgev} \\ & = M_{er} \cdot C_{per}(T_{e2} - T_{ai}) + M_{cw} \cdot C_{pcw}(T_{c2} - T_{ai}) + M_{ce} \cdot C_{pw}(T_{w2} - T_{ai}) - 333500 M_{ce} \end{aligned}$$

.....6.41

where,

$$M_w = M_{ce}$$

$$h_{ce2} - h_{ce1} = 0$$

Let,

$$T_{chn} = \frac{T_{c2} + T_{c1}}{2} = \frac{T_{c2} + T_{ai}}{2}$$

and,

$$T_{e2} = T_{c2} \equiv 0^{\circ} \text{C} \equiv 273.15 \text{ K}$$

Equation 6.29 also becomes,

$$\begin{aligned} & \pi.ki.Dov.Div. \frac{(T_{bn} - T_{chn})}{Rov - Riv} \\ &= [2hvc.(Ll.Lh + Lb.Lh) + hbc.Ll.Lb + htc.Ll.Lb](Tan - Tbn) \\ &+ Etb.\sigma(2Ll.Lh + 2Lb.Lh + 2Ll.Lb)(Tan^4 - Tbn^4) \dots\dots\dots 6.42 \end{aligned}$$

Equations 6.42 and 6.41 can be solved for T_{bn} and M_{ce} (or M_w). The masses M_{er} and M_{cw} are to be estimated.

6.6 Storage of Fresh Fish

For the preservation of fresh fish overnight in the cold chamber, Equation 6.28 becomes,

$$\begin{aligned} & t_1.\pi.ki.Dov.Div. \frac{(T_{bn} - T_{chn})}{Rov - Riv} - m(1 - y).hf_{gev} \\ &= M_{er}.C_{per}(T_{e2} - T_{e1}) + M_{cw}.C_{pcw}(T_{c2} - T_{c1}) + M_{fs}.C_{pfs}(T_{f2} - T_{f1}) \\ &+ M_{fz}.(hf_{z1} - hf_{s2}) + M_{fz}.(hf_{z2} - hf_{z1}) \dots\dots\dots 6.43 \end{aligned}$$

where,

$$M_{gt} = M_{gz} = 0$$

$$M_w = M_{ce} = 0$$

and,

$$t = t_1, \quad T_b = T_{bn}, \quad T_{ch} = T_{chn}$$

Let,

$$T_{e1} = T_{c1} = T_{f1} = T_{ai}$$

$$T_{f2} \equiv -2^{\circ}\text{C} \equiv 271.15\text{ K}$$

and,

$$h_{fz1} - h_{fs2} = -276000$$

(Latent heat of fish at the freezing point (-2°C) is 276 kJ/kg)

For maximum amount of fish to be frozen, ie for fish to be frozen whose temperature at sunrise after the evaporation process is to be -2°C , Equation 6.43 becomes,

$$\begin{aligned} & t_1 . \pi . k_i . D_{ov} . Div . \frac{(T_{bn} - T_{chn})}{R_{ov} - R_{iv}} - m(1 - y) . h_{fgev} \\ & = M_{er} . C_{per}(T_{e2} - T_{ai}) + M_{cw} . C_{pcw}(T_{c2} - T_{ai}) + M_{fz} . C_{pfs}(T_{f2} - T_{ai}) - 276000 M_{fz} \\ & \dots\dots\dots 6.44 \end{aligned}$$

where,

$$M_{fs} = M_{fz}$$

$$h_{fz2} - h_{fz1} = 0$$

Let,

$$T_{e2} = T_{c2} \equiv -2^{\circ}\text{C} \equiv 271.15\text{ K}$$

$$T_a = T_{an}$$

and,

$$T_{chn} = \frac{T_{c2} + T_{c1}}{2} = \frac{T_{c2} + T_{ai}}{2}$$

Equation 6.29 also becomes,

$$\pi.ki.Dov.Div.\frac{(Tbn - Tchn)}{Rov - Riv}$$

$$= [2hvc.(Ll.Lh + Lb.Lh) + hbc.Ll.Lb + htc.Ll.Lb](Tan - Tbn)$$

$$+ Etb.\sigma(2Ll.Lh + 2Lb.Lh + 2Ll.Lb)(Tan^4 - Tbn^4) \dots\dots\dots 6.45$$

Equations 6.45 and 6.44 can be solved for Tbn and Mfz (or Mfs). The masses Mer and Mcw are to be estimated.

Fish, especially fish caught in the afternoon, can be preserved overnight by storing it in the cold chamber. The fish can then be processed or marketed the following morning.

If fish is to be stored in the cold chamber for 24 hours or more, then ice could be produced first in enough quantities in the cold chamber and used to maintain the temperature of the fish below freezing especially during daytime. Appropriate equations can be derived, making use of Equations 6.28 and 6.29.

It is to be noted that very low temperatures are required to store fish over a long period of time (eg -12.2°C for 4 to 6 months) and these temperatures might not be obtained in the cold chamber, or the cold chamber temperatures might not remain that very low over 24 hours or over a longer period of time.

CHAPTER 7

SIMULATION/DESIGN PROGRAMMES

7.1 Collector Simulation Programme

7.1.1 Introduction

The collector simulation programme is a computer programme, which incorporates the condenser design programme. The simulation programme simulates the solar collector temperatures, the methanol concentrations and the pressures in the collector plate. The programme also computes the average condensing temperature and pressure, the average evaporating temperature and pressure, the hourly collector efficiencies, the overall collector efficiency and the COP of the refrigerator. The programme can be used for the design of the solar collector as well as the condenser. The flow chart of the simulation programme is shown in fig. 7.1.

The collector simulation programme (attached to the report) was written and compiled by the author of this thesis and it is written in BASIC.

7.1.2 Input File

An input file (for the collector simulation programme) is created for the hourly values of the following for the 24 hours of the day: time, Tim; hour angles H1, H2, HH; global radiation (ie insolation) I or JJ; velocity V; and atmospheric temperature Ta.

7.1.3 Simulation Programme Initial Computations

The values of the following are constants and are fixed in the simulation programme:

σ , g, α_p , E_p , E_g , E_t , Etc, Δt (Dt), ρ_c , ρ_d , k_c , k_t , k_d , h_{pc} , C_{pt} , C_t , C_c , C_g , C_d , W_o , n, D, π , Ru,

M, K (or KG), w (or WRS).

When the simulation programme is run the following are entered:

- (i) Month
- (ii) Latitude and angle of tilt of collector: λ , β (all in degrees)
- (iii) The day of the year, declination, average atmospheric temperature during desorption/condensation, and average dew point temperature: NN, GGA(degrees), TAFN (K), Tdp (°C)
- (iv) Dimensions of solar collector and collector plate, thickness of outer tube end cap, thickness of glass cover, number of outer tubes, inside radius of outer tube, outside radius of inner tube, masses of collector tubes, mass of charcoal, mass of glass cover (excluding the frame) and thermal conductivity of bottom insulation of collector: L, LW, LB, LE, LS, LD, LG, Ns, Ro, Ri, Mot, Mit, Mdt, Mc, Mg, k_b ($k_b=k_e$).
(How Mot, Mit, Mdt, Mc and Mg are estimated are shown in appendix C)
- (v) Diameters and lengths of condenser tubes and size of water tank:
DCY (ins.), DRI (ins.), LCI (m), LRI (m), S (m).
- (vi) Values of initial methanol concentrations (ie at state 1 of fig. 3.3):
 $X_{c_{i0}}, X_{c_{i1}}, X_{c_{i2}}, X_{c_{i3}}, X_{c_{i4}}, X_{c_{i5}}, X_{c_{i6}}$.
- (vii) Initial time (usually 6am for Kumasi) and atmospheric temperature (ie at state 1 of fig. 3.3); and initial charcoal temperatures, collector tubes temperatures, and glass cover temperature (ie all at state 1): Tim, Ta, $T_{c_{i0}}, T_{c_{i1}}, T_{c_{i2}}, T_{c_{i3}}, T_{c_{i4}}, T_{c_{i5}}, T_{c_{i6}}, T_{d_{i1}}, T_{d_{i2}}, T_{d_{i3}}, T_{d_{i4}}, T_{d_{i5}}, T_t, T_p, T_g$.

For the closed adsorption cycle, if the removable bottom insulation of the solar collector is removed at night to facilitate heat dissipation, the initial temperatures of the collector tubes and the charcoal, and also TC1, will be close to the initial atmospheric temperature.

The simulation programme estimates the average evaporating pressure $P1$ using TC1, X_{mi} and the Equations 5.2, 5.9 and 3.4, and also estimates the average condensing pressure $P2$ using T_{cd} (initially estimated from TAFN) and Equation 5.9. The average evaporating temperature T_{ev} is also estimated by iteration using $P1$ and Equation 5.9.

The simulation programme reads records from the input file. For each set of records read, ie the hour values of T_{im} , $H1$, $H2$, HH , JJ , V and TA , computations are made before the next set of records (ie the next hour values of the input file) are read. The solar energy absorbed by the collector plate and the glass cover, ie S_p and S_g , Equations 4.22 and 4.50 respectively, are calculated; the properties of air k , α , Pr , β' , and ν at the various film temperatures are estimated by interpolation using air properties data in the programme; the Nusselt numbers Nu , Nu_b , Nu_{bw} , Nu_{bt} , Nu_g and Nu_{gw} are also calculated; the collector temperatures $T_{c_{f0}}$, $T_{c_{f1}}$,, $T_{c_{f6}}$, $T_{d_{f1}}$, $T_{d_{f2}}$,, $T_{d_{f5}}$, T_{p_f} , T_{t_f} , and T_{g_f} with the methanol concentrations $X_{c_{f0}}$, $X_{c_{f1}}$,, $X_{c_{f5}}$ and $X_{c_{f6}}$ and the heats of adsorption H_{dm0} , H_{dm1} ,, H_{dm5} and H_{dm6} are computed using the SOR method (see chapter 4); the methanol vapour pressure, P , the average temperatures T_{mf} and T_{dmf} , and the methanol concentration, X_{mff} , are computed; and the solar collector efficiency for the hour, Eff , is also computed. The computed temperatures and concentrations for the end of the hour become the initial temperatures and concentrations for the next hour computations. The vapour pressure P_O is calculated at each of the hour computations.

The simulation programme starts the hourly computations from state 1 (6am for Kumasi)

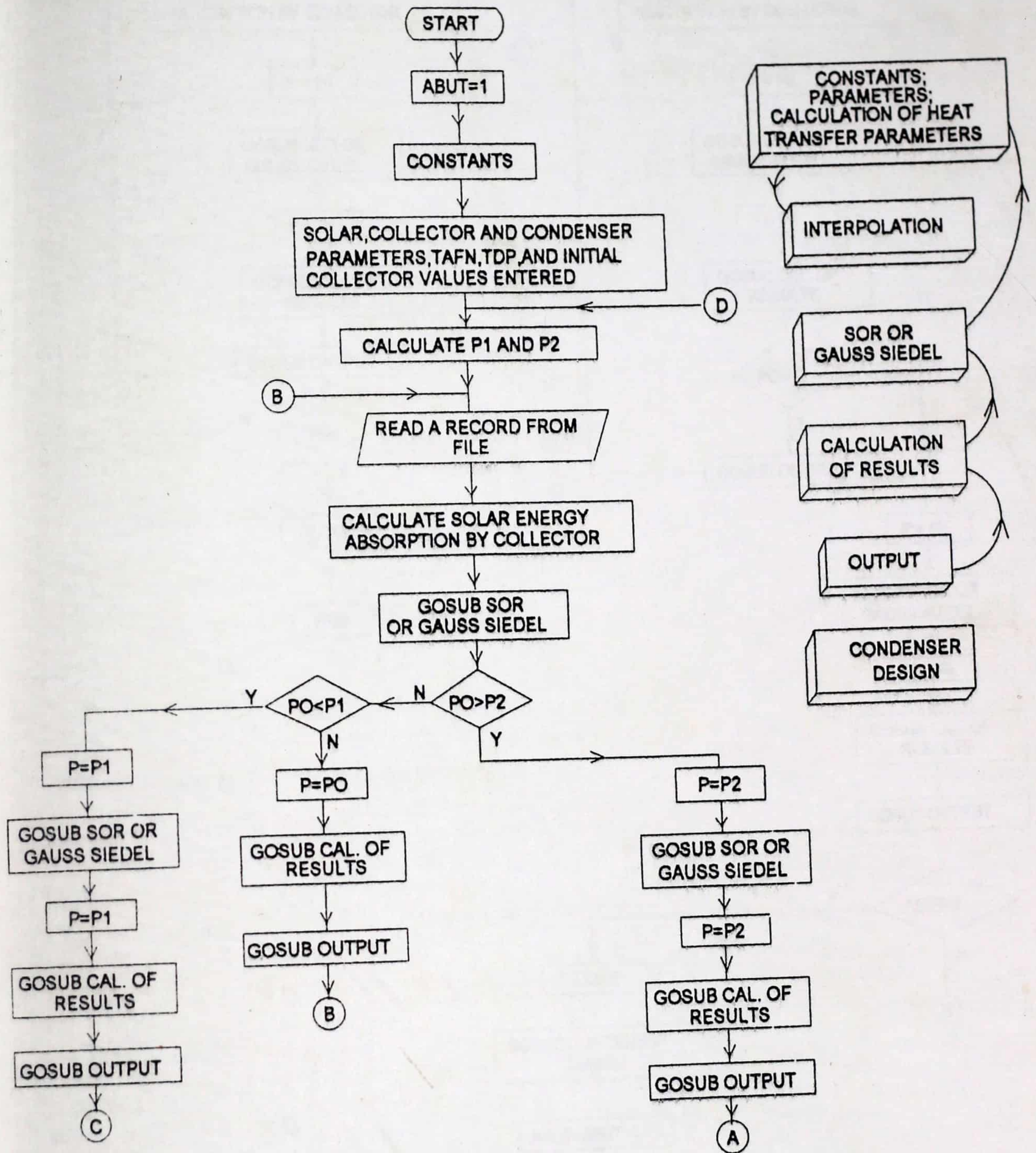
and proceeds to state 2. From state 1 to state 2, P_O increases with time and as it reaches the value of P_2 , at state 2, desorption starts. The methanol vapour pressure P is made equal to P_2 as the value of P_O remains equal to or more than P_2 . From state 2, the programme computations continue for the next sets of hourly data read until state 3 is reached, where the maximum charcoal temperature (or minimum methanol concentration, X_{min}) is reached and the value of P_O begins to fall below P_2 . After the hour computations at state 3 are completed, the condenser design programme comes into play to compute a better estimate for T_{cd} (T_{sat}).

7.1.4 Condenser Design Programme

The condenser design programme is used to determine the effectiveness of the lengths and diameters of the condenser tubes and the water tank size (ie DC , DR , $LC1$, LRI and S) for the methanol condensation, and it estimates T_{sat} (T_{cd}), TI and TE . The programme is a subroutine of the collector simulation programme.

The selected values of S , DC , DR , LCI and LRI are entered at the beginning of the running of the collector simulation programme. The initial values of T_{sat} , TI and TE are estimated from TAFN.

The condenser design programme starts running after the collector simulation programme finishes the initial computations from state 1 to 3. C_{pl} , ρ_l , k_l and μ_l are calculated using the film temperature T_{fm} and the Equations 5.1 to 5.4. H_{vi} and H_{vf} are calculated using Equation 5.7 and temperatures T_{vi} and T_{vf} (ie T_{sat}) respectively; and P_s and k_v are also calculated using Equations 5.9 and 5.6 and the temperatures T_{sat} and T_V respectively. The maximum root (Z) of Equation 5.12 is computed, by using the Newton-



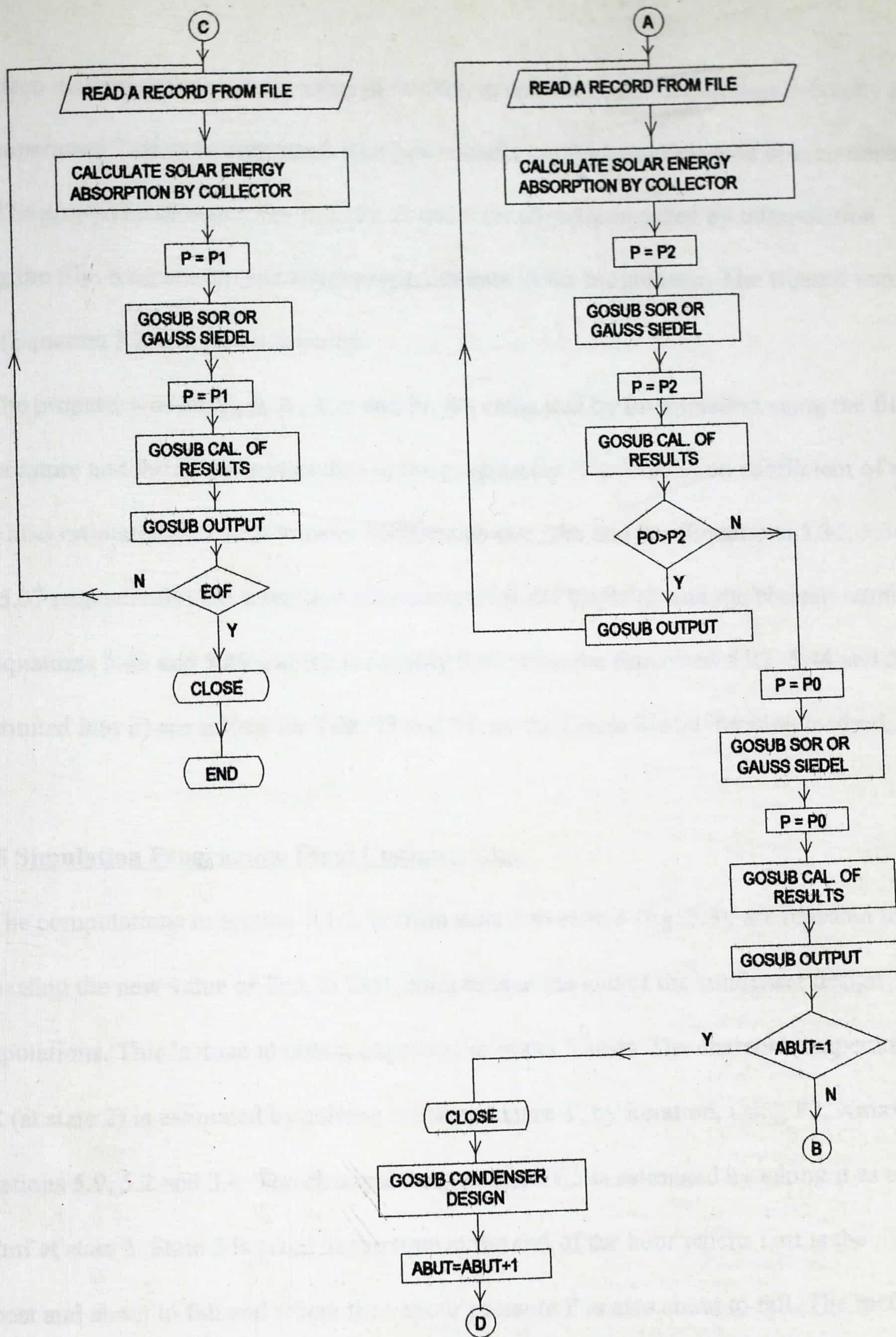


Fig. 7.1 Flow chart of the charcoal/methanol solar collector simulation programme

Raphson method with a starting value of 0.9949, to enable the methanol vapour density ρ_v at temperature T_{sat} to be computed. The heat transfer coefficient h_D is then also computed.

The properties of water, C_p , k , μ , Pr , β' and ν (or ρ), are computed by interpolation using the film temperature and water properties data in the programme. The Nusselt number Nu_L (Equation 5.23) is then computed.

The properties of air, ρ , α , μ , k , ν and Pr , are estimated by interpolation using the film temperature and the air properties data in the programme. The expansion coefficient of air, β' , is also estimated. The heat transfer coefficients h_{vc} , h_{bc} and h_{tc} (Equations 5.31, 5.34 and 5.37 respectively) are computed after computing the Rayleigh and the Nusselt numbers.

Equations 5.48 and 5.49 and the Inequality 5.47 (with the Equations 5.22, 5.44 and 5.46 substituted into it) are solved for T_{sat} , T_I and T_E by the Gauss Siedel iteration method.

7.1.5 Simulation Programme Final Computations

The computations in section 7.1.3, ie from state 1 to state 3 (fig. 3.3), are repeated this time using the new value of T_{cd} , ie T_{sat} , computed at the end of the condenser design computations. This is done to obtain improved or better results. The charcoal temperature TC_2 (at state 2) is estimated by solving for temperature T , by iteration, using P_2 , X_{max} and Equations 5.9, 5.2 and 3.4. The charcoal temperature TC_3 is estimated by taking it as equal to T_{mf} at state 3. State 3 is taken as the state at the end of the hour where T_{mf} is the highest and about to fall and where the vapour pressure P is also about to fall. The methanol concentration, X_{mff} , at state 3 is also taken as X_{min} .

From state 3 the vapour pressure P falls below P_2 and the computations for $T_{c_{f0}}$, $T_{c_{f1}}$, , $T_{c_{f6}}$, $T_{d_{f1}}$, $T_{d_{f2}}$, , $T_{d_{f5}}$, T_{p_f} , T_{t_f} , T_{g_f} , $X_{c_{f0}}$, $X_{c_{f1}}$, $X_{c_{f2}}$, , $X_{c_{f6}}$, X_{mff} , T_{mf} , T_{dmf} ,

P, and Eff are continued along the Xmin line until P reaches the value of P1. The time period the collector bottom insulation is taken as lowered (to enhance heat dissipation) is 5pm to 6am for Kumasi.

When the pressure P falls to the value of P1, evaporation of liquid methanol in the evaporator starts taking place leading to adsorption in the solar collector. The computations for the hour are continued, with P made equal to P1, until the last or 24th hour computations are done. After the last or 24th hour computations, the overall COP and the overall collector efficiency, Effcy, are computed and the collector simulation programme completes running. For the closed cycle, if the difference between TC1 and Tmf of the 24th hour computations, and also between Xmax and Xmff of the 24th hour computations, are beyond the acceptable limits, the simulation programme is run all over again with a new value of TC1. The new value of TC1 is selected between the value of TC1 to be changed and the Tmf of the 24th hour computations.

Two output files are created. The first output file gives the temperatures of the collector tubes, the glass cover and the charcoal finite-difference regions (ie $T_{c_{f0}}, T_{c_{f1}}, \dots, T_{c_{f6}}, T_{d_{f1}}, T_{d_{f2}}, \dots, T_{d_{f5}}, T_{p_f}, T_{t_f}$, and T_{g_f}). The second output file gives the following: the methanol concentrations (ie $X_{c_{f0}}, X_{c_{f1}}, X_{c_{f2}}, \dots, X_{c_{f6}}$ and X_{mff}), the charcoal temperatures Tcf, the collector tube temperatures (ie T_{p_f}, T_{t_f} and T_{d_f}), the glass cover temperatures T_{g_f} , the atmospheric temperatures Ta (or Tamb), the vapour pressures in the collector plate P, and the solar collector efficiency for the hour, Eff. The initial values of the above, ie at state 1, are included as the first data of the output files. Effcy, COP, TC1, TC2, TC3, TC4, Tev, Tcd, TI, TE, S, DC/L and DR/L are also included in the second output file.

7.2 Evaporator Box Design Programme

The evaporator box design programme (a computer programme) is used to select the dimensions of the evaporator box inside and outside walls, the thickness of the evaporator walls and the inside walls of the evaporator box, and the thickness of insulation between the evaporator box inside and outside walls. It is also used to estimate the cold chamber temperatures and the masses of food items that can be stored or the amount of ice that can be produced. The evaporator box outside wall temperatures are also estimated.

The evaporator box design programme (attached to the report) is written using the Mathcad 4.0 software. The specific heat capacities and densities of the metals with which the evaporator and the evaporator box inside and outside walls are to be made are fixed as constants in the programme. The other constants, in the programme, are the specific heat capacities of water, tomatoes and fish; the thermal conductivity of the evaporator box insulation; and the emissivity of the evaporator box outside walls.

The values of the following are to be provided to run the programme:

- i. the mass of charcoal in the solar collector (M_c), and the maximum and minimum methanol concentrations ($X_{\max}$ and $X_{\min}$),
- ii. the average condensing and evaporating temperatures (T_{sat} and T_{ev})
- iii. the average daytime and nighttime atmospheric temperatures (T_{ad} and T_{an})
- iv. the atmospheric temperature at the beginning of the evaporation process or at sunset (T_{ai})
- v. the evaporation period, or time between sunset and sunrise (t_1)
- vi. the period after the evaporation process or sunrise and before the condensed methanol enters the evaporator (t_2)

- vii. the period condensed methanol enters the evaporator and just before evaporation begins (t_3)
- viii. the thickness of insulation between the inside and the outside walls of the evaporator box (t_k)
- ix. the dimensions and thickness of the inside walls and the thickness of the outside walls of the evaporator box (L_{li} , L_{bi} , L_{hi} , t_{kc} and t_{kb})
- x. the surface area and thickness of the evaporator walls (A_e and t_{ke})

The properties of air, ρ , α , μ , k , ν and Pr , during the day and in the night are estimated by interpolation (by the programme) using the film temperatures and the air properties data in the programme. The expansion coefficients of air (β') for the day and night are estimated as the inverse of the film temperatures. The programme computes the heat transfer coefficients h_{tc} , h_{bc} and h_{vc} (Equations 6.22, 6.21 and 6.20) by first computing the Nusselt numbers (Equations 5.35 or 5.36, 5.32, and 5.28 or 5.29). The temperature of the liquid methanol in the evaporator just before evaporation begins, T_m , has to be given (ie $T_m = T_{cd}$ or $T_m = T_{m1}$) and the enthalpies h_{fcd} , h_{fm} , h_{fev} and h_{fgev} (Equations 6.1 to 6.4) are computed. The mass of methanol distilled, m , (equation 6.6), and the dryness fractions y and x (Equations 6.8 and 6.10) are also computed.

For the short-term storage of vegetables or fruits, and for the evaporation period in the night, Equations 6.31 (or 6.32) and 6.33 (with T_{m1} and T_{g1} known and T_{m2} chosen) are solved simultaneously for T_{bn} and M_{gt} or M_{gtf} . Equations 6.35 and 6.36, with M_{gt} and T_{m2} known, are also solved for T_{m3} and T_{bd1} , for the period of the vegetable or fruit storage after the evaporation process and before the condensed methanol enters or is

introduced into the evaporator. Equations 6.38 and 6.39, with T_{m3} and M_{gt} known, are also solved for T_{bd2} and T_{m4} , for the period of the vegetable or fruit storage when the condensed methanol is introduced into the evaporator and just before evaporation starts [section 6.4].

For ice production and for the maximum amount of ice that can be produced, Equations 6.41 and 6.42 are solved for T_{bn} and M_{ce} [section 6.5].

Also for the storage of fresh fish overnight and for the maximum amount of fish that can be frozen, Equations 6.44 and 6.45 are solved for M_{fz} and T_{bn} [section 6.6].

CHAPTER 8

NUMERICAL RESULTS

8.1 Results from Collector Simulation Computer Programme

The collector simulation programme is run using Kumasi meteorological data to predict the temperatures and the efficiency of the collector of a charcoal/methanol solar refrigerator model and also to determine the overall COP of the model. The collector surface area is taken to be about 1 m^2 and the inclination of the collector is taken to be towards the south at an angle equal to the local latitude ie $6^\circ 43'$. The Kumasi solar radiation data used are shown in table 8.1, which gives the monthly average hourly global radiation for the period June 1987 – May 1989. The other meteorological data used which are also the average values for each month for the period 1988/89 are shown in tables 8.2 to 8.6. The data given by tables 8.2 to 8.5 are for the atmospheric temperatures, the average wind velocities and the relative humidity. And that given by table 8.6 are for the average day of the month and the corresponding declination angle, the latitude, the average atmospheric temperature during condensation, and the average dew-point temperature. The data for the input file (section 7.1.2) are compiled for each month, using the data in tables 8.1 to 8.4, and are given in tables A.1 to A.12, appendix A. Also shown in table 8.7 are the angle of tilt of the collector, the dimensions of the collector, the condenser tubes and the water tank; the number, radii and masses of the collector plate tubes; and the masses of the outer tube end caps, the glass cover and the activated charcoal. How the above masses are estimated is shown in appendix C. The outputs (simulation results) obtained from the running of the simulation programme for all the months are shown in appendix B.

Table 8.1 Solar Radiation Station: U.S.T/Kumasi Solar Energy Laboratory, Department of Mechanical Engineering
 Latitude: 06° 43' N Period: June 1987- May 1989 Inst.: Licor Pyranometer
 Longitude: 01° 36' W

Hour	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVE.
7	6.9	8.4	18.3	35.1	51.5	35.7	21.7	16.8	23.1	37.6	28.2	12.3	24.6
8	66.7	84.9	123.5	153.4	183.8	132.2	98.4	76.2	97.6	145.8	126.7	76.9	113.8
9	181.4	221.6	287.5	324.7	342.4	255.9	201.6	155.2	204.8	278.7	266.2	184.3	242.0
10	323.2	367.5	467.2	494.5	486.2	361.6	321.1	243.3	328.4	425.4	423.3	333.1	381.2
11	451.4	521.0	624.6	650.4	620.3	464.1	426.3	344.9	439.0	552.1	547.2	461.6	508.6
12	544.8	634.8	728.2	730.3	706.2	543.4	484.6	403.5	500.5	645.8	623.9	558.1	592.0
13	568.4	663.9	740.8	737.5	718.4	621.7	511.6	438.7	519.9	673.4	670.0	573.5	619.8
14	532.1	619.1	694.2	685.2	658.0	591.5	492.9	424.0	543.4	619.0	605.5	510.7	581.3
15	442.3	507.2	577.6	556.3	559.2	486.0	463.4	394.6	461.3	513.8	478.4	405.8	487.1
16	299.6	343.6	410.7	389.8	390.3	358.6	344.1	324.1	333.2	326.7	317.7	267.2	342.1
17	151.0	183.2	227.3	207.4	203.1	201.2	204.0	187.9	182.4	156.5	128.4	119.4	179.3
18	38.7	54.3	74.8	66.9	63.6	70.8	76.9	66.6	52.8	37.1	21.1	21.9	53.8
Daily sum (kWh/m ²)	3.6	4.2	5.0	5.0	5.0	4.1	3.6	3.1	3.7	4.4	4.2	3.5	4.1

Table 8.2 Average Dry Bulb Temperatures (°C) for Kumasi in 1988/89

HRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
00:00	23.5	25.4	24.7	24.6	24.3	23.1	22.7	22.4	22.6	23.1	24.2	23.4
03:00	22.0	24.0	23.7	23.7	23.5	22.5	22.3	21.8	22.2	22.5	23.4	22.3
06:00	21.0	23.2	23.2	23.2	23.2	22.3	22.0	21.5	21.9	22.3	23.0	22.2
09:00	23.7	25.8	25.7	26.1	26.0	24.6	23.6	23.1	23.6	24.4	25.6	24.0
12:00	29.1	31.2	30.5	30.3	29.5	27.5	26.4	25.5	26.2	28.2	29.5	28.6
15:00	32.1	34.4	32.9	31.9	31.1	28.7	27.7	26.9	27.8	29.5	31.5	30.6
18:00	29.6	31.6	30.5	29.5	28.6	26.2	25.9	25.6	25.8	26.4	28.4	27.9
21:00	25.9	28.0	26.4	25.9	25.7	23.9	23.7	23.5	23.6	24.1	25.7	25.0

Table 8.3 Average Maximum Temperatures (°C) for Kumasi in 1988/89

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
32.5	35	33.6	32.7	32.0	29.9	28.7	28.2	29.0	30.8	32.3	31.3

Table 8.4 Average Monthly Wind Speed in Knots for Kumasi in 1988/89

JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
2.3	2.65	3.05	3.25	2.65	2.8	2.85	3.4	2.6	2.05	3.6	1.55

Table 8.5 Average Relative Humidity (%) for Kumasi in 1988/89

HRS	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
06:00	78	81	93	95	96	97	97	97	97	98	96	91
09:00	68	71	83	84	84	88	89	89	91	88	86	83
12:00	47	47	62	66	68	75	75	79	78	73	68	62
15:00	36	35	52	59	62	70	72	74	72	68	59	53

Table 8.6 Collector Design Parameters (constants)

	JAN.	FEB.	MAR.	APR.	MAY	JUNE	JULY	AUG.	SEPT.	OCT.	NOV.	DEC.
NN	17	47	75	105	135	162	198	228	258	288	318	344
δ or GGA (degrees)	-20.9	-13	-2.4	9.4	18.8	23.1	21.2	13.5	2.2	-9.6	-18.9	-23
λ (degrees)	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167	6.7167
TDP (°C)	16.6	18.8	22.2	22.9	22.9	22.4	21.7	21.4	22	22.5	22.7	20.5
TAFN (K)	303.67	305.92	304.83	304.22	303.48	301.35	300.32	299.95	300.32	302.05	303.63	302.7

Table 8.7 Collector and Condenser Design Parameters (final values)

β (degrees)	L (m)	LW (m)	LB (m)	LE (m)	LS (m)	MOT (kg)	MIT (kg)	MDT (kg)	MG (kg)	MC (kg)	NS	LG (m)
6.7167	1.178	0.848	0.1	0.1	0.04	43.01	10.052	1.612	8.37	19.432	14	0.0032

RO (m)	RI (m)	LD (m)	KB (W/m.K)	DCY (ins.)	DRI (ins.)	LCI (m)	LRI (m)	S (m)
0.0285	0.00686	0.003	0.05	0.995	3.857	3.8	0.4	1.15

Table 8.8 Evaporator Box Design Parameters (final values)

Ll (m)	Lb (m)	Lh (m)	Lli (m)	Lbi (m)	Lhi (m)	tk (m)	tke (ins.)	tkc (ins.)	tkb (ins.)	Ae (cm ²)
0.4	0.4	0.55	0.3	0.3	0.45	0.05	1/16	1/16	1/16	2106.0595

Table 8.9 Design Constants

α_p	Et	Eg	Ep	ρ_g	hpc (W/m ² .K)	Δt (s)	w	K (m ⁻¹)	Etc	Etb
0.95	0.95	0.88	0.45	0.2	47.5	3600	1.5	18	0.13	0.9

The average daily global radiation (H) in June of $4.123 \text{ kWh/m}^2\text{-day}$ (table A.1) is about the same as the average of the monthly daily global radiation of all the months. Fig. 8.1 shows the histogram of the hourly total solar radiation incident on the horizontal surface for the month of June. The simulation results show that the overall refrigerator COP for June, about 0.107, is also about the same as the average of the refrigerator COP of all the months. Similarly, the overall collector efficiency for May which is about 0.314 is about the same as the average of the overall collector efficiencies of all the months. And that for June which is about 0.308 is a little lower than that for May.

Heat losses from the solar collector to the atmosphere during daytime in comparison with the incident solar radiation are very high for each month, as can be seen from the simulation results. In the period between the time the collector temperatures start rising to the time desorption ends, the heat loss for the hour expressed as a fraction of the hour incident radiation is the highest towards or at the end of desorption. After desorption the incident radiation is not effective, and it has become less than the heat loss from the collector, and the temperatures of the collector plate and the charcoal begin to fall. The hourly efficiencies of the collector during the daytime in May and June are shown in fig.8.2. In the morning before significant desorption begins the hourly efficiency rises to maximum (44.6% for May and 49.9% for June) and then falls as the collector temperatures increase. When desorption begins the efficiency rises again (to 44% for May and 40% for June) and falls as the collector temperatures further increase until after desorption when the efficiency goes down to zero.

April, May and March have the highest average daily global radiation, about $5 \text{ kWh/m}^2\text{-day}$. The highest desorption occurs in March and April, X_{min} for March and

April having the values of 0.064 kg/kg and 0.065 kg/kg respectively. The overall collector efficiency and the COP are however highest in October. The average daily global radiation in October, 4.412 kWh/m²-day, is the next highest after that of April, May and March; and the daytime and nighttime collector and atmospheric temperatures in October are lower than that in April, May and March. Hence X_{min} and T_{ev} in October are higher and lower respectively than those of the other three months. Also the heat losses from the collector plate to the atmosphere (during daytime before the end of desorption) are also lower in October than in any of the other three months. And when expressed as fractions of the incident radiation, the heat losses are to a lower extent in October than in any other month. The overall collector efficiency in October of about 0.33 becomes the highest for the year and as a result of this and with a low T_{ev} in October the overall COP in October of about 0.12 also becomes the highest for the year.

The COP, T_{ev} , overall collector efficiency (Effcy) and the average daily global radiation (H) for all the months are shown in fig. 8.3. August has the lowest H, Effcy, T_{ev} and COP, with values 3.08 kWh /m²-day, 0.29, -4° C and 0.08 respectively. The highest T_{ev} , about -1° C, occurs in February, and this is due to the fact that February has the highest daytime and nighttime atmospheric temperatures. The T_{ev} in October of about -2.7° C is the nearest to the average T_{ev} for all the months, which is about -2.4° C. The average daily incident total radiation (ITT) on the collector ($\beta = 6.72^\circ$, facing south) and the refrigeration effect (Q_e) for all the months are shown in fig. 8.4. March and April have the highest ITT, about 5 kWh/m²-day, and August has the lowest, about 3.06 kWh/m²-day. As a result March has the highest refrigeration effect of about 2,100 kJ and August has the lowest of about 900kJ. The ITT and the refrigeration effect in June of 4.07 kWh/m²-day and 1,600 kJ respectively

are about the same as the average ITT and the average refrigeration effect for all the months.

Fig. 8.5 shows the graph of COP, Effcy and T_{ev} against X_{max} (the initial concentration of methanol charged into the charcoal) for the month of June. The mass of charcoal is fixed at 19.432 kg. As X_{max} increase from 0.14 to 0.20, COP, Effcy and T_{ev} also increase from 0.09 to 0.15, 0.29 to 0.34 and -7.2°C to 5.4°C respectively; however T_{ev} , in $^{\circ}\text{C}$, becomes less negative, then zero and then positive. Fig. 8.6 also shows the graph of COP against the collector plate outer tube inside diameter (or mass of charcoal) for June and August. The diameters of the collector plate tubes are that of stainless steel pipes (table C.1, appendix C, shows the dimensions and weights of steel pipes). The collector plate inner tube outside diameter is fixed at 1.4 cm (0.54"). X_{max} is also fixed at 0.16. In June where the daily global radiation is about the same as the average radiation for the year, the COP increases from 0.09 to 0.12 as the collector plate outer tube inside diameter increases from 4.5 cm to 9.7cm, ie 1.77" to 3.834" (corresponding to charcoal mass, M_c , from 14.62 kg to 35.2 kg). In August where the daily global radiation is the lowest, the COP rises to a maximum of 0.08 at the outer tube inside diameter of 5.7 cm (2.245"), ie about the charcoal mass of 19.432 kg, and falls as the outer tube inside diameter increases. Collector plate outer tube of inside diameter 5.7 cm and outside diameter 6 cm (2.375") and X_{max} of 0.16 are used in running the simulation programme for all the months.

The daytime and nighttime collector and ambient temperatures for the month of June are given by the curves in fig. 8.7. The collector temperatures T_{pf} , T_{cf} and T_{gf} rise to maximum of 80.9°C , 79.5°C and 46°C respectively in the afternoon, at the end of desorption (about 3pm), and then fall afterwards. In the night T_{pf} , T_{cf} and T_{gf} approach

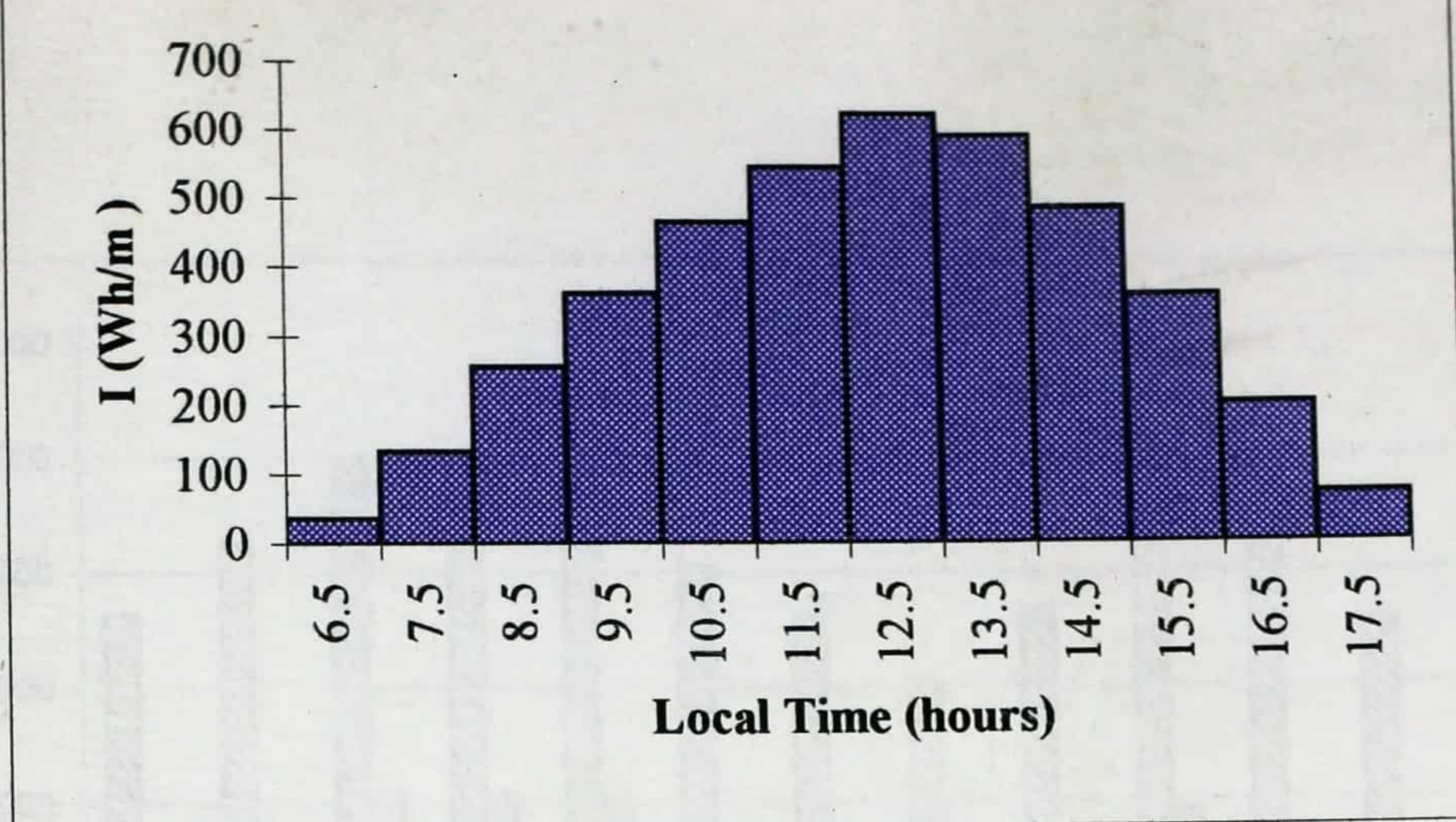


Fig. 8.1 Graph of average hourly total solar radiation on the horizontal surface against time for the month of June

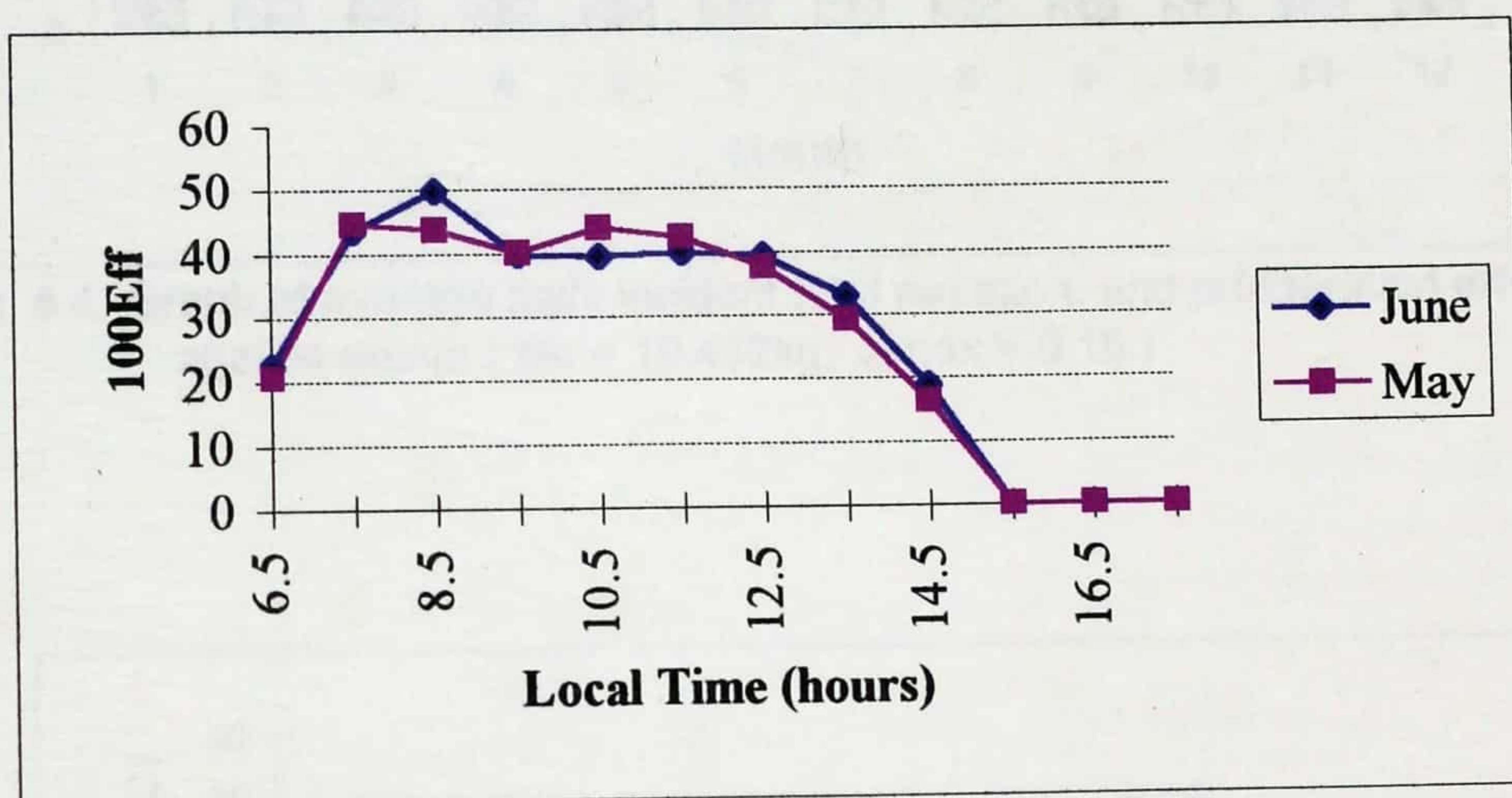


Fig. 8.2 Graph of collector efficiency for the hour against time, for May and June ($M_c=19.432$, $X_{max}=0.16$)

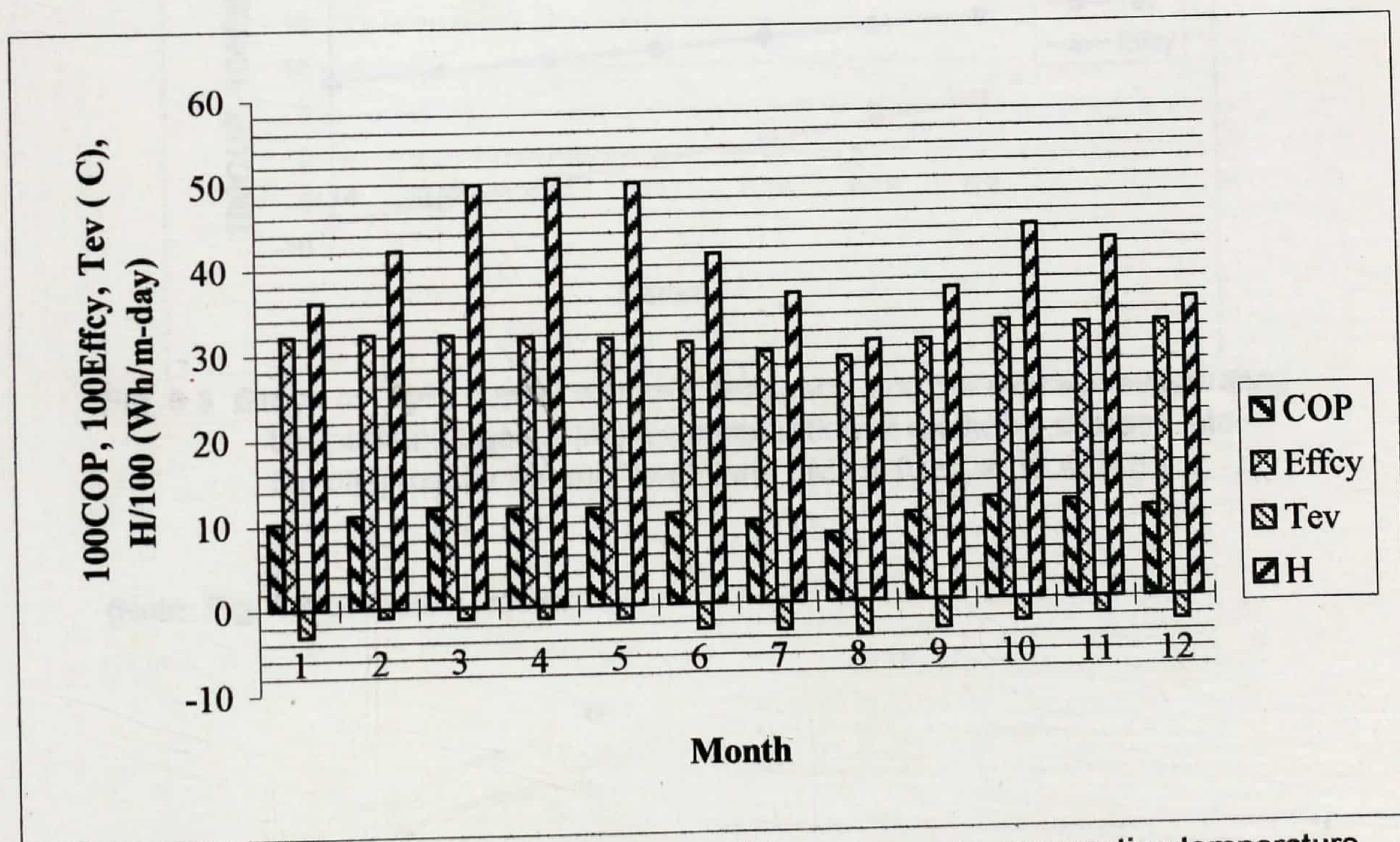


Fig. 8.3 Graph of COP, overall collector efficiency, average evaporating temperature, and monthly average daily global radiation against month ($M_c=19.432$, $X_{max}=0.16$)

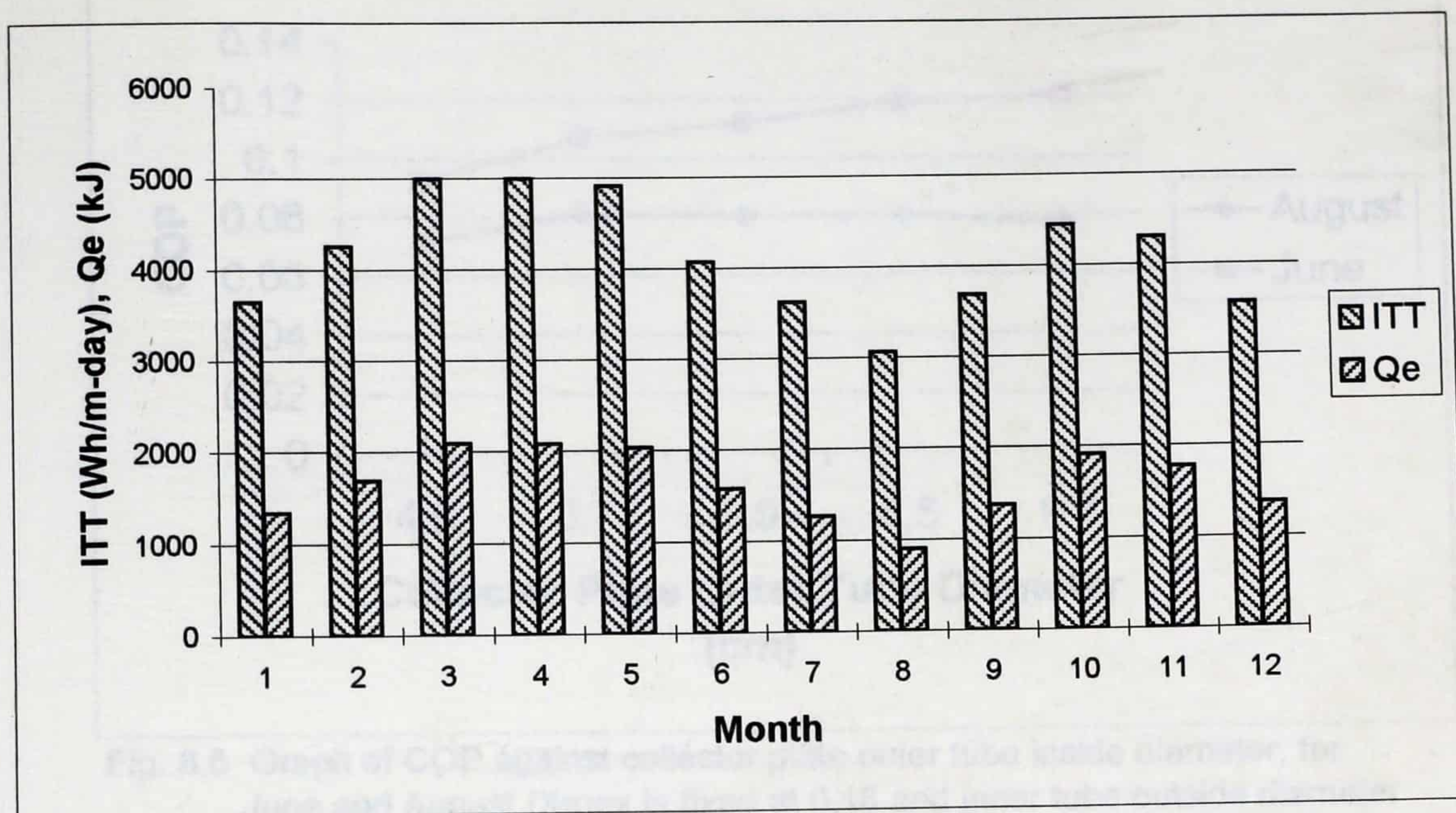


Fig. 8.4 Graph of average daily incident total radiation, and refrigeration effect against month ($M_c = 19.432\text{kg}$, $X_{\text{max}} = 0.16$)

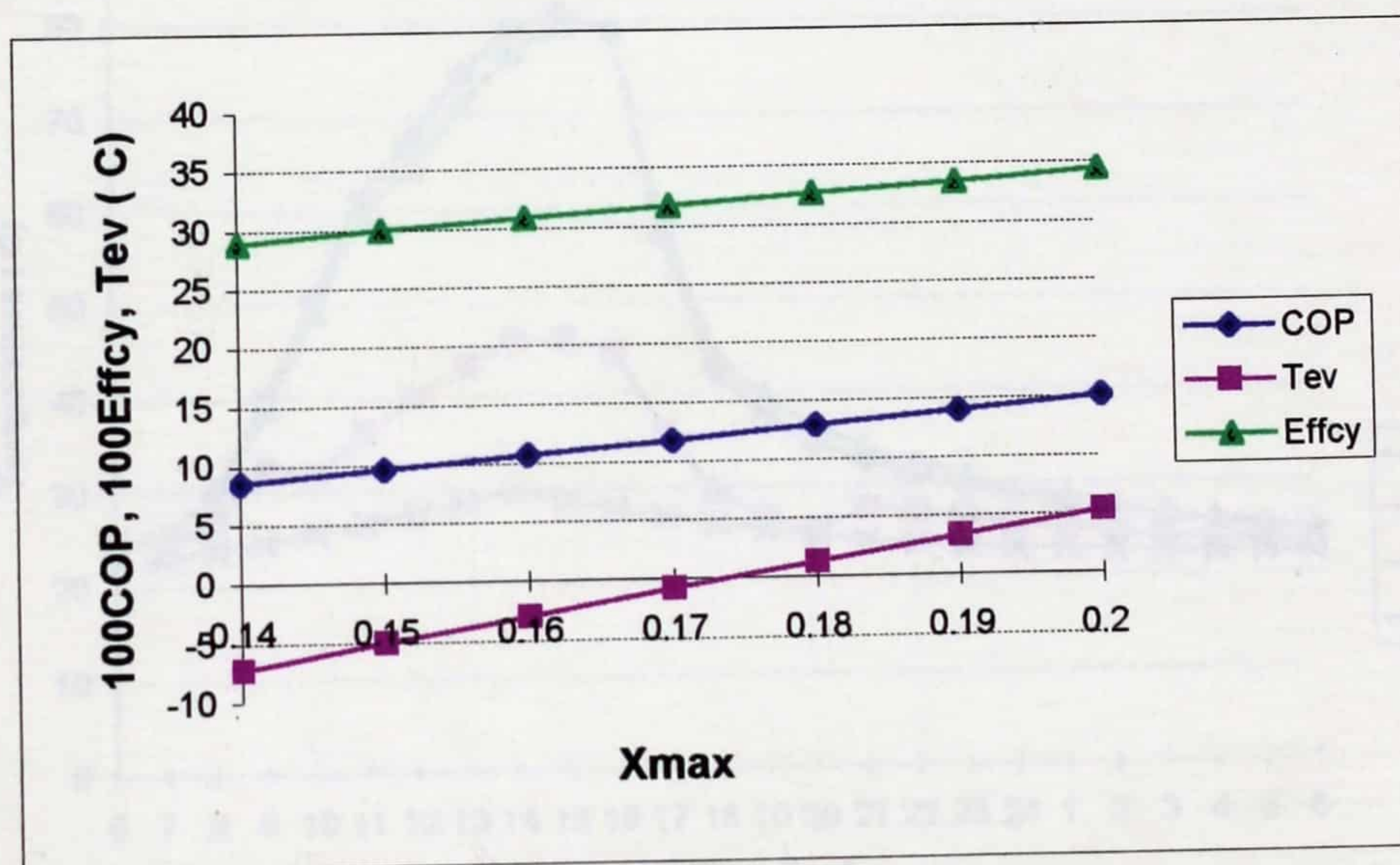


Fig. 8.5 Graph of COP, overall collector efficiency, and the average evaporating temperature against initial concentration of methanol charged into the charcoal for the month of June (M_c is fixed at 19.432kg)

(Note: Fig. 8.5 original in colour)

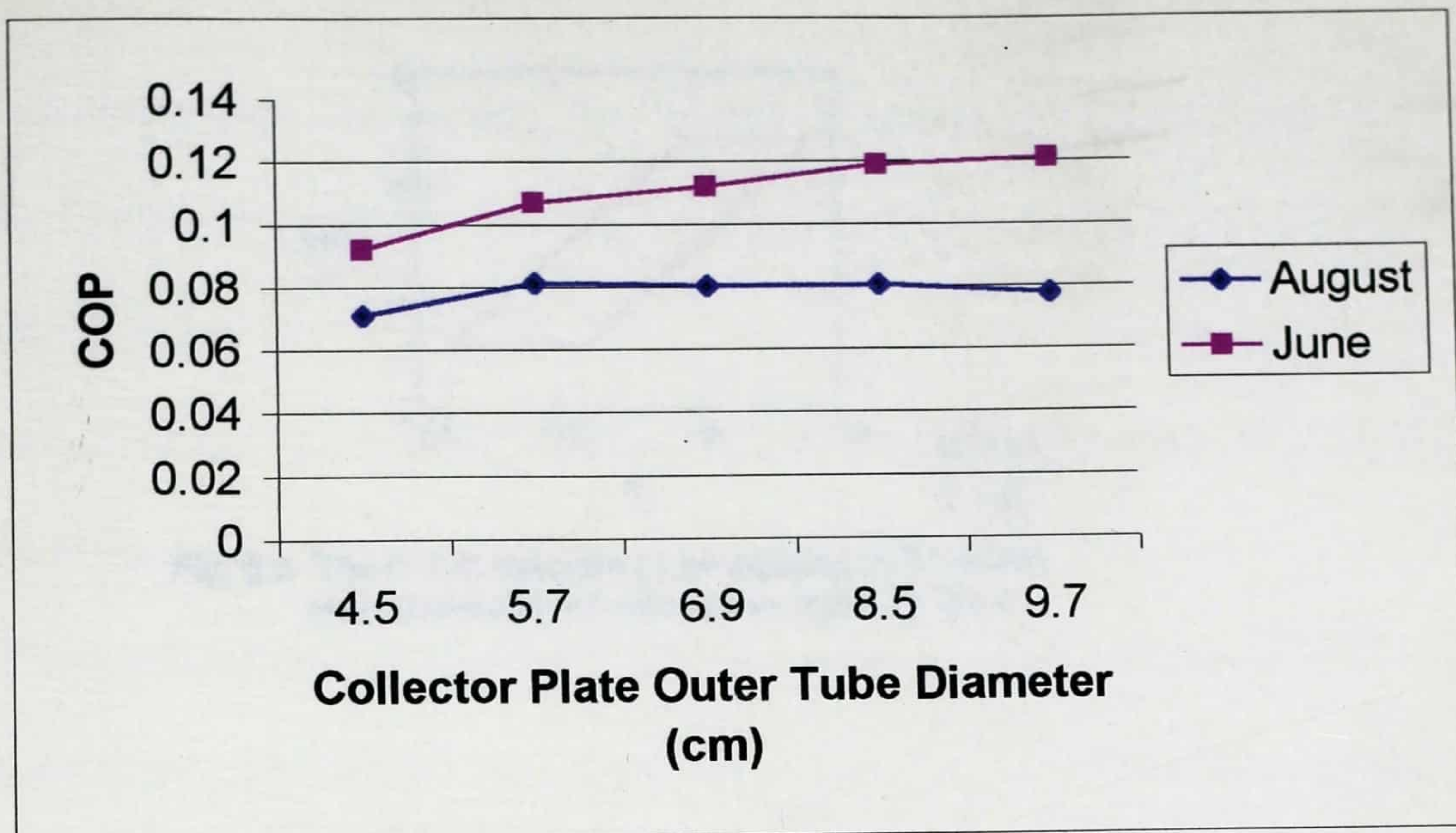


Fig. 8.6 Graph of COP against collector plate outer tube inside diameter, for June and August (X_{max} is fixed at 0.16 and inner tube outside diameter is fixed at 1.4cm)

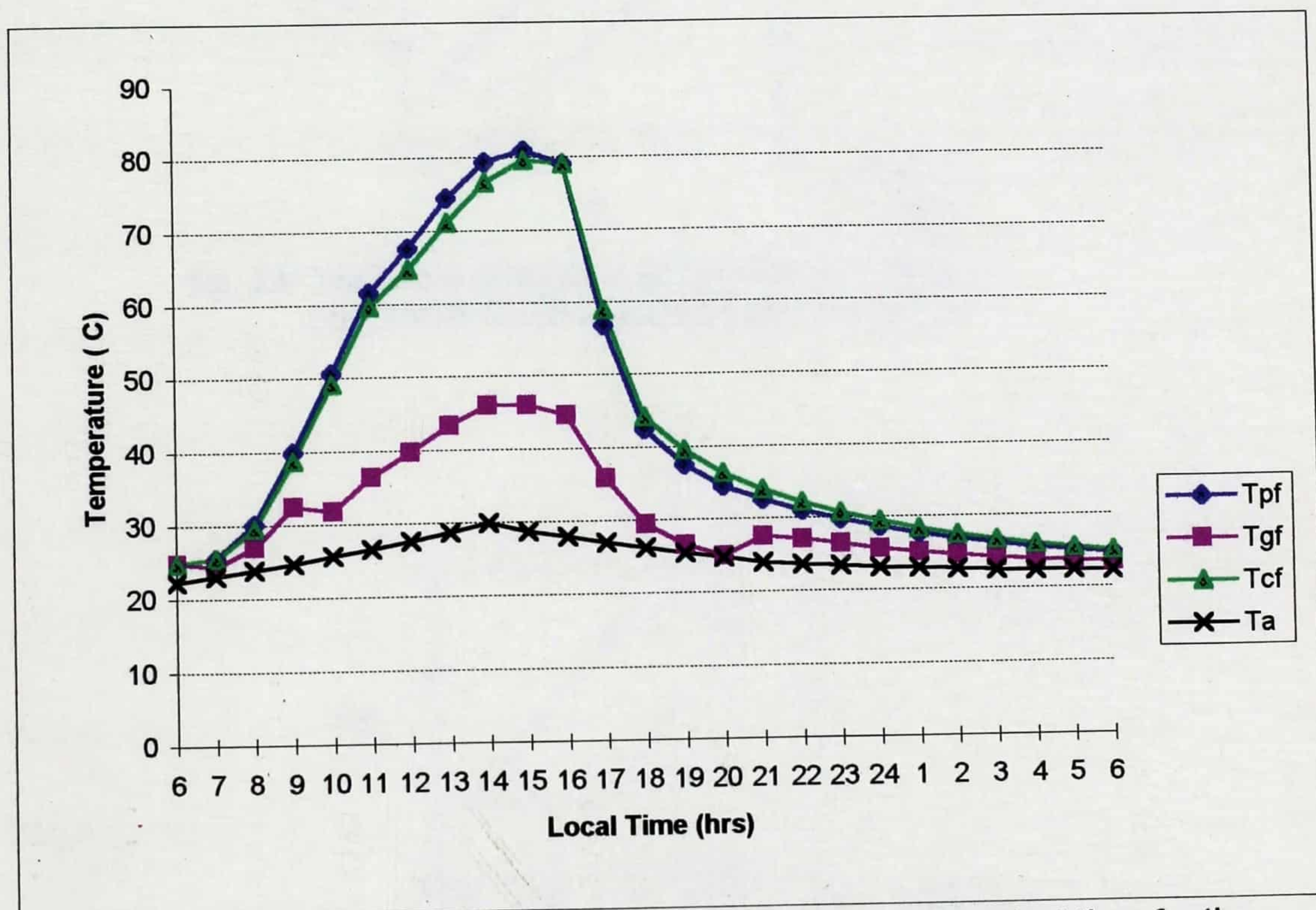


Fig. 8.7 Graph of solar collector and ambient temperatures against time for the month of June ($M_c=19.432$, $X_{max}=0.16$)

(Note: Graphs original in colour)

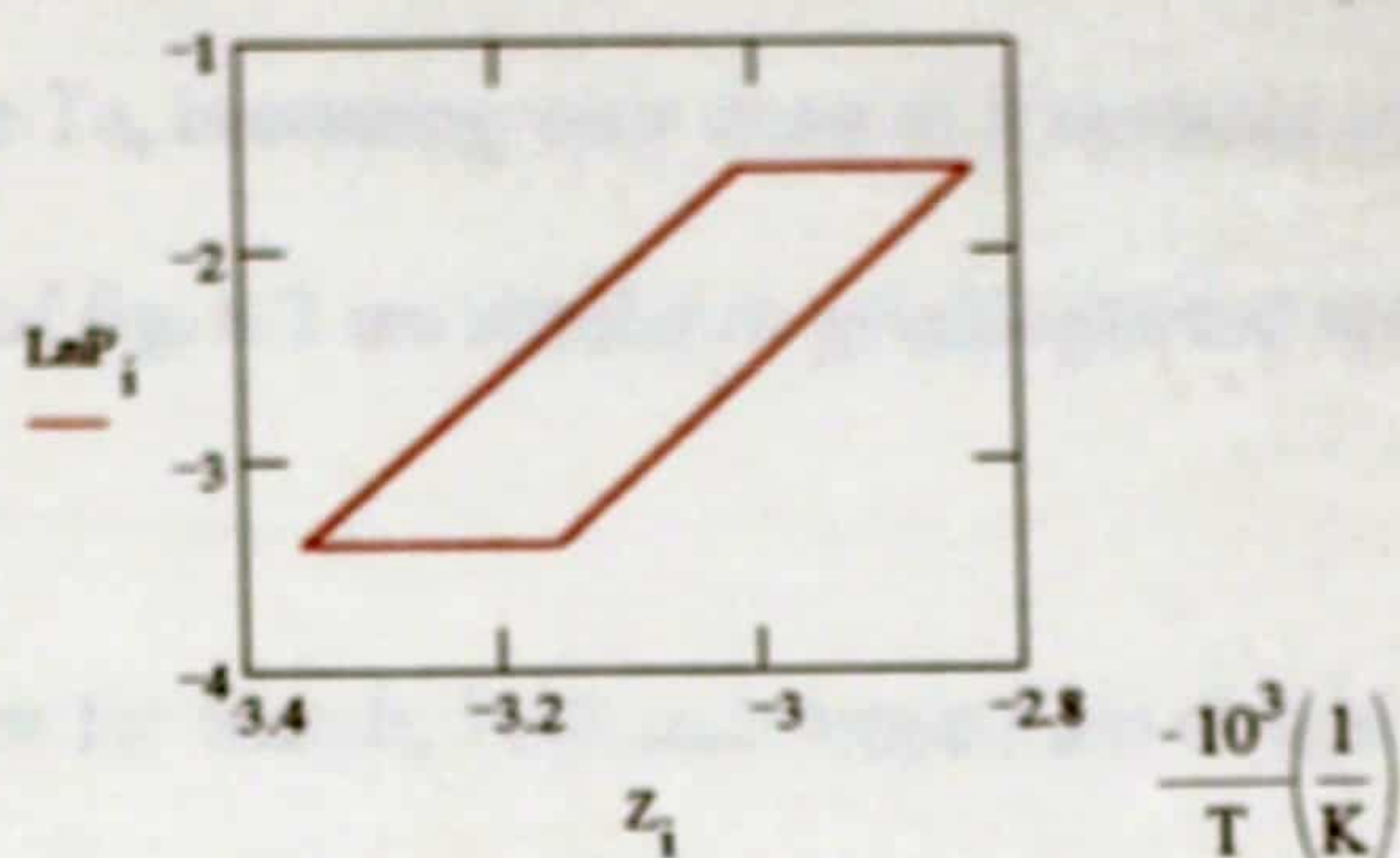


Fig. 8.8 The P-T-X diagram ($\text{Ln}P_i$ against $-1/T$) of the charcoal/methanol adsorption cycle for June

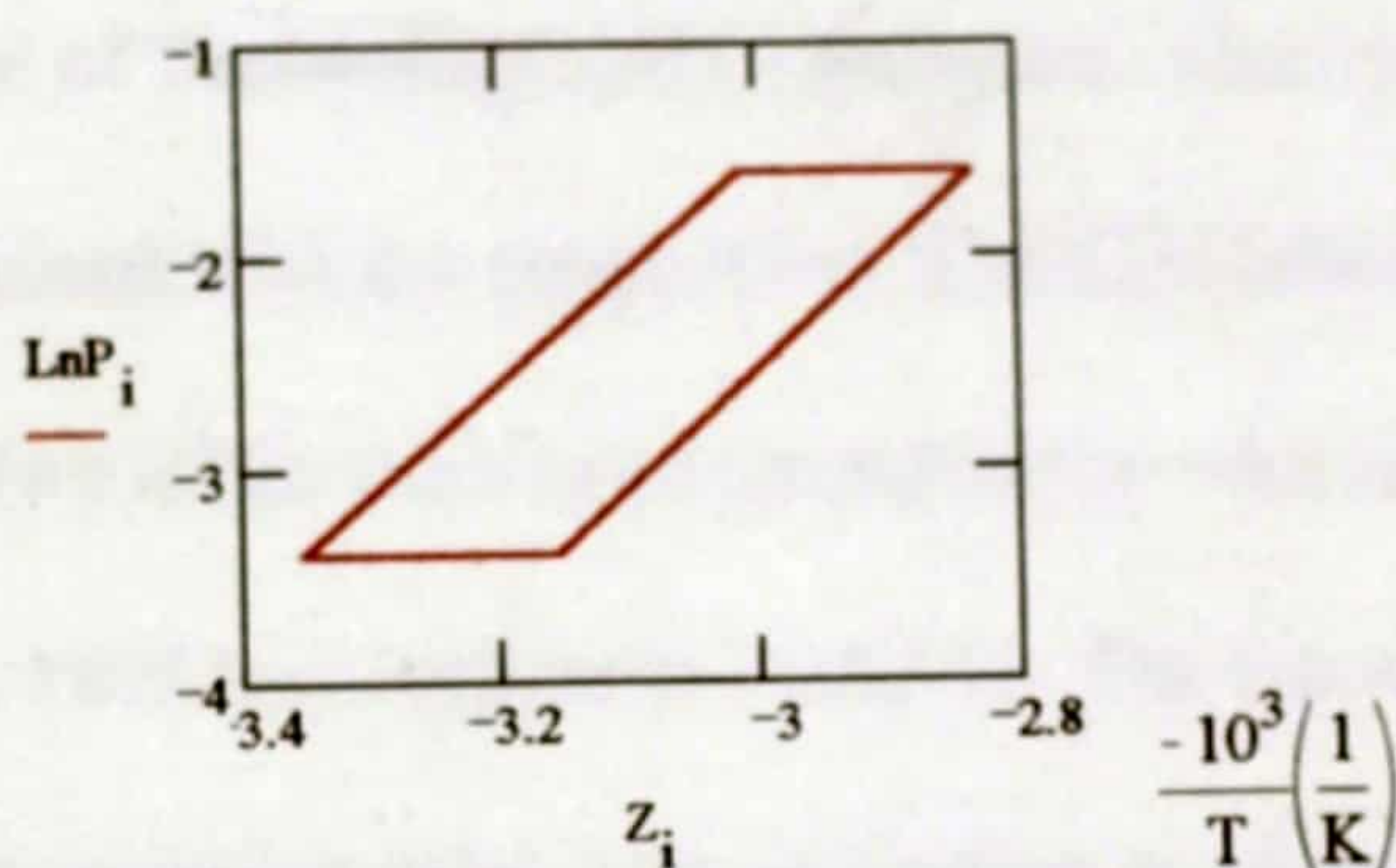


Fig. 8.9 The P-T-X diagram ($\text{Ln}P_i$ against $-1/T$) of the charcoal/methanol adsorption cycle for March

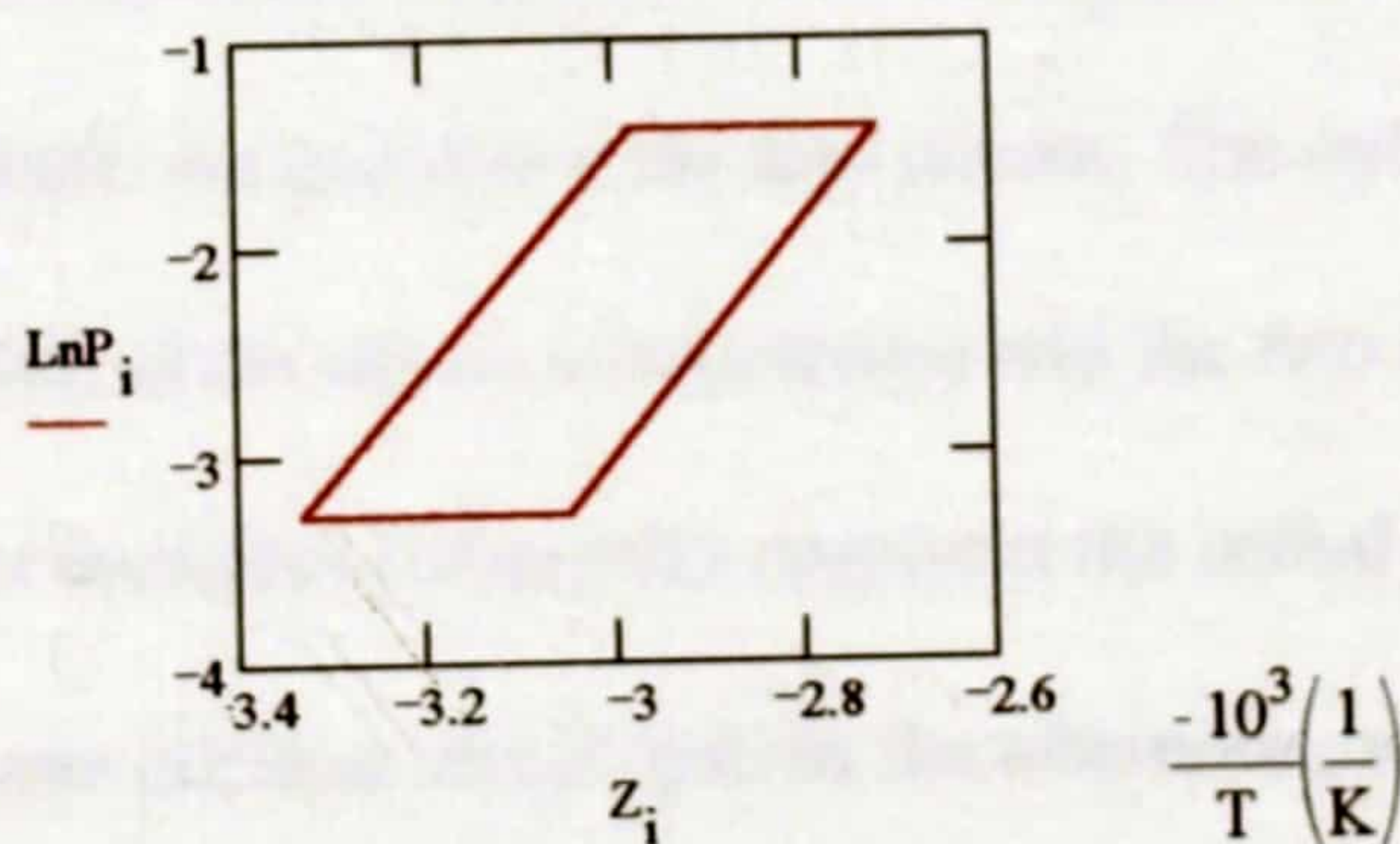


Fig. 8.10 The P-T-X diagram ($\text{Ln}P_i$ against $-1/T$) of the charcoal/methanol adsorption cycle for August

the ambient temperature T_a , becoming very close to it towards sunrise (T_{gf} can even fall below T_a). The graphs of fig. 8.7 are similar to graphs plotted with experimental data (Exell et al 1993).

The adsorption cycles for March, June and August are shown in figures 8.8 to 8.10. The desorption pressure and the adsorption pressure are average pressures.

The collector simulation programme is also used (in this project) to simulate the temperatures of the collector of the charcoal/methanol solar refrigerator built and tested in 1987 at the Asian Institute of Technology (AIT), Bangkok. The overall COP of the refrigerator is also determined with the programme. The simulation of the collector temperatures is done for two of the days experimental data were taken (in Bangkok), ie 17th October and 29th October 1987 (see Appendix D and E). The input data used in running the simulation programme are shown in table 8.10 and tables A.13 and A.14, appendix A. The simulation results are also shown in tables B.25 to B.28, appendix B. The simulated collector plate and charcoal temperatures (T_{pf} and T_{cf}) for 29th October are compared with the actual collector plate and charcoal temperatures as shown, plotted against time, in figs. 8.11 and 8.12. The atmospheric temperatures are also shown. The curve of the simulated temperatures is similar to that of the actual temperatures and the two are almost the same. The simulated temperatures therefore adequately represent the actual temperatures. The highest collector temperatures occur at about 3pm in the afternoon, with the simulated and the actual collector plate temperatures reaching 113° C and the simulated and the actual charcoal temperatures reaching 111° C and 112° C respectively. The average deviations (absolute values are used) between the simulated and the actual temperatures of the collector plate and the charcoal from 6am to 6am (ie 24 hours) are about 1.8° C and 2° C

respectively. The overall COP computed by the simulation programme is 0.138 and that calculated using the test results is 0.145 ($\beta=14^\circ$ and $ITT=5850.853 \text{ Wh/m}^2\text{-day}$). The comparison between the simulated and the actual collector plate, charcoal and also glass cover temperatures (T_{pf} , T_{cf} and T_g) for 17th October are shown in figs. 8.13, 8.14 and 8.15. Again the simulated temperatures adequately represent the actual temperatures. The average deviations between the simulated and the actual temperatures of the collector plate, the charcoal and the glass cover are about 3°C each. The collector simulation programme is validated.

The computer simulated collector plate temperatures (T_{pf}) for April, Kumasi, are compared with the simulated AIT collector plate temperatures for 29th October 1987. The comparison is being made using the April temperatures, since the average daily global solar radiation for April, which is $5.03 \text{ kWh/m}^2\text{-day}$, the highest for the year for Kumasi is the closest to the incident global radiation for 29th October 1987, Bangkok, which is $5.47 \text{ kWh/m}^2\text{-day}$. The atmospheric temperatures at those times for Kumasi and Bangkok are also similar. Fig. 8.16 shows the graph of the simulated collector plate temperatures for April (Kumasi) and that for 29th October (Bangkok) against time. The shapes of the graphs are similar and the average deviation between the temperatures is about 5°C . The temperatures for 29th October (Bangkok) are higher than that for April (Kumasi). This is mainly due to the fact that the incident global radiation for 29th October 1987, Bangkok, is higher than the average daily incident global radiation for April (1988-1989), Kumasi.

The condenser tubes surface temperature, the water tank walls temperature and the heat transfer coefficient (Equation 5.27) between the surface of the condenser tubes and the walls of the water tank are computed for each month (heat storage in condenser tube walls

Table 8.10 Parameters for AIT Solar Collector

L (m)	LW (m)	LB (m)	LE (m)	LS (m)	LG (m)	Ro (m)	Ri (m)	LD (m)	NS
1.2	0.81	0.1	0.1	0.032	0.004	0.0255	0.00476	0.0015	15

MOT (kg)	MIT (kg)	MDT (kg)	MG (kg)	MC (kg)	Xmax (kg/kg)	DCY (ins.)	S (m)	LCI (m)	NN for 17 th Oct.	NN for 29 th Oct.
38	8.4	0.76	8.37	17.8	0.178	0.5	0.654	8.77	290	302

δ (degrees)	λ (degrees)	β (degrees)	TDP ($^{\circ}\text{C}$)	PD (kg/m^3)	CD (J/kg.K)	CT (J/kg.K)	KD (W/m.K)	KT (W/m.K)	KB (W/m.K)
-10.3	13.7	14	22.9	8530	380	385	110	385	0.026

(The collector tubes were copper tubes and the end caps were made with brass)

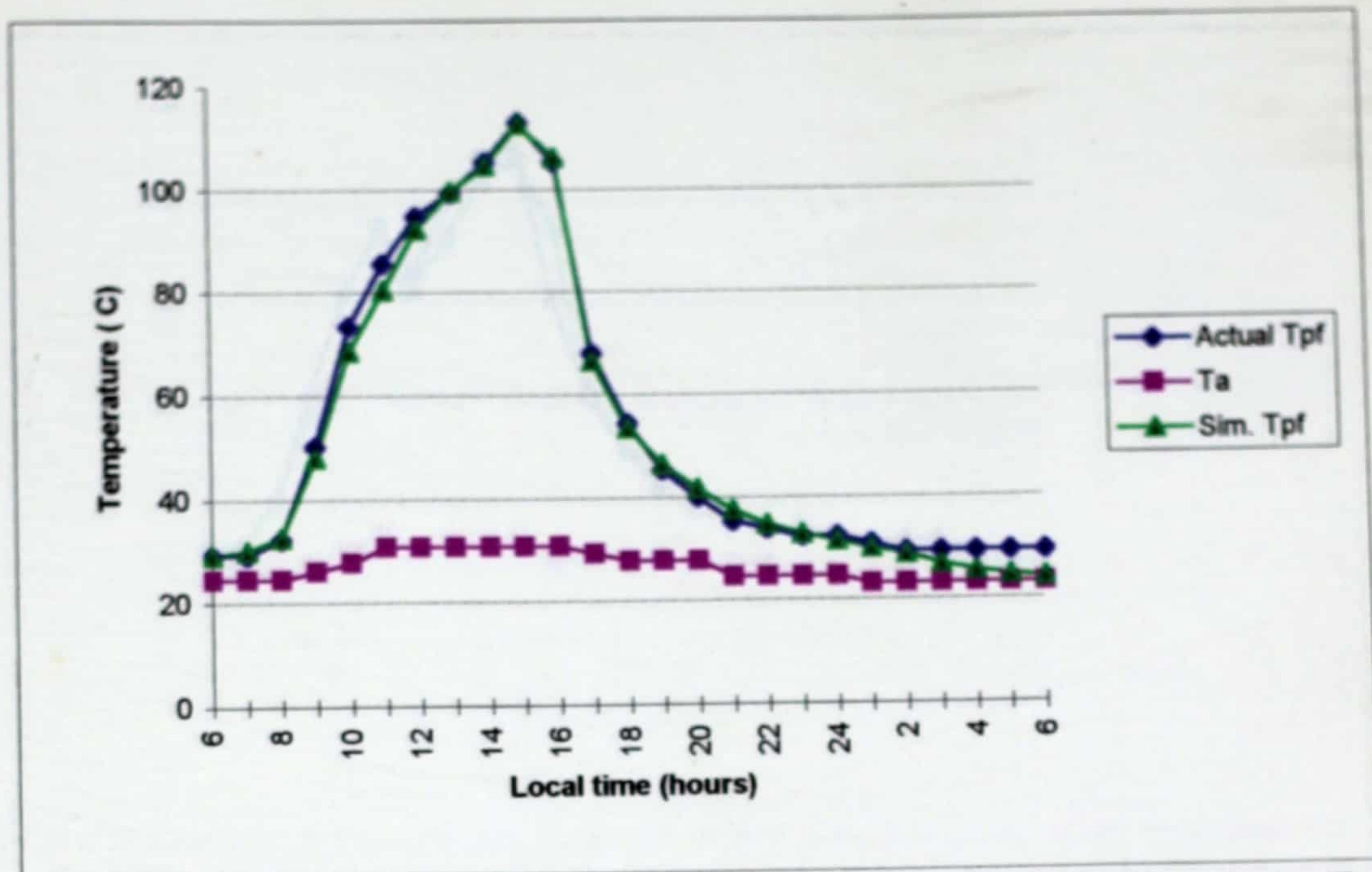


Fig.8.11 Comparison of the simulated and the actual collector plate temperatures (Tpf) of the AIT charcoal/methanol solar refrigerator(test date 29th Oct.1987)

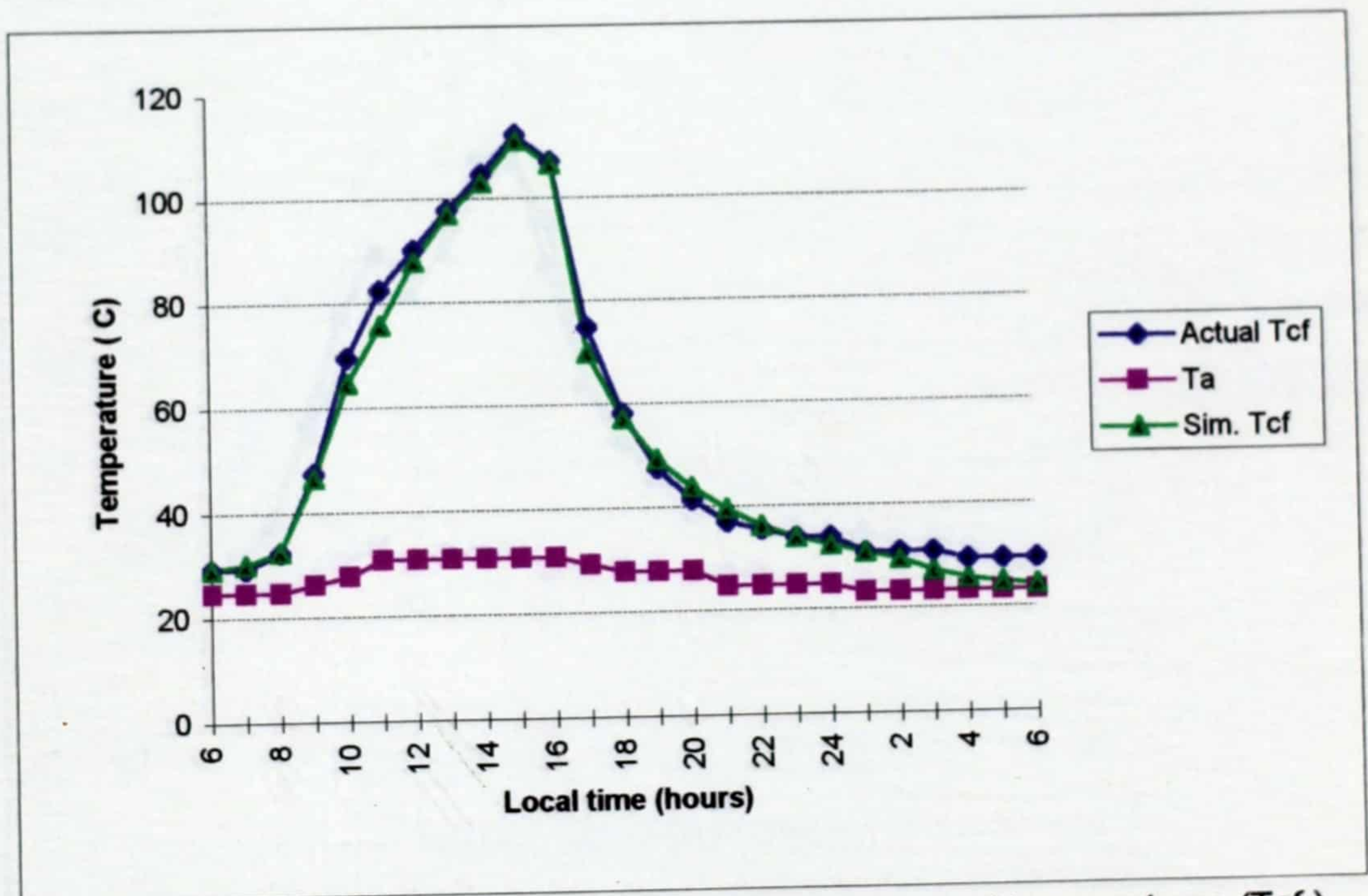


Fig. 8.12 Comparison of the simulated and the actual charcoal temperatures (Tcf) of the AIT charcoal/methanol solar refrigerator (test date, 29th Oct. 1987)

(Note: Graphs original in colour)

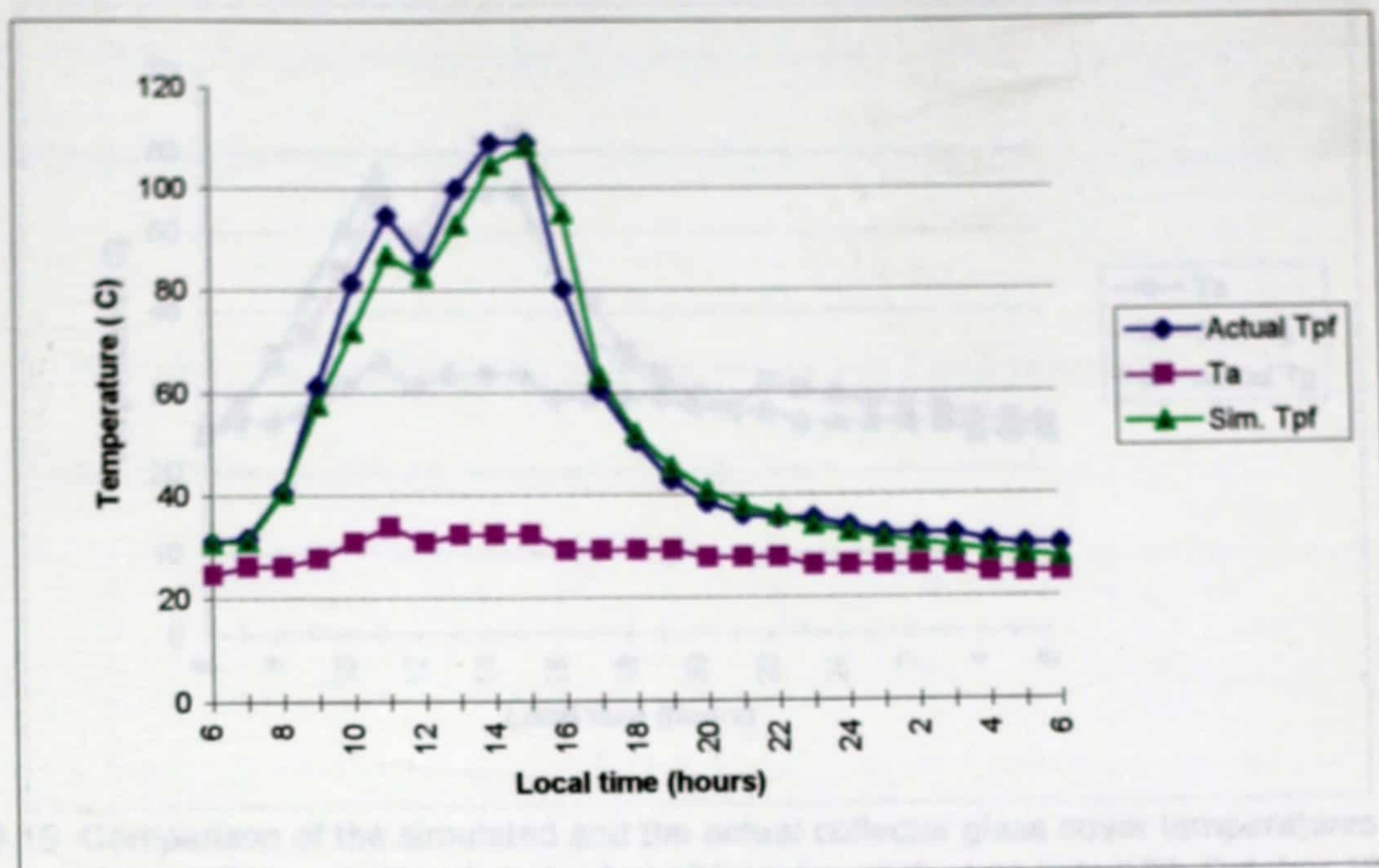


Fig. 8.13 Comparison of the simulated and the actual collector plate temperatures (Tpf) of the AIT charcoal/methanol solar refrigerator, of the test date 17th Oct. 1987

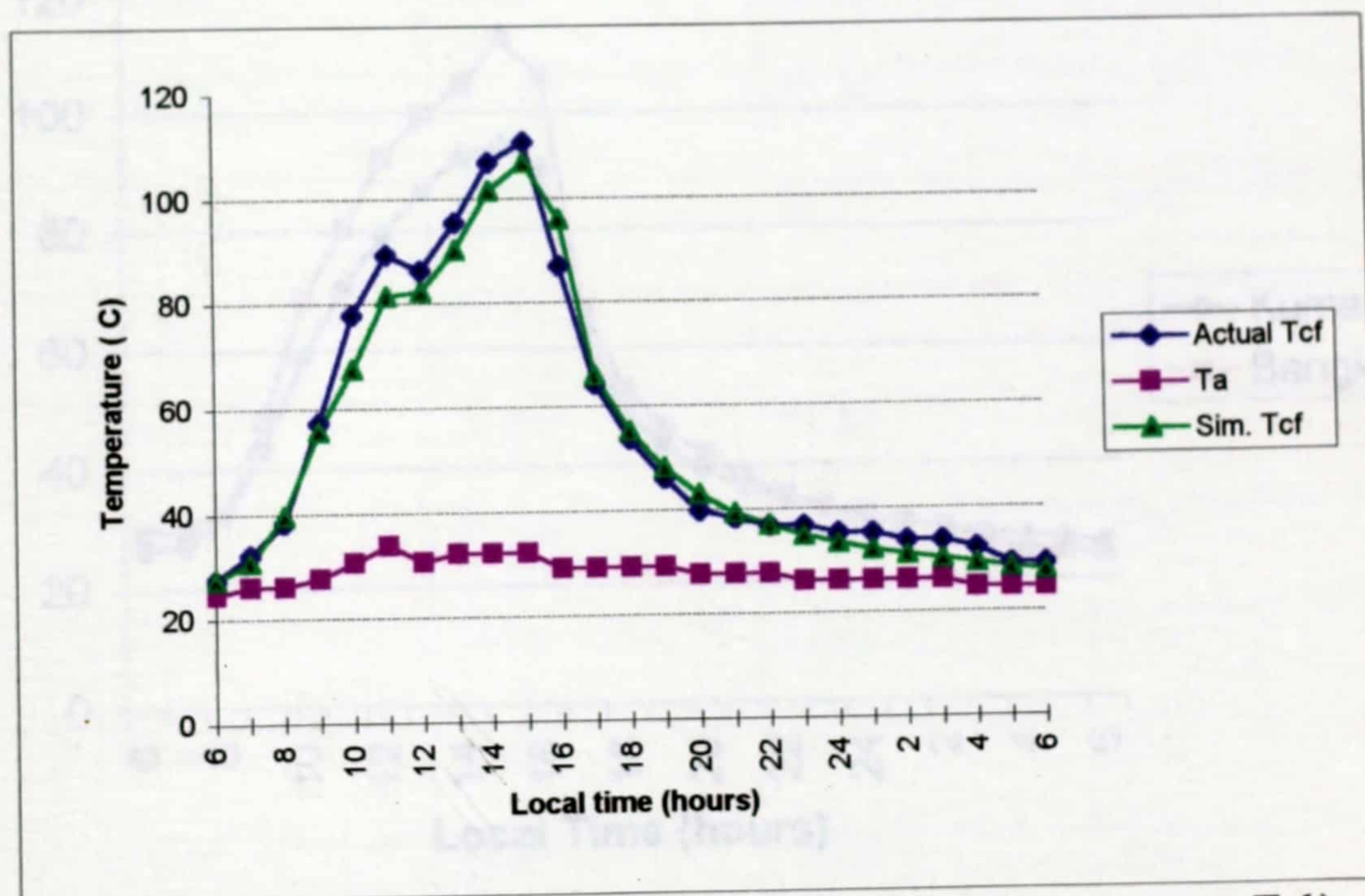


Fig. 8.14 Comparison of the simulated and the actual charcoal temperatures (Tcf) of the AIT charcoal/methanol solar refrigerator, of the test date 17th Oct. 1987

(Note: Graphs original in colour)

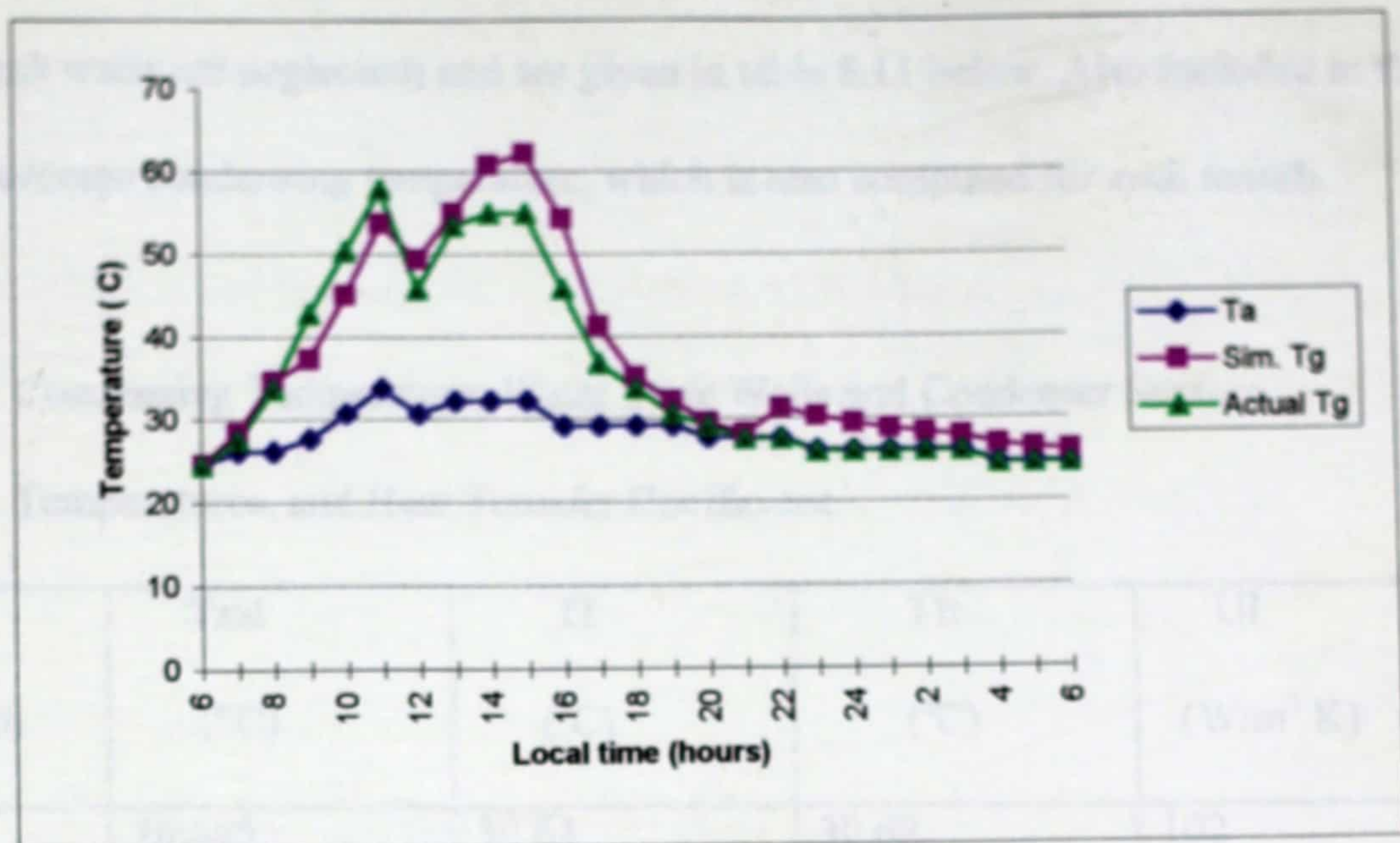


Fig. 8.15 Comparison of the simulated and the actual collector glass cover temperatures (T_g) of the AIT charcoal/methanol solar refrigerator, of the test date 17th October 1987

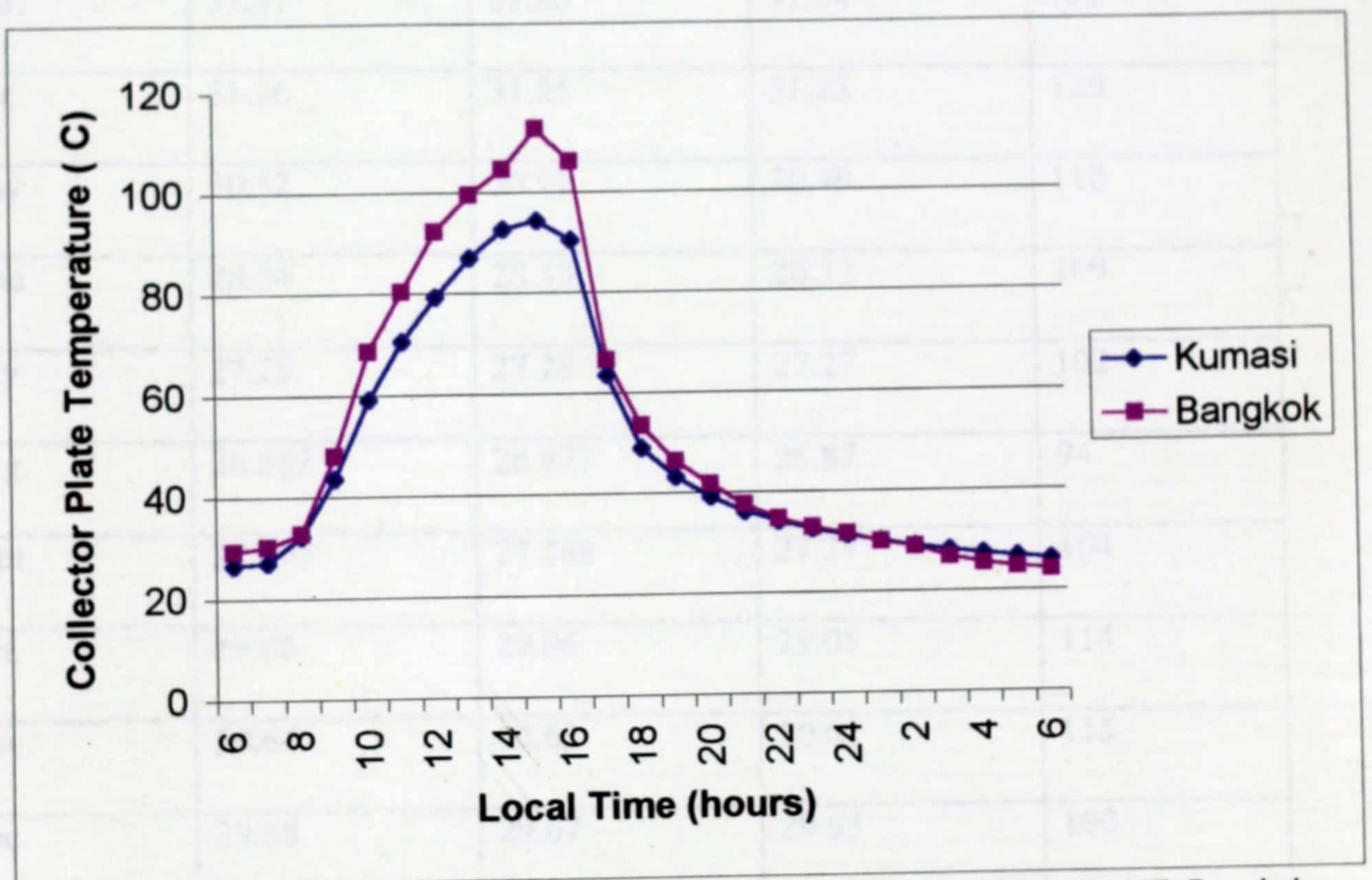


Fig. 8.16 Graph of simulated collector plate temperatures against time for the AIT, Bangkok, solar refrigerator (29th Oct. 1987 temperatures; $I=5.467$ kWh/m-day) and the theoretical model for Kumasi (April temperatures; $I=5.03$ kWh/m-day)

(Note: Graphs original in colour)

and water tank walls are neglected) and are given in table 8.11 below. Also included in the table is the average condensing temperature, which is also computed for each month.

Table 8.11 Condensing Temperature, Water Tank Walls and Condenser Surface Temperatures, and Heat Transfer Coefficient.

Month	T _{sat} (°C)	T _I (°C)	T _E (°C)	UI (W/m ² .K)
Jan.	30.645	30.64	30.62	102
Feb.	32.92	32.91	32.9	116
Mar.	31.87	31.86	31.84	121
Apr.	31.26	31.25	31.23	120
May	30.52	30.51	30.49	118
June	28.34	28.33	28.32	109
July	27.29	27.28	27.27	102
Aug.	26.882	26.877	26.87	94
Sept.	27.295	27.288	27.27	104
Oct.	29.08	29.06	29.05	114
Nov.	30.64	30.63	30.62	115
Dec.	29.68	29.67	29.65	100

8.2 Results from Evaporator Box Design Programme

The dimensions of the evaporator box and the evaporator, chosen finally in the running of the evaporator box design programme are given in table 8.8.

The maximum amount of ice that could be produced in the cold chamber each night (6pm – 6am) in March, June and August are computed, and are given in table 8.12.

Table 8.12 Ice Production

Month	Max. mass of ice that could be produced each night kg	Final temp. of ice (at 6am) °C	Initial temp. of water and cold chamber (at 6pm) °C	Tev °C
March	3.73	0	30.5	-1.3
June	2.74	0	26.2	-3
August	1.25	0	25.6	-4

The maximum mass of fresh fish (or pork or lamb) that could be stored overnight (6pm – 6am) to freezing temperature in the cold chamber in March, June and August are also computed, and are given in table 8.13. Though in March the average evaporating temperature, T_{ev} , is -1.3°C , the evaporating temperature will fall quite below -2°C .

Table 8.13 Fresh Fish Storage

Month	Max. mass of fish that could be stored each night kg	Final temp. of fish (at 6am) °C	Initial temp. of fish and cold chamber (at 6pm) °C	Tev °C
March	4.45	-2	30.5	-1.3
June	3.23	-2	26.2	-3
August	1.43	-2	25.6	-4

The amount of tomatoes that could be stored above freezing temperatures in the cold chamber in March, June and August, and the storage temperatures involved, are computed and are shown in tables 8.14 to 8.16.

Table 8.14 Tomato Storage in March (in three days)

	Time period	Tomatoes already in cold chamber, before the period kg	Fresh tomatoes to be placed in cold chamber at start of period kg; °C	Total mass of tomatoes in cold chamber kg	Temperature of tomatoes and cold chamber at end of period °C
1 st Night	6pm-6am	-	14.2; 30.5	14.2	0
2 nd Day	6am-3pm	14.2	-	14.2	7.6
"	3pm-6pm	14.2	-	14.2	11.2
2 nd Night	6pm-6am	14.2	8.5; 30.5	22.7	0
3 rd Day	6am-3pm	22.7	-	22.7	5.1

3 rd Day	6am-3pm	22.7	-	22.7	5.1	-
"	3pm-6pm	22.7	-	22.7	7.7	-
3 rd Night	6pm-6am	22.7	7.9; 30.5	30.6	0	-1.3

Table 8.15 Tomato Storage in June (in four days)

	Time period	Tomatoes already in cold chamber, before the period kg	Fresh tomatoes to be placed in cold chamber at start of period kg; °C	Total mass of tomatoes in cold chamber kg	Temperature of tomatoes and cold chamber at end of period °C	Tev °C
1 st Night	6pm-6am	-	11.6; 26.2	11.6	0	-3
2 nd Day	6am-3pm	11.6	-	11.6	8	-
"	3pm-6pm	11.6	-	11.6	11.2	-
2 nd Night	6pm-6am	11.6	6.1; 26.2	17.7	0	-3
3 rd Day	6am-3pm	17.7	-	17.7	5.7	-
"	3pm-6pm	17.7	-	17.7	8.2	-
3 rd Night	6pm-6am	17.7	5.4; 26.2	23.1	0	-3
4 th Day	6am-3pm	23.1	-	23.1	4.5	-
"	3pm-6pm	23.1	-	23.1	6.6	-
4 th Night	6pm-6am	23.1	5.1; 26.2	28.2	0	-3

Table 8.16 Tomato Storage in August (in five days)

	Time period	Tomatoes already in cold chamber, before the period kg	Fresh tomatoes to be placed in cold chamber at start of period kg; °C	Total mass of tomatoes in cold chamber kg	Temperature of tomatoes and cold chamber at end of period °C	Tev °C
1 st Night	6pm-6am	-	5.4; 25.6	5.4	0	-4
1 st Day	6am-3pm	5.4	-	5.4	13	-
"	3pm-6pm	5.4	-	5.4	16.2	-
2 nd Night	6pm-6am	5.4	1.5; 25.6	6.9	0	-4
2 nd Day	6am-3pm	6.9	-	6.9	11.1	-
"	3pm-6pm	6.9	-	6.9	14.3	-
3 rd Night	6pm-6am	6.9	0.95; 25.6	7.8	0	-4
3 rd Day	6am-3pm	7.8	-	7.8	10.2	-
"	3pm-6pm	7.8	-	7.8	13.2	-
4 th Night	6pm-6am	7.8	0.7; 25.6	8.5	0	-4
4 th Day	6am-3pm	8.5	-	8.5	9.6	-
"	3pm-6pm	8.5	-	8.5	12.5	-
5 th Night	6pm-6am	8.5	0.5; 25.6	9	0	-4

8.3 Pressure Drop in the Solar Refrigerator Tubes

The flow of methanol vapour from one area to another in the tubes of the solar refrigerator will be against friction. If the pressure of the methanol vapour is not able to overcome the friction, the motion will cease. The flow of very low pressure methanol vapour is more likely to be adversely affected by friction. The lowest pressures in the refrigerator occur in the night during the evaporation and the adsorption processes.

The average evaporating pressure in August (Kumasi) is the lowest. The pressure is about 0.0314 bar and the average evaporating temperature is also about -4° C.

Average mass flow rate during evaporation/adsorption:

$$\dot{m} = \frac{Mc.(X \text{ max} - X \text{ min})}{3600.t_1} \dots\dots\dots 8.1$$

Average velocity of methanol vapour:

$$V = \frac{\dot{m}.v}{A} = \frac{4\dot{m}.v}{\pi D^2} \dots\dots\dots 8.2$$

Reynolds number:

$$Re = \frac{V.D}{\nu} = \frac{4\dot{m}}{\pi D.\mu} \dots\dots\dots 8.3$$

The average viscosity of the methanol vapour (in the night) flowing in the condenser tube and the connecting tube between the condenser and the collector during the evaporation and the adsorption processes is estimated with the method of Chung et al (see Reid et al, 1987) to be about 9.66x10⁻⁶ Pa.sec for August. The average specific volume of the methanol vapour in the tubes is also estimated to be about 24.4 m³ /kg.

The average mass flow rate of methanol vapour in August during adsorption, using

Equation 8.1 to calculate, with $t_1 = 12$, is about 1.825×10^{-5} kg/s. The Reynolds numbers (using equation 8.3 to calculate) for the flows in the condenser tube (2.5 cm, ID) and the connecting tube (3 cm, ID) between the condenser and the collector are 95 and 80 respectively for August. The Reynolds numbers are less than 2000 for both tubes and therefore the flows are laminar.

Friction factor for laminar flow:

$$f = 16/Re \dots\dots\dots 8.4$$

Pressure (piezometric) drop per unit length due to friction is:

$$\frac{dP^*}{dx} = \frac{4f.V^2}{2v.D} \dots\dots\dots 8.5$$

$$\frac{dP^*}{dx} = \frac{32\mu.V}{D^2} \dots\dots\dots 8.6$$

In the condenser tube and the connecting tube between the condenser and the collector, the pressure drops per unit length due to friction, using Equations 8.2 and 8.6 to calculate, are about 0.43 Pa/m (0.43×10^{-5} bar/m) and 0.21 Pa/m respectively for August.

In the connecting tube between the condenser and the evaporator (2.5 cm, ID), the pressure drop per unit length for August is about 0.35 Pa/m (the estimated average for μ and v for August are about 8.8×10^{-6} Pa.sec and $22 \text{ m}^3/\text{kg}$ respectively).

The pressure drop of the methanol vapour in the charcoal would be very small, since the thickness of the charcoal given by the difference between the radii of the outer tube and the inner tube of the collector plate is small, about 22 mm.

The friction against the flow of methanol vapour in the solar refrigerator would be negligible (the condenser and the connecting tubes are less than 8 m long) and the flow would not be hindered.

CHAPTER 9

THE DESIGNED CHARCOAL/METHANOL SOLAR REFRIGERATOR

9.1 Introduction

A charcoal/methanol solar refrigerator is designed based on the collector simulation and the evaporator box design results given in chapter 8. The design is shown in fig. 9.1. It consists of a solar collector, a condenser in a tank of water, and an evaporator box containing an evaporator. The design and how it is to be constructed are described in this chapter. The construction and test of the refrigerator do not form part of the project.

9.2 Solar Collector

The solar collector is shown in fig. 9.2. It consists of:

- (i) a collector plate containing activated charcoal
- (ii) a wooden box, with insulation in the sides and bottom, containing the collector plate
- (iii) a glass cover (glass in a wooden frame) covering the top of the wooden box and,
- (iv) a rubber gasket (seal) between the glass cover and the wooden box

The collector plate, shown in fig. 9.3, consists of fourteen stainless steel outer tubes (OD=6 cm, ID=5.7 cm) to be welded together, fourteen stainless steel inner tubes (OD=14 mm, ID=10.4 mm) centrally placed in the outer tubes, and a stainless steel header tube (OD=3.3 cm, ID=3 cm) to be welded to the inner tube ends extending from the outer tubes. The inner tubes open into the header tube. Stainless steel cover plates (not more than 3 mm thick) are to be welded to the ends of the outer tubes. The header tube is also to be welded at one end to a cover plate and at the other end to an adaptor. The adaptor is connected, by PVC pipe and a rubber hose, to another adaptor, which is to be welded at the

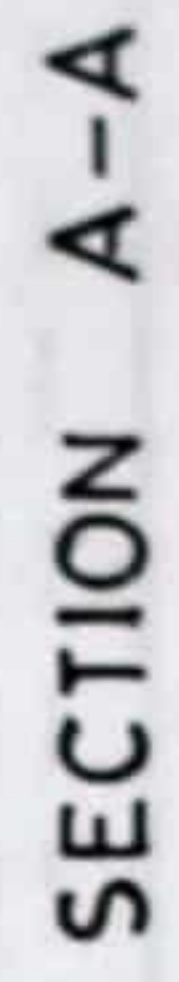


FIG. 9.2 SOLAR COLLECTOR

opposite end to a stainless steel tube, which leads to the condenser. Activated charcoal fills the annular spaces between the outer and the inner tubes. The surfaces of the inner tubes inside the outer tubes are perforated for methanol vapour to flow through. This ensures even distribution of methanol vapour in the charcoal during adsorption.

The estimated masses of the collector plate tubes and the charcoal are given in table 8.7. The surface area of the collector plate (ie $L \times LW$) is about 1 m^2 .

Copper tubes should not be used in making the collector plate, though copper has a lower specific heat capacity and far higher thermal conductivity than stainless steel. This is because copper catalyses the decomposition of methanol to formaldehyde and dimethyl ether (section 2.2.3). These products if formed in the solar refrigerator will cause its performance to deteriorate.

The top surface of the collector plate (ie outer tubes top surface) is to be covered with SOLKOTE Hi/Sorb-II optical coating to form a selective surface. The solar absorptance will range from 0.92 to 0.97, and the long-wave emittance from 0.28 to 0.49. The bottom surface of the outer tubes is to be painted black (with black paint) for the effective dissipation of heat by the collector plate during the night when the bottom insulation is lowered/removed.

The collector wooden box is to be made with hard wood of thickness 1.6 cm ($\frac{5}{8}$ "). Insulation is to be provided in the sides and bottom of the box (for the insulation of the collector plate). The insulation material is jute fibre or wool. The bottom insulation, which is beneath the collector plate outer tubes, can be lowered and it consists of a 1.3 cm ($\frac{1}{2}$ ") thick plywood container filled with insulation.

The glass cover is a 3 mm ($\frac{1}{8}$ ") glass sheet fitted (at the sides) into a 1.6 cm thick hard wood frame. The glass cover (fig. 9.2) covers the top of the wooden box, and there is a rubber seal (gasket) between the glass cover frame and the wooden box. The space above the top surface of the collector plate outer tubes is covered by glass only.

The wooden surface of the solar collector has to be painted with oil paint to prevent early decay of the wood and extend the life span of the collector. The solar collector is to be inclined towards the south at an angle of 7° to 10° to the horizontal (ie for Kumasi).

9.3 Condenser and Water Tank

The condenser is to be made with 2.9 cm OD (ID 2.5 cm) and 10.5 cm OD (ID 9.8 cm) copper tubes of lengths 380 cm and 40 cm respectively. The 2.9cm tube is shaped in the form as shown in fig. 9.4. The 10.5cm tube forms the lower end of the condenser and also serves as the receiver (for liquid methanol). The condenser is fixed in a tank full of water.

The tank is cubical of side 115 cm, and is to be made with 1.6 mm ($\frac{1}{16}$ ") galvanized steel plates. A shed has to be provided for the water tank to prevent it from being heated up in the sun.

9.4 Evaporator and Evaporator Box

The evaporator is to be made with 1.6 mm brass sheet and it has the cross-section as shown in fig. 9.5. The evaporator is suspended from the top of the cold chamber in the evaporator box.

The evaporator box (fig. 9.5) has inside and outside walls with insulation between them. The insulation material is jute fibre or wool. If polyurethane foam is available it should be

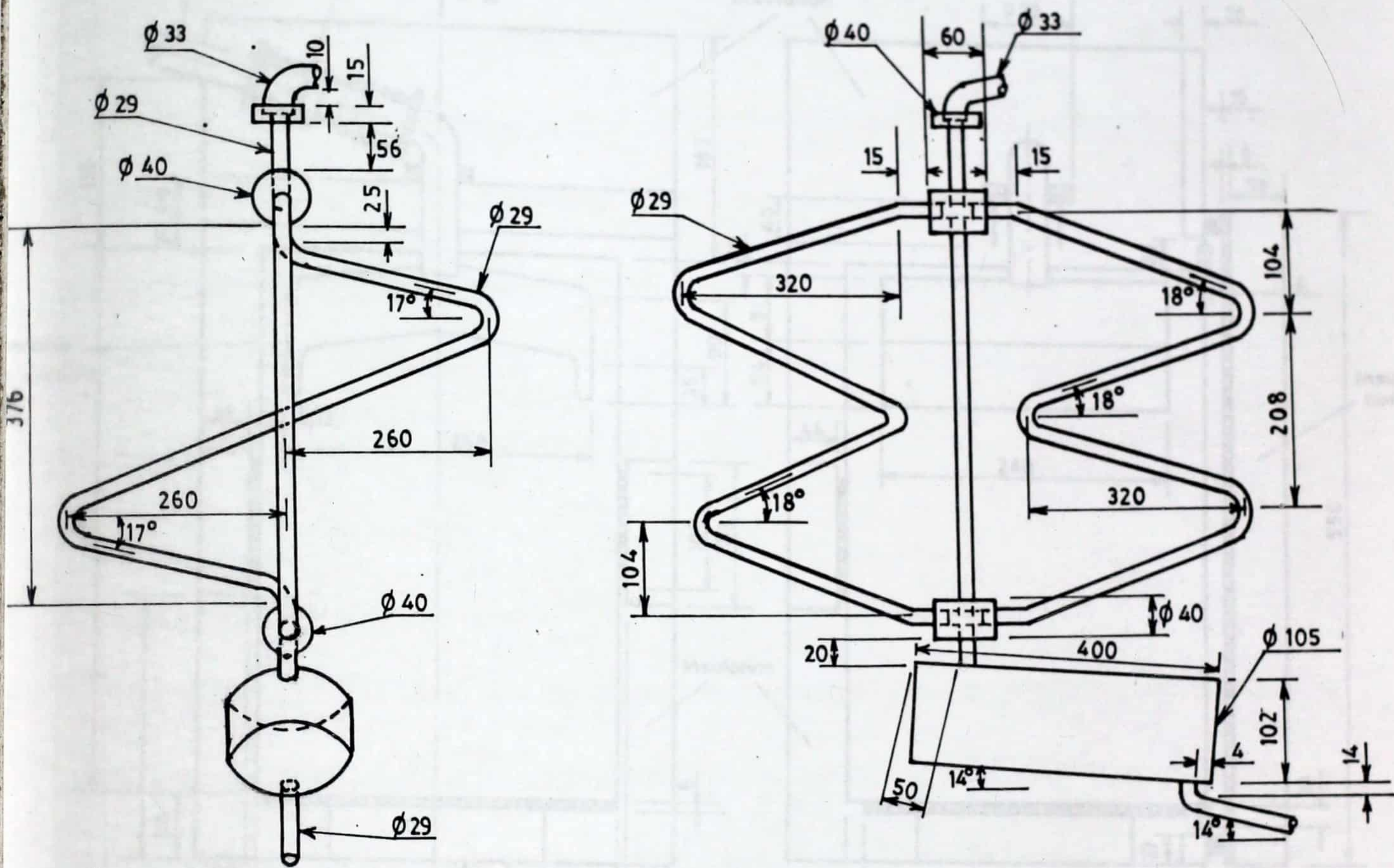


FIG. 9.4 CONDENSER

ALL DIMENSIONS IN mm

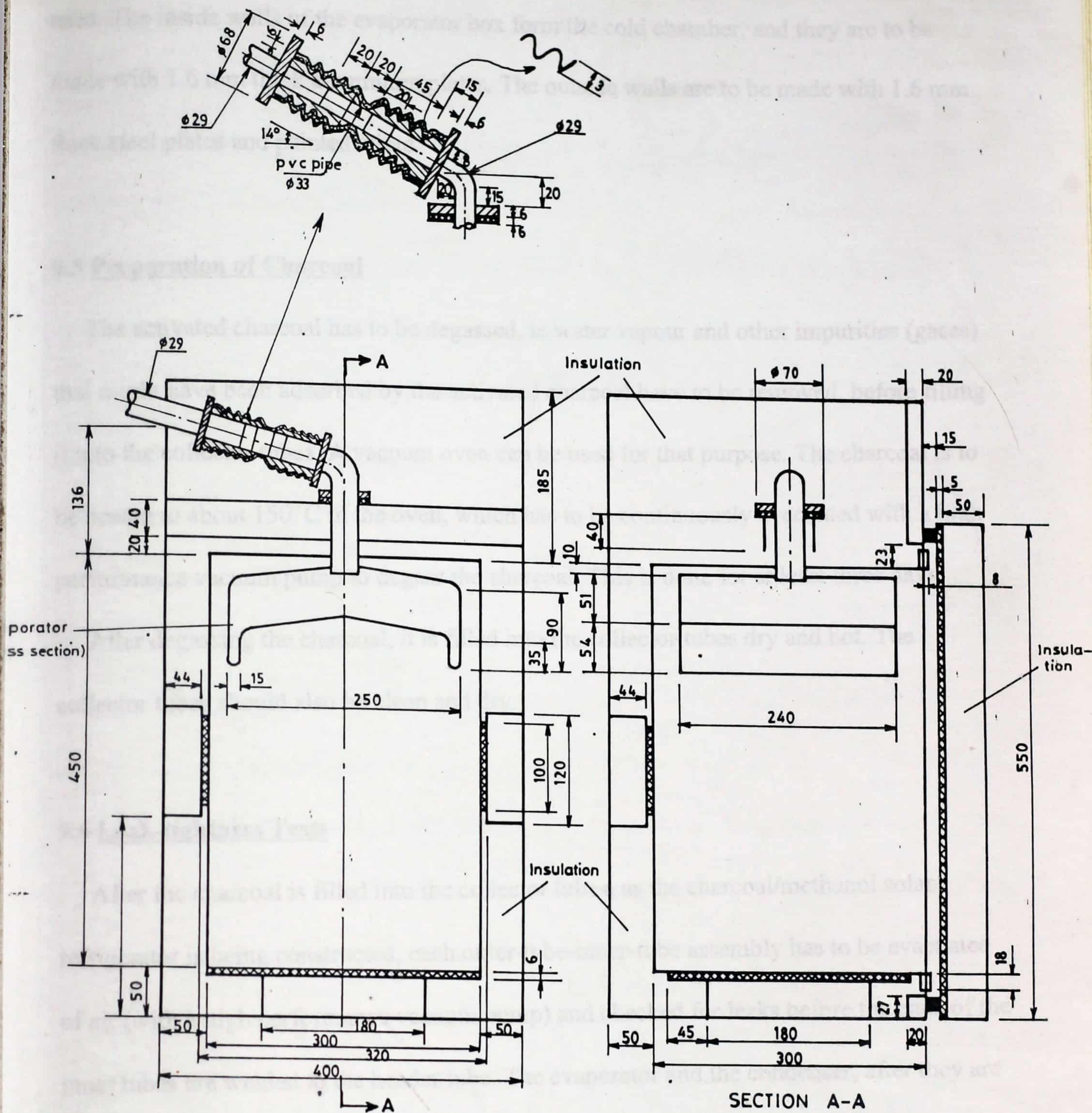


Fig. 9.5 EVAPORATOR BOX

ALL DIMENSIONS IN mm

used. The inside walls of the evaporator box form the cold chamber, and they are to be made with 1.6 mm thick aluminium plates. The outside walls are to be made with 1.6 mm thick steel plates and painted white.

9.5 Preparation of Charcoal

The activated charcoal has to be degassed, ie water vapour and other impurities (gases) that might have been adsorbed by the activated charcoal have to be removed, before filling it into the collector tubes. A vacuum oven can be used for that purpose. The charcoal is to be heated to about 150° C in the oven, which has to be continuously evacuated with a high performance vacuum pump to degass the charcoal. This is done for at least three days.

After degassing the charcoal, it is filled into the collector tubes dry and hot. The collector tubes should also be clean and dry.

9.6 Leak-tightness Tests

After the charcoal is filled into the collector tubes, as the charcoal/methanol solar refrigerator is being constructed, each outer-tube-inner-tube assembly has to be evacuated of air (with a high performance vacuum pump) and checked for leaks before the ends of the inner tubes are welded to the header tube. The evaporator and the condenser, after they are made, before assembling them in the evaporator box and the water tank respectively, are also to be tested under pressure as well as under vacuum conditions for leaks.

After the whole solar refrigerator is assembled, the system has to be evacuated of air (to a pressure of less than 10^{-2} torr) and checked for vacuum tightness over a period of at least three days.

9.7 Degassing the Charcoal in the Collector and Charging with Methanol

After the charcoal/methanol solar refrigerator is constructed, the charcoal in the collector tubes should be degassed by placing the refrigerator in the sun (to heat up the collector plate and the charcoal) and continuously evacuate it of gases. An evacuating system with a methanol feeding arrangement as shown in fig. 9.6 (schematic diagram) is to be used (Exell et al, 1993). The degassing is done for several days to ensure the gases in the deep pores of the charcoal are also driven out. The methanol feeding bottle is separately evacuated of air and a small amount of methanol is allowed to boil to ensure that no dissolved air remains in the methanol.

After degassing the charcoal, with the refrigerator and the methanol feeding bottle evacuated of air, about four litres (3.12 kg) of methanol from the methanol feeding bottle is charged into the refrigerator in the night. Valves (fig. 9.6) are operated to connect the methanol feeding bottle to the refrigerator so that the charcoal in the collector plate adsorbs the methanol from the feeding bottle. During the adsorption the temperature of the methanol feeding bottle will fall and it may be necessary to warm the bottle to maintain its temperature close to the atmospheric temperature. The collector bottom insulation is to be lowered during the adsorption to enhance heat dissipation by the collector plate. The liquid methanol could also be charged from the methanol feeding bottle directly into the evaporator. The methanol will then be adsorbed from the evaporator. The methanol concentration in the charcoal after complete adsorption of the four litres methanol will be about 0.16.

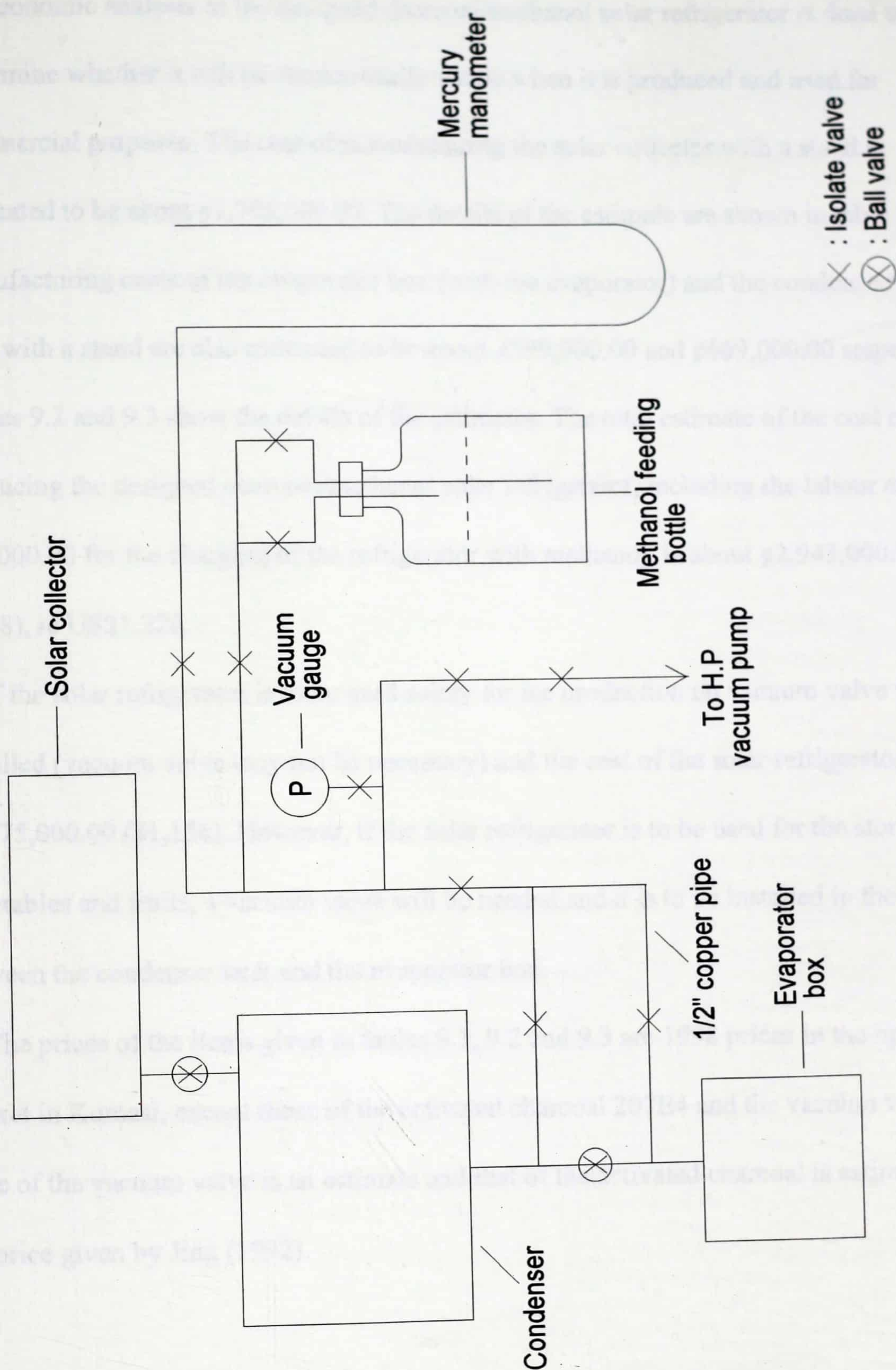


Fig. 9.6 Schematic diagram showing an evacuating system with a methanol feeding arrangement

9.8 Economic Analysis

Economic analysis of the designed charcoal/methanol solar refrigerator is done to determine whether it will be economically viable when it is produced and used for commercial purposes. The cost of manufacturing the solar collector with a stand is estimated to be about ₦1,795,000.00. The details of the estimate are shown in table 9.1. The manufacturing costs of the evaporator box (with the evaporator) and the condenser/water tank with a stand are also estimated to be about ₦399,000.00 and ₦669,000.00 respectively. Tables 9.2 and 9.3 show the details of the estimates. The total estimate of the cost of producing the designed charcoal/methanol solar refrigerator, including the labour cost of ₦80,000.00 for the charging of the refrigerator with methanol, is about ₦2,943,000.00 (1998), ie US\$1,226.

If the solar refrigerator is to be used solely for ice production no vacuum valve will be installed (vacuum valve may not be necessary) and the cost of the solar refrigerator will be ₦2,775,000.00 (\$1,156). However, if the solar refrigerator is to be used for the storage of vegetables and fruits, a vacuum valve will be needed and it is to be installed in the pipe between the condenser tank and the evaporator box.

The prices of the items given in tables 9.1, 9.2 and 9.3 are 1998 prices in the open market in Kumasi, except those of the activated charcoal 207E4 and the vacuum valve. The price of the vacuum valve is an estimate and that of the activated charcoal is estimated from the price given by Jing (1992).

Table 9.1 Estimated Cost of Solar Collector and a Stand

Quantity	Item	Cost ¢
2 ³ / ₄	610cm long, 6cm OD, 5.7cm ID stainless steel pipe	437,000.00
2 ⁵ / ₆	610cm long, 14mm OD, 10.4mm ID, stainless steel pipe	96,000.00
1	210cm long, 3.3cm OD (1.315") stainless steel pipe	31,000.00
19.5 kg	207E4 activated charcoal	609,000.00
4 litres	methanol	87,000.00
1	13cm long, ϕ 5cm stainless steel rod	8,000.00
1	14cm x 7cm x 0.3cm (¹ / ₈ " thick) brass plate	6,000.00
1 quart	SOLKOTE Hi /Sorb-II Selective Coating	48,000.00
2 ¹ / ₂ galls.	Oil paint	65,000.00
1	123cm x 91cm x 0.3cm (¹ / ₈ " thick) glass sheet	20,000.00
1	450cm long rubber gasket	20,000.00
	Insulation (Jute fibre)	10,000.00
2	255cm x 10cm x 5cm hard wood	5,000.00
13	240cm x 19cm x 1.6cm (⁵ / ₈ " thick) hard wood	19,000.00
6	128cm x 39cm x 1.6cm (⁵ / ₈ " thick) hard wood	12,000.00
6	160cm x 12cm x 12cm hard wood	27,000.00
1	135cm x 105cm x 1.3cm (¹ / ₂ " thick) plywood	15,000.00
	Labour and others	280,000.00
	Total	1,795,000.00

(Note: Based on 1998 prices in Kumasi)

Table 9.2 Estimated Cost of Evaporator Box

Quantity	Item	Cost ¢
1	25cm long, 2.5cm ID (0.995") copper pipe	4,000.00
2	13cm long, ϕ 5cm brass rod	50,000.00
1	24cm x 10cm x 0.6cm ($\frac{1}{4}$ " thick) brass plate	27,000.00
1	80cm x 40cm x 0.16cm ($\frac{1}{16}$ " thick) brass plate	85,000.00
1	200cm x 35cm x 0.16cm ($\frac{1}{16}$ " thick) aluminium sheet	12,000.00
1	243.8cm x 80cm x 0.16cm ($\frac{1}{16}$ " thick) steel plate	40,000.00
1	40cm x 38cm x 0.6cm ($\frac{1}{4}$ " thick) plastic	4,000.00
1	55cm x 40cm x 0.5cm ($\frac{3}{16}$ " thick) plastic	5,000.00
1	45cm x 18cm x 0.3cm ($\frac{1}{8}$ " thick) plastic	2,000.00
1	185cm long rubber gasket	20,000.00
	Insulation (Jute fibre)	4,000.00
1 gallon	Oil paint	26,000.00
	Labour and others	120,000.00
	Total	399,000.00

(Note: Based on 1998 prices in Kumasi)

Table 9.3 Estimated Cost of Condenser/Water Tank and a Stand

Quantity	Item	Cost ¢
1	460cm long, 2.5cm ID (0.995") copper pipe	75,000.00
1	40cm long, 9.8cm ID (3.857") copper pipe	48,000.00
1	Vacuum valve	168,000.00
3	243.8cm x 121.9cm x 0.16cm ($\frac{1}{16}$ " thick) galvanized steel sheet	240,000.00
3	128cm x 39cm x 1.6cm ($\frac{5}{8}$ " thick) hard wood	6,000.00
9	44cm x 10cm x 10cm hard wood	9,000.00
1	115cm x 12cm x 9cm hard wood	3,000.00
	Labour and others	120,000.00
	Total	669,000.00

(Note: Based on 1998 prices in Kumasi)

Estimated labour cost of charging the solar refrigerator with methanol = ¢80,000.00

Total estimated cost of solar refrigerator = ¢2,943,000.00 (1998)

(US\$1,226)

The economic viability of the charcoal/methanol solar refrigerator can be determined using the Net Present Value (NPV) method. The NPV can be expressed as (see Duffie and Beckman, 1991; Jing, 1992):

$$NPV = (INC - EXP)(1 + f) \frac{1}{DR - f} \left(1 - \left(\frac{1 + f}{1 + DR} \right)^N \right) - IC + RV \frac{(1 + f)^N}{(1 + DR)^N}$$

where,

NPV: Net present value

INC: Annual income (known as of the beginning of the first time period)

EXP: Annual expenditure (known as of the beginning of the first time period)

IC: Investment cost (the time period the investment is made is taken as zero)

N: Service life of project (or business) or number of compounding periods

DR: Market discount rate

f: General inflation rate

RV: Residual value of project (or business)

The project is profitable when over its service life (ie life span) $NPV > 0$. The number of years less than the project life span that makes NPV equal to zero (RV not included) is the investment payback period, and after this period the investment will be yielding profits.

For the charcoal/methanol solar refrigerator, EXP is taken as zero. In Ghana the general inflation rate is about 25%. Interest rate on borrowed money has been taken as the market discount rate. The effective interest rate per year is taken as 32%.

If the solar refrigerator is to be used for ice production (in Kumasi), it is assumed that for a year the ice production (per day) will be about 2.74 kg ice per day, which is the

average ice production in June. This assumption is made as the average daily global solar radiation in June is about the same as the average of the monthly daily global radiation of all the months and also as the average refrigerator COP in June is about the same as the average of the refrigerator COP of all the months. The price of ice is ¢270/kg (1998), and taking 365 days of ice production in the year, the payback period will be about 16 years (using the NPV method and noting that $IC = \text{¢}2,775,000$) which is less than the life-span of a solar refrigerator, estimated to be 20-25 years.

If the solar refrigerator is to be used for the storage of tomatoes (see section 8.2) it is assumed that in a year about 5kg of tomatoes (which could be more) per week will be saved from getting spoilt. And taking the average price of tomatoes to be ¢1,500/kg (1998), and for the 52 weeks in the year, the savings in a year will be ¢390,000. It will take (using the NPV method) about 10 years for the savings to pay back the cost of the solar refrigerator ($IC = \text{¢}2,943,000$).

The charcoal/methanol solar refrigerator will be economically viable when produced and used for commercial purposes. The cost of producing the solar refrigerator may be very much reduced if the activated charcoal is produced locally in Ghana. The activated charcoal 207E4, manufactured in UK, is very expensive, though it is suitable for making charcoal/methanol solar refrigerators for use in Ghana.

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

10.1 Conclusions

This research clearly demonstrates that the collector simulation computer programme is quite effective. It can be used to design and predict the performance of a charcoal/methanol solar refrigerator and consequently optimize the design parameters.

The performance of the collector of the AIT solar refrigerator on 17th and 19th October 1987 is simulated with the above mentioned collector simulation programme and the results are compared with the experimental data (published). The comparison shows that the simulated collector temperatures are very close to the actual collector temperatures. It is seen that the simulated temperatures adequately represent the actual temperatures. It is noted that the average deviations between the simulated and the actual temperatures of the collector plate and the charcoal (from 6am to 6am ie 24 hours) are about 1.8° C and 2° C respectively for 29th October 1987 and about 3° C each for 17th October 1987. The overall COP computed by the simulation programme for 29th October 1987 is 0.138 and that calculated using the test results is 0.145; the two values are thus very close. The collector simulation programme is validated.

The computer simulated collector plate temperatures (T_{pf}) for April, Kumasi, are compared with the simulated AIT collector plate temperatures for 29th October 1987. The temperatures are close to each other with the April (Kumasi) temperatures being lower. This is so as the average daily global solar radiation for April, which is 5.03 kWh/m²-day, the highest for Kumasi is lower than, though close to, the incident global radiation for 29th October 1987, Bangkok, which is 5.47 kWh/m²-day. The average deviation (absolute values

are used) between the simulated collector plate temperatures for April, Kumasi, and 29th October 1987, Bangkok, is about 5°C. As the AIT charcoal/methanol solar refrigerator operated successfully in Bangkok (Exell et al, 1993), it is expected that when the designed charcoal/methanol solar refrigerator (chapter 9) is built it will also operate successfully in Kumasi. This indicates that it is highly probable charcoal/methanol solar refrigeration will be feasible in Ghana.

The simulation results for Kumasi show that the average incident total radiation (ITT) on the collector ($\beta = 6.72^\circ$) in June of 4.07 kWh/m²-day is about the same as the average of the incident radiation (ITT) of all the months. The refrigeration effect (Q_e) and the overall COP in June are about 1,600 kJ and 0.107 respectively; and these values also happen to be about the same as the averages of the refrigeration effects and the COP of all the months. The overall collector efficiency in May of 0.314 however happens to be the average for the year and that for June is 0.308 which is a bit lower. The ITT and the overall collector efficiency in August of 3.06 kWh/m²-day and 0.29 respectively are the lowest for the year; thus the refrigeration effect and the overall COP in August of about 900 kJ and 0.08 respectively are also the lowest for the year. August also has the lowest average evaporating temperature (T_{ev}) which is about -4°C. March and April have the highest ITT of about 5 kWh/m²-day. Thus the refrigeration effect of about 2,100 kJ for March happens to be the highest for the year. The overall collector efficiency and the overall COP in October, which are 0.33 and 0.12 respectively, are the highest for the year. February also has the highest average evaporating temperature for the year, which is about -1°C, since February has the highest atmospheric temperatures in the year.

The results produced with the evaporator box design programme show that the designed

charcoal/methanol solar refrigerator (1m^2 surface area) when built will on the average distil about 1.384 kg methanol a day and produce about 2.74 kg ice a day or freeze and so preserve about 3.23 kg fresh fish overnight. The average evaporating temperature being about -2.9°C . The refrigerator can also cumulatively chill about 28 kg of tomatoes in four days for short-term preservation of tomatoes. The average ice production of 2.74 kg a day compares quite favourably with the up to 4 kg of ice a day that the AIT solar refrigerator was able to produce during clear days (Exell et al, 1993).

An economic analysis of the designed charcoal/methanol solar refrigerator indicates that the refrigerator will be economically viable when it is produced and used for commercial purposes. The solar refrigerator will cost about ₦2,943,000.00 (1998), ie US\$1,226, to produce. This may be reduced to ₦2,775,000.00 (\$1,156) if the solar refrigerator is to be used solely for ice production since, in this case, no vacuum valve is required. The economic analysis shows that for ice production the payback period (using the net present value, NPV, method) will be 16 years. And for the storage of tomatoes the savings that will be made resulting from the reduction in spoilage will pay back the cost of the refrigerator in 10 years. These payback periods are thus less than the life-span of a solar refrigerator, which is estimated to be 20-25 years.

The collector simulation programme obviously can be used to determine the performance of a charcoal/methanol solar refrigerator for any area in Ghana on the basis of available solar radiation data for that particular area. The potential for solar refrigeration anywhere in Ghana can thus be determined. The simulation programme can also be used to design charcoal/methanol solar refrigerators for other countries (especially countries in the Northern Hemisphere) and predict the performance.

10.2 Recommendations

It is recommended that the charcoal/methanol solar refrigerator, described in this work, be produced and tested to determine its performance. The test results should be compared with simulation results to determine the extent of agreement. Following this, the charcoal/methanol solar refrigerator should be developed further with a few built for use especially in the rural areas. The development should include large capacity charcoal/methanol solar refrigerators, to be built for use in both rural and urban areas.

It is also recommended that the solar collector simulation programme be modified to compute the condenser temperature and pressure every hour especially during desorption and condensation.

Again, the finite-difference method can be applied to the evaporator box to solve heat equations (to be derived) for the estimation of the temperatures in the evaporator box at every hour or less. A computer simulation programme can therefore be written for the simulation of the evaporator box performance. The simulation programme if written should be incorporated into the collector simulation programme.

Finally, it is recommended that attempts be made to produce activated charcoals in Ghana for making charcoal/methanol solar refrigerators if the need arises.

Charcoal/methanol solar refrigerators made with imported activated charcoals may be more expensive than those made with locally produced activated charcoals, since the prices of imported activated charcoals may be much higher (see Jing, 1992).

NOMENCLATURE

	Area (m^2); or ratio of Areas
	Collector surface area (m^2)
	Surface area of evaporator; or surface area of edge of solar collector (m^2)
T	Asian Institute of Technology, Bangkok, Thailand
	Surface area of tube (m^2)
	Absorptance of collector plate top surface for solar radiation
CC	Specific heat capacity of activated charcoal (700 J/kg-K)
CD	Specific heat capacity of outer tube end caps (Stainless steel: 49 J/kg-K)
CG	Specific heat capacity of glass (820 J/kg-K)
m	Specific heat capacity of methanol (J/kg-K)
mi	Specific heat capacity of adsorbed methanol (liquid) in the charcoal of the finite-difference region of node i (J/kg-K)
$m_0, C_{m1}, \dots, C_{m6}$	Specific heat capacities of adsorbed methanol in the charcoal of the finite-difference regions $i = 0, 1, 2, \dots, 6$ (J/kg-K)
mm	Average specific heat capacity of adsorbed methanol (J/kg-K)
P	Specific heat capacity (J/kg-K)
pt	Specific heat capacity of collector plate outer tube (Stainless steel: 491 J/kg-K)
CT	Specific heat capacity of collector plate inner tube (Stainless steel : 491 J/kg-K)
COP	Coefficient of performance
Cp	Specific heat capacity (J/kg-K)
Cpb	Specific heat capacity of evaporator box outside walls (Steel plate: 434 J/kg-K)
Cpcw	Specific heat capacity of cold chamber walls (Aluminium: 963 J/kg-K)
Cper	Specific heat capacity of evaporator material (Brass: 380 J/kg-K)
Cpfs	Specific heat capacity of fish (3180 J/kg-K)
Cpgt	Specific heat capacity of vegetable or fruit (Tomatoes: 3980 J/kg-K)
Cpl	Specific heat capacity of liquid methanol (J/kg-K)
Cpw	Specific heat capacity of water (4190 J/kg-K)
D	A parameter of the D-A equation (K^{-n}); or diameter of tube (m)
DC	Diameter of tube (m)
DCY	Diameter of condenser upper tube (inches)
DC/L	Diameter and length of condenser upper tube (m)
Di	Diameter of a hypothetical inner sphere of a volume equal to the volume of the condenser tubes (m)
Div	Diameter of a hypothetical inner sphere of a volume equal to the volume formed by the inner walls of the evaporator box (m)
Do	Diameter of a hypothetical outer sphere of a volume equal to the volume of the condenser water tank (m)
Dov	Diameter of a hypothetical outer sphere of a volume equal to the volume formed by the evaporator box outer walls (m)
DRI	Diameter of condenser lower tube (inches)
DR/L	Diameter and length of condenser lower tube (m)
DT	Time interval (one hour: 3600 s)
DX	Thickness of finite-difference region (m)

Equation of time (minutes)
 Efficiency of the solar collector at the hour
 Overall solar collector efficiency
 Emittance or emissivity of glass (0.88)
 Emittance or emissivity of collector plate top surface
 Emittance or emissivity of collector plate bottom surface
 Emittance or emissivity of outer surface of evaporator box outside walls.
 Emittance or emissivity of outer surface of condenser tank walls
 Exponential

Acceleration due to gravity (9.81 m/s^2)

Declination (degrees)

Grashof number

Specific enthalpy (J/kg); or hour angle (degrees); or hour

Enthalpy (J); or hour angle at the middle or mid-point of the hour (degrees)

Monthly average daily global radiation ($\text{Wh/m}^2\text{-day}$)

Convection heat transfer coefficient for the bottom surface of collector plate ($\text{W/m}^2\text{-K}$)

Heat of adsorption/desorption (J/kg)

Heat of adsorption/desorption (J/kg)

Heat of adsorption/desorption of methanol in the charcoal finite-difference region of node i (J/kg)

Average heat of adsorption/desorption (J/kg)

Heats of adsorption/desorption of methanol in the charcoal finite-difference regions of nodes $i = 0, 1, 2, \dots, 6$ (J/kg)

Heat transfer coefficient at the boundary between the charcoal and the collector plate outer or inner tube ($47.5 \text{ W/m}^2\text{-K}$)

Hour angle at the beginning of the hour (degrees)

Hour angle at the end of the hour (degrees)

Convection heat transfer coefficient for the bottom surface of horizontal plate ($\text{W/m}^2\text{-K}$)

Specific enthalpy of ice (J/kg)

Specific enthalpy of ice at the freezing temperature 0°C (J/kg)

Specific enthalpy of cold chamber walls (J/kg)

Average convection heat transfer coefficient ($\text{W/m}^2\text{-K}$)

Height of the edge of the solar collector (m)

Specific enthalpy of evaporator box outside walls (J/kg)

Specific enthalpy of evaporator (J/kg)

Specific enthalpy of liquid methanol at temperature T_{cd} (J/kg)

Specific enthalpy of liquid methanol at temperature T_{ev} (J/kg)

Latent heat (J/kg)

Modified latent heat (J/kg)

Latent heat of vaporization of methanol at temperature T_{ev} (J/kg)

Specific enthalpy of liquid methanol at temperature T_m , just before evaporation begins (J/kg)

Specific enthalpy of fish (J/kg)

Specific enthalpy of fish at the freezing temperature -2°C (J/kg)

Specific enthalpy of frozen fish (J/kg)

Specific enthalpy of frozen fish at the freezing temperature -2°C (J/kg)

Specific enthalpy of fruits or vegetables (J/kg)

Specific enthalpy of frozen vegetables or fruits (J/kg)

Hour angle at the middle or mid-point of the hour (degrees)
 Specific enthalpy of evaporator box insulation (J/kg)
 Specific enthalpy of liquid methanol (kJ/kg)
 Number of hours
 Convection heat transfer coefficient for the top surface of a horizontal plate ($\text{W/m}^2\text{-K}$)
 Specific enthalpy of methanol vapour (kJ/kg)
 Convection heat transfer coefficient for the vertical surface ($\text{W/m}^2\text{-K}$)
 Specific enthalpy of methanol vapour at temperature T_{sat} (J/kg)
 Specific enthalpy of methanol vapour at temperature T_{vi} (J/kg)
 Specific enthalpy of water (J/kg)
 Specific enthalpy of water at the freezing temperature 0°C (J/kg)
 Hourly total solar radiation incident on the horizontal surface ie hourly global radiation (Wh/m^2)
 Hourly beam solar radiation incident on the horizontal surface (Wh/m^2)
 Hourly diffuse solar radiation incident on the horizontal surface (Wh/m^2)
 Inner diameter of tube (mm or cm or m)
 Incident radiation
 Extraterrestrial hourly solar radiation incident on a horizontal surface (Wh/m^2)
 Reflected radiation
 Hourly total solar radiation incident on the tilted surface (Wh/m^2)
 Same as T_{gf} ($^\circ\text{C}$)
 Same as T_{pf} ($^\circ\text{C}$)
 Daily solar radiation incident on the tilted surface ($\text{Wh/m}^2\text{-day}$)
 Same as T_{tf} ($^\circ\text{C}$)
 Hourly total solar radiation incident on the horizontal surface (Wh/m^2)
 Thermal conductivity (W/m-K); or a parameter of the D-R equation (K^{-2})
 Extinction coefficient of glass (18 m^{-1} , average for glass)
 Thermal conductivity of air between collector plate and glass cover (W/m-K)
 Thermal conductivity of air above glass cover (W/m-K)
 Thermal conductivity of solar collector bottom insulation
 (Jute fibre or wool: 0.05 W/m-K , polyurethane: 0.026 W/m-K)
 Conductivity of activated charcoal (0.175 W/m-K)
 Conductivity of outer tube end caps (stainless steel: 15 W/m-K)
 Conductivity of solar collector edge insulation (Jute fibre or wool: 0.05 W/m.K)
 Thermal conductivity of liquid methanol (W/m-K)
 Hourly clearness index
 Thermal conductivity of methanol vapour (W/m-K)
 Thermal conductivity of water (W/m-K)
 Thermal conductivity of evaporator box insulation (Jute fibre or wool: 0.05 W/m-K , polyurethane: 0.026 W/m-K)
 Thermal conductivity of collector plate tubes (Stainless Steel: 15 W/m-K)
 Thermal conductivity of evaporator box insulation (W/m-K)
 Length of collector plate (m)
 Longitude of the location in question (degrees west positive)
 Standard meridian for the local time zone [0° for Ghana] (degrees west positive)
 Breadth of evaporator box; thickness of solar collector bottom insulation (m)

	Thickness of solar collector bottom insulation (m)
	Breadth of cold chamber (m)
	Characteristic length (m)
	Total length of condenser upper tubes (m)
	Equivalent total length of condenser tubes (m)
D, Ld	Thickness of outer tube end cap (m)
E, Le	Thickness of solar collector edge insulation (m)
	Length of condenser tube condensation of methanol takes place (m)
G, Lg	Thickness of glass cover (m)
ga.	Characteristic length of glass cover (m)
gw	Characteristic length of glass cover (m)
h	Height of evaporator box (m)
hi	Height of cold chamber (m)
	Length of evaporator box (m)
li	Length of cold chamber (m)
o	Hypothetical gap width, also characteristic length (m)
pa	Characteristic length of collector plate (m)
pw	Characteristic length (for wind) of collector plate (m)
RI	Length of condenser lower tube (m)
S, Ls	Average distance between top surface of collector plate and bottom surface of glass cover (m)
t	Length of condenser tube for cooling methanol vapour to the saturation temperature (m)
w	Breadth of collector plate (m)
n	Mass (kg)
M	Mass (kg), or molecular weight of adsorbate or methanol
MC, Mc	Mass of activated charcoal (kg)
Mce	Mass of ice (kg)
Mcw	Mass of cold chamber walls (kg)
MDT, Mdt	Total mass of end covers of collector plate outer tubes (kg)
Meb	Mass of evaporator box outer walls (kg)
Mer	Mass of evaporator (kg)
Mfs	Mass of fish (kg)
Mfz	Mass of frozen fish (kg)
MG, Mg	Mass of glass cover (kg)
Mgt	Mass of vegetables or fruits (kg)
Mgtc	Mass of vegetables or fruits in the cold chamber cooled the previous night (kg)
Mgtf	Mass of fresh vegetables or fruits (kg)
Mgz	Mass of frozen vegetables or fruits (kg)
mi	Mass of finite-difference region of node i (kg)
Mi	Mass of evaporator box insulation (kg)
MiL	Mass of water or fish to be frozen (kg)
MIT, Mit	Total mass of collector plate inner tubes including the mass of the header tube and the adaptor (kg)
ino	Mass flow rate, or rate of condensation (kg/s)
MOT, Mot	Total mass of collector plate outer tubes (kg)
Mw	Mass of water (kg)

A parameter of the D-A equation

Refractive index

Average day of the month given in days in the year (NN in section 7.1.3.)

Refractive index of medium 1

Refractive index of medium 2

Number of outer tubes or inner tubes of collector plate

Nusselt number

Nusselt number for the bottom of the collector plate

Nusselt numbers for the bottom of the collector plate

Nusselt number for flow in a tube

Nusselt numbers for the glass cover

Average Nusselt number

Outer diameter of tube (mm or cm or m)

Pressure, or equilibrium pressure (bar)

Average evaporating pressure (bar)

Average condensing pressure (bar)

Bulk density of activated charcoal 207E4 (490 kg/m^3); critical pressure of methanol (80.9 bar)

Density of outer tube end cap (Stainless steel: 7978 kg/m^3)

Perimeter (m)

Pressure (bar)

P_i , π

Equilibrium pressure at the beginning of the period Δt (bar)

Prandtl number

Saturation vapour pressure of adsorbate or methanol at temperature T (bar)

Heat flow rate (W)

Rate of heat generation per unit volume (W/m^3)

Heat flow (J)

Heat flow rate (W)

Heat flow rate (W)

Rate of heat generation per unit volume due to adsorption or desorption (W/m^3)

Heat loss by radiation or convection from the glass cover to the open air (W)

Heat flow by radiation or convection from the bottom surface of the solar collector plate to the ambient air when the bottom insulation is lowered (W)

Heat flow by conduction through the bottom insulation of the solar collector (W)

Heat flow from the collector plate outer tubes to the charcoal and the outer tubes' end caps (W)

Heat flow by conduction through the edge insulation of the solar collector (W)

Heat transfer by radiation or convection from the top surface of the collector plate to the glass cover (W)

Heat flow by radiation (W)

Rate of heat transfer from the condensing vapour to the condenser tube walls (W)

Heat flow from the water tank to the ambient air (W)

Heat flow from the inner tubes of the collector plate to the charcoal and the outer tubes' end caps (W)

Heat flow rate from the ambient air to the evaporator box (W)

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Refrigeration effect (J)

Heat released by the methanol liquid to the cold chamber (J)

Radius (m)

Gas constant; universal gas constant (J/kg-K or J/kmol-K)

Rayleigh number

Ratio of beam radiation incident on a tilted plane to beam radiation incident on the horizontal plane

Reynolds number

Outer radius of collector plate inner tube (m)

Radius of a hypothetical inner sphere of volume equal to the volume of the condenser tubes (m)

Radius of a hypothetical inner sphere of volume equal to the volume formed by the walls of the cold chamber (m)

Inner radius of collector plate outer tube (m)

Radius of a hypothetical outer sphere of volume equal to the volume of the condenser water tank (m)

Radius of a hypothetical outer sphere of volume equal to the volume formed by the evaporator box outer walls (m)

Universal gas constant (8314.4 J/kmol-K)

Side length of water tank (m)

Solar radiation absorbed by the glass cover per unit area (W/m^2)

Solar radiation absorbed by the collector plate per unit area (W/m^2)

Time or time period (s); also hour from midnight (in Eqn 4.45)

Temperature (K)

Temperature of charcoal at the boundary between charcoal and inner tube (K)

Time periods (s)

Temperature of charcoal at the boundary between charcoal and outer tube (K)

Atmospheric temperature (K or $^{\circ}\text{C}$)

Average atmospheric temperature during daytime (K)

Average atmospheric temperatures during daytime (K)

Average atmospheric temperature during condensation (K)

The atmospheric temperature when the fresh fruits, vegetables, water or fish are/is placed in the cold chamber before the beginning of the evaporation process (K or $^{\circ}\text{C}$)

Atmospheric temperature at the end of the hour ($^{\circ}\text{C}$)

Average atmospheric temperature during the evaporation process in the night (K)

Temperature of the bottom of solar collector; or temperature of evaporator box outside walls (K)

Average temperatures of evaporator box outside walls during daytime (K)

Average temperature of evaporator box outside walls during the evaporation process in the night (K)

Critical temperature of methanol (512.6K)

Temperatures at the end of the hour of the charcoal finite-difference regions (K)

Initial temperatures, or temperatures at the beginning of the hour, of the charcoal finite-difference regions (K)

Average temperatures, at the hour, of the charcoal finite-difference regions (K)

Average initial temperature of charcoal at the maximum methanol concentration; or the average temperature of charcoal at the end of adsorption (K or $^{\circ}\text{C}$)

T_{c1}, T_{c2}	Cold chamber wall temperatures (K or °C)
T_{c3}	Average temperature of charcoal at the beginning of desorption (K or °C)
T_{c4}	Average temperature of charcoal at the end of desorption (K or °C)
T_{c5}, T_{c6}	Cold chamber wall temperatures (K or °C)
T_{c7}	Average temperature of charcoal at the beginning of adsorption (K or °C)
T_{cd}	Condensation temperature (K or °C)
T_{cf}, T_{cf}	Average temperature of charcoal at the end of the hour (°C)
T_{ch}	Average cold chamber wall temperature (K)
T_{chl}, T_{ch2}	Average cold chamber wall temperatures during daytime (K)
T_{chn}	Average cold chamber wall temperature during the evaporation process in the night (K)
$T_{d1}, T_{d2}, \dots, T_{d5}$	Temperatures, at the end of the hour, of the outer tube end cap finite-difference regions (K)
$T_{d11}, T_{d12}, \dots, T_{d15}$	Initial temperatures, or temperatures at the beginning of the hour, of the outer tube end cap finite-difference regions (K)
T_{DF}	Average temperature of the outer tube end cap at the end of the hour (°C)
T_{dmi}	Average temperature of the outer tube end cap at the beginning of the hour (K)
T_{dmf}	Average temperature of the outer tube end cap at the end of the hour (K)
T_{DP}, T_{dp}	Average dew point temperature (°C)
T_E	Average temperature of the water tank walls during condensation (K or °C)
T_{e1}, T_{e2}	Temperatures of the evaporator material (K or °C)
T_{e3}, T_{e4}	Temperatures of the evaporator material (K or °C)
T_{ev}	Average evaporating temperature (K or °C)
T_f	Film temperature (K)
T_{f1}	Temperature of fresh fish when it is placed in the cold chamber before the beginning of the evaporation process (K or °C)
T_{f2}	Freezing temperature of fish (K or °C)
T_{fm}	Film temperature of liquid methanol (K)
T_g	Temperature of glass cover (K or °C)
T_{g1}	Initial temperature or temperature at the beginning of the hour of the glass cover (K or °C)
T_{gf}, T_{gr}	Temperature of the glass cover at the end of the hour (K or °C)
T_{g1}, T_{g2}	Temperatures of fruits or vegetables in the cold chamber (K or °C)
T_{g3}, T_{g4}	Temperatures of fruits or vegetables in the cold chamber (K or °C)
T_i	Temperature of evaporator box insulation (K)
T_I	Average temperature of the condenser tube walls during condensation (K or °C)
T_{IM}, T_{im}	Local time in hours from midnight; or end of the hour
t_k	Thickness of insulation of the evaporator box (m)
t_{kb}	Thickness of evaporator box outside walls (m)
t_{kc}	Thickness of cold chamber walls (m)
t_{ke}	Thickness of evaporator material (m)
T_m	Temperature of liquid methanol in the evaporator just before evaporation begins (°C)
T_{m1}	Temperature of cold chamber just before evaporation begins (K or °C)
T_{m2}	Temperature of cold chamber at the end of the evaporation process (K or °C)
T_{m3}	Temperature of cold chamber just before the condensed methanol is introduced into the evaporator from the condenser (Valve K being operated) (K or °C)
T_{m4}	Temperature of cold chamber after the condensed methanol is introduced into the evaporator and just before the beginning of the evaporation process (K or °C)
T_{mf}	Average temperature of charcoal at the end of the hour (K)
T_{mi}	Average temperature of charcoal at the beginning of the hour (K)

mv	Average temperature of charcoal at the hour (K)
p	Temperature of collector plate outer tube (K)
p _i	Initial temperature or temperature at the beginning of the hour of collector plate outer tube (K)
pf, T _{pr}	Temperature of collector plate outer tube at the end of the hour (K or °C)
s	Equivalent blackbody sky temperature (K)
sat	Saturation temperature (K or °C)
t	Temperature of collector plate inner tube (K)
t _i	Initial temperature or temperature at the beginning of the hour of collector plate inner tube (K)
t _f , T _{tf}	Temperature of collector plate inner tube at the end of the hour (K)
T _{w1}	Temperature of fresh water when it is placed in the cold chamber before the beginning of the evaporation process (K or °C)
T _{w2}	Freezing temperature of water (K or °C)
T _{wi}	Initial temperature of water in the condenser tank (K)
T _{vi}	Average temperature of methanol vapour at entry to the condenser (K)
U	Wind velocity (m/s)
UI	Heat transfer coefficient (W/m ² -K)
v	Specific volume (cm ³ /mol or m ³ /kg)
V	Velocity (m/s); volume (m ³)
V _o	Volume of water in the condenser tank (m ³)
vs	Specific volume of methanol vapour (in Eqn 5.15 the unit is cm ³ /mol)
w	Relaxation parameter
W	Volume filled by the adsorbate (litres/kg)
W _o	Maximum volume of the adsorption space (litres/kg)
WRS	Relaxation parameter
x	Dryness fraction
X	Adsorbate or methanol concentration in charcoal (kg/kg)
X _{av}	Average methanol concentration (over the period Δt) in a charcoal finite-difference region (kg/kg)
X _{Cf0} , X _{Cf1} , ..., X _{Cf6}	Methanol concentrations in the charcoal finite-difference regions at the end of the hour (kg/kg)
X _{Ci0} , X _{Ci1} , ..., X _{Ci6}	Methanol concentrations in the charcoal finite-difference regions at the beginning of the hour, or initial methanol concentrations in the charcoal finite-difference regions (kg/kg)
X _{max}	Maximum methanol concentration (kg/kg)
X _{mff}	Average methanol concentration in the whole charcoal at the end of the hour (kg/kg)
X _{mi}	Average methanol concentration in the whole charcoal at the beginning of the hour (kg/kg)
X _{min}	Minimum methanol concentration (kg/kg)
y	Dryness fraction
Z	Compressibility factor
z _i	Inverse of temperature (-1/K)
ZRA	Rackett compressibility factor

reek	Thermal diffusivity (m^2/s); also altitude angle (degrees)
gb	Absorptance of glass cover for solar beam radiation
gd	Absorptance of glass cover for diffuse solar radiation
gr	Absorptance of glass cover for ground-reflected solar radiation
α_p, α_p	Absorptance of collector plate top surface for solar radiation
	Angle of tilt of solar collector (degrees)
	Volumetric coefficient of expansion ($1/\text{K}$)
	Declination (degrees)
δx	Thickness of finite-difference region (m)
Δt	Time interval (one hour: 3600s)
λ	Latitude angle (degrees)
μ	Absolute viscosity (Pa s)
μ_l	Viscosity of liquid methanol (Pa s) [in Eqn. 5.4 the unit is cP]
μ_v	Viscosity of vapour (Pa s)
ν	Kinematic viscosity (m^2/s)
ρ	Density (kg/m^3)
ρ_c	Bulk density of activated charcoal 207E4 ($490 \text{ kg}/\text{m}^3$)
ρ_d	Density of outer tube end cap (Stainless steel: $7978 \text{ kg}/\text{m}^3$)
ρ_g	Ground reflectance
ρ_l	Density of liquid methanol (kg/m^3)
ρ_m	Density of adsorbate or adsorbed methanol at temperature T or T_{mf} (kg/m^3)
ρ_v	Density of methanol vapour at temperature T [inverse of ν_s] (kg/m^3)
σ	Stefan-Boltzman constant ($5.6697 \times 10^{-8} \text{ W}/\text{m}^2 \cdot \text{K}^4$)
τ	Transmittance
τ_a	Transmittance with only absorption losses considered
$(\tau \cdot \alpha_p)_{av}$	Average transmittance-absorptance product
$(\tau \cdot \alpha_p)_b$	Transmittance-absorptance product for beam radiation
$(\tau \cdot \alpha_p)_d$	Transmittance-absorptance product for diffuse radiation
$(\tau \cdot \alpha_p)_g$	Transmittance-absorptance product for ground-reflected radiation
θ_{ed}	Effective incidence angle for diffuse radiation (degrees)
θ_{er}	Effective incidence angle for ground-reflected radiation (degrees)
θ_i	Angle of incidence (degrees)
θ_1	Angle of incidence (degrees)
θ_2	Angle of refraction (degrees)

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APPENDIX A

DATA FOR THE INPUT FILE OF THE COLLECTOR SIMULATION PROGRAMME

Table A.1 Data For January, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-93.93	-78.93	-86.43	6.9	1.18	295.05
8	-78.93	-63.93	-71.43	66.7	1.18	295.95
9	-63.93	-48.93	-56.43	181.4	1.18	296.85
10	-48.93	-33.93	-41.43	323.2	1.18	298.65
11	-33.93	-18.93	-26.43	451.4	1.18	300.45
12	-18.93	-3.93	-11.43	544.8	1.18	302.25
13	-3.93	11.07	3.57	568.4	1.18	303.95
14	11.07	26.07	18.57	532.1	1.18	305.65
15	26.07	41.07	33.57	442.3	"	305.25
16	41.07	56.07	48.57	299.6	"	304.45
17	56.07	71.07	63.57	151.0	"	303.55
18	71.07	86.07	78.57	38.7	"	302.75
19	86.07	101.07	93.57	0.0	"	301.55
20	101.07	116.07	108.57	0.0	"	300.25
21	116.07	131.07	123.57	0.0	"	299.05
22	131.07	146.07	138.57	0.0	"	298.25
23	146.07	161.07	153.57	0.0	"	297.45
24	161.07	176.07	168.57	0.0	"	296.65
1	176.07	-168.93	-176.43	0.0	"	296.15
2	-168.93	-153.93	-161.43	0.0	"	295.65
3	-153.93	-138.93	-146.43	0.0	"	295.15
4	-138.93	-123.93	-131.43	0.0	"	294.85
5	-123.93	-108.93	-116.43	0.0	"	294.45
6	-108.93	-93.93	-101.43	0.0	"	294.15

Note:

The difference between solar time and standard time in minutes is given as (Duffie and Beckman, 1991),

$$\text{Solar time} - \text{Standard time} = 4(L_{st} - L_{loc}) + E$$

where,

$$E = 229.2(0.000075 + 0.001868 \cos B - 0.032077 \sin B - 0.014615 \cos 2B - 0.04089 \sin 2B)$$

$$B = (n - 1) \frac{360}{365}$$

$$n = \text{day of the year} \quad 1 \leq n \leq 365$$

Table A.2 Data For February, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-95.16	-80.16	-87.66	8.4	1.36	297.25
8	-80.16	-65.16	-72.66	84.9	1.36	298.05
9	-65.16	-50.16	-57.66	221.6	1.36	298.95
10	-50.16	-35.16	-42.66	367.5	1.36	300.75
11	-35.16	-20.16	-27.66	521	1.36	302.55
12	-20.16	-5.16	-12.66	634.8	1.36	304.35
13	-5.16	9.84	2.34	663.9	1.36	306.25
14	9.84	24.84	17.34	619.1	1.36	308.15
15	24.84	39.84	32.34	507.2	"	307.55
16	39.84	54.84	47.34	343.6	"	306.65
17	54.84	69.84	62.34	183.2	"	305.65
18	69.84	84.84	77.34	54.3	"	304.75
19	84.84	99.84	92.34	0.0	"	303.55
20	99.84	114.84	107.34	0.0	"	302.35
21	114.84	129.84	122.34	0.0	"	301.15
22	129.84	144.84	137.34	0.0	"	300.25
23	144.84	159.84	152.34	0.0	"	299.45
24	159.84	174.84	167.34	0.0	"	298.55
1	174.84	-170.16	-177.66	0.0	"	298.05
2	-170.16	-155.16	-162.66	0.0	"	297.65
3	-155.16	-140.16	-147.66	0.0	"	297.15
4	-140.16	-125.16	-132.66	0.0	"	296.85
5	-125.16	-110.16	-117.66	0.0	"	296.65
6	-110.16	-95.16	-102.66	0.0	"	296.35

Table A.3 Data For March, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-93.94	-78.94	-86.44	18.3	1.57	297.15
8	-78.94	-63.94	-71.44	123.5	1.57	298.05
9	-63.94	-48.94	-56.44	287.5	1.57	298.85
10	-48.94	-33.94	-41.44	467.2	1.57	300.45
11	-33.94	-18.94	-26.44	624.6	1.57	302.05
12	-18.94	-3.94	-11.44	728.2	1.57	303.65
13	-3.94	11.06	3.56	740.8	1.57	305.25
14	11.06	26.06	18.56	694.2	1.57	306.75
15	26.06	41.06	33.56	577.6	"	306.05
16	41.06	56.06	48.56	410.7	"	305.25
17	56.06	71.06	63.56	227.3	"	304.45
18	71.06	86.06	78.56	74.8	"	303.65
19	86.06	101.06	93.56	0.0	"	302.25
20	101.06	116.06	108.56	0.0	"	300.95
21	116.06	131.06	123.56	0.0	"	299.55
22	131.06	146.06	138.56	0.0	"	298.95
23	146.06	161.06	153.56	0.0	"	298.45
24	161.06	176.06	168.56	0.0	"	297.85
1	176.06	-168.94	-176.44	0.0	"	297.55
2	-168.94	-153.94	-161.44	0.0	"	297.15
3	-153.94	-138.94	-146.44	0.0	"	296.85
4	-138.94	-123.94	-131.44	0.0	"	296.65
5	-123.94	-108.94	-116.44	0.0	"	296.55
6	-108.94	-93.94	-101.44	0.0	"	296.35

Table A.4 Data For April, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-91.66	-76.66	-84.16	35.1	1.67	297.35
8	-76.66	-61.66	-69.16	153.4	1.67	298.25
9	-61.66	-46.66	-54.16	324.7	1.67	299.25
10	-46.66	-31.66	-39.16	494.5	1.67	300.65
11	-31.66	-16.66	-24.16	650.4	1.67	302.05
12	-16.66	-1.66	-9.16	730.3	1.67	303.45
13	-1.66	13.34	5.84	737.5	1.67	304.65
14	13.34	28.34	20.84	685.2	1.67	305.85
15	28.34	43.34	35.84	556.3	"	305.05
16	43.34	58.34	50.84	389.8	"	304.25
17	58.34	73.34	65.84	207.4	"	303.45
18	73.34	88.34	80.84	66.9	"	302.65
19	88.34	103.34	95.84	0.0	"	301.45
20	103.34	118.34	110.84	0.0	"	300.25
21	118.34	133.34	125.84	0.0	"	299.05
22	133.34	148.34	140.84	0.0	"	298.65
23	148.34	163.34	155.84	0.0	"	298.15
24	163.34	178.34	170.84	0.0	"	297.75
1	178.34	-166.66	-174.16	0.0	"	297.45
2	-166.66	-151.66	-159.16	0.0	"	297.15
3	-151.66	-136.66	-144.16	0.0	"	296.85
4	-136.66	-121.66	-129.16	0.0	"	296.65
5	-121.66	-106.66	-114.16	0.0	"	296.55
6	-106.66	-91.66	-99.16	0.0	"	296.35

Table A.5 Data For May, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-90.62	-75.62	-83.12	51.5	1.36	297.25
8	-75.62	-60.62	-68.12	183.8	1.36	298.25
9	-60.62	-45.62	-53.12	342.4	1.36	299.15
10	-45.62	-30.62	-38.12	486.2	1.36	300.35
11	-30.62	-15.62	-23.12	620.3	1.36	301.45
12	-15.62	-0.62	-8.12	706.2	1.36	302.65
13	-0.62	14.38	6.88	718.4	1.36	303.95
14	14.38	29.38	21.88	658	1.36	305.15
15	29.38	44.38	36.88	559.2	"	304.25
16	44.38	59.38	51.88	390.3	"	303.45
17	59.38	74.38	66.88	203.1	"	302.55
18	74.38	89.38	81.88	63.6	"	301.75
19	89.38	104.38	96.88	0.0	"	300.75
20	104.38	119.38	111.88	0.0	"	299.85
21	119.38	134.38	126.88	0.0	"	298.85
22	134.38	149.38	141.88	0.0	"	298.35
23	149.38	164.38	156.88	0.0	"	297.95
24	164.38	179.38	171.88	0.0	"	297.45
1	179.38	-165.62	-173.12	0.0	"	297.15
2	-165.62	-150.62	-158.12	0.0	"	296.95
3	-150.62	-135.62	-143.12	0.0	"	296.65
4	-135.62	-120.62	-128.12	0.0	"	296.55
5	-120.62	-105.62	-113.12	0.0	"	296.45
6	-105.62	-90.62	-98.12	0.0	"	296.35

Table A.6 Data For June, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-91.4	-76.4	-83.9	35.7	1.44	296.25
8	-76.4	-61.4	-68.9	132.2	1.44	296.95
9	-61.4	-46.4	-53.9	255.9	1.44	297.75
10	-46.4	-31.4	-38.9	361.6	1.44	298.75
11	-31.4	-16.4	-23.9	464.1	1.44	299.65
12	-16.4	-1.4	-8.9	543.4	1.44	300.65
13	-1.4	13.6	6.1	621.7	1.44	301.85
14	13.6	28.6	21.1	591.5	1.44	303.05
15	28.6	43.6	36.1	486	"	301.85
16	43.6	58.6	51.1	358.6	"	301.05
17	58.6	73.6	66.1	201.2	"	300.15
18	73.6	88.6	81.1	70.8	"	299.35
19	88.6	103.6	96.1	0.0	"	298.55
20	103.6	118.6	111.1	0.0	"	297.85
21	118.6	133.6	126.1	0.0	"	297.05
22	133.6	148.6	141.1	0.0	"	296.75
23	148.6	163.6	156.1	0.0	"	296.55
24	163.6	178.6	171.1	0.0	"	296.25
1	178.6	-166.4	-173.9	0.0	"	296.05
2	-166.4	-151.4	-158.9	0.0	"	295.85
3	-151.4	-136.4	-143.9	0.0	"	295.65
4	-136.4	-121.4	-128.9	0.0	"	295.55
5	-121.4	-106.4	-113.9	0.0	"	295.55
6	-106.4	-91.4	-98.9	0.0	"	295.45

Table A.8 Data For August, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-92.77	-77.77	-85.27	16.8	1.75	295.15
8	-77.77	-62.77	-70.27	76.2	1.75	295.75
9	-62.77	-47.77	-55.27	155.2	1.75	296.25
10	-47.77	-32.77	-40.27	243.3	1.75	297.05
11	-32.77	-17.77	-25.27	344.9	1.75	297.85
12	-17.77	-2.77	-10.27	403.5	1.75	298.65
13	-2.77	12.23	4.73	438.7	1.75	300.05
14	12.23	27.23	19.73	424.0	1.75	301.35
15	27.23	42.23	34.73	394.6	"	300.05
16	42.23	57.23	49.73	324.1	"	299.65
17	57.23	72.23	64.73	187.9	"	299.15
18	72.23	87.23	79.73	66.6	"	298.75
19	87.23	102.23	94.73	0.0	"	298.05
20	102.23	117.23	109.73	0.0	"	297.35
21	117.23	132.23	124.73	0.0	"	296.65
22	132.23	147.23	139.73	0.0	"	296.25
23	147.23	162.23	154.73	0.0	"	295.95
24	162.23	177.23	169.73	0.0	"	295.55
1	177.23	-167.77	-175.27	0.0	"	295.35
2	-167.77	-152.77	-160.27	0.0	"	295.15
3	-152.77	-137.77	-145.27	0.0	"	294.95
4	-137.77	-122.77	-130.27	0.0	"	294.85
5	-122.77	-107.77	-115.27	0.0	"	294.75
6	-107.77	-92.77	-100.27	0.0	"	294.65

Table A.9 Data For September, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-90.44	-75.44	-82.94	23.1	1.34	295.65
8	-75.44	-60.44	-67.94	97.6	1.34	296.15
9	-60.44	-45.44	-52.94	204.8	1.34	296.75
10	-45.44	-30.44	-37.94	328.4	1.34	297.65
11	-30.44	-15.44	-22.94	439	1.34	298.45
12	-15.44	-0.44	-7.94	500.5	1.34	299.35
13	-0.44	14.56	7.06	519.9	1.34	300.75
14	14.56	29.56	22.06	543.4	1.34	302.15
15	29.56	44.56	37.06	461.3	"	300.95
16	44.56	59.56	52.06	333.2	"	300.25
17	59.56	74.56	67.06	182.4	"	299.65
18	74.56	89.56	82.06	52.8	"	298.95
19	89.56	104.56	97.06	0.0	"	298.25
20	104.56	119.56	112.06	0.0	"	297.45
21	119.56	134.56	127.06	0.0	"	296.75
22	134.56	149.56	142.06	0.0	"	296.45
23	149.56	164.56	157.06	0.0	"	296.05
24	164.56	179.56	172.06	0.0	"	295.75
1	179.56	-165.44	-172.94	0.0	"	295.65
2	-165.44	-150.44	-157.94	0.0	"	295.45
3	-150.44	-135.44	-142.94	0.0	"	295.35
4	-135.44	-120.44	-127.94	0.0	"	295.25
5	-120.44	-105.44	-112.94	0.0	"	295.15
6	-105.44	-90.44	-97.94	0.0	"	295.05

Table A.10 Data For October, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-88	-73	-80.5	37.6	1.06	296.15
8	-73	-58	-65.5	145.8	1.06	296.85
9	-58	-43	-50.5	278.7	1.06	297.55
10	-43	-28	-35.5	425.4	1.06	298.85
11	-28	-13	-20.5	552.1	1.06	300.05
12	-13	2	-5.5	645.8	1.06	301.35
13	2	17	9.5	673.4	1.06	302.65
14	17	32	24.5	619.0	1.06	303.95
15	32	47	39.5	513.8	"	302.65
16	47	62	54.5	326.7	"	301.65
17	62	77	69.5	156.5	"	300.55
18	77	92	84.5	37.1	"	299.55
19	92	107	99.5	0.0	"	298.75
20	107	122	114.5	0.0	"	298.05
21	122	137	129.5	0.0	"	297.25
22	137	152	144.5	0.0	"	296.95
23	152	167	159.5	0.0	"	296.55
24	167	-178	174.5	0.0	"	296.25
1	-178	-163	-170.5	0.0	"	296.05
2	-163	-148	-155.5	0.0	"	295.85
3	-148	-133	-140.5	0.0	"	295.65
4	-133	-118	-125.5	0.0	"	295.55
5	-118	-103	-110.5	0.0	"	295.55
6	-103	-88	-95.5	0.0	"	295.45

Table A.11 Data For November, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-87.77	-72.77	-80.27	28.2	1.85	297.05
8	-72.77	-57.77	-65.27	126.7	1.85	297.85
9	-57.77	-42.77	-50.27	266.2	1.85	298.75
10	-42.77	-27.77	-35.27	423.3	1.85	300.05
11	-27.77	-12.77	-20.27	547.2	1.85	301.35
12	-12.77	2.23	-5.27	623.9	1.85	302.65
13	2.23	17.23	9.73	670	1.85	304.05
14	17.23	32.23	24.73	605.5	1.85	305.45
15	32.23	47.23	39.73	478.4	"	304.65
16	47.23	62.23	54.73	317.7	"	303.65
17	62.23	77.23	69.73	128.4	"	302.55
18	77.23	92.23	84.73	21.1	"	301.55
19	92.23	107.23	99.73	0.0	"	300.65
20	107.23	122.23	114.73	0.0	"	299.75
21	122.23	137.23	129.73	0.0	"	298.85
22	137.23	152.23	144.73	0.0	"	298.35
23	152.23	167.23	159.73	0.0	"	297.85
24	167.23	-177.77	174.73	0.0	"	297.35
1	-177.77	-162.77	-170.27	0.0	"	297.05
2	-162.77	-147.77	-155.27	0.0	"	296.85
3	-147.77	-132.77	-140.27	0.0	"	296.55
4	-132.77	-117.77	-125.27	0.0	"	296.45
5	-117.77	-102.77	-110.27	0.0	"	296.25
6	-102.77	-87.77	-95.27	0.0	"	296.15

Table A.12 Data For December, Kumasi

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-89.82	-74.82	-82.32	12.3	0.8	295.95
8	-74.82	-59.82	-67.32	76.9	0.8	296.55
9	-59.82	-44.82	-52.32	184.3	0.8	297.15
10	-44.82	-29.82	-37.32	333.1	0.8	298.65
11	-29.82	-14.82	-22.32	461.6	0.8	300.25
12	-14.82	0.18	-7.32	558.1	0.8	301.75
13	0.18	15.18	7.68	573.5	0.8	303.15
14	15.18	30.18	22.68	510.7	0.8	304.45
15	30.18	45.18	37.68	405.8	"	303.75
16	45.18	60.18	52.68	267.2	"	302.85
17	60.18	75.18	67.68	119.4	"	301.95
18	75.18	90.18	82.68	21.9	"	301.05
19	90.18	105.18	97.68	0.0	"	300.05
20	105.18	120.18	112.68	0.0	"	299.15
21	120.18	135.18	127.68	0.0	"	298.15
22	135.18	150.18	142.68	0.0	"	297.65
23	150.18	165.18	157.68	0.0	"	297.05
24	165.18	-179.82	172.68	0.0	"	296.55
1	-179.82	-164.82	-172.32	0.0	"	296.15
2	-164.82	-149.82	-157.32	0.0	"	295.85
3	-149.82	-134.82	-142.32	0.0	"	295.45
4	-134.82	-119.82	-127.32	0.0	"	295.45
5	-119.82	-104.82	-112.32	0.0	"	295.35
6	-104.82	-89.82	-97.32	0.0	"	295.35

Table A.13 Data For The Input File; For 29th Oct. 1987, Bangkok, Thailand

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-90	-75	-82.5	17.61	1	297.77
8	-75	-60	-67.5	96.14	1	297.77
9	-60	-45	-52.5	421.31	1	299.3
10	-45	-30	-37.5	679.83	1	300.83
11	-30	-15	-22.5	768.22	1	303.89
12	-15	0	-7.5	818.08	1	303.89
13	0	15	7.5	710.06	1	303.89
14	15	30	22.5	642.83	1	303.89
15	30	45	37.5	724.97	"	303.89
16	45	60	52.5	419.67	"	303.89
17	60	75	67.5	148.42	"	302.36
18	75	90	82.5	20.17	"	300.83
19	90	105	97.5	0.0	"	300.83
20	105	120	112.5	0.0	"	300.83
21	120	135	127.5	0.0	"	297.77
22	135	150	142.5	0.0	"	297.77
23	150	165	157.5	0.0	"	297.77
24	165	180	172.5	0.0	"	297.77
1	-180	-165	-172.5	0.0	"	296.24
2	-165	-150	-157.5	0.0	"	296.24
3	-150	-135	-142.5	0.0	"	296.24
4	-135	-120	-127.5	0.0	"	296.24
5	-120	-105	-112.5	0.0	"	296.24
6	-105	-90	-97.5	0.0	"	296.24

(Note: Here standard time is approximated to solar time)

Table A.14 Data For The Input File; For 17th Oct. 1987, Bangkok, Thailand

Tim (hours)	H1 (degrees)	H2 (degrees)	H (degrees)	I (JJ) (Wh/m ²)	V (m/s)	Ta (K)
7	-90	-75	-82.5	57	1	299.3
8	-75	-60	-67.5	267.28	1	299.3
9	-60	-45	-52.5	502.72	1	300.83
10	-45	-30	-37.5	684.86	1	303.89
11	-30	-15	-22.5	892.11	1	306.95
12	-15	0	-7.5	323.33	1	303.89
13	0	15	7.5	689.94	1	305.42
14	15	30	22.5	810.06	1	305.42
15	30	45	37.5	630.89	"	305.42
16	45	60	52.5	267.11	"	302.36
17	60	75	67.5	195.19	"	302.36
18	75	90	82.5	30.72	"	302.36
19	90	105	97.5	0.0	"	302.36
20	105	120	112.5	0.0	"	300.83
21	120	135	127.5	0.0	"	300.83
22	135	150	142.5	0.0	"	300.83
23	150	165	157.5	0.0	"	299.3
24	165	180	172.5	0.0	"	299.3
1	-180	-165	-172.5	0.0	"	299.3
2	-165	-150	-157.5	0.0	"	299.3
3	-150	-135	-142.5	0.0	"	299.3
4	-135	-120	-127.5	0.0	"	297.77
5	-120	-105	-112.5	0.0	"	297.77
6	-105	-90	-97.5	0.0	"	297.77

(Note: Here standard time is approximated to solar time)

SIMULATION RESULTS

The charcoal/methanol solar collector simulation results for Kumasi are for the closed adsorption cycle.

Table B.1 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for January
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.750	24.750	24.750	24.750	24.750	21.000	0.033	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.367	24.389	24.408	24.434	23.274	21.900	0.033	0.000	7.000
0.161	0.160	0.160	0.160	0.160	0.160	0.159	0.160	26.376	26.265	26.164	26.038	24.583	22.800	0.036	0.373	8.000
0.162	0.162	0.161	0.161	0.160	0.159	0.158	0.160	33.614	33.180	32.787	32.275	28.799	23.700	0.053	0.508	9.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	46.424	45.607	44.871	43.887	36.719	25.500	0.103	0.514	10.000
0.164	0.164	0.163	0.161	0.160	0.158	0.156	0.160	59.590	58.681	57.864	56.735	35.660	27.300	0.197	0.390	11.000
0.147	0.148	0.147	0.145	0.143	0.140	0.136	0.143	68.022	66.905	65.147	64.271	39.960	29.100	0.226	0.412	12.000
0.127	0.127	0.127	0.125	0.123	0.120	0.117	0.123	73.857	72.703	70.775	69.968	43.470	30.800	0.226	0.383	13.000
0.111	0.111	0.110	0.109	0.107	0.105	0.103	0.107	78.112	77.163	75.615	74.910	46.157	32.500	0.226	0.322	14.000
0.101	0.101	0.101	0.100	0.099	0.098	0.097	0.099	79.666	79.137	78.310	77.877	46.575	32.100	0.226	0.195	15.000
0.099	0.099	0.099	0.099	0.099	0.099	0.099	0.099	77.044	77.070	77.104	77.108	44.873	31.300	0.214	0.000	16.000
0.096	0.096	0.097	0.098	0.099	0.101	0.103	0.099	56.436	57.508	58.460	59.828	36.533	30.400	0.089	0.000	17.000
0.096	0.097	0.097	0.098	0.100	0.101	0.103	0.099	43.556	44.408	45.115	46.275	30.585	29.600	0.045	0.000	18.000
0.101	0.101	0.101	0.102	0.103	0.104	0.105	0.103	37.771	38.309	38.911	39.552	32.692	28.400	0.033	0.000	19.000
0.109	0.109	0.109	0.110	0.110	0.112	0.113	0.110	35.513	35.969	36.708	37.048	31.384	27.100	0.033	0.000	20.000
0.116	0.116	0.116	0.117	0.118	0.119	0.120	0.118	33.651	34.063	34.753	35.041	29.870	25.900	0.033	0.000	21.000
0.123	0.123	0.123	0.123	0.124	0.125	0.127	0.124	32.070	32.438	33.058	33.313	28.624	25.100	0.033	0.000	22.000
0.129	0.129	0.129	0.129	0.130	0.131	0.132	0.130	30.669	31.001	31.564	31.792	27.498	24.300	0.033	0.000	23.000
0.134	0.134	0.134	0.135	0.136	0.137	0.138	0.136	29.402	29.706	30.224	30.431	26.449	23.500	0.033	0.000	24.000
0.139	0.139	0.140	0.140	0.141	0.142	0.143	0.141	28.309	28.582	29.047	29.232	25.616	23.000	0.033	0.000	1.000
0.144	0.144	0.144	0.145	0.145	0.146	0.147	0.145	27.335	27.582	28.003	28.169	24.866	22.500	0.033	0.000	2.000
0.148	0.148	0.148	0.149	0.149	0.150	0.151	0.149	26.453	26.678	27.063	27.213	24.168	22.000	0.033	0.000	3.000
0.152	0.152	0.152	0.153	0.153	0.154	0.155	0.153	25.689	25.890	26.235	26.369	23.615	21.700	0.033	0.000	4.000
0.156	0.156	0.156	0.156	0.157	0.157	0.158	0.157	24.985	25.169	25.485	25.607	23.066	21.300	0.033	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	24.358	24.525	24.811	24.922	22.594	21.000	0.033	0.000	6.000

OVERALL COL. EFFCY = .3211907 OVERALL COP = .1013561 TEV = -3.077179 TCD = 30.64481 TI = 30.6358 TE = 30.62024 QE = 1326758
 TC1 = 24.74997 TC2 = 60.7742 TC3 = 78.31028 TC4 = 39.92188 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 3639.972

Table B.2 Charcoal/Methanol Solar Collector Simulation Temperatures For January
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM HRS
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	
297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	297.90	6.00
297.58	297.58	297.57	297.57	297.56	297.55	297.53	297.52	297.52	297.53	297.54	297.55	297.57	297.58	296.42	7.00
299.20	299.22	299.24	299.27	299.31	299.37	299.44	299.53	299.49	299.44	299.39	299.34	299.27	299.19	297.73	8.00
305.46	305.54	305.64	305.77	305.95	306.17	306.44	306.76	306.61	306.44	306.25	306.03	305.76	305.42	301.95	9.00
317.10	317.24	317.44	317.71	318.05	318.48	318.99	319.57	319.28	318.96	318.60	318.19	317.68	317.04	309.87	10.00
329.94	330.10	330.34	330.66	331.06	331.55	332.11	332.74	332.41	332.06	331.66	331.20	330.63	329.88	308.81	11.00
337.12	337.05	337.26	337.67	338.28	339.07	340.06	341.17	340.80	340.37	339.87	339.27	338.50	337.42	313.11	12.00
342.71	342.59	342.79	343.24	343.90	344.77	345.83	347.01	346.62	346.18	345.67	345.05	344.24	343.12	316.62	13.00
347.74	347.64	347.82	348.20	348.76	349.47	350.33	351.26	350.95	350.58	350.16	349.65	348.99	348.06	319.31	14.00
350.85	350.81	350.92	351.15	351.47	351.87	352.33	352.82	352.64	352.44	352.20	351.92	351.55	351.03	319.73	15.00
350.23	350.22	350.23	350.25	350.27	350.27	350.25	350.19	350.21	350.22	350.23	350.24	350.25	350.26	318.02	16.00
332.81	332.60	332.34	332.00	331.58	331.04	330.36	329.59	329.97	330.39	330.85	331.40	332.08	332.98	309.68	17.00
319.31	319.13	318.89	318.58	318.21	317.76	317.26	316.71	317.01	317.34	317.71	318.15	318.70	319.42	303.74	18.00
312.71	312.66	312.52	312.31	312.03	311.71	311.33	310.92	311.10	311.31	311.55	311.83	312.20	312.70	305.84	19.00
310.35	310.39	310.30	310.12	309.86	309.53	309.12	308.66	308.82	308.99	309.19	309.44	309.75	310.20	304.53	20.00
308.34	308.38	308.31	308.15	307.91	307.60	307.22	306.80	306.94	307.10	307.28	307.50	307.79	308.19	303.02	21.00
306.60	306.64	306.57	306.43	306.21	305.94	305.60	305.22	305.34	305.48	305.65	305.85	306.10	306.46	301.77	22.00
305.06	305.10	305.05	304.92	304.72	304.47	304.16	303.82	303.93	304.06	304.20	304.38	304.62	304.94	300.65	23.00
303.69	303.73	303.68	303.56	303.38	303.15	302.86	302.55	302.65	302.77	302.90	303.07	303.28	303.58	299.60	24.00
302.48	302.52	302.47	302.36	302.20	301.99	301.74	301.46	301.55	301.65	301.78	301.92	302.11	302.38	298.77	1.00
301.41	301.44	301.40	301.30	301.16	300.97	300.74	300.49	300.57	300.66	300.77	300.90	301.08	301.32	298.02	2.00
300.45	300.48	300.44	300.35	300.22	300.05	299.84	299.60	299.68	299.76	299.86	299.99	300.14	300.36	297.32	3.00
299.60	299.62	299.59	299.51	299.39	299.23	299.05	298.84	298.91	298.98	299.07	299.18	299.32	299.52	296.76	4.00
298.83	298.85	298.82	298.75	298.64	298.50	298.33	298.14	298.20	298.27	298.35	298.45	298.58	298.76	296.22	5.00
298.14	298.16	298.13	298.06	297.97	297.84	297.68	297.51	297.56	297.63	297.70	297.79	297.91	298.07	295.74	6.00

Table B.3 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for February
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	27.000	27.000	27.000	27.000	27.000	23.200	0.038	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.603	26.625	26.646	26.672	25.483	24.100	0.037	0.000	7.000
0.161	0.161	0.160	0.160	0.160	0.160	0.159	0.160	29.149	29.008	28.878	28.717	27.018	24.900	0.043	0.372	8.000
0.163	0.162	0.162	0.161	0.160	0.159	0.157	0.160	37.931	37.402	36.923	36.299	31.991	25.800	0.067	0.505	9.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	50.110	49.338	48.624	47.662	32.141	27.600	0.125	0.435	10.000
0.163	0.162	0.161	0.160	0.158	0.156	0.153	0.158	65.714	64.697	63.640	62.381	38.971	29.400	0.253	0.420	11.000
0.138	0.139	0.138	0.136	0.134	0.130	0.126	0.133	73.936	72.561	70.243	69.310	43.886	31.200	0.253	0.430	12.000
0.114	0.115	0.114	0.112	0.110	0.106	0.103	0.110	81.156	79.752	77.425	76.427	48.033	33.100	0.253	0.398	13.000
0.095	0.095	0.095	0.094	0.092	0.090	0.087	0.092	86.547	85.415	83.605	82.735	51.288	35.000	0.253	0.329	14.000
0.085	0.085	0.085	0.084	0.083	0.082	0.081	0.083	88.467	87.865	86.947	86.433	51.748	34.400	0.253	0.193	15.000
0.083	0.083	0.083	0.083	0.083	0.083	0.083	0.083	85.514	85.545	85.584	85.593	49.837	33.500	0.239	0.000	16.000
0.080	0.080	0.081	0.082	0.083	0.085	0.087	0.083	62.066	63.272	64.314	65.880	40.416	32.500	0.090	0.000	17.000
0.080	0.081	0.081	0.082	0.083	0.085	0.086	0.083	47.574	48.517	49.277	50.579	33.784	31.600	0.042	0.000	18.000
0.091	0.090	0.091	0.092	0.093	0.095	0.096	0.093	42.553	43.265	44.308	44.941	35.999	30.400	0.038	0.000	19.000
0.101	0.101	0.101	0.102	0.103	0.104	0.106	0.103	39.697	40.290	41.259	41.699	34.474	29.200	0.038	0.000	20.000
0.110	0.110	0.110	0.111	0.112	0.113	0.115	0.112	37.341	37.858	38.716	39.085	32.712	28.000	0.038	0.000	21.000
0.118	0.118	0.118	0.119	0.120	0.121	0.123	0.120	35.369	35.821	36.577	36.895	31.223	27.100	0.038	0.000	22.000
0.125	0.125	0.125	0.126	0.127	0.128	0.129	0.127	33.681	34.079	34.750	35.027	29.943	26.300	0.038	0.000	23.000
0.132	0.131	0.132	0.132	0.133	0.134	0.136	0.133	32.170	32.530	33.139	33.386	28.727	25.400	0.038	0.000	24.000
0.138	0.137	0.138	0.138	0.139	0.140	0.141	0.139	30.895	31.212	31.752	31.969	27.798	24.900	0.038	0.000	1.000
0.143	0.143	0.143	0.143	0.144	0.145	0.146	0.144	29.804	30.083	30.558	30.748	27.033	24.500	0.038	0.000	2.000
0.148	0.147	0.148	0.148	0.149	0.150	0.151	0.149	28.823	29.074	29.503	29.671	26.295	24.000	0.038	0.000	3.000
0.152	0.152	0.152	0.152	0.153	0.154	0.154	0.153	27.982	28.203	28.583	28.732	25.709	23.700	0.038	0.000	4.000
0.155	0.155	0.155	0.155	0.156	0.157	0.158	0.156	27.262	27.456	27.789	27.919	25.242	23.500	0.038	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	26.611	26.784	27.083	27.199	24.776	23.200	0.038	0.000	6.000

OVERALL COL. EFFCY = .3231874 OVERALL COP = .109654 TEV = -.9873658 TCD = 32.92401 TI = 32.91428 TE = 32.8988 QE = 1674465
 TC1 = 26.99994 TC2 = 63.18354 TC3 = 86.94662 TC4 = 47.57108 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4246.273

Table B.4 Charcoal/Methanol Solar Collector Simulation Temperatures For February
Kumasi

TCF0 K	TCF1 K	TCF2 K	TCF3 K	TCF4 K	TCF5 K	TCF6 K	TPF K	TDF5 K	TDF4 K	TDF3 K	TDF2 K	TDF1 K	TTF K	TGF K	TIM HRS
300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	300.15	6.00
299.82	299.82	299.81	299.80	299.80	299.78	299.77	299.75	299.76	299.77	299.78	299.79	299.80	299.82	298.63	7.00
301.88	301.90	301.94	301.98	302.03	302.10	302.19	302.30	302.25	302.19	302.13	302.06	301.97	301.87	300.17	8.00
309.49	309.58	309.71	309.87	310.09	310.36	310.69	311.08	310.89	310.68	310.45	310.19	309.86	309.45	305.14	9.00
320.88	321.01	321.21	321.47	321.81	322.22	322.71	323.26	322.99	322.69	322.35	321.95	321.46	320.81	305.29	10.00
335.60	335.74	336.00	336.36	336.83	337.41	338.10	338.86	338.51	338.12	337.67	337.14	336.47	335.53	312.12	11.00
341.99	341.85	342.07	342.58	343.35	344.37	345.64	347.09	346.63	346.10	345.49	344.75	343.80	342.46	317.04	12.00
349.09	348.95	349.19	349.74	350.55	351.61	352.89	354.31	353.84	353.30	352.68	351.92	350.95	349.58	321.18	13.00
355.52	355.42	355.63	356.09	356.75	357.60	358.60	359.70	359.32	358.89	358.38	357.77	356.99	355.89	324.44	14.00
359.40	359.36	359.49	359.75	360.11	360.56	361.07	361.62	361.42	361.19	360.92	360.59	360.17	359.58	324.90	15.00
358.72	358.71	358.72	358.73	358.75	358.75	358.72	358.66	358.68	358.69	358.70	358.72	358.73	358.74	322.99	16.00
338.83	338.59	338.29	337.90	337.42	336.82	336.07	335.22	335.65	336.12	336.64	337.26	338.02	339.03	313.57	17.00
323.59	323.39	323.12	322.77	322.36	321.88	321.32	320.72	321.06	321.42	321.84	322.32	322.93	323.73	306.93	18.00
318.25	318.26	318.12	317.84	317.45	316.96	316.36	315.70	315.94	316.21	316.53	316.91	317.40	318.09	309.15	19.00
315.04	315.10	314.99	314.76	314.42	313.97	313.44	312.85	313.04	313.27	313.53	313.86	314.27	314.85	307.62	20.00
312.41	312.47	312.38	312.17	311.87	311.49	311.01	310.49	310.66	310.86	311.09	311.37	311.73	312.24	305.86	21.00
310.21	310.26	310.18	310.00	309.74	309.39	308.98	308.52	308.67	308.84	309.04	309.29	309.60	310.05	304.37	22.00
308.32	308.37	308.30	308.14	307.91	307.60	307.24	306.83	306.96	307.11	307.29	307.51	307.79	308.18	303.09	23.00
306.67	306.71	306.65	306.51	306.30	306.02	305.69	305.32	305.44	305.58	305.74	305.93	306.18	306.54	301.88	24.00
305.24	305.28	305.22	305.10	304.91	304.67	304.37	304.04	304.15	304.27	304.41	304.59	304.81	305.12	300.95	1.00
304.00	304.04	303.99	303.88	303.71	303.50	303.24	302.95	303.05	303.15	303.28	303.43	303.62	303.90	300.18	2.00
302.92	302.95	302.90	302.81	302.66	302.47	302.23	301.97	302.06	302.15	302.26	302.40	302.57	302.82	299.45	3.00
301.97	301.99	301.96	301.87	301.74	301.57	301.36	301.13	301.21	301.29	301.39	301.51	301.66	301.88	298.86	4.00
301.14	301.17	301.14	301.06	300.94	300.79	300.61	300.41	300.48	300.55	300.64	300.74	300.88	301.07	298.39	5.00
300.42	300.44	300.41	300.34	300.24	300.10	299.94	299.76	299.82	299.88	299.96	300.06	300.18	300.35	297.93	6.00

Table B.5 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for March
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.700	26.700	26.700	26.700	26.700	23.200	0.038	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.725	26.749	26.752	26.759	25.430	24.000	0.038	0.030	7.000
0.161	0.161	0.161	0.160	0.160	0.159	0.159	0.160	30.724	30.498	30.292	30.032	27.772	24.900	0.046	0.405	8.000
0.163	0.163	0.162	0.161	0.160	0.158	0.156	0.160	42.018	41.329	40.704	39.888	33.998	25.700	0.083	0.504	9.000
0.165	0.164	0.163	0.162	0.160	0.158	0.155	0.160	57.045	56.057	55.161	53.951	35.218	27.300	0.173	0.425	10.000
0.149	0.149	0.148	0.146	0.143	0.140	0.136	0.143	69.739	68.391	66.416	65.240	41.085	28.900	0.240	0.448	11.000
0.120	0.121	0.120	0.118	0.115	0.111	0.107	0.115	78.925	77.299	74.580	73.450	46.031	30.500	0.240	0.436	12.000
0.095	0.095	0.094	0.093	0.090	0.087	0.084	0.090	87.006	85.473	82.992	81.845	50.301	32.100	0.240	0.387	13.000
0.076	0.076	0.075	0.074	0.073	0.071	0.069	0.073	93.255	92.061	90.207	89.240	53.703	33.600	0.240	0.311	14.000
0.066	0.066	0.066	0.065	0.064	0.064	0.063	0.064	95.641	95.021	94.108	93.552	54.314	32.900	0.240	0.177	15.000
0.065	0.065	0.065	0.064	0.064	0.064	0.065	0.064	92.778	92.806	92.840	92.846	52.514	32.100	0.228	0.000	16.000
0.061	0.062	0.062	0.063	0.065	0.066	0.068	0.064	65.662	67.036	68.177	70.000	41.839	31.300	0.075	0.000	17.000
0.066	0.067	0.067	0.068	0.070	0.071	0.073	0.070	50.126	51.250	52.408	53.822	34.763	30.500	0.038	0.000	18.000
0.082	0.082	0.083	0.084	0.085	0.087	0.090	0.085	43.955	44.957	46.536	47.322	31.108	29.100	0.038	0.000	19.000
0.096	0.096	0.096	0.097	0.099	0.101	0.104	0.099	39.898	40.731	42.091	42.707	28.823	27.800	0.038	0.000	20.000
0.108	0.108	0.109	0.110	0.111	0.113	0.115	0.111	36.708	37.413	38.583	39.090	26.879	26.400	0.038	0.000	21.000
0.118	0.118	0.118	0.119	0.120	0.122	0.124	0.120	34.721	35.249	36.126	36.509	29.493	25.800	0.038	0.000	22.000
0.126	0.126	0.126	0.127	0.128	0.129	0.131	0.128	33.031	33.462	34.182	34.486	28.905	25.300	0.038	0.000	23.000
0.133	0.133	0.133	0.133	0.134	0.136	0.137	0.134	31.548	31.918	32.544	32.800	27.934	24.700	0.038	0.000	24.000
0.139	0.139	0.139	0.139	0.140	0.141	0.142	0.140	30.317	30.634	31.172	31.390	27.156	24.400	0.038	0.000	1.000
0.144	0.144	0.144	0.144	0.145	0.146	0.147	0.145	29.244	29.521	29.994	30.182	26.427	24.000	0.038	0.000	2.000
0.149	0.148	0.149	0.149	0.150	0.150	0.151	0.150	28.323	28.565	28.979	29.143	25.816	23.700	0.038	0.000	3.000
0.153	0.152	0.153	0.153	0.154	0.154	0.155	0.154	27.539	27.750	28.110	28.253	25.325	23.500	0.038	0.000	4.000
0.156	0.156	0.156	0.156	0.157	0.158	0.158	0.157	26.883	27.064	27.373	27.496	24.949	23.400	0.038	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	26.299	26.458	26.730	26.837	24.574	23.200	0.038	0.000	6.000

OVERALL COL. EFFCY = .3207827 OVERALL COP = .1164145 TEV = -1.267273 TCD = 31.87326 TI = 31.86032 TE = 31.84143 QE = 2088406
 TC1 = 26.70001 TC2 = 62.07273 TC3 = 94.10754 TC4 = 54.54038 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4988.433

Table B.6 Charcoal/Methanol Solar Collector Simulation Temperatures for March
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	299.85	6.00
299.92	299.92	299.91	299.91	299.90	299.89	299.89	299.88	299.88	299.90	299.91	299.91	299.92	299.91	298.58	7.00
303.20	303.24	303.29	303.36	303.45	303.56	303.70	303.87	303.79	303.70	303.61	303.49	303.35	303.18	300.92	8.00
313.09	313.21	313.38	313.60	313.88	314.23	314.66	315.17	314.92	314.65	314.35	314.00	313.58	313.04	307.15	9.00
327.17	327.34	327.59	327.93	328.36	328.88	329.50	330.20	329.84	329.46	329.02	328.52	327.90	327.10	308.37	10.00
338.12	338.10	338.36	338.85	339.56	340.47	341.61	342.89	342.43	341.92	341.32	340.60	339.68	338.39	314.24	11.00
346.04	345.87	346.15	346.77	347.69	348.91	350.40	352.08	351.53	350.91	350.19	349.31	348.18	346.60	319.18	12.00
354.49	354.35	354.63	355.24	356.13	357.27	358.64	360.16	359.64	359.06	358.38	357.55	356.49	355.00	323.45	13.00
362.03	361.95	362.19	362.67	363.36	364.24	365.27	366.40	366.01	365.55	365.02	364.37	363.55	362.39	326.85	14.00
366.54	366.51	366.64	366.91	367.27	367.72	368.24	368.79	368.58	368.35	368.07	367.74	367.31	366.70	327.46	15.00
365.98	365.97	365.97	365.99	366.00	366.00	365.98	365.93	365.94	365.95	365.96	365.97	365.98	366.00	325.66	16.00
342.91	342.62	342.26	341.82	341.27	340.59	339.76	338.81	339.30	339.84	340.44	341.13	342.00	343.15	314.99	17.00
326.90	326.74	326.45	326.03	325.50	324.86	324.11	323.28	323.66	324.10	324.59	325.18	325.93	326.97	307.91	18.00
320.76	320.82	320.63	320.25	319.70	318.98	318.09	317.11	317.44	317.82	318.27	318.81	319.50	320.47	304.26	19.00
316.13	316.20	316.06	315.73	315.25	314.63	313.88	313.05	313.33	313.64	314.01	314.47	315.04	315.86	301.97	20.00
312.48	312.55	312.43	312.15	311.74	311.21	310.57	309.86	310.09	310.36	310.68	311.06	311.55	312.24	300.03	21.00
309.85	309.90	309.81	309.59	309.28	308.88	308.40	307.87	308.05	308.25	308.48	308.77	309.14	309.66	302.64	22.00
307.79	307.84	307.76	307.59	307.34	307.01	306.61	306.18	306.32	306.49	306.68	306.91	307.21	307.64	302.05	23.00
306.09	306.13	306.07	305.92	305.70	305.42	305.08	304.70	304.82	304.96	305.13	305.33	305.59	305.95	301.08	24.00
304.66	304.70	304.64	304.52	304.33	304.08	303.79	303.47	303.57	303.69	303.83	304.01	304.23	304.54	300.31	1.00
303.44	303.47	303.42	303.31	303.15	302.94	302.68	302.39	302.49	302.59	302.72	302.87	303.06	303.33	299.58	2.00
302.39	302.42	302.37	302.28	302.13	301.95	301.72	301.47	301.55	301.65	301.75	301.89	302.05	302.29	298.97	3.00
301.48	301.51	301.47	301.39	301.26	301.10	300.91	300.69	300.76	300.84	300.93	301.05	301.20	301.40	298.47	4.00
300.72	300.74	300.71	300.63	300.53	300.39	300.22	300.03	300.09	300.16	300.24	300.34	300.47	300.65	298.10	5.00
300.05	300.07	300.04	299.98	299.88	299.76	299.61	299.45	299.50	299.56	299.63	299.72	299.83	299.99	297.72	6.00

Table B.7 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for April
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.540	26.540	26.540	26.540	26.540	23.200	0.037	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.954	26.955	26.939	26.920	25.659	24.200	0.038	0.155	7.000
0.161	0.161	0.161	0.161	0.160	0.159	0.158	0.160	32.230	31.928	31.651	31.300	28.603	25.100	0.050	0.434	8.000
0.163	0.163	0.162	0.161	0.160	0.158	0.157	0.160	43.499	42.824	42.195	41.365	29.394	26.100	0.089	0.452	9.000
0.165	0.164	0.163	0.162	0.160	0.158	0.155	0.160	58.958	57.945	57.026	55.786	35.741	27.500	0.189	0.416	10.000
0.145	0.145	0.144	0.142	0.139	0.136	0.131	0.139	70.472	69.060	66.857	65.738	41.463	28.900	0.233	0.451	11.000
0.117	0.117	0.116	0.114	0.112	0.108	0.103	0.112	79.249	77.645	74.972	73.848	46.042	30.300	0.233	0.428	12.000
0.092	0.093	0.092	0.090	0.088	0.085	0.082	0.088	86.988	85.514	83.139	82.026	49.916	31.500	0.233	0.376	13.000
0.075	0.075	0.074	0.073	0.072	0.070	0.068	0.072	92.758	91.642	89.917	89.007	52.931	32.700	0.233	0.296	14.000
0.066	0.066	0.066	0.066	0.065	0.064	0.063	0.065	94.386	93.868	93.114	92.640	53.134	31.900	0.233	0.149	15.000
0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065	90.543	90.640	90.730	90.833	50.940	31.100	0.211	0.000	16.000
0.062	0.062	0.063	0.064	0.065	0.067	0.069	0.065	63.541	64.920	66.064	67.898	40.396	30.300	0.068	0.000	17.000
0.069	0.069	0.070	0.071	0.072	0.074	0.076	0.072	48.873	50.017	51.281	52.646	33.722	29.500	0.037	0.000	18.000
0.084	0.084	0.085	0.086	0.088	0.090	0.092	0.088	43.018	44.009	45.577	46.350	30.371	28.300	0.037	0.000	19.000
0.098	0.098	0.099	0.100	0.101	0.103	0.106	0.101	39.099	39.920	41.262	41.867	28.224	27.100	0.037	0.000	20.000
0.110	0.110	0.111	0.112	0.113	0.115	0.117	0.113	36.038	36.727	37.872	38.367	26.455	25.900	0.037	0.000	21.000
0.120	0.120	0.120	0.121	0.122	0.123	0.125	0.122	34.147	34.660	35.511	35.883	29.019	25.500	0.037	0.000	22.000
0.127	0.127	0.128	0.128	0.129	0.131	0.132	0.129	32.517	32.935	33.636	33.931	28.453	25.000	0.037	0.000	23.000
0.134	0.134	0.134	0.135	0.136	0.137	0.138	0.136	31.127	31.482	32.080	32.326	27.620	24.600	0.037	0.000	24.000
0.140	0.140	0.140	0.140	0.141	0.142	0.143	0.141	29.957	30.260	30.775	30.983	26.891	24.300	0.037	0.000	1.000
0.145	0.145	0.145	0.145	0.146	0.147	0.148	0.146	28.954	29.217	29.664	29.843	26.248	24.000	0.037	0.000	2.000
0.149	0.149	0.149	0.150	0.150	0.151	0.152	0.150	28.082	28.312	28.705	28.861	25.673	23.700	0.037	0.000	3.000
0.153	0.153	0.153	0.153	0.154	0.155	0.155	0.154	27.338	27.538	27.881	28.016	25.206	23.500	0.037	0.000	4.000
0.156	0.156	0.156	0.157	0.157	0.158	0.158	0.157	26.714	26.886	27.181	27.297	24.850	23.400	0.037	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	26.156	26.308	26.568	26.669	24.490	23.200	0.037	0.000	6.000

OVERALL COL. EFFCY = .3168699 OVERALL COP = .1157045 TEV = -1.417297 TCD = 31.26328 TI = 31.24951 TE = 31.23065 QE = 2079106
 TC1 = 26.53998 TC2 = 61.4227 TC3 = 93.11419 TC4 = 54.12418 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4996.695

Table B.8 Charcoal/Methanol Solar Collector Simulation Temperatures for April
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	299.69	6.00
300.08	300.08	300.08	300.08	300.09	300.09	300.10	300.10	300.11	300.11	300.11	300.11	300.10	300.07	298.81	7.00
304.48	304.53	304.60	304.69	304.81	304.96	305.15	305.38	305.27	305.15	305.02	304.87	304.68	304.45	301.75	8.00
314.58	314.70	314.86	315.09	315.37	315.72	316.16	316.65	316.41	316.15	315.85	315.51	315.08	314.52	302.54	9.00
329.01	329.18	329.44	329.78	330.22	330.75	331.39	332.11	331.74	331.35	330.91	330.39	329.76	328.94	308.89	10.00
338.53	338.45	338.71	339.23	339.98	340.98	342.22	343.62	343.15	342.61	341.98	341.22	340.25	338.89	314.61	11.00
346.45	346.28	346.55	347.17	348.09	349.29	350.76	352.40	351.86	351.25	350.54	349.67	348.56	347.00	319.19	12.00
354.70	354.57	354.84	355.42	356.28	357.37	358.69	360.14	359.65	359.08	358.43	357.63	356.61	355.18	323.07	13.00
361.83	361.75	361.97	362.43	363.07	363.89	364.86	365.91	365.53	365.11	364.61	364.01	363.24	362.16	326.08	14.00
365.65	365.63	365.75	365.97	366.28	366.66	367.08	367.54	367.36	367.17	366.94	366.66	366.29	365.79	326.28	15.00
363.95	363.93	363.92	363.91	363.89	363.85	363.79	363.69	363.73	363.77	363.81	363.86	363.91	363.98	324.09	16.00
340.81	340.51	340.15	339.71	339.15	338.47	337.64	336.69	337.18	337.72	338.32	339.02	339.90	341.05	313.55	17.00
325.78	325.65	325.36	324.94	324.39	323.71	322.91	322.02	322.42	322.85	323.36	323.96	324.73	325.80	306.87	18.00
319.79	319.85	319.67	319.29	318.74	318.02	317.15	316.17	316.50	316.88	317.32	317.85	318.54	319.50	303.52	19.00
315.29	315.36	315.22	314.90	314.42	313.81	313.07	312.25	312.52	312.83	313.20	313.64	314.21	315.02	301.37	20.00
311.76	311.83	311.71	311.43	311.03	310.51	309.88	309.19	309.42	309.68	309.99	310.36	310.84	311.52	299.60	21.00
309.22	309.27	309.18	308.97	308.67	308.27	307.81	307.30	307.47	307.66	307.89	308.17	308.53	309.03	302.17	22.00
307.23	307.28	307.21	307.04	306.79	306.47	306.09	305.67	305.81	305.97	306.15	306.38	306.67	307.08	301.60	23.00
305.61	305.65	305.59	305.45	305.24	304.96	304.64	304.28	304.40	304.53	304.69	304.88	305.13	305.48	300.77	24.00
304.25	304.28	304.23	304.11	303.93	303.70	303.42	303.11	303.21	303.32	303.46	303.62	303.83	304.13	300.04	1.00
303.09	303.12	303.08	302.97	302.82	302.62	302.37	302.10	302.19	302.29	302.41	302.55	302.73	302.99	299.40	2.00
302.10	302.13	302.09	302.00	301.86	301.68	301.47	301.23	301.31	301.40	301.50	301.62	301.78	302.01	298.82	3.00
301.24	301.27	301.23	301.15	301.03	300.88	300.69	300.49	300.55	300.63	300.72	300.83	300.97	301.17	298.36	4.00
300.51	300.53	300.51	300.44	300.33	300.20	300.04	299.86	299.92	299.99	300.06	300.16	300.28	300.45	298.00	5.00
299.88	299.90	299.87	299.81	299.72	299.60	299.46	299.31	299.36	299.41	299.48	299.56	299.67	299.82	297.64	6.00

Table B.9 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for May
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.350	26.350	26.350	26.350	26.350	23.200	0.037	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	27.111	27.093	27.058	27.017	25.783	24.100	0.038	0.192	7.000
0.162	0.162	0.161	0.161	0.160	0.159	0.158	0.160	33.465	33.097	32.761	32.332	29.408	25.100	0.053	0.441	8.000
0.163	0.163	0.162	0.161	0.160	0.158	0.156	0.160	44.820	44.116	43.470	42.609	30.001	26.000	0.096	0.438	9.000
0.165	0.164	0.163	0.162	0.160	0.158	0.155	0.160	59.365	58.399	57.524	56.336	36.021	27.200	0.194	0.403	10.000
0.145	0.145	0.144	0.142	0.140	0.136	0.132	0.140	69.350	68.038	65.948	64.944	41.088	28.300	0.225	0.440	11.000
0.118	0.119	0.118	0.116	0.113	0.110	0.105	0.113	77.664	76.145	73.605	72.548	45.421	29.500	0.225	0.424	12.000
0.095	0.095	0.094	0.093	0.090	0.088	0.084	0.090	85.116	83.695	81.397	80.334	49.291	30.800	0.225	0.376	13.000
0.078	0.078	0.077	0.076	0.075	0.073	0.071	0.075	90.381	89.325	87.685	86.828	52.131	32.000	0.225	0.294	14.000
0.069	0.069	0.069	0.068	0.067	0.067	0.066	0.067	92.434	91.884	91.069	90.580	52.521	31.100	0.225	0.165	15.000
0.067	0.067	0.067	0.067	0.067	0.067	0.068	0.067	88.923	88.996	89.067	89.137	50.440	30.300	0.206	0.000	16.000
0.064	0.065	0.065	0.066	0.068	0.069	0.071	0.067	62.221	63.584	64.720	66.526	39.709	29.400	0.067	0.000	17.000
0.071	0.071	0.072	0.073	0.074	0.076	0.078	0.074	47.729	48.865	50.127	51.475	32.910	28.600	0.037	0.000	18.000
0.087	0.087	0.087	0.088	0.090	0.092	0.095	0.090	42.109	43.082	44.625	45.380	29.678	27.600	0.037	0.000	19.000
0.100	0.100	0.101	0.102	0.103	0.105	0.108	0.103	38.379	39.177	40.485	41.071	27.743	26.700	0.037	0.000	20.000
0.112	0.112	0.112	0.113	0.115	0.116	0.119	0.115	35.472	36.138	37.245	37.722	26.139	25.700	0.037	0.000	21.000
0.121	0.121	0.121	0.122	0.123	0.125	0.126	0.123	33.655	34.151	34.976	35.335	28.755	25.200	0.037	0.000	22.000
0.129	0.128	0.129	0.129	0.130	0.132	0.133	0.130	32.106	32.508	33.183	33.467	28.275	24.800	0.037	0.000	23.000
0.135	0.135	0.135	0.136	0.138	0.138	0.139	0.137	30.746	31.091	31.674	31.912	27.409	24.300	0.037	0.000	24.000
0.141	0.140	0.141	0.141	0.142	0.143	0.144	0.142	29.602	29.898	30.402	30.605	26.673	24.000	0.037	0.000	1.000
0.145	0.145	0.145	0.146	0.147	0.147	0.148	0.147	28.643	28.897	29.331	29.504	26.080	23.800	0.037	0.000	2.000
0.150	0.149	0.150	0.150	0.151	0.151	0.152	0.151	27.799	28.022	28.403	28.553	25.514	23.500	0.037	0.000	3.000
0.153	0.153	0.153	0.154	0.154	0.155	0.156	0.154	27.099	27.290	27.618	27.747	25.103	23.400	0.037	0.000	4.000
0.156	0.156	0.156	0.157	0.157	0.158	0.159	0.157	26.503	26.668	26.949	27.060	24.758	23.300	0.037	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	25.990	26.133	26.376	26.472	24.457	23.200	0.037	0.000	6.000

OVERALL COL. EFFCY = .3142486 OVERALL COP = .1150243 TEV = -1.58728 TCD = 30.51825 TI = 30.50522 TE = 30.48667 QE = 2029632
 TC1 = 26.34998 TC2 = 60.63764 TC3 = 91.06912 TC4 = 52.89954 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4906.638

Table B.10 Charcoal/Methanol Solar Collector Simulation Temperatures for May
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	299.50	6.00
300.18	300.18	300.19	300.20	300.21	300.22	300.24	300.26	300.26	300.25	300.24	300.23	300.21	300.17	298.93	7.00
305.51	305.58	305.66	305.77	305.92	306.10	306.34	306.61	306.48	306.34	306.18	305.99	305.77	305.48	302.56	8.00
315.82	315.94	316.12	316.35	316.65	317.01	317.46	317.97	317.72	317.44	317.14	316.78	316.33	315.76	303.15	9.00
329.55	329.72	329.97	330.30	330.72	331.23	331.84	332.51	332.17	331.79	331.37	330.88	330.27	329.49	309.17	10.00
337.73	337.64	337.88	338.36	339.07	340.01	341.18	342.50	342.06	341.56	340.98	340.27	339.37	338.09	314.24	11.00
345.17	345.01	345.27	345.85	346.72	347.86	349.26	350.81	350.31	349.73	349.05	348.23	347.18	345.70	318.57	12.00
353.02	352.89	353.15	353.71	354.53	355.59	356.87	358.27	357.79	357.25	356.62	355.85	354.87	353.48	322.44	13.00
359.66	359.59	359.80	360.22	360.84	361.62	362.53	363.53	363.18	362.78	362.31	361.73	361.00	359.98	325.28	14.00
363.58	363.55	363.67	363.91	364.23	364.63	365.09	365.58	365.40	365.19	364.95	364.65	364.27	363.73	325.67	15.00
362.26	362.24	362.24	362.23	362.23	362.20	362.15	362.07	362.10	362.13	362.16	362.20	362.24	362.29	323.59	16.00
339.44	339.15	338.80	338.36	337.81	337.13	336.31	335.37	335.86	336.39	336.98	337.68	338.54	339.68	312.86	17.00
324.61	324.48	324.20	323.78	323.23	322.56	321.76	320.88	321.27	321.70	322.21	322.81	323.57	324.63	306.06	18.00
318.82	318.88	318.70	318.33	317.79	317.08	316.22	315.26	315.58	315.95	316.39	316.91	317.59	318.53	302.83	19.00
314.49	314.56	314.42	314.11	313.65	313.05	312.33	311.53	311.79	312.10	312.45	312.89	313.44	314.22	300.89	20.00
311.10	311.17	311.06	310.79	310.41	309.90	309.29	308.62	308.84	309.10	309.39	309.76	310.22	310.87	299.29	21.00
308.66	308.72	308.63	308.43	308.13	307.75	307.30	306.80	306.97	307.16	307.38	307.65	308.00	308.49	301.90	22.00
306.76	306.81	306.74	306.58	306.34	306.03	305.66	305.26	305.39	305.54	305.72	305.94	306.22	306.62	301.42	23.00
305.19	305.23	305.17	305.03	304.83	304.57	304.25	303.90	304.01	304.14	304.30	304.48	304.72	305.06	300.56	24.00
303.87	303.90	303.85	303.73	303.56	303.33	303.05	302.75	302.85	302.96	303.10	303.26	303.46	303.76	299.82	1.00
302.75	302.78	302.74	302.64	302.49	302.29	302.05	301.79	301.88	301.97	302.09	302.23	302.40	302.65	299.23	2.00
301.79	301.82	301.78	301.69	301.56	301.39	301.18	300.95	301.02	301.11	301.21	301.33	301.48	301.70	298.66	3.00
300.97	300.99	300.96	300.89	300.77	300.62	300.45	300.25	300.31	300.39	300.47	300.57	300.71	300.90	298.25	4.00
300.27	300.29	300.27	300.20	300.10	299.98	299.82	299.65	299.71	299.77	299.84	299.93	300.05	300.21	297.91	5.00
299.68	299.69	299.67	299.61	299.53	299.42	299.29	299.14	299.19	299.24	299.31	299.38	299.48	299.62	297.61	6.00

Table B.11 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for June
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.900	24.900	24.900	24.900	24.900	22.300	0.034	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	25.413	25.409	25.387	25.362	24.356	23.100	0.035	0.188	7.000
0.161	0.161	0.161	0.160	0.160	0.159	0.159	0.160	29.838	29.583	29.350	29.053	26.839	23.800	0.044	0.424	8.000
0.163	0.163	0.162	0.161	0.160	0.159	0.157	0.160	39.608	39.001	38.453	37.728	32.304	24.600	0.073	0.497	9.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	50.328	49.602	48.950	48.051	31.736	25.600	0.127	0.399	10.000
0.159	0.159	0.158	0.157	0.155	0.153	0.150	0.155	61.439	60.577	59.553	58.594	36.303	26.500	0.201	0.395	11.000
0.140	0.140	0.139	0.138	0.136	0.133	0.129	0.136	67.587	66.505	64.675	63.941	39.699	27.500	0.201	0.400	12.000
0.118	0.119	0.118	0.116	0.114	0.111	0.107	0.114	74.327	73.078	70.984	70.120	43.260	28.700	0.201	0.396	13.000
0.100	0.100	0.100	0.099	0.097	0.095	0.092	0.097	79.303	78.254	76.555	75.767	45.976	29.900	0.201	0.331	14.000
0.090	0.091	0.090	0.089	0.089	0.088	0.086	0.089	80.948	80.389	79.529	79.059	45.977	28.700	0.201	0.191	15.000
0.089	0.089	0.089	0.089	0.089	0.089	0.089	0.089	79.196	79.172	79.162	79.102	44.632	27.900	0.198	0.000	16.000
0.085	0.086	0.087	0.088	0.089	0.091	0.093	0.089	56.911	58.052	59.047	60.517	35.855	27.000	0.077	0.000	17.000
0.085	0.086	0.087	0.088	0.089	0.090	0.092	0.089	42.703	43.625	44.376	45.642	29.485	26.200	0.036	0.000	18.000
0.098	0.098	0.099	0.100	0.101	0.103	0.105	0.101	37.551	38.347	39.582	40.226	26.563	25.400	0.034	0.000	19.000
0.110	0.110	0.110	0.111	0.112	0.114	0.117	0.112	34.540	35.208	36.314	36.794	25.009	24.700	0.034	0.000	20.000
0.119	0.119	0.119	0.120	0.121	0.123	0.125	0.121	32.630	33.137	33.980	34.345	27.562	23.900	0.034	0.000	21.000
0.127	0.127	0.127	0.127	0.128	0.130	0.131	0.128	31.055	31.464	32.150	32.439	27.106	23.600	0.034	0.000	22.000
0.133	0.133	0.133	0.134	0.135	0.136	0.137	0.135	29.745	30.086	30.660	30.897	26.399	23.400	0.034	0.000	23.000
0.139	0.138	0.139	0.139	0.140	0.141	0.142	0.140	28.622	28.913	29.407	29.608	25.698	23.100	0.034	0.000	24.000
0.143	0.143	0.143	0.144	0.144	0.145	0.146	0.144	27.677	27.927	28.352	28.522	25.121	22.900	0.034	0.000	1.000
0.147	0.147	0.147	0.148	0.148	0.149	0.150	0.148	26.868	27.084	27.452	27.599	24.619	22.700	0.034	0.000	2.000
0.151	0.151	0.151	0.151	0.152	0.152	0.153	0.152	26.167	26.355	26.677	26.804	24.174	22.500	0.034	0.000	3.000
0.154	0.154	0.154	0.154	0.155	0.155	0.156	0.155	25.576	25.738	26.016	26.126	23.828	22.400	0.034	0.000	4.000
0.157	0.157	0.157	0.157	0.157	0.158	0.158	0.157	25.091	25.228	25.463	25.556	23.587	22.400	0.034	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	24.663	24.782	24.986	25.066	23.338	22.300	0.034	0.000	6.000

OVERALL COL. EFFCY = .3082247 OVERALL COP = .1071052 TEV = -2.937195 TCD = 28.34393 TI = 28.3349 TE = 28.32025 QE = 1567312
 TC1 = 24.89996 TC2 = 58.33319 TC3 = 79.52872 TC4 = 43.42591 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4069.129

Table B.12 Charcoal/Methanol Solar Collector Simulation Temperatures for June
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	298.05	6.00
298.53	298.53	298.53	298.53	298.54	298.54	298.54	298.55	298.56	298.56	298.56	298.56	298.55	298.55	297.51	7.00
302.23	302.27	302.33	302.41	302.51	302.63	302.80	302.99	302.89	302.79	302.68	302.56	302.40	302.20	299.99	8.00
310.92	311.03	311.18	311.37	311.62	311.94	312.32	312.76	312.54	312.30	312.04	311.73	311.35	310.88	305.45	9.00
321.25	321.38	321.57	321.82	322.14	322.52	322.97	323.48	323.22	322.93	322.62	322.25	321.79	321.20	304.89	10.00
331.72	331.79	331.99	332.31	332.72	333.25	333.88	334.59	334.29	333.96	333.58	333.13	332.55	331.74	309.45	11.00
336.71	336.60	336.78	337.18	337.79	338.60	339.60	340.74	340.38	339.96	339.48	338.90	338.15	337.09	312.85	12.00
342.83	342.70	342.91	343.39	344.10	345.04	346.19	347.48	347.06	346.58	346.03	345.35	344.49	343.27	316.41	13.00
348.57	348.47	348.66	349.08	349.70	350.48	351.42	352.45	352.10	351.70	351.24	350.67	349.94	348.92	319.13	14.00
352.03	351.99	352.11	352.35	352.69	353.11	353.59	354.10	353.91	353.70	353.45	353.15	352.76	352.21	319.13	15.00
352.24	352.24	352.26	352.29	352.33	352.36	352.36	352.35	352.34	352.33	352.32	352.30	352.28	352.25	317.78	16.00
333.48	333.25	332.97	332.61	332.16	331.59	330.88	330.06	330.47	330.91	331.41	331.99	332.71	333.67	309.01	17.00
318.66	318.46	318.20	317.87	317.46	316.99	316.44	315.85	316.18	316.54	316.94	317.41	318.01	318.79	302.64	18.00
313.59	313.63	313.48	313.18	312.74	312.17	311.48	310.70	310.97	311.27	311.63	312.05	312.60	313.38	299.71	19.00
310.17	310.24	310.12	309.86	309.47	308.97	308.36	307.69	307.91	308.17	308.46	308.83	309.29	309.94	298.16	20.00
307.68	307.73	307.64	307.44	307.14	306.75	306.29	305.78	305.95	306.14	306.37	306.64	307.00	307.49	300.71	21.00
305.74	305.78	305.71	305.55	305.31	304.99	304.62	304.20	304.34	304.50	304.68	304.90	305.19	305.59	300.26	22.00
304.17	304.21	304.15	304.02	303.82	303.55	303.24	302.89	303.01	303.14	303.29	303.47	303.71	304.05	299.55	23.00
302.87	302.90	302.85	302.74	302.56	302.34	302.07	301.77	301.87	301.98	302.11	302.27	302.47	302.76	298.85	24.00
301.77	301.80	301.75	301.65	301.51	301.31	301.08	300.83	300.91	301.00	301.12	301.25	301.43	301.67	298.27	1.00
300.83	300.86	300.82	300.73	300.61	300.44	300.24	300.02	300.09	300.17	300.27	300.39	300.54	300.75	297.77	2.00
300.03	300.05	300.02	299.94	299.83	299.69	299.51	299.32	299.38	299.45	299.54	299.64	299.77	299.95	297.32	3.00
299.34	299.36	299.33	299.27	299.17	299.04	298.89	298.73	298.78	298.84	298.91	299.00	299.12	299.28	296.98	4.00
298.76	298.78	298.75	298.70	298.62	298.51	298.38	298.24	298.29	298.34	298.40	298.47	298.57	298.71	296.74	5.00
298.26	298.28	298.26	298.21	298.14	298.05	297.93	297.81	297.85	297.90	297.95	298.02	298.10	298.22	296.49	6.00

Table B.13 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for July
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.510	24.510	24.510	24.510	24.510	22.000	0.033	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.718	24.731	24.725	24.721	23.673	22.500	0.033	0.132	7.000
0.161	0.161	0.161	0.160	0.160	0.160	0.159	0.160	27.827	27.651	27.489	27.285	25.441	23.100	0.039	0.397	8.000
0.162	0.162	0.161	0.161	0.160	0.159	0.158	0.160	35.520	35.047	34.620	34.058	29.614	23.600	0.059	0.493	9.000
0.163	0.163	0.162	0.161	0.160	0.158	0.157	0.160	45.444	44.789	44.200	43.397	29.020	24.500	0.099	0.411	10.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	57.167	56.372	55.656	54.672	33.776	25.500	0.177	0.371	11.000
0.149	0.149	0.148	0.147	0.145	0.142	0.139	0.145	63.487	62.557	61.053	60.356	37.116	26.400	0.191	0.389	12.000
0.131	0.132	0.131	0.130	0.128	0.125	0.122	0.128	68.332	67.359	65.720	65.049	39.865	27.600	0.191	0.368	13.000
0.117	0.117	0.116	0.115	0.114	0.112	0.109	0.114	72.091	71.255	69.878	69.270	42.010	28.700	0.191	0.315	14.000
0.106	0.106	0.106	0.105	0.104	0.103	0.101	0.104	74.574	73.967	72.989	72.524	42.529	27.700	0.191	0.236	15.000
0.103	0.103	0.103	0.103	0.103	0.102	0.102	0.103	73.701	73.579	73.420	73.278	41.677	27.100	0.191	0.023	16.000
0.099	0.100	0.101	0.101	0.101	0.104	0.106	0.103	54.274	55.231	56.107	57.339	34.264	26.500	0.083	0.000	17.000
0.099	0.100	0.101	0.102	0.103	0.104	0.106	0.103	41.518	42.347	43.042	44.163	28.665	25.900	0.042	0.000	18.000
0.106	0.106	0.106	0.107	0.108	0.109	0.111	0.108	35.826	36.419	37.163	37.797	30.063	25.200	0.033	0.000	19.000
0.115	0.114	0.115	0.115	0.116	0.118	0.120	0.116	33.515	34.011	34.824	35.187	28.846	24.400	0.033	0.000	20.000
0.122	0.122	0.122	0.123	0.124	0.125	0.127	0.124	31.698	32.128	32.849	33.149	27.589	23.700	0.033	0.000	21.000
0.129	0.129	0.129	0.130	0.131	0.132	0.133	0.131	30.236	30.602	31.219	31.473	26.662	23.400	0.033	0.000	22.000
0.135	0.135	0.135	0.136	0.136	0.137	0.139	0.136	28.988	29.304	29.840	30.057	25.833	23.000	0.033	0.000	23.000
0.140	0.140	0.140	0.141	0.141	0.142	0.143	0.141	27.930	28.204	28.669	28.856	25.145	22.700	0.033	0.000	24.000
0.144	0.144	0.145	0.145	0.146	0.146	0.147	0.146	27.063	27.296	27.692	27.851	24.649	22.600	0.033	0.000	1.000
0.148	0.148	0.148	0.149	0.149	0.150	0.151	0.149	26.310	26.512	26.856	26.993	24.184	22.400	0.033	0.000	2.000
0.152	0.152	0.152	0.152	0.152	0.153	0.154	0.152	25.677	25.850	26.146	26.263	23.819	22.300	0.033	0.000	3.000
0.155	0.155	0.155	0.155	0.155	0.156	0.156	0.155	25.135	25.284	25.540	25.640	23.506	22.200	0.033	0.000	4.000
0.157	0.157	0.157	0.157	0.158	0.158	0.159	0.158	24.666	24.795	25.017	25.104	23.231	22.100	0.033	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	24.257	24.370	24.564	24.640	22.986	22.000	0.033	0.000	6.000

OVERALL COL. EFFCY = .2965099 OVERALL COP = 9.736916E-02 TEV = -3.29715 TCD = 27.28574 TI = 27.27872 TE = 27.26642 QE = 1265824
 TC1 = 24.50998 TC2 = 57.21494 TC3 = 73.41968 TC4 = 38.7143 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 3614.999

Table B.14 Charcoal/Methanol Solar Collector Simulation Temperatures for July
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	297.66	6.00
297.88	297.88	297.88	297.88	297.87	297.87	297.87	297.87	297.88	297.88	297.89	297.89	297.89	297.87	296.82	7.00
300.45	300.48	300.52	300.57	300.64	300.73	300.84	300.98	300.91	300.84	300.77	300.68	300.57	300.44	298.59	8.00
307.24	307.33	307.44	307.59	307.79	308.03	308.33	308.67	308.50	308.31	308.11	307.87	307.58	307.21	302.76	9.00
316.59	316.71	316.88	317.10	317.38	317.72	318.13	318.59	318.36	318.10	317.82	317.49	317.07	316.55	302.17	10.00
327.87	328.01	328.22	328.50	328.85	329.27	329.76	330.32	330.03	329.72	329.38	328.97	328.47	327.82	306.93	11.00
333.23	333.16	333.32	333.67	334.18	334.86	335.69	336.64	336.33	335.97	335.56	335.06	334.41	333.51	310.27	12.00
337.85	337.75	337.91	338.29	338.85	339.58	340.48	341.48	341.16	340.79	340.35	339.83	339.15	338.20	313.01	13.00
342.13	342.04	342.19	342.53	343.02	343.65	344.41	345.24	344.96	344.64	344.27	343.82	343.24	342.42	315.16	14.00
345.47	345.41	345.53	345.78	346.14	346.60	347.14	347.72	347.52	347.29	347.02	346.69	346.27	345.67	315.68	15.00
346.39	346.38	346.42	346.49	346.59	346.68	346.77	346.85	346.81	346.77	346.71	346.64	346.55	346.43	314.83	16.00
330.32	330.14	329.91	329.61	329.23	328.75	328.13	327.42	327.76	328.13	328.55	329.04	329.66	330.49	307.41	17.00
317.20	317.03	316.80	316.50	316.14	315.71	315.21	314.67	314.96	315.28	315.65	316.07	316.61	317.31	301.81	18.00
311.00	310.97	310.83	310.60	310.29	309.91	309.47	308.98	309.18	309.40	309.67	309.98	310.38	310.95	303.21	19.00
308.50	308.55	308.46	308.27	307.98	307.61	307.16	306.67	306.83	307.02	307.24	307.51	307.85	308.34	302.00	20.00
306.45	306.50	306.43	306.26	306.01	305.68	305.28	304.85	304.99	305.15	305.35	305.58	305.88	306.30	300.74	21.00
304.76	304.80	304.74	304.59	304.37	304.10	303.76	303.39	303.51	303.65	303.81	304.01	304.26	304.62	299.81	22.00
303.32	303.36	303.31	303.18	303.00	302.75	302.46	302.14	302.24	302.36	302.50	302.68	302.90	303.21	298.98	23.00
302.11	302.14	302.10	301.99	301.82	301.61	301.36	301.08	301.17	301.28	301.40	301.55	301.74	302.01	298.30	24.00
301.09	301.12	301.08	300.98	300.85	300.67	300.45	300.21	300.29	300.38	300.48	300.61	300.77	301.00	297.80	1.00
300.22	300.24	300.21	300.13	300.01	299.85	299.67	299.46	299.53	299.60	299.69	299.80	299.94	300.14	297.33	2.00
299.48	299.50	299.47	299.40	299.30	299.17	299.00	298.83	298.88	298.95	299.03	299.12	299.24	299.41	296.97	3.00
298.85	298.87	298.84	298.78	298.69	298.58	298.44	298.28	298.33	298.39	298.46	298.54	298.64	298.79	296.66	4.00
298.30	298.32	298.30	298.25	298.17	298.07	297.95	297.82	297.86	297.91	297.97	298.04	298.13	298.25	296.38	5.00
297.83	297.85	297.83	297.78	297.72	297.63	297.52	297.41	297.44	297.49	297.54	297.60	297.68	297.79	296.14	6.00

Table B.15 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for August
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	23.730	23.730	23.730	23.730	23.730	21.500	0.031	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	23.947	23.960	23.953	23.948	22.974	22.000	0.032	0.177	7.000
0.161	0.161	0.160	0.160	0.160	0.160	0.159	0.160	26.415	26.275	26.147	25.985	24.383	22.600	0.036	0.407	8.000
0.162	0.162	0.161	0.161	0.160	0.159	0.158	0.160	32.399	32.032	31.700	31.262	27.556	23.100	0.050	0.497	9.000
0.163	0.162	0.162	0.161	0.160	0.159	0.157	0.160	41.419	40.833	40.307	39.596	32.608	23.900	0.081	0.487	10.000
0.163	0.163	0.162	0.161	0.160	0.158	0.157	0.160	50.962	50.306	49.719	48.903	31.034	24.700	0.132	0.373	11.000
0.159	0.159	0.158	0.157	0.156	0.154	0.152	0.156	59.316	58.633	57.813	57.056	34.357	25.500	0.187	0.351	12.000
0.145	0.145	0.145	0.144	0.142	0.140	0.137	0.142	63.473	62.699	61.393	60.863	36.998	26.900	0.187	0.347	13.000
0.132	0.133	0.132	0.131	0.130	0.128	0.126	0.130	66.504	65.813	64.658	64.171	38.963	28.200	0.187	0.304	14.000
0.123	0.124	0.123	0.123	0.122	0.120	0.119	0.122	68.300	67.808	67.003	66.634	39.000	26.900	0.187	0.221	15.000
0.120	0.120	0.120	0.120	0.119	0.119	0.118	0.119	68.136	67.965	67.710	67.551	38.591	26.500	0.187	0.067	16.000
0.116	0.117	0.117	0.118	0.119	0.121	0.123	0.119	51.204	52.035	52.817	53.864	32.377	26.000	0.091	0.000	17.000
0.116	0.116	0.117	0.118	0.119	0.121	0.123	0.119	39.732	40.484	41.133	42.133	27.600	25.600	0.049	0.000	18.000
0.117	0.117	0.118	0.119	0.119	0.120	0.121	0.119	33.346	33.815	34.207	34.856	28.602	24.900	0.033	0.000	19.000
0.123	0.123	0.123	0.124	0.125	0.126	0.127	0.125	31.023	31.385	31.929	32.242	27.405	24.200	0.031	0.000	20.000
0.129	0.129	0.129	0.130	0.130	0.131	0.132	0.130	29.626	29.949	30.492	30.717	26.339	23.500	0.031	0.000	21.000
0.134	0.134	0.134	0.135	0.135	0.136	0.137	0.135	28.487	28.771	29.252	29.446	25.549	23.100	0.031	0.000	22.000
0.139	0.139	0.139	0.139	0.140	0.141	0.142	0.140	27.523	27.770	28.191	28.360	24.918	22.800	0.031	0.000	23.000
0.143	0.143	0.143	0.143	0.144	0.145	0.146	0.144	26.662	26.882	27.259	27.407	24.304	22.400	0.031	0.000	24.000
0.147	0.147	0.147	0.147	0.148	0.148	0.149	0.148	25.934	26.127	26.456	26.586	23.841	22.200	0.031	0.000	1.000
0.150	0.150	0.150	0.150	0.151	0.151	0.152	0.151	25.301	25.470	25.759	25.873	23.437	22.000	0.031	0.000	2.000
0.153	0.153	0.153	0.153	0.153	0.154	0.155	0.153	24.743	24.892	25.148	25.249	23.071	21.800	0.031	0.000	3.000
0.155	0.155	0.155	0.155	0.156	0.156	0.157	0.156	24.269	24.399	24.622	24.709	22.792	21.700	0.031	0.000	4.000
0.157	0.157	0.157	0.158	0.158	0.158	0.159	0.158	23.857	23.971	24.166	24.242	22.550	21.600	0.031	0.000	5.000
0.159	0.159	0.159	0.160	0.160	0.160	0.161	0.160	23.496	23.596	23.767	23.834	22.332	21.500	0.031	0.000	6.000

OVERALL COL. EFFCY = .2896196 OVERALL COP = 8.160373E-02 TEV = -4.027069 TCD = 26.8815 TI = 26.87677 TE = 26.8678 QE = 898530.4
 TC1 = 23.73001 TC2 = 56.78067 TC3 = 67.70972 TC4 = 33.29074 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 3061.817

Table B.16 Charcoal/Methanol Solar Collector Simulation Temperatures for August
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	296.88	6.00
297.11	297.11	297.11	297.10	297.10	297.10	297.10	297.10	297.10	297.11	297.12	297.12	297.12	297.10	296.12	7.00
299.15	299.17	299.20	299.25	299.30	299.37	299.46	299.57	299.51	299.46	299.40	299.33	299.24	299.14	297.53	8.00
304.44	304.51	304.59	304.71	304.86	305.05	305.28	305.55	305.42	305.27	305.11	304.93	304.70	304.41	300.71	9.00
312.79	312.89	313.04	313.23	313.48	313.79	314.15	314.57	314.36	314.13	313.87	313.58	313.21	312.75	305.76	10.00
322.10	322.21	322.38	322.61	322.90	323.25	323.66	324.11	323.88	323.62	323.34	323.00	322.59	322.05	304.18	11.00
330.18	330.23	330.39	330.64	330.98	331.40	331.91	332.47	332.23	331.97	331.67	331.31	330.85	330.21	307.51	12.00
333.74	333.66	333.79	334.08	334.52	335.10	335.82	336.62	336.36	336.07	335.73	335.31	334.77	334.01	310.15	13.00
337.07	337.00	337.12	337.39	337.80	338.32	338.96	339.65	339.42	339.16	338.85	338.48	338.00	337.32	312.11	14.00
339.61	339.56	339.65	339.86	340.15	340.53	340.97	341.45	341.29	341.10	340.88	340.61	340.27	339.78	312.15	15.00
340.64	340.63	340.67	340.76	340.87	341.00	341.15	341.29	341.23	341.17	341.09	340.99	340.87	340.70	311.74	16.00
326.88	326.72	326.53	326.28	325.95	325.53	324.99	324.35	324.65	324.97	325.33	325.76	326.29	327.01	305.53	17.00
315.19	315.04	314.84	314.57	314.24	313.84	313.38	312.88	313.15	313.44	313.77	314.16	314.64	315.28	300.75	18.00
307.95	307.86	307.72	307.54	307.32	307.07	306.79	306.50	306.66	306.84	307.05	307.29	307.60	308.01	301.75	19.00
305.48	305.50	305.42	305.28	305.08	304.82	304.51	304.17	304.29	304.43	304.59	304.79	305.04	305.39	300.55	20.00
303.98	304.02	303.96	303.84	303.65	303.40	303.11	302.78	302.88	303.01	303.15	303.33	303.55	303.87	299.49	21.00
302.70	302.74	302.69	302.57	302.41	302.19	301.93	301.64	301.73	301.84	301.97	302.12	302.32	302.60	298.70	22.00
301.60	301.63	301.59	301.49	301.35	301.16	300.93	300.67	300.76	300.85	300.96	301.09	301.27	301.51	298.07	23.00
300.64	300.67	300.63	300.54	300.41	300.24	300.04	299.81	299.89	299.97	300.07	300.19	300.34	300.56	297.45	24.00
299.81	299.83	299.80	299.72	299.61	299.46	299.28	299.08	299.15	299.22	299.31	299.41	299.55	299.74	296.99	1.00
299.09	299.11	299.08	299.01	298.91	298.78	298.62	298.45	298.51	298.57	298.65	298.74	298.86	299.02	296.59	2.00
298.46	298.47	298.45	298.39	298.30	298.19	298.05	297.89	297.94	298.00	298.07	298.15	298.25	298.40	296.22	3.00
297.91	297.93	297.90	297.85	297.77	297.67	297.55	297.42	297.46	297.51	297.57	297.64	297.73	297.86	295.94	4.00
297.44	297.45	297.43	297.39	297.32	297.23	297.12	297.01	297.05	297.09	297.14	297.20	297.28	297.39	295.70	5.00
297.02	297.04	297.02	296.98	296.92	296.84	296.75	296.65	296.68	296.72	296.76	296.82	296.89	296.98	295.48	6.00

Table B.17 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for September
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.500	24.500	24.500	24.500	24.500	21.900	0.033	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	24.888	24.891	24.876	24.859	23.761	22.500	0.034	0.221	7.000
0.161	0.161	0.161	0.160	0.160	0.160	0.159	0.160	28.277	28.083	27.905	27.679	25.621	23.000	0.040	0.437	8.000
0.162	0.162	0.162	0.161	0.160	0.159	0.157	0.160	36.319	35.822	35.374	34.783	30.100	23.600	0.062	0.506	9.000
0.163	0.163	0.162	0.161	0.160	0.158	0.157	0.160	46.572	45.893	45.283	44.450	29.581	24.500	0.105	0.414	10.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	58.690	57.867	57.126	56.108	34.466	25.300	0.190	0.370	11.000
0.146	0.146	0.146	0.144	0.142	0.139	0.136	0.142	64.461	63.470	61.795	61.118	37.687	26.200	0.191	0.397	12.000
0.128	0.128	0.128	0.126	0.124	0.122	0.119	0.124	69.384	68.375	66.678	65.978	40.553	27.600	0.191	0.370	13.000
0.111	0.111	0.111	0.109	0.108	0.105	0.103	0.108	74.420	73.426	71.783	71.069	43.457	29.000	0.191	0.347	14.000
0.100	0.100	0.100	0.099	0.098	0.097	0.095	0.098	76.458	75.853	74.897	74.413	43.669	27.800	0.191	0.223	15.000
0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	75.152	75.082	75.015	74.907	42.544	27.100	0.191	0.000	16.000
0.094	0.095	0.096	0.097	0.098	0.100	0.102	0.098	54.392	55.424	56.359	57.697	34.492	26.500	0.078	0.000	17.000
0.095	0.095	0.096	0.097	0.098	0.100	0.101	0.098	41.062	41.931	42.650	43.831	28.503	25.800	0.038	0.000	18.000
0.103	0.103	0.104	0.105	0.106	0.107	0.109	0.106	36.272	36.902	37.786	38.379	30.258	25.100	0.033	0.000	19.000
0.113	0.112	0.113	0.114	0.115	0.116	0.118	0.115	33.899	34.422	35.285	35.666	29.067	24.300	0.033	0.000	20.000
0.121	0.121	0.121	0.122	0.123	0.124	0.126	0.123	31.993	32.444	33.200	33.516	27.766	23.600	0.033	0.000	21.000
0.128	0.128	0.128	0.129	0.129	0.131	0.132	0.129	30.460	30.843	31.487	31.753	26.791	23.300	0.033	0.000	22.000
0.134	0.134	0.134	0.135	0.135	0.136	0.138	0.135	29.156	29.486	30.044	30.271	25.924	22.900	0.033	0.000	23.000
0.139	0.139	0.139	0.140	0.141	0.142	0.143	0.141	28.054	28.339	28.823	29.018	25.205	22.600	0.033	0.000	24.000
0.144	0.144	0.144	0.144	0.145	0.146	0.147	0.145	27.151	27.393	27.805	27.970	24.682	22.500	0.033	0.000	1.000
0.148	0.148	0.148	0.148	0.149	0.150	0.150	0.149	26.369	26.579	26.936	27.078	24.196	22.300	0.033	0.000	2.000
0.151	0.151	0.151	0.152	0.152	0.153	0.154	0.152	25.712	25.892	26.199	26.320	23.814	22.200	0.033	0.000	3.000
0.154	0.154	0.154	0.155	0.155	0.156	0.156	0.155	25.150	25.305	25.570	25.674	23.486	22.100	0.033	0.000	4.000
0.157	0.157	0.157	0.157	0.158	0.158	0.159	0.158	24.664	24.799	25.029	25.119	23.200	22.000	0.033	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	24.242	24.359	24.560	24.638	22.945	21.900	0.033	0.000	6.000

OVERALL COL. EFFCY = .3072189 OVERALL COP = .103434 TEV = -3.307129 TCD = 27.2948 TI = 27.28763 TE = 27.27448 QE = 1368322
 TC1 = 24.5 TC2 = 57.224 TC3 = 75.01508 TC4 = 40.08841 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 3678.588

Table B.18 Charcoal/Methanol Solar Collector Simulation Temperatures for September
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM HRS
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	
297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	297.65	6.00
298.02	298.02	298.02	298.02	298.03	298.03	298.03	298.04	298.04	298.04	298.05	298.04	298.04	298.01	296.91	7.00
300.85	300.88	300.93	300.98	301.06	301.16	301.28	301.43	301.36	301.28	301.20	301.10	300.98	300.83	298.77	8.00
307.97	308.06	308.18	308.34	308.54	308.80	309.11	309.47	309.29	309.09	308.88	308.63	308.32	307.93	303.25	9.00
317.65	317.77	317.94	318.17	318.46	318.82	319.25	319.72	319.48	319.21	318.92	318.57	318.15	317.60	302.73	10.00
329.31	329.46	329.67	329.96	330.32	330.75	331.27	331.84	331.55	331.23	330.87	330.45	329.93	329.26	307.62	11.00
333.93	333.83	333.99	334.36	334.92	335.65	336.57	337.61	337.28	336.90	336.46	335.93	335.24	334.27	310.84	12.00
338.77	338.66	338.83	339.22	339.81	340.57	341.50	342.53	342.20	341.81	341.36	340.82	340.12	339.13	313.70	13.00
343.88	343.78	343.95	344.34	344.92	345.66	346.57	347.57	347.24	346.86	346.42	345.88	345.19	344.22	316.61	14.00
347.36	347.31	347.43	347.69	348.05	348.51	349.04	349.61	349.41	349.18	348.91	348.58	348.16	347.56	316.82	15.00
348.04	348.04	348.07	348.12	348.18	348.24	348.28	348.30	348.28	348.25	348.22	348.18	348.13	348.06	315.69	16.00
330.67	330.47	330.21	329.89	329.48	328.96	328.30	327.54	327.91	328.31	328.76	329.29	329.95	330.85	307.64	17.00
316.86	316.68	316.44	316.12	315.74	315.29	314.78	314.21	314.52	314.86	315.24	315.68	316.24	316.98	301.65	18.00
311.65	311.65	311.51	311.27	310.93	310.50	309.99	309.42	309.63	309.87	310.15	310.49	310.92	311.53	303.41	19.00
308.99	309.05	308.95	308.75	308.44	308.05	307.58	307.05	307.22	307.42	307.66	307.94	308.30	308.82	302.22	20.00
306.83	306.88	306.80	306.62	306.36	306.02	305.60	305.14	305.29	305.46	305.67	305.91	306.22	306.67	300.92	21.00
305.04	305.09	305.02	304.87	304.64	304.35	304.00	303.61	303.74	303.88	304.05	304.26	304.53	304.90	299.94	22.00
303.54	303.58	303.53	303.40	303.20	302.95	302.64	302.31	302.42	302.54	302.69	302.87	303.10	303.42	299.07	23.00
302.27	302.31	302.26	302.15	301.98	301.76	301.50	301.20	301.30	301.41	301.53	301.69	301.89	302.17	298.35	24.00
301.21	301.24	301.20	301.10	300.96	300.77	300.55	300.30	300.38	300.47	300.58	300.71	300.88	301.12	297.83	1.00
300.31	300.33	300.30	300.21	300.09	299.93	299.73	299.52	299.59	299.67	299.76	299.88	300.02	300.23	297.35	2.00
299.54	299.56	299.53	299.46	299.35	299.21	299.05	298.86	298.92	298.99	299.07	299.17	299.29	299.47	296.96	3.00
298.88	298.90	298.88	298.81	298.72	298.60	298.46	298.30	298.35	298.41	298.48	298.56	298.67	298.82	296.64	4.00
298.32	298.34	298.31	298.26	298.18	298.08	297.95	297.81	297.86	297.91	297.97	298.04	298.14	298.27	296.35	5.00
297.83	297.85	297.83	297.78	297.71	297.62	297.51	297.39	297.43	297.48	297.53	297.59	297.67	297.79	296.09	6.00

Table B.19 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for October
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	25.150	25.150	25.150	25.150	25.150	22.300	0.034	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	25.959	25.938	25.901	25.857	24.638	23.000	0.036	0.276	7.000
0.162	0.161	0.161	0.161	0.160	0.159	0.158	0.160	31.352	31.038	30.753	30.387	27.715	23.700	0.048	0.467	8.000
0.163	0.162	0.162	0.161	0.160	0.159	0.157	0.160	41.202	40.632	40.082	39.352	27.642	24.400	0.080	0.460	9.000
0.164	0.164	0.163	0.161	0.160	0.158	0.156	0.160	54.458	53.589	52.803	51.739	33.358	25.700	0.154	0.410	10.000
0.151	0.151	0.150	0.148	0.146	0.143	0.139	0.146	65.572	64.408	62.716	61.689	38.934	26.900	0.209	0.437	11.000
0.126	0.126	0.125	0.123	0.121	0.117	0.113	0.121	73.574	72.146	69.744	68.766	43.388	28.200	0.209	0.432	12.000
0.102	0.102	0.101	0.100	0.097	0.094	0.091	0.097	80.984	79.571	77.257	76.226	47.350	29.500	0.209	0.393	13.000
0.084	0.084	0.083	0.082	0.081	0.079	0.077	0.081	86.281	85.195	83.484	82.623	50.298	30.800	0.209	0.314	14.000
0.075	0.075	0.074	0.074	0.073	0.072	0.071	0.073	88.150	87.592	86.756	86.266	50.435	29.500	0.209	0.175	15.000
0.073	0.073	0.073	0.073	0.073	0.073	0.073	0.073	83.504	83.632	83.751	83.892	47.684	28.500	0.183	0.000	16.000
0.069	0.070	0.071	0.072	0.073	0.075	0.077	0.073	57.912	59.234	60.344	62.086	37.008	27.400	0.061	0.000	17.000
0.077	0.077	0.078	0.079	0.080	0.082	0.084	0.080	44.327	45.420	46.657	47.936	30.301	26.400	0.034	0.000	18.000
0.092	0.092	0.092	0.093	0.095	0.097	0.100	0.095	39.325	40.239	41.699	42.400	27.404	25.600	0.034	0.000	19.000
0.105	0.105	0.105	0.106	0.108	0.110	0.112	0.108	35.944	36.693	37.928	38.473	25.691	24.900	0.034	0.000	20.000
0.116	0.116	0.116	0.117	0.118	0.120	0.122	0.118	33.295	33.920	34.962	35.406	24.282	24.100	0.034	0.000	21.000
0.124	0.124	0.125	0.125	0.126	0.128	0.129	0.126	31.694	32.152	32.914	33.244	27.169	23.800	0.034	0.000	22.000
0.131	0.131	0.131	0.132	0.133	0.134	0.136	0.133	30.290	30.661	31.285	31.546	26.801	23.400	0.034	0.000	23.000
0.137	0.137	0.137	0.138	0.139	0.140	0.141	0.139	29.084	29.398	29.930	30.147	26.091	23.100	0.034	0.000	24.000
0.142	0.142	0.142	0.143	0.144	0.144	0.146	0.144	28.069	28.338	28.793	28.977	25.461	22.900	0.034	0.000	1.000
0.147	0.147	0.147	0.147	0.148	0.149	0.150	0.148	27.203	27.434	27.828	27.985	24.910	22.700	0.034	0.000	2.000
0.151	0.150	0.151	0.151	0.152	0.152	0.153	0.152	26.454	26.655	26.998	27.134	24.424	22.500	0.034	0.000	3.000
0.154	0.154	0.154	0.154	0.155	0.155	0.156	0.155	25.822	25.995	26.292	26.409	24.042	22.400	0.034	0.000	4.000
0.157	0.157	0.157	0.157	0.157	0.158	0.159	0.157	25.303	25.449	25.700	25.799	23.768	22.400	0.034	0.000	5.000
0.159	0.159	0.159	0.159	0.160	0.160	0.161	0.160	24.846	24.973	25.191	25.276	23.495	22.300	0.034	0.000	6.000

OVERALL COL. EFFCY = .3285719 OVERALL COP = .119486 TEV = -2.707214 TCD = 29.07614 TI = 29.06482 TE = 29.04697 QE = 1908756
 TC1 = 25.14996 TC2 = 59.10544 TC3 = 86.75611 TC4 = 49.27982 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4442.115

Table B.20 Charcoal/Methanol Solar Collector Simulation Temperatures for October
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM HRS
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	
298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	298.30	6.00
299.02	299.02	299.03	299.04	299.05	299.07	299.09	299.11	299.10	299.10	299.09	299.07	299.05	299.01	297.79	7.00
303.56	303.62	303.69	303.79	303.91	304.07	304.27	304.50	304.39	304.27	304.13	303.97	303.78	303.54	300.86	8.00
312.57	312.67	312.82	313.01	313.25	313.56	313.93	314.35	314.15	313.93	313.68	313.39	313.02	312.50	300.79	9.00
324.95	325.10	325.32	325.62	325.99	326.45	327.00	327.61	327.30	326.96	326.58	326.14	325.59	324.89	306.51	10.00
334.62	334.60	334.83	335.25	335.86	336.65	337.62	338.72	338.33	337.88	337.37	336.75	335.95	334.84	312.08	11.00
341.42	341.27	341.50	342.05	342.86	343.92	345.25	346.72	346.25	345.70	345.07	344.30	343.31	341.92	316.54	12.00
348.90	348.77	349.02	349.57	350.39	351.45	352.72	354.13	353.66	353.12	352.50	351.73	350.75	349.38	320.50	13.00
355.44	355.35	355.56	356.00	356.64	357.44	358.39	359.43	359.07	358.65	358.17	357.58	356.83	355.77	323.45	14.00
359.26	359.22	359.35	359.58	359.92	360.33	360.80	361.30	361.11	360.90	360.65	360.35	359.96	359.42	323.59	15.00
357.00	356.97	356.96	356.94	356.91	356.86	356.77	356.65	356.70	356.75	356.81	356.87	356.94	357.04	320.83	16.00
335.01	334.74	334.40	333.97	333.44	332.78	331.98	331.06	331.54	332.05	332.63	333.30	334.13	335.24	310.16	17.00
321.09	320.97	320.70	320.30	319.77	319.11	318.34	317.48	317.85	318.27	318.75	319.33	320.06	321.09	303.45	18.00
315.83	315.89	315.72	315.37	314.86	314.20	313.38	312.48	312.78	313.13	313.54	314.03	314.66	315.55	300.55	19.00
311.88	311.95	311.82	311.52	311.09	310.53	309.85	309.09	309.34	309.63	309.96	310.37	310.89	311.62	298.84	20.00
308.78	308.84	308.73	308.49	308.12	307.65	307.08	306.44	306.65	306.89	307.17	307.51	307.94	308.56	297.43	21.00
306.56	306.61	306.53	306.34	306.07	305.72	305.30	304.84	305.00	305.17	305.37	305.62	305.94	306.39	300.32	22.00
304.83	304.88	304.81	304.66	304.44	304.16	303.81	303.44	303.56	303.70	303.87	304.07	304.33	304.70	299.95	23.00
303.41	303.45	303.40	303.27	303.08	302.84	302.55	302.23	302.34	302.46	302.60	302.77	302.99	303.30	299.24	24.00
302.23	302.26	302.21	302.11	301.95	301.74	301.49	301.22	301.31	301.41	301.53	301.68	301.86	302.13	298.61	1.00
301.22	301.25	301.21	301.12	300.98	300.80	300.59	300.35	300.43	300.52	300.62	300.75	300.91	301.13	298.06	2.00
300.36	300.39	300.35	300.27	300.15	300.00	299.81	299.60	299.67	299.75	299.84	299.95	300.09	300.28	297.57	3.00
299.63	299.65	299.62	299.55	299.45	299.31	299.15	298.97	299.03	299.10	299.17	299.27	299.39	299.56	297.19	4.00
299.01	299.02	299.00	298.94	298.85	298.74	298.60	298.45	298.50	298.56	298.62	298.70	298.80	298.95	296.92	5.00
298.48	298.49	298.47	298.42	298.34	298.24	298.13	298.00	298.04	298.09	298.14	298.21	298.30	298.43	296.64	6.00

Table B.21 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for November
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.010	26.010	26.010	26.010	26.010	23.000	0.036	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	26.571	26.564	26.540	26.512	25.233	23.900	0.037	0.257	7.000
0.161	0.161	0.161	0.160	0.160	0.159	0.159	0.160	31.139	30.875	30.634	30.328	27.739	24.700	0.047	0.453	8.000
0.163	0.163	0.162	0.161	0.160	0.158	0.157	0.160	41.581	40.934	40.349	39.577	33.447	25.600	0.081	0.504	9.000
0.164	0.164	0.163	0.161	0.160	0.158	0.156	0.160	54.971	54.085	53.283	52.194	34.045	26.900	0.158	0.416	10.000
0.153	0.153	0.152	0.150	0.148	0.145	0.142	0.148	66.559	65.428	63.853	62.795	39.100	28.200	0.226	0.425	11.000
0.129	0.130	0.129	0.127	0.124	0.121	0.117	0.124	73.963	72.626	70.379	69.458	43.051	29.500	0.226	0.414	12.000
0.105	0.106	0.105	0.104	0.101	0.098	0.095	0.101	81.365	79.978	77.694	76.695	46.884	30.900	0.226	0.387	13.000
0.088	0.088	0.088	0.087	0.085	0.083	0.081	0.085	86.210	85.170	83.526	82.706	49.582	32.300	0.226	0.302	14.000
0.080	0.080	0.080	0.080	0.079	0.078	0.077	0.079	87.143	86.690	86.019	85.610	49.450	31.500	0.226	0.141	15.000
0.079	0.079	0.079	0.079	0.079	0.079	0.079	0.079	82.510	82.658	82.794	82.963	46.868	30.500	0.197	0.000	16.000
0.075	0.076	0.077	0.078	0.079	0.081	0.083	0.079	57.522	58.822	59.927	61.631	37.100	29.400	0.067	0.000	17.000
0.080	0.081	0.082	0.083	0.084	0.086	0.088	0.084	44.239	45.244	46.300	47.548	31.101	28.400	0.036	0.000	18.000
0.094	0.094	0.095	0.096	0.097	0.099	0.102	0.097	39.729	40.559	41.885	42.524	28.597	27.500	0.036	0.000	19.000
0.106	0.106	0.107	0.108	0.109	0.111	0.113	0.109	36.614	37.303	38.441	38.940	26.974	26.600	0.036	0.000	20.000
0.116	0.116	0.116	0.117	0.118	0.120	0.121	0.118	34.580	35.105	35.975	36.356	29.298	25.700	0.036	0.000	21.000
0.124	0.124	0.124	0.125	0.126	0.127	0.128	0.126	32.875	33.304	34.022	34.326	28.667	25.200	0.036	0.000	22.000
0.131	0.130	0.131	0.131	0.132	0.133	0.135	0.132	31.411	31.777	32.394	32.649	27.755	24.700	0.036	0.000	23.000
0.136	0.136	0.137	0.137	0.138	0.139	0.140	0.138	30.143	30.462	31.003	31.222	26.890	24.200	0.036	0.000	24.000
0.142	0.141	0.142	0.142	0.143	0.144	0.145	0.143	29.078	29.354	29.824	30.012	26.209	23.900	0.036	0.000	1.000
0.146	0.146	0.146	0.147	0.147	0.148	0.149	0.147	28.184	28.422	28.827	28.989	25.671	23.700	0.036	0.000	2.000
0.150	0.150	0.150	0.151	0.151	0.152	0.153	0.151	27.394	27.603	27.960	28.101	25.148	23.400	0.036	0.000	3.000
0.154	0.153	0.154	0.154	0.154	0.155	0.156	0.154	26.738	26.918	27.225	27.346	24.776	23.300	0.036	0.000	4.000
0.157	0.156	0.157	0.157	0.157	0.158	0.159	0.157	26.156	26.314	26.584	26.690	24.407	23.100	0.036	0.000	5.000
0.159	0.159	0.159	0.160	0.160	0.160	0.161	0.160	25.662	25.799	26.033	26.125	24.121	23.000	0.036	0.000	6.000

OVERALL COL. EFFCY = .3242505 OVERALL COP = .1146217 TEV = -1.907227 TCD = 30.64407 TI = 30.63287 TE = 30.61643 QE = 1772867
 TC1 = 26.01001 TC2 = 60.77347 TC3 = 86.01859 TC4 = 47.98169 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 4300.964

Table B.22 Charcoal/Methanol Solar Collector Simulation Temperatures for November
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	299.16	6.00
299.68	299.68	299.68	299.68	299.69	299.70	299.71	299.72	299.72	299.72	299.72	299.71	299.70	299.66	298.38	7.00
303.50	303.55	303.61	303.69	303.79	303.92	304.09	304.29	304.19	304.09	303.98	303.84	303.68	303.48	300.89	8.00
312.78	312.89	313.05	313.26	313.52	313.85	314.26	314.73	314.50	314.24	313.96	313.64	313.23	312.73	306.60	9.00
325.41	325.56	325.79	326.09	326.47	326.94	327.50	328.12	327.80	327.46	327.07	326.62	326.06	325.34	307.20	10.00
335.77	335.78	336.01	336.43	337.01	337.75	338.67	339.71	339.32	338.89	338.39	337.79	337.02	335.94	312.25	11.00
342.14	342.00	342.23	342.74	343.50	344.49	345.73	347.11	346.67	346.16	345.56	344.84	343.91	342.61	316.20	12.00
349.38	349.24	349.48	350.02	350.82	351.86	353.12	354.52	354.05	353.52	352.91	352.16	351.20	349.84	320.03	13.00
355.53	355.44	355.64	356.07	356.68	357.45	358.37	359.36	359.01	358.62	358.15	357.59	356.87	355.86	322.73	14.00
358.63	358.60	358.70	358.91	359.18	359.52	359.90	360.29	360.14	359.97	359.77	359.52	359.21	358.76	322.60	15.00
356.08	356.04	356.02	355.99	355.95	355.89	355.79	355.66	355.72	355.77	355.84	355.91	356.00	356.11	320.02	16.00
334.57	334.30	333.97	333.55	333.02	332.37	331.58	330.67	331.14	331.64	332.21	332.87	333.69	334.78	310.25	17.00
320.65	320.52	320.26	319.88	319.40	318.82	318.14	317.39	317.73	318.12	318.56	319.09	319.76	320.70	304.25	18.00
315.93	315.99	315.83	315.51	315.04	314.44	313.70	312.88	313.16	313.47	313.84	314.29	314.87	315.67	301.75	19.00
312.32	312.39	312.27	312.00	311.60	311.08	310.46	309.76	309.99	310.26	310.56	310.94	311.42	312.09	300.12	20.00
309.69	309.75	309.65	309.44	309.13	308.73	308.25	307.73	307.90	308.10	308.34	308.62	308.99	309.51	302.45	21.00
307.63	307.68	307.60	307.43	307.18	306.85	306.46	306.03	306.17	306.33	306.52	306.76	307.05	307.48	301.82	22.00
305.93	305.98	305.91	305.77	305.55	305.27	304.93	304.56	304.68	304.82	304.99	305.18	305.44	305.80	300.90	23.00
304.49	304.53	304.47	304.35	304.16	303.91	303.62	303.29	303.40	303.52	303.66	303.84	304.06	304.37	300.04	24.00
303.27	303.30	303.25	303.14	302.98	302.77	302.51	302.23	302.32	302.42	302.55	302.70	302.89	303.16	299.36	1.00
302.23	302.26	302.22	302.12	301.98	301.80	301.58	301.33	301.41	301.50	301.61	301.74	301.90	302.14	298.82	2.00
301.33	301.36	301.32	301.24	301.11	300.95	300.76	300.54	300.61	300.69	300.79	300.90	301.05	301.25	298.30	3.00
300.56	300.59	300.56	300.48	300.38	300.24	300.07	299.89	299.95	300.02	300.10	300.19	300.32	300.50	297.93	4.00
299.90	299.92	299.89	299.83	299.74	299.62	299.47	299.31	299.36	299.42	299.49	299.57	299.68	299.84	297.56	5.00
299.33	299.35	299.32	299.27	299.19	299.08	298.95	298.81	298.86	298.91	298.97	299.04	299.14	299.27	297.27	6.00

Table B.23 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for December
Kumasi

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	25.120	25.120	25.120	25.120	25.120	22.200	0.034	0.000	6.000
0.160	0.160	0.160	0.160	0.160	0.160	0.160	0.160	25.299	25.314	25.310	25.307	24.199	22.800	0.035	0.201	7.000
0.161	0.161	0.160	0.160	0.160	0.160	0.159	0.160	27.878	27.732	27.599	27.430	25.782	23.400	0.040	0.419	8.000
0.162	0.162	0.161	0.161	0.160	0.159	0.158	0.160	35.240	34.791	34.386	33.854	30.168	24.000	0.058	0.511	9.000
0.164	0.163	0.162	0.161	0.160	0.158	0.156	0.160	46.441	45.734	45.085	44.210	30.159	25.500	0.104	0.439	10.000
0.164	0.164	0.163	0.161	0.160	0.158	0.156	0.160	60.178	59.255	58.421	57.285	36.430	27.100	0.202	0.393	11.000
0.144	0.145	0.144	0.142	0.140	0.136	0.132	0.140	68.225	67.022	65.039	64.175	41.193	28.600	0.215	0.431	12.000
0.123	0.123	0.123	0.121	0.119	0.116	0.112	0.119	74.238	73.027	71.006	70.155	44.716	30.000	0.215	0.395	13.000
0.107	0.107	0.107	0.106	0.104	0.102	0.100	0.104	77.997	77.092	75.630	74.943	46.991	31.300	0.215	0.312	14.000
0.099	0.099	0.099	0.099	0.098	0.097	0.096	0.098	78.800	78.378	77.731	77.367	46.919	30.600	0.215	0.158	15.000
0.098	0.098	0.098	0.098	0.098	0.098	0.098	0.098	75.113	75.217	75.318	75.427	44.674	29.700	0.193	0.000	16.000
0.094	0.095	0.096	0.097	0.098	0.100	0.102	0.098	54.085	55.192	56.167	57.585	35.809	28.800	0.078	0.000	17.000
0.095	0.095	0.096	0.096	0.098	0.100	0.101	0.098	41.455	42.299	42.994	44.148	29.657	27.900	0.039	0.000	18.000
0.103	0.103	0.103	0.104	0.105	0.107	0.108	0.105	37.203	37.786	38.603	39.154	31.941	26.900	0.034	0.000	19.000
0.112	0.111	0.112	0.112	0.113	0.115	0.116	0.113	35.001	35.485	36.281	36.634	30.858	26.000	0.034	0.000	20.000
0.119	0.119	0.119	0.120	0.121	0.122	0.124	0.121	33.140	33.567	34.283	34.582	29.438	25.000	0.034	0.000	21.000
0.126	0.126	0.126	0.127	0.128	0.129	0.130	0.128	31.606	31.977	32.602	32.860	28.318	24.500	0.034	0.000	22.000
0.132	0.132	0.132	0.133	0.133	0.134	0.136	0.133	30.266	30.594	31.150	31.375	27.299	23.900	0.034	0.000	23.000
0.137	0.137	0.138	0.138	0.139	0.140	0.141	0.139	29.101	29.392	29.887	30.085	26.417	23.400	0.034	0.000	24.000
0.142	0.142	0.142	0.143	0.143	0.144	0.145	0.143	28.090	28.348	28.788	28.962	25.668	23.000	0.034	0.000	1.000
0.147	0.146	0.147	0.147	0.148	0.148	0.149	0.148	27.218	27.445	27.834	27.987	25.042	22.700	0.034	0.000	2.000
0.150	0.150	0.151	0.151	0.151	0.152	0.153	0.151	26.426	26.631	26.983	27.120	24.434	22.300	0.034	0.000	3.000
0.154	0.154	0.154	0.154	0.155	0.155	0.156	0.155	25.794	25.969	26.268	26.387	24.060	22.300	0.034	0.000	4.000
0.157	0.157	0.157	0.157	0.157	0.158	0.159	0.158	25.246	25.398	25.657	25.759	23.723	22.200	0.034	0.000	5.000
0.159	0.159	0.159	0.160	0.160	0.160	0.161	0.160	24.793	24.922	25.142	25.229	23.475	22.200	0.034	0.000	6.000

OVERALL COL. EFFCY = .3255499 OVERALL COP = .1063174 TEV = -2.737244 TCD = 29.67984 TI = 29.66913 TE = 29.65259 QE = 1362444
 TC1 = 25.11994 TC2 = 59.74918 TC3 = 77.73105 TC4 = 40.76547 S = 1.15 DC/L = .025273 / 3.8 DR/L = 9.796781E-02 / .4 ITT = 3563.451

Table B.24 Charcoal/Methanol Solar Collector Simulation Temperatures for December
Kumasi

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	298.27	6.00
298.47	298.47	298.46	298.46	298.46	298.46	298.45	298.45	298.46	298.47	298.47	298.47	298.48	298.46	297.35	7.00
300.59	300.62	300.65	300.69	300.75	300.82	300.92	301.03	300.98	300.92	300.85	300.78	300.69	300.58	298.93	8.00
307.04	307.12	307.23	307.37	307.55	307.78	308.06	308.39	308.23	308.05	307.86	307.63	307.35	307.00	303.32	9.00
317.42	317.54	317.72	317.96	318.26	318.64	319.09	319.59	319.34	319.06	318.76	318.39	317.95	317.36	303.31	10.00
330.50	330.66	330.89	331.21	331.62	332.10	332.68	333.33	333.00	332.64	332.24	331.77	331.18	330.44	309.58	11.00
336.95	336.84	337.05	337.50	338.16	339.03	340.13	341.37	340.97	340.51	339.98	339.33	338.50	337.33	314.34	12.00
342.88	342.75	342.96	343.43	344.13	345.05	346.16	347.39	346.98	346.52	345.98	345.33	344.49	343.30	317.87	13.00
347.79	347.70	347.87	348.24	348.78	349.46	350.27	351.15	350.85	350.50	350.10	349.61	348.98	348.09	320.14	14.00
350.38	350.35	350.44	350.63	350.89	351.21	351.57	351.95	351.81	351.65	351.46	351.23	350.93	350.52	320.07	15.00
348.55	348.52	348.51	348.50	348.48	348.44	348.37	348.26	348.30	348.34	348.39	348.44	348.50	348.58	317.82	16.00
330.57	330.35	330.07	329.72	329.28	328.72	328.03	327.23	327.63	328.06	328.54	329.11	329.81	330.74	308.96	17.00
317.18	317.01	316.77	316.46	316.09	315.65	315.15	314.60	314.90	315.23	315.60	316.03	316.58	317.30	302.81	18.00
312.42	312.42	312.29	312.06	311.74	311.35	310.87	310.35	310.55	310.77	311.03	311.34	311.74	312.30	305.09	19.00
309.95	310.00	309.91	309.72	309.44	309.08	308.64	308.15	308.31	308.50	308.71	308.97	309.31	309.78	304.01	20.00
307.89	307.93	307.86	307.69	307.44	307.12	306.72	306.29	306.43	306.59	306.78	307.02	307.31	307.73	302.59	21.00
306.14	306.19	306.12	305.98	305.76	305.48	305.13	304.76	304.88	305.02	305.19	305.39	305.65	306.01	301.47	22.00
304.65	304.68	304.63	304.50	304.31	304.06	303.75	303.42	303.53	303.65	303.80	303.97	304.20	304.52	300.45	23.00
303.34	303.38	303.33	303.21	303.04	302.82	302.55	302.25	302.35	302.46	302.59	302.75	302.95	303.23	299.57	24.00
302.21	302.24	302.20	302.10	301.94	301.75	301.51	301.24	301.33	301.42	301.54	301.68	301.86	302.11	298.82	1.00
301.22	301.25	301.21	301.12	300.99	300.81	300.60	300.37	300.44	300.53	300.63	300.75	300.91	301.14	298.19	2.00
300.35	300.37	300.34	300.26	300.14	299.98	299.79	299.58	299.64	299.72	299.81	299.92	300.07	300.27	297.58	3.00
299.60	299.63	299.60	299.53	299.42	299.29	299.12	298.94	299.00	299.07	299.15	299.24	299.36	299.54	297.21	4.00
298.97	298.99	298.96	298.90	298.81	298.69	298.55	298.40	298.45	298.50	298.57	298.65	298.76	298.91	296.87	5.00
298.43	298.45	298.42	298.37	298.29	298.19	298.07	297.94	297.99	298.03	298.09	298.16	298.25	298.38	296.62	6.00

Table B.25 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for 29th October 1987, Bangkok

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTf °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	29.230	29.230	29.230	29.230	29.230	24.620	0.054	0.000	6.000
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	30.117	30.139	30.098	30.112	27.581	24.620	0.057	0.547	7.000
0.178	0.178	0.178	0.178	0.178	0.178	0.177	0.178	32.641	32.558	32.401	32.403	29.047	24.620	0.065	0.276	8.000
0.180	0.180	0.180	0.179	0.178	0.177	0.174	0.178	47.969	47.467	46.497	46.505	32.179	26.150	0.138	0.356	9.000
0.153	0.156	0.156	0.155	0.152	0.148	0.142	0.151	68.526	67.718	64.531	65.479	41.706	27.680	0.242	0.524	10.000
0.114	0.117	0.117	0.116	0.113	0.109	0.104	0.112	80.360	79.439	75.686	77.014	48.945	30.740	0.242	0.469	11.000
0.080	0.082	0.082	0.081	0.079	0.076	0.073	0.078	92.248	91.368	87.935	89.088	54.394	30.740	0.242	0.408	12.000
0.060	0.061	0.061	0.061	0.060	0.058	0.057	0.059	99.552	98.994	96.912	97.564	57.537	30.740	0.242	0.290	13.000
0.049	0.050	0.050	0.050	0.049	0.048	0.047	0.049	104.596	104.254	103.036	103.392	59.654	30.740	0.242	0.194	14.000
0.038	0.038	0.038	0.038	0.038	0.037	0.036	0.038	112.709	112.301	110.952	111.312	63.479	30.740	0.203	0.199	15.000
0.038	0.038	0.038	0.038	0.038	0.038	0.038	0.038	106.142	106.244	106.436	106.470	60.097	30.740	0.054	0.000	16.000
0.047	0.046	0.046	0.047	0.048	0.049	0.052	0.048	66.521	67.386	69.938	69.727	42.852	29.210	0.054	0.000	17.000
0.074	0.072	0.072	0.073	0.075	0.078	0.081	0.076	53.399	54.158	57.066	56.149	34.911	27.680	0.054	0.000	18.000
0.097	0.095	0.095	0.096	0.098	0.101	0.104	0.099	46.215	46.777	49.072	48.280	31.559	27.680	0.054	0.000	19.000
0.116	0.114	0.114	0.115	0.116	0.118	0.121	0.117	41.550	41.971	43.734	43.105	29.686	27.680	0.054	0.000	20.000
0.132	0.131	0.131	0.131	0.133	0.135	0.138	0.133	37.406	37.777	39.353	38.780	26.497	24.620	0.054	0.000	21.000
0.146	0.145	0.145	0.145	0.147	0.148	0.151	0.147	34.525	34.819	36.082	35.617	25.268	24.620	0.054	0.000	22.000
0.156	0.155	0.155	0.155	0.156	0.158	0.159	0.156	32.787	32.992	33.885	33.554	28.225	24.620	0.054	0.000	23.000
0.163	0.163	0.163	0.163	0.164	0.165	0.166	0.164	31.385	31.544	32.232	31.977	28.002	24.620	0.054	0.000	24.000
0.171	0.170	0.170	0.170	0.171	0.172	0.173	0.171	29.867	30.019	30.675	30.429	26.665	23.090	0.054	0.000	1.000
0.177	0.176	0.176	0.176	0.177	0.178	0.179	0.177	28.718	28.845	29.396	29.189	25.948	23.090	0.054	0.000	2.000
0.178	0.177	0.177	0.178	0.178	0.178	0.179	0.178	26.721	26.802	27.034	26.998	24.989	23.090	0.048	0.000	3.000
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	25.401	25.450	25.558	25.557	24.278	23.090	0.044	0.000	4.000
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	24.565	24.595	24.659	24.660	23.821	23.090	0.042	0.000	5.000
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	24.039	24.058	24.098	24.099	23.536	23.090	0.040	0.000	6.000

OVERALL COL. EFFCY = .3140674
TC1 = 29.22995 TC2 = 57.90241

OVERALL COP = .138052
TC3 = 110.9516 TC4 =

TEV = 4.686005
S = .654

TCD = 32.05719
DC/L = .0127 / 8.770001

TI = 32.02078
DR/L = 0 / 0

TE = 31.91168
ITT = 5850.853

QE = 2826381

Table B.26 Charcoal/Methanol Solar Collector Simulation Temperatures For 29th October 1987, Bangkok

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	302.38	6.00
303.26	303.25	303.24	303.24	303.24	303.25	303.26	303.27	303.28	303.29	303.30	303.30	303.30	303.30	300.73	7.00
305.48	305.46	305.47	305.50	305.54	305.60	305.69	305.79	305.76	305.72	305.69	305.65	305.60	305.55	302.20	8.00
319.21	319.10	319.15	319.32	319.59	319.98	320.48	321.12	320.92	320.71	320.49	320.24	319.94	319.66	305.33	9.00
337.07	336.39	336.34	336.72	337.45	338.53	339.96	341.68	341.41	341.10	340.72	340.25	339.61	338.63	314.86	10.00
348.16	347.28	347.21	347.67	348.57	349.87	351.54	353.51	353.19	352.83	352.41	351.88	351.19	350.16	322.09	11.00
360.39	359.60	359.55	360.00	360.86	362.07	363.60	365.40	365.09	364.75	364.34	363.85	363.19	362.24	327.54	12.00
369.59	369.11	369.09	369.39	369.93	370.69	371.62	372.70	372.51	372.29	372.03	371.72	371.31	370.71	330.69	13.00
375.89	375.62	375.61	375.79	376.11	376.56	377.11	377.75	377.63	377.49	377.33	377.14	376.89	376.54	332.80	14.00
383.76	383.48	383.48	383.67	384.02	384.51	385.12	385.86	385.71	385.55	385.36	385.14	384.85	384.46	336.63	15.00
379.67	379.68	379.67	379.64	379.60	379.53	379.43	379.29	379.33	379.37	379.42	379.47	379.54	379.62	333.25	16.00
343.91	344.32	344.27	343.90	343.24	342.32	341.11	339.67	339.96	340.30	340.70	341.20	341.86	342.88	316.00	17.00
330.80	331.44	331.48	331.12	330.42	329.41	328.10	326.55	326.81	327.11	327.46	327.89	328.46	329.30	308.06	18.00
322.65	323.18	323.23	322.94	322.38	321.58	320.56	319.36	319.56	319.77	320.03	320.36	320.79	321.43	304.71	19.00
317.20	317.62	317.66	317.44	317.00	316.39	315.61	314.70	314.84	315.01	315.20	315.44	315.77	316.25	302.84	20.00
312.78	313.15	313.19	312.99	312.61	312.07	311.37	310.56	310.68	310.83	311.00	311.21	311.50	311.93	299.65	21.00
309.45	309.75	309.78	309.63	309.32	308.88	308.32	307.67	307.77	307.89	308.02	308.20	308.42	308.77	298.42	22.00
307.19	307.41	307.43	307.32	307.10	306.78	306.39	305.94	306.01	306.09	306.18	306.30	306.46	306.70	301.38	23.00
305.50	305.67	305.69	305.60	305.43	305.19	304.89	304.53	304.59	304.65	304.72	304.82	304.94	305.13	301.15	24.00
303.93	304.09	304.11	304.03	303.87	303.65	303.36	303.02	303.07	303.13	303.20	303.28	303.40	303.58	299.81	1.00
302.64	302.77	302.79	302.72	302.58	302.39	302.15	301.87	301.91	301.96	302.02	302.09	302.19	302.34	299.10	2.00
300.27	300.31	300.31	300.27	300.20	300.10	299.99	299.87	299.90	299.93	299.97	300.01	300.07	300.15	298.14	3.00
298.76	298.78	298.77	298.75	298.71	298.66	298.61	298.55	298.57	298.59	298.61	298.64	298.67	298.71	297.43	4.00
297.84	297.85	297.85	297.83	297.81	297.78	297.75	297.71	297.73	297.74	297.75	297.77	297.79	297.81	296.97	5.00
297.27	297.27	297.27	297.26	297.25	297.23	297.21	297.19	297.20	297.20	297.21	297.22	297.23	297.25	296.69	6.00

Table B.27 Charcoal/Methanol Solar Collector Simulation Results and Refrigerator Performance for 17th October 1987, Bangkok

XCF0 KG/KG	XCF1 KG/KG	XCF2 KG/KG	XCF3 KG/KG	XCF4 KG/KG	XCF5 KG/KG	XCF6 KG/KG	XMFF KG/KG	ITPF °C	TDF °C	TCF °C	ITTF °C	ITGF °C	TAMB °C	P BAR	EFF	TIM HRS
0.178	0.178	0.178	0.178	0.178	0.178	0.178	0.178	30.750	30.750	27.550	30.750	24.620	24.620	0.049	0.000	6.000
0.178	0.178	0.178	0.178	0.178	0.178	0.177	0.178	31.058	31.053	30.851	30.954	28.381	26.150	0.060	0.307	7.000
0.179	0.179	0.179	0.179	0.178	0.177	0.176	0.178	40.441	40.128	39.530	39.538	34.645	26.150	0.096	0.340	8.000
0.180	0.180	0.181	0.180	0.178	0.176	0.174	0.178	57.481	56.901	55.757	55.769	37.206	27.680	0.219	0.340	9.000
0.144	0.147	0.147	0.146	0.143	0.139	0.133	0.142	71.877	71.078	67.589	68.823	44.992	30.740	0.250	0.523	10.000
0.099	0.102	0.102	0.101	0.098	0.094	0.088	0.097	86.896	85.806	81.423	82.957	53.625	33.800	0.250	0.481	11.000
0.095	0.096	0.096	0.095	0.095	0.094	0.094	0.095	82.607	82.540	82.201	82.316	49.282	30.740	0.250	0.002	12.000
0.076	0.077	0.077	0.076	0.075	0.073	0.071	0.075	92.831	92.287	90.244	90.912	54.944	32.270	0.250	0.326	13.000
0.054	0.054	0.054	0.054	0.053	0.051	0.050	0.053	104.584	103.911	101.490	102.228	60.707	32.270	0.250	0.315	14.000
0.044	0.045	0.045	0.045	0.044	0.044	0.043	0.044	108.239	107.951	106.930	107.221	62.129	32.270	0.159	0.159	15.000
0.044	0.044	0.044	0.044	0.044	0.044	0.045	0.044	95.098	95.359	95.876	95.944	54.179	29.210	0.049	0.000	16.000
0.050	0.050	0.050	0.050	0.051	0.053	0.055	0.052	63.239	63.939	65.972	65.830	41.239	29.210	0.049	0.000	17.000
0.075	0.073	0.073	0.074	0.075	0.078	0.081	0.076	51.859	52.517	55.053	54.246	35.044	29.210	0.049	0.000	18.000
0.095	0.094	0.094	0.094	0.096	0.098	0.101	0.096	45.479	45.975	47.998	47.300	32.130	29.210	0.049	0.000	19.000
0.112	0.111	0.111	0.111	0.113	0.115	0.117	0.113	40.873	41.270	42.923	42.334	29.511	27.680	0.049	0.000	20.000
0.126	0.125	0.125	0.125	0.126	0.128	0.130	0.127	37.691	37.996	39.288	38.820	28.249	27.680	0.049	0.000	21.000
0.135	0.135	0.135	0.135	0.136	0.137	0.139	0.136	35.817	36.026	36.920	36.593	31.267	26.150	0.049	0.000	22.000
0.144	0.143	0.143	0.143	0.144	0.145	0.147	0.145	33.946	34.128	34.908	34.621	30.226	26.150	0.049	0.000	23.000
0.151	0.150	0.150	0.151	0.151	0.152	0.153	0.151	32.530	32.679	33.316	33.081	29.422	26.150	0.049	0.000	24.000
0.157	0.156	0.156	0.156	0.157	0.158	0.159	0.157	31.404	31.525	32.045	31.852	28.794	26.150	0.049	0.000	1.000
0.161	0.161	0.161	0.161	0.162	0.162	0.163	0.162	30.496	30.595	31.021	30.863	28.296	26.150	0.049	0.000	2.000
0.165	0.165	0.165	0.165	0.165	0.166	0.167	0.166	29.757	29.838	30.189	30.058	27.898	26.150	0.049	0.000	3.000
0.170	0.169	0.169	0.169	0.170	0.170	0.171	0.170	28.795	28.884	29.271	29.126	26.781	24.620	0.049	0.000	4.000
0.173	0.173	0.173	0.173	0.173	0.174	0.175	0.173	28.091	28.168	28.499	28.375	26.313	24.620	0.049	0.000	5.000
0.176	0.176	0.176	0.176	0.176	0.177	0.177	0.176	27.522	27.586	27.863	27.759	26.004	24.620	0.049	0.000	6.000

OVERALL COL. EFFCY = .3109749 OVERALL COP = .1361461 TEV = 3.096161 TCD = 32.65473 TI = 32.62094 TE = 32.517 QE = 2688941
TC1 = 27.55002 TC2 = 58.52997 TC3 = 106.9305 TC4 = 70.31576 S = .654 DC/L = .0127 / 8.770001 DR/L = 0 / 0 ITT = 5644.262

Table B.28 Charcoal/Methanol Solar Collector Simulation Temperatures for 17th October 1987, Bangkok

TCF0	TCF1	TCF2	TCF3	TCF4	TCF5	TCF6	TPF	TDF5	TDF4	TDF3	TDF2	TDF1	TTF	TGF	TIM
K	K	K	K	K	K	K	K	K	K	K	K	K	K	K	HRS
300.70	300.70	300.70	300.70	300.70	300.70	300.70	303.90	303.90	303.90	303.90	303.90	303.90	303.90	297.77	6.00
304.01	303.95	303.94	303.95	303.98	304.04	304.12	304.21	304.21	304.21	304.21	304.20	304.17	304.10	301.53	7.00
312.41	312.34	312.37	312.48	312.65	312.88	313.20	313.59	313.47	313.34	313.20	313.04	312.86	312.69	307.80	8.00
328.38	328.24	328.30	328.51	328.85	329.31	329.90	330.63	330.40	330.16	329.90	329.62	329.27	328.92	310.36	9.00
340.19	339.39	339.30	339.70	340.48	341.64	343.18	345.03	344.77	344.46	344.09	343.61	342.97	341.97	318.14	10.00
353.77	352.76	352.67	353.21	354.27	355.79	357.74	360.05	359.67	359.24	358.74	358.12	357.30	356.11	326.77	11.00
355.22	355.09	355.10	355.20	355.35	355.53	355.67	355.76	355.74	355.71	355.68	355.64	355.58	355.47	322.43	12.00
363.00	362.55	362.52	362.77	363.25	363.95	364.87	365.98	365.79	365.58	365.33	365.02	364.63	364.06	328.09	13.00
374.10	373.58	373.55	373.87	374.48	375.34	376.44	377.73	377.50	377.23	376.92	376.55	376.06	375.38	333.86	14.00
379.82	379.59	379.59	379.74	380.02	380.40	380.86	381.39	381.29	381.17	381.04	380.88	380.67	380.37	335.28	15.00
369.27	369.31	369.28	369.20	369.06	368.86	368.59	368.25	368.35	368.45	368.57	368.71	368.88	369.09	327.33	16.00
339.80	340.12	340.07	339.77	339.24	338.50	337.54	336.39	336.62	336.90	337.22	337.62	338.16	338.98	314.39	17.00
328.71	329.27	329.30	328.99	328.38	327.50	326.36	325.01	325.23	325.49	325.80	326.17	326.67	327.40	308.19	18.00
321.52	321.99	322.03	321.78	321.29	320.58	319.69	318.63	318.80	318.99	319.22	319.51	319.88	320.45	305.28	19.00
316.37	316.76	316.79	316.59	316.19	315.61	314.88	314.02	314.16	314.31	314.49	314.72	315.03	315.48	302.66	20.00
312.67	312.98	313.00	312.84	312.53	312.08	311.51	310.84	310.94	311.06	311.20	311.38	311.62	311.97	301.40	21.00
310.23	310.45	310.47	310.35	310.13	309.82	309.42	308.97	309.04	309.12	309.21	309.34	309.50	309.74	304.42	22.00
308.19	308.38	308.40	308.30	308.11	307.84	307.50	307.10	307.16	307.23	307.31	307.42	307.56	307.77	303.38	23.00
306.58	306.73	306.75	306.67	306.51	306.29	306.01	305.68	305.73	305.79	305.86	305.94	306.06	306.23	302.57	24.00
305.29	305.41	305.42	305.36	305.23	305.05	304.82	304.55	304.59	304.64	304.70	304.77	304.86	305.00	301.94	1.00
304.24	304.35	304.36	304.30	304.20	304.05	303.86	303.65	303.68	303.72	303.76	303.82	303.90	304.01	301.45	2.00
303.40	303.48	303.49	303.45	303.36	303.24	303.09	302.91	302.93	302.97	303.00	303.05	303.11	303.21	301.05	3.00
302.48	302.58	302.59	302.54	302.45	302.32	302.15	301.94	301.97	302.01	302.05	302.10	302.17	302.28	299.93	4.00
301.70	301.79	301.79	301.75	301.67	301.56	301.41	301.24	301.27	301.30	301.33	301.38	301.44	301.52	299.46	5.00
301.06	301.13	301.13	301.10	301.03	300.94	300.81	300.67	300.69	300.72	300.75	300.78	300.83	300.91	299.15	6.00

APPENDIX C

ESTIMATION OF THE MASSES MOT, MIT, MDT, MC AND MG

Table C.1 Dimensions and weights of steel pipes

Nominal pipe size (in.)	Outside diameter (in.)	Schedule No.	Wall thickness (in.)	Inside diameter (in.)	Weight of plain-end pipe (lb/ft)
1/8	0.405	10S	0.049	0.307	0.19
		40ST, 40S	0.068	0.269	0.24
		80XS, 80S	0.095	0.215	0.31
1/4	0.540	10S	0.065	0.410	0.33
		40ST, 40S	0.088	0.364	0.42
		80XS, 80S	0.119	0.302	0.54
3/8	0.675	10S	0.065	0.545	0.42
		40ST, 40S	0.091	0.493	0.57
		80XS, 80S	0.126	0.423	0.74
1/2	0.840	5S	0.065	0.710	0.54
		10S	0.083	0.674	0.67
		40ST, 40S	0.109	0.622	0.85
		80XS, 80S	0.147	0.546	1.09
		160	0.188	0.464	1.31
		XX	0.294	0.252	1.71
3/4	1.050	5S	0.065	0.920	0.69
		10S	0.083	0.884	0.86
		40ST, 40S	0.113	0.824	1.13
		80XS, 80S	0.154	0.742	1.47
		160	0.219	0.612	1.94
		XX	0.308	0.434	2.44
1	1.315	5S	0.065	1.185	0.87
		10S	0.109	1.097	1.40
		40ST, 40S	0.133	1.049	1.68
		80XS, 80S	0.179	0.957	2.17
		160	0.250	0.815	2.84
		XX	0.358	0.599	3.66
1 1/4	1.660	5S	0.065	1.530	1.11
		10S	0.109	1.442	1.81
		40ST, 40S	0.140	1.380	2.27
		80XS, 80S	0.191	1.278	3.00
		160	0.250	1.160	3.76
		XX	0.382	0.896	5.21
1 1/2	1.900	5S	0.065	1.770	1.28
		10S	0.109	1.682	2.09
		40ST, 40S	0.145	1.610	2.72
		80XS, 80S	0.200	1.500	3.63
		160	0.281	1.338	4.86
		XX	0.400	1.100	6.41

Table C.1 Continued

2	2.375	5S	0.065	2.245	1.61
		10S	0.109	2.157	2.64
		40ST, 40S	0.154	2.067	3.65
		80XS, 80S	0.218	1.939	5.02
		160	0.344	1.687	7.46
		XX	0.436	1.503	9.03
2 1/2	2.875	5S	0.083	2.709	2.48
		10S	0.120	2.635	3.53
		40ST, 40S	0.203	2.469	5.79
		80XS, 80S	0.276	2.323	7.66
		160	0.375	2.125	10.01
		XX	0.552	1.771	13.69
3	3.500	5S	0.083	3.334	3.03
		10S	0.120	3.260	4.33
		40ST, 40S	0.216	3.068	7.58
		80XS, 80S	0.300	2.900	10.25
		160	0.438	2.624	14.32
		XX	0.600	2.300	18.58
3 1/2	4.0	5S	0.083	3.834	3.48
		10S	0.120	3.760	4.97
		40ST, 40S	0.226	3.548	9.11
		80XS, 80S	0.318	3.364	12.50
4	4.5	5S	0.083	4.334	3.92
		10S	0.120	4.260	5.61
		40ST, 40S	0.237	4.026	10.79
		80XS, 80S	0.337	3.826	14.98

(Figures taken from Perry's Chemical Engineers' Handbook, Sixth Edition)

Schedules 5S, 10S, 40S and 80S are stainless steel pipes austenitic or ferritic.

Schedule 5S and 10S wall thicknesses do not permit threading in accordance with ASA B2.1

1. Collector Plate Outer Tubes [material: stainless steel]

Nominal pipe size = 2"

Outer diameter of tube = 2.375"

Inner diameter of tube = 2.245"

Thickness of tube = 0.065"

Weight of tube = 1.61 lb/ft

Number of tubes = 14

Length of each tube = 1.178 m

$$\text{Mass of Outer Tubes} = 1.61 \times \frac{1.178 \times 14}{0.3048 \times 2.205} = 39.507 \text{ kg}$$

Estimated mass of welding material ≈ 3.5 kg

$$M_{ot} = 39.507 + 3.5 \approx 43.01 \text{ kg}$$

2. Collector Plate Inner Tubes [material: stainless steel]

Nominal pipe size = 1/4"

Outer diameter of tube = 0.540" Inner diameter of tube = 0.410"

Thickness of tube = 0.065" Weight of tube = 0.33 lb/ft

Number of tubes = 14

Length of each tube = 1.178 + 0.05 = 1.228 m

$$\text{Mass of Inner Tubes} = 0.33 \times \frac{1.228 \times 14}{0.3048 \times 2.205} = 8.4414 \text{ kg}$$

3. Inner Tube End Caps [material: stainless steel]

Thickness of each end cap = 0.003 m

Number of end caps = 14

$$\text{Mass of Inner Tube End Caps} = \frac{\pi}{4} \times (0.54 \times 0.0254)^2 \times 0.003 \times 14 \times 7978 \approx 0.05 \text{ kg}$$

4. Collector Header Tube [material: stainless steel]

Nominal pipe size = 1"

Outer diameter of tube = 1.315" Inner diameter of tube = 1.185"

Thickness of tube = 0.065" Weight of tube = 0.87 lb/ft

Length of tube = 0.868 m

$$\text{Mass of Collector Header Tube} = \frac{0.87 \times 0.868}{0.3048 \times 2.205} = 1.1236 \text{ kg}$$

5. Collector Header End Cap [material: stainless steel]

Thickness of end cap = 0.003 m

$$\text{Volume} = \frac{\pi}{4} \times (0.04)^2 \times 0.006 - \frac{\pi}{4} \times (0.034)^2 \times 0.003 = 4.816 \times 10^{-6} \text{ m}^3$$

$$\text{Mass of Collector Header End Cap} = 4.816 \times 10^{-6} \times 7978 = 0.0384 \text{ kg}$$

6. Collector Header Adaptor [material: stainless steel]

Estimated Mass of Adaptor ≈ 0.3985 kg

$$M_{it} = 8.4414 + 0.05 + 1.1236 + 0.0384 + 0.3985 = 10.052 \text{ kg}$$

7. Outer Tube End Caps [material: stainless steel]

Thickness of each end cap = 0.003 m

Number of end caps = 28

$$\begin{aligned} \text{Mass of Outer Tube End Caps} &= 28 \times \frac{\pi}{4} \times (2.245^2 - 0.54^2) \times 0.0254^2 \times 0.003 \times 7978 \\ &= 1.612 \text{ kg} \end{aligned}$$

$$M_{dt} = 1.612 \text{ kg}$$

8. Activated Charcoal (207E4)

Bulk density of charcoal = 490 kg/m³

$$\begin{aligned} \text{Mass of Charcoal in each Tube Assy.} &= \frac{\pi}{4} \times (2.245^2 - 0.54^2) \times 0.0254^2 \times 1.178 \times 490 \\ &= 1.3888 \text{ kg} \end{aligned}$$

Mass of charcoal in each tube assembly is taken as 1.388 kg

$$\text{Total Mass of Charcoal} = 1.388 \times 14 = 19.432 \text{ kg}$$

$$M_c = 19.432 \text{ kg}$$

9. Glass Cover [material: glass]

Density of glass = 2515 kg/m³

$$\text{Length of glass} = 1.178 + 0.02 = 1.198 \text{ m}$$

$$\text{Width of glass} = 0.848 + 0.02 = 0.868 \text{ m}$$

$$\text{Thickness of glass} = 1/8" \equiv 0.0032 \text{ m}$$

$$\begin{aligned} \text{Mass of glass cover} &= 1.198 \times 0.868 \times 0.0032 \times 2515 \\ &= 8.37 \text{ kg} \end{aligned}$$

$$M_g = 8.37 \text{ kg}$$

The Experimental Observations of the AIT Charcoal-Methanol Solar Refrigerator (17 October, 1987).

Local Time	Amb Temp.	Collector Temperatures						Condenser Temperatures				Receiver		Evaporator		Level Glass	Incident Radiation	Remarks
		Glass	Coll. Top	Coll. Bot	Char Top	Char. Bot	Vapour	Liquid	Tube	Water	Top	Bot.	Evap.	Ice				
(Hr)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(kJ)	
6.00	24.62	24.52	30.63	30.87	27.55	24.73	27.53	24.50	27.14	27.10	-8.80	-8.94	-2.85	-1.38	-	0.00		
7.00	26.15	27.55	32.15	30.87	32.10	32.38	27.53	26.02	27.14	27.10	1.91	-8.94	-2.85	-1.38	-	205.20		
8.00	26.15	33.61	41.24	40.05	38.16	38.50	33.59	26.02	27.34	27.10	11.09	0.24	-1.32	-1.38	-	962.20		
9.00	27.68	42.70	60.93	61.47	56.34	58.39	41.17	27.53	28.03	27.79	18.74	15.54	-1.32	-1.38	-	1809.80		
10.00	30.74	50.28	81.38	81.36	76.03	79.81	53.29	30.56	30.41	28.49	27.92	21.66	0.21	-1.38	4.00	2465.50		
10.50	33.04	54.06	86.99	87.79	80.58	85.93	60.10	30.56	31.40	28.98	27.92	19.37	0.98	-1.38	6.20	1452.30		
11.00	33.80	57.85	94.26	95.13	86.64	92.05	63.89	33.59	32.19	29.58	29.45	18.60	1.74	-1.38	9.00	1759.30		
11.50	30.74	51.79	89.72	90.54	88.15	92.05	51.77	31.32	31.40	30.17	27.92	18.60	4.80	-1.38	10.30	756.00		
12.00	30.74	45.73	85.17	85.95	85.12	87.46	47.23	30.56	31.10	30.37	26.39	17.07	4.80	-1.38	10.40	408.00		
12.50	32.27	48.76	92.75	92.07	91.18	93.58	55.56	32.08	31.60	30.66	28.69	17.84	7.10	-1.38	10.40	1101.30		
13.00	32.27	53.31	100.32	99.72	94.21	96.64	60.86	32.08	31.89	30.86	29.45	18.60	6.33	-1.38	11.90	1382.50		
13.50	33.80	57.85	106.38	105.84	100.27	104.29	63.89	33.59	32.49	31.36	30.22	26.25	7.86	-1.38	13.80	1642.20		
14.00	32.27	54.82	109.41	108.90	104.82	108.88	60.86	32.08	32.39	31.85	29.45	20.13	9.39	-1.38	15.30	1274.00	*	
14.50	33.04	63.91	113.20	113.49	104.82	113.47	63.89	32.83	32.78	32.15	27.92	20.13	9.39	-1.38	16.10	1340.40		
15.00	32.27	54.82	109.41	108.90	109.36	111.94	53.29	32.08	32.39	32.45	27.92	20.13	9.39	-1.38	16.60	930.80		
15.50	32.27	45.73	91.23	92.07	100.27	99.70	45.71	30.56	32.39	32.25	23.33	18.60	29.28	29.22	17.00	308.30		
16.00	29.21	45.73	80.63	79.83	86.64	87.46	44.20	29.05	-	-	15.68	17.07	20.10	21.57	15.60	653.30		
17.00	29.21	36.64	60.93	59.94	63.91	64.51	39.65	22.99	-	-	4.97	6.36	10.92	10.86	13.40	702.70		
18.00	29.21	33.61	50.33	50.76	53.31	53.80	36.62	21.47	-	-	-1.15	0.24	6.33	6.27	11.40	110.60		
19.00	29.21	30.58	42.75	43.11	45.73	46.15	33.59	24.50	-	-	-5.74	-4.35	1.74	1.68	10.10	0.00		
20.00	27.68	29.07	38.21	38.52	39.67	40.03	33.59	26.02	-	-	-5.74	-4.35	0.21	0.15	9.20	0.00		
21.00	27.68	27.55	36.69	35.46	38.16	38.50	32.08	26.02	-	-	-7.27	-5.88	-1.32	-1.38	8.30	0.00		
22.00	27.68	27.55	35.18	35.46	36.64	36.97	30.56	26.02	-	-	-8.80	-5.88	-1.32	-1.38	7.50	0.00		
23.00	26.15	26.04	35.18	35.46	36.64	36.97	30.56	26.02	-	-	-8.80	-7.41	-1.32	-1.38	6.50	0.00		
24.00	26.15	26.04	33.66	33.93	35.13	35.44	30.56	26.02	-	-	-8.80	-7.41	-2.85	-2.91	5.70	0.00		
1.00	26.15	26.04	32.15	32.40	35.13	35.44	30.56	26.02	-	-	-8.80	-7.41	-2.85	-2.91	-	0.00		
2.00	26.15	26.04	32.15	32.40	33.61	33.91	29.05	26.02	-	-	-8.80	-7.41	-2.85	-2.91	-	0.00		
3.00	26.15	26.04	32.15	32.40	33.61	33.91	29.05	24.50	-	-	-8.80	-7.41	-2.85	-2.91	-	0.00		
4.00	24.62	24.52	30.63	30.87	32.10	32.38	29.05	24.50	-	-	-8.80	-7.41	-2.85	-2.91	-	0.00		
5.00	24.62	24.52	30.63	29.34	29.07	29.32	29.05	24.50	-	-	-7.27	-7.41	-2.85	-2.91	-	0.00		
6.00	24.62	24.52	30.63	29.34	29.07	29.32	29.05	24.50	-	-	-1.15	-7.41	-4.38	-4.44	0.00	0.00	*	

Total Incident Solar Radiation = 19265.0

* End of Adsorption.

APPENDIX E

The Experimental Observations of the AIT Charcoal-Methanol Solar Refrigerator (29 October, 1987).

Local Time	Amb Temp.	Collector Temperatures					Condenser Temperatures				Receiver		Evaporator		Level Glass	Incident Radiation	Remark
		Glass	Coll. Top	Coll. Bot	Char. Top	Char. Bot	Vapour	Liquid	Tube	Water	Top	Bot.	Evap.	Ice	(Cm)	(kJ)	
(Hr)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)	(C)			
6.00	24.62	24.52	29.12	29.34	29.07	29.32	26.02	22.99	25.16	25.12	0.38	-7.41	-5.91	-5.97	-	0.00	
7.00	24.62	23.01	29.12	29.34	29.07	29.32	27.53	22.99	25.46	25.52	4.97	-7.41	-4.38	-4.44	-	63.40	
8.00	24.62	26.04	32.15	32.40	32.10	32.38	29.05	24.50	25.46	25.52	8.03	-2.82	-2.85	-2.91	-	346.10	
9.00	26.15	35.13	50.33	50.00	47.25	47.68	35.11	26.02	25.75	25.62	15.68	9.42	-1.32	-1.38	-	1516.70	
10.00	27.68	41.19	73.05	73.71	68.46	70.63	45.71	27.53	27.04	26.11	27.92	27.78	0.21	0.15	3.90	2447.40	
10.50	29.21	44.22	79.11	79.83	73.00	76.75	48.74	27.53	29.02	26.51	26.39	18.60	-1.32	-1.38	5.80	1410.90	
11.00	30.74	47.25	85.17	85.95	80.58	84.40	51.77	29.05	29.62	26.80	24.86	17.07	-1.32	-1.38	6.70	1354.70	
11.50	30.74	47.25	86.69	87.48	83.61	85.93	51.77	29.05	30.41	27.89	24.86	15.54	-1.32	-1.38	8.80	1379.10	
12.00	30.74	50.28	94.26	95.13	88.15	92.05	56.32	29.80	30.51	28.19	26.39	15.54	-1.32	-1.38	10.40	1566.00	
12.50	30.74	50.28	94.26	95.13	91.18	95.11	54.80	29.80	30.11	28.68	26.39	15.54	0.21	0.15	12.00	1263.10	
13.00	30.74	51.79	98.81	99.72	95.73	99.70	56.32	30.56	30.41	29.28	26.39	15.54	3.27	3.21	13.00	1293.10	
13.50	30.74	54.82	103.35	104.31	100.27	104.29	56.32	30.56	30.31	29.58	26.39	15.54	4.80	4.74	14.00	1253.90	
14.00	30.74	53.31	104.87	105.84	103.30	105.82	54.80	30.56	30.11	30.37	26.39	15.54	3.27	3.21	15.00	1060.30 *	
14.50	30.74	57.85	110.93	111.96	107.85	110.41	60.86	32.08	31.10	30.37	27.92	15.54	4.80	4.74	16.50	1411.80	
15.00	30.74	56.34	112.44	113.49	110.88	113.47	56.32	32.08	30.90	30.76	26.39	17.07	6.33	6.27	17.00	1198.10	
15.50	30.74	51.79	109.41	110.43	110.88	111.94	50.26	30.56	-	-	26.39	17.07	7.86	7.80	16.90	748.60	
16.00	30.74	50.28	104.87	105.84	106.33	107.35	51.77	32.08	-	-	24.86	20.13	29.28	29.22	16.90	762.20	
17.00	29.21	39.67	68.51	67.59	74.52	75.22	41.17	24.50	-	-	9.56	9.42	15.51	15.45	14.50	534.30	
18.00	27.68	33.61	54.87	53.82	57.85	58.39	36.62	16.93	-	-	0.38	1.77	7.86	7.80	12.50	72.60	
19.00	27.68	30.58	45.78	44.64	47.25	47.68	35.11	16.93	-	-	-4.21	-2.82	3.27	3.21	11.00	0.00	
20.00	27.68	30.58	39.72	40.05	41.19	41.56	32.08	26.02	-	-	-4.21	-4.35	0.21	0.15	10.20	0.00	
21.00	24.62	27.55	35.18	35.46	36.64	36.97	29.05	24.50	-	-	-8.80	-7.41	-1.32	-1.38	9.20	0.00	
22.00	24.62	26.04	33.66	33.93	35.13	35.44	29.05	24.50	-	-	-8.80	-7.41	-1.32	-1.38	7.90	0.00	
23.00	24.62	24.52	32.15	32.40	33.61	33.91	29.05	24.50	-	-	-8.80	-8.94	-1.32	-1.38	7.00	0.00	
24.00	24.62	24.52	32.15	32.40	33.61	33.91	29.05	24.50	-	-	-8.80	-7.41	-2.85	-2.91	6.40	0.00	
1.00	23.09	23.01	30.63	30.87	30.58	30.85	27.53	24.50	-	-	-10.33	-10.47	-2.85	-2.91	-	0.00	
2.00	23.09	23.01	29.12	29.34	30.58	30.85	27.53	22.99	-	-	-8.80	-8.94	-2.85	-2.91	-	0.00	
3.00	23.09	23.01	29.12	29.34	30.58	30.85	27.53	22.99	-	-	-8.80	-8.94	-2.85	-2.91	-	0.00	
4.00	23.09	23.01	29.12	29.34	29.07	29.32	27.53	22.99	-	-	-8.80	-8.94	-2.85	-2.91	-	0.00	
5.00	23.09	23.01	29.12	29.34	29.07	29.32	27.53	22.99	-	-	-8.80	-8.94	-4.38	-4.44	-	0.00	
6.00	23.09	23.01	29.12	29.34	29.07	29.32	27.53	22.99	-	-	0.38	-8.94	-4.38	-4.44	0.00	0.00 †	

Total Incident Solar Radiation = 19682.3

† End of Adsorption.

KEY OFF

CLS

PRINT " THIS PROGRAM IS FOR CREATING INPUT FILE FOR RUNNING THE "
PRINT "ACTIVATED CHARCOAL/METHANOL FLAT PLATE COLLECTOR SIMULATION PROGRAM"
PRINT "-----":P

NT

REM PROGRAM TO CREATE FILE
OPEN "PROFL.BAS" FOR OUTPUT AS #1
PRINT "ENTER A RECORD: [F,TIM,HH1,HH2,HH,JJ,V,TA] VERTICALLY"
PRINT "NOTE: F IS JUST FOR NUMBERING THE RECORDS IN SEQUENCE.USE 1 TO 24"
INPUT F
INPUT TIM
INPUT HH1
INPUT HH2
INPUT HH
INPUT JJ
INPUT V
INPUT TA
PRINT #1,F,TIM,HH1,HH2,HH,JJ,V,TA
INPUT "MORE RECORDS? ANSWER[Y/N] :",REPLY\$
00 IF REPLY\$="Y" THEN GOTO 60
10 CLOSE #1
20 END


```

KEY OFF
CLS
PRINT "ACTIVATED CHARCOAL/METHANOL FLAT PLATE COLLECTOR SIMULATION PROGRAMME"
PRINT "WRITTEN AND COMPILED BY MR. FRANCIS E. QUAGRAINE "
PRINT "PRINT "MAKE SURE YOU HAVE RUN THE INPUT FILE [INFL] BEFORE YOU RUN THIS
PROGRAMME"
PRINT :PRINT "PRESS F5 KEY TO CONTINUE":STOP:CLS
0 DIM VK(20),Z(20),VT(20),VA(20),VV(20),VPR(20),VBR(20),QP1(20),QP2(20)
1 DIM QK1(20),QK2(20),QT1(20),QT2(20),QA1(20),QA2(20),QV1(20),QV2(20)
3 REM THESE ARE CONSTANTS
4 INPUT "ENTER [MONTH] ",MNH$:OUTF$=LEFT$(MNH$,3):PRINT
5 PRINT "PLEASE TYPE [";OUTF$;"1,";OUTF$;"2] TO CONTINUE (NB: THESE ARE YOUR OU
PUT FILES)":INPUT OUTFL1$,OUTFL2$:PRINT
6 INPUT "ENTER [LAMDA,BETA (IN DEGREES)] ",LM0,BT0:PRINT
7 PRINT "ENTER NN,GGA,TAFN,TDP(TAFN IN KELVIN AND TDP IN CELSIUS)"
8 INPUT NN,GGA,TAFN,TDP:PRINT
9 PRINT "ENTER L,LW,LB,LE,LS,LD,LG,RO,RI,NS (IN METRES, AND NS A NUMBER)"
10 INPUT L,LW,LB,LE,LS,LD,LG,RO,RI,NS:PRINT
22 PRINT "ENTER MOT,MIT,MDT,MC,MG,KB (IN KILOGRAMMES, AND KB IN W/M.K)"
23 INPUT MOT,MIT,MDT,MC,MG,KB:PRINT
25 INPUT "ENTER [DCY,DRI (BOTH IN INCHES)] ",DCY,DRI:PRINT
27 INPUT "ENTER [S,LCI,LRI (ALL IN METRES)] ",S,LCI,LRI:PRINT
30 TCD=TAFN+.35:ABUT=1
32 BE=5.6697E-08:G=9.810001:EP=.45:EG=.88:AP=.95:ET=.95:DT=3600
34 CD=491:PD=7978:KE=KB
50 KC=.175:KT=15:KD=15:HPC=47.5:CT=491:CC=700:PC=490:WO=.000365:N=1.34
55 DX=(RO-RI)/6:D=1.4962E-04:GX=DX
60 CG=820:KG=18:PI=3.1415927#:R=8314.401:M=32.042:WRS=1.5
70 AC=L*LW:PE=2*(L+LW):AE=2*(L+LW+2*LE)*(2*RO+.1283):A=AE/AC
71 LM=LM0*PI/180:BT=BT0*PI/180:PG=.2
72 PRINT TAB(25);"ENTERING INITIAL VALUES":PRINT TAB(25);"-----
--":PRINT
74 PRINT "ENTER XCI0,XCI1,XCI2,XCI3,XCI4,XCI5,XCI6"
75 INPUT TXCI0,TXCI1,TXCI2,TXCI3,TXCI4,TXCI5,TXCI6:PRINT
76 XCI0=TXCI0:XCI1=TXCI1:XCI2=TXCI2:XCI3=TXCI3:XCI4=TXCI4:XCI5=TXCI5:XCI6=TXCI6
77 PRINT "ENTER TIM,TA,TCI0,TCI1,TCI2,TCI3,TCI4,TCI5,TCI6,TDI1,TDI2,TDI3,TDI4,TD
I5,TTI,TPI,TGI"
78 INPUT YTIM,YTA,YTCI0,YTCI1,YTCI2,YTCI3,YTCI4,YTCI5,YTCI6,YTDI1,YTDI2,YTDI3,YT
DI4,YTDI5,YTTI,YTPI,YTGI
79 TIM=YTIM:TA=YTA:TCI0=YTCI0:TCI1=YTCI1:TCI2=YTCI2:TCI3=YTCI3:TCI4=YTCI4:TCI5=Y
TCI5:TCI6=YTCI6:TDI1=YTDI1:TDI2=YTDI2:TDI3=YTDI3:TDI4=YTDI4:TDI5=YTDI5:TTI=YTTI:
TPI=YTPI:TGI=YTGI:CLS:PRINT TAB(23)"PLEASE WAIT FOR YQUR RESULTS"
80 TDV1=TDI1+2:TDV2=TDI2+2:TDV3=TDI3+2:TDV4=TDI4+2:TDV5=TDI5+2:TTV=TTI+2:TPV=TPI
+2:TGV=TGI+2
81 TCV0=TCI0+2:TCV1=TCI1+2:TCV2=TCI2+2:TCV3=TCI3+2:TCV4=TCI4+2:TCV5=TCI5+2:TCV6=
TCI6+2
82 XMMI=2*PI*GX*((RI+GX)*XCI1+(RI+2*GX)*XCI2+(RI+3*GX)*XCI3+(RI+4*GX)*XCI4+(RI+5
*GX)*XCI5+.5*(RO-.25*GX)*XCI6+.5*(RI+.25*GX)*XCI0)/(PI*(RO^2-RI^2)):XMI=XMMI
84 XMI=XMMI:ITI=0:QCI=0
85 OPEN OUTFL1$ FOR OUTPUT AS #1
86 OPEN OUTFL2$ FOR OUTPUT AS #2
87 OPEN "PROFL.BAS" FOR INPUT AS #3
88 PRINT #1,TAB(58);"COLLECTOR TEMPERATURES":PRINT #1,TAB(66);MNH$ :PRINT #1
1,TAB(63);"-----"
89 PRINT #1,TAB(10);" TCF0 "; TCF1 "; TCF2 "; TCF3 "; TCF4 "; TC
5 "; TCF6 "; TPF "; TDF5 "; TDF4 "; TDF3 "; TDF2 "; TDF1
"; TTF "; TGF "; TIM "

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0 IO=(12*1367/PI)*(1+.033*COS((2*PI*NN)/365))*(COS(LM)*COS(GA)*(SIN(H2)-SIN(H1
+(H2-H1)*SIN(LM)*SIN(GA))
0 IF IO=0 THEN KT=0:GOTO 250
0 KT=JJ/IO
0 ID1=(1-9.000001E-02*KT)*JJ
0 ID2=(.9511-.1604*KT+4.388*KT^2-16.638*KT^3+12.336*KT^4)*JJ:ID3=.165*JJ
0 IF KT>.22 THEN ID4=ID2 ELSE ID4=ID1
0 IF KT>.8 THEN ID=ID3 ELSE ID=ID4
0 IB=JJ-ID
0 IT=IB*RB+ID*((1+COS(BT))/2)+JJ*PG*((1-COS(BT))/2)
0 SP=.9696*T*AP*IT
0 TG1=PI/2-.5788*BT+.002693*BT^2
0 TD1=59.7*PI/180-.1388*BT+.001497*BT^2
0 TG2=ATN(SIN(TG1)/((1.526^2-SIN(TG1)^2)^.5)):TAG=EXP((-1*KG*LG)/COS(TG2))
0 RRG=SIN(TG2-TG1)^2/SIN(TG2+TG1)^2
0 RLG=TAN(TG2-TG1)^2/TAN(TG2+TG1)^2
0 AGR=((1-TAG)/2)*((1-RRG)/(1-RRG*TAG)+(1-RLG)/(1-RLG*TAG))
0 TD2=ATN(SIN(TD1)/((1.526^2-SIN(TD1)^2)^.5)):TAD=EXP((-1*KG*LG)/COS(TD2))
0 RRD=SIN(TD2-TD1)^2/SIN(TD2+TD1)^2
0 RLD=TAN(TD2-TD1)^2/TAN(TD2+TD1)^2
0 AGD=((1-TAD)/2)*((1-RRD)/(1-RRD*TAD)+(1-RLD)/(1-RLD*TAD))
0 SG=IB*RB*AGB+ID*AGD*((1+COS(BT))/2)+JJ*PG*AGR*((1-COS(BT))/2)
0 GOSUB 1450
0 IF PO>P2 THEN 486
0 IF PO<P1 THEN 422
0 P=PO
0 GOSUB 1659
0 GOSUB 570:PV=P:GOTO 125
0 DT=3600
0 DT=3600:GOTO 433
0 P=P1
0 GOSUB 1450
0 P=P1
0 GOSUB 1659
0 TIM=TIM-1+DT/3600
0 GOSUB 570
0 DT=3600-DT
0 TIM=TIM+DT/3600
0 IF XMI=XMMI THEN P=PO ELSE P=P1
0 GOSUB 1450
0 IF XMI=XMMI THEN P=PO ELSE P=P1
0 GOSUB 1659
0 GOSUB 570
0 GOSUB 1800
0 DT=3600
0 IF EOF(3) THEN 1900
0 INPUT #3,F,TIM,HH1,HH2,HH,JJ,V,TA
0 H1=HH1*PI/180:H2=HH2*PI/180:H=HH*PI/180:GA=GGA*PI/180
0 RB=(SIN(LM-BT)*SIN(GA)+COS(LM-BT)*COS(GA)*COS(H))/(SIN(LM)*SIN(GA)+COS(LM)*C
OS(GA)*COS(H))
0 RB0=SIN(LM-BT)*SIN(GA)+COS(LM-BT)*COS(GA)*COS(H):TO1=ATN((1-RB0^2)^.5/RB0)
0 TO2=ATN(SIN(TO1)/((1.526^2-SIN(TO1)^2)^.5)):TAW=EXP(-1*KG*LG/COS(TO2))
0 RR2=SIN(TO2-TO1)^2/(SIN(TO2+TO1)^2):RL2=TAN(TO2-TO1)^2/(TAN(TO2+TO1)^2)
0 R2=(RR2+RL2)/2
0 RR3=((1.526-1)/(1.526+1))^2:RL3=((1.526-1)/(1.526+1))^2
0 IF TO1>0 THEN RR=RR2 ELSE RR=RR3
0 IF TO1>0 THEN RL=RL2 ELSE RL=RL3
0 T=(TAW/2)*(((1-RR)/(1+RR))*((1-RR^2)/(1-(RR*TAW)^2))+((1-RL)/(1+RL))*((1-RL^
2)/(1-(RL*TAW)^2)))

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T=(TAW/2)*(((1-RR)/(1+RR))*((1-RR^2)/(1-RR*TAW)^2))+((1-RL)/(1+RL))*((1-RL^2)/(1-RL*TAW)^2))
AGB=((1-TAW)/2)*((1-RR)/(1-RR*TAW)+(1-RL)/(1-RL*TAW))
IO=(12*1367/PI)*(1+.033*COS((2*PI*NN)/365))*(COS(LM)*COS(GA)*(SIN(H2)-SIN(H1))-(H2-H1)*SIN(LM)*SIN(GA))
IF IO=0 THEN KT=0:GOTO 523
KT=JJ/IO
ID1=(1-9.000001E-02*KT)*JJ
ID2=(.9511-.1604*KT+4.388*KT^2-16.638*KT^3+12.336*KT^4)*JJ:ID3=.165*JJ
IF KT>.22 THEN ID4=ID2 ELSE ID4=ID1
IF KT>.8 THEN ID=ID3 ELSE ID=ID4
IB=JJ-ID
IT=IB*RB+ID*((1+COS(BT))/2)+JJ*PG*((1-COS(BT))/2)
SP=.9696*T*AP*IT
TG1=PI/2-.5788*BT+.002693*BT^2
TD1=59.7*PI/180-.1388*BT+.001497*BT^2
TG2=ATN(SIN(TG1)/((1.526^2-SIN(TG1)^2)^.5)):TAG=EXP((-1*KG*LG)/COS(TG2))
RRG=SIN(TG2-TG1)^2/SIN(TG2+TG1)^2
RLG=TAN(TG2-TG1)^2/TAN(TG2+TG1)^2
AGR=((1-TAG)/2)*((1-RRG)/(1-RRG*TAG)+(1-RLG)/(1-RLG*TAG))
TD2=ATN(SIN(TD1)/((1.526^2-SIN(TD1)^2)^.5)):TAD=EXP((-1*KG*LG)/COS(TD2))
RRD=SIN(TD2-TD1)^2/SIN(TD2+TD1)^2
RLD=TAN(TD2-TD1)^2/TAN(TD2+TD1)^2
AGD=((1-TAD)/2)*((1-RRD)/(1-RRD*TAD)+(1-RLD)/(1-RLD*TAD))
SG=IB*RB*AGB+ID*AGD*((1+COS(BT))/2)+JJ*PG*AGR*((1-COS(BT))/2)
P=P2
GOSUB 1450
P=P2
GOSUB 1659
IF PO>=P2 THEN 566
P=PO:XMIN=XMI:TC3=TMI:HRR2=TIM-1
GOSUB 1450
P=PO
GOSUB 1659
GOSUB 570:IF ABUT=1 THEN 1912
GOTO 125
GOSUB 570
GOTO 508
570 REM PROGRAM FOR OUTPUT
572 TCI0=TCF0:TCI1=TCF1:TCI2=TCF2:TCI3=TCF3:TCI4=TCF4:TCI5=TCF5:TCI6=TCF6
573 TPI=TPF:TTI=TTF:TGI=TGF:TDI1=TDF1:TDI2=TDF2:TDI3=TDF3:TDI4=TDF4:TDI5=TDF5
574 TCV0=TCF0:TCV1=TCF1:TCV2=TCF2:TCV3=TCF3:TCV4=TCF4:TCV5=TCF5:TCV6=TCF6
575 TPV=TPF:TPV=TTF:TGV=TGF:TDV1=TDF1:TDV2=TDF2:TDV3=TDF3:TDV4=TDF4:TDV5=TDF5
576 XCI0=XCF0:XCI1=XCF1:XCI2=XCF2:XCI3=XCF3:XCI4=XCF4:XCI5=XCF5:XCI6=XCF6:XMI=XM
FF:ITI=ITT:QCI=QCF
577 PRINT #1,TAB(10);USING "###.##";TCF0;TCF1;TCF2;TCF3;TCF4;TCF5;TCF6;TPF;TDF
5;TDF4;TDF3;TDF2;TDF1;TTF;TGF;TIM
578 PRINT #2,TAB(5);USING "###.###";XCF0;XCF1;XCF2;XCF3;XCF4;XCF5;XCF6;XMFF;ITP
F;TDF;TCF;ITTF;ITGF;TAMB;P;EFF;TIM
579 RETURN
580 REM PROGRAM FOR INTERPOLATION
582 FOR I=1 TO 8
584 READ VT(I),VK(I),VA(I),VV(I),VPR(I)
586 IF VT(I)>TEM THEN 598
588 NEXT I
590 DATA 273.15,.0242,1.86E-5,1.33E-5,.72
591 DATA 293.15,.0257,2.12E-5,1.50E-5,.71
592 DATA 313.15,.0272,2.40E-5,1.69E-5,.70
593 DATA 333.14,.0287,2.69E-5,1.88E-5,.70

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001 NUBT=.56*(GR4*PR4*COS(TH4))*.25:HBAT=NUBT*K4/L
002 IF NUBT>0 THEN HB=HBAT ELSE HB=HBA
003 IF NUBT>0 THEN HB=HBAT ELSE HB=HBA
004 TS=TA*(.711+.0056*TDP+.000073*TDP^2+.013*COS(15*TIM*PI/180))*.25:TAS=TS
005 IF TPF<=TA THEN TPF=TA:TS=TA
006 IF TGF<=TA THEN TGF=TA:TAS=TA
007 IF TIM=15 THEN TDS=TS
008 TCF0=2*TCV0-TCI0:TCF1=2*TCV1-TCI1
009 TCF2=2*TCV2-TCI2:TCF3=2*TCV3-TCI3
010 TCF4=2*TCV4-TCI4:TCF5=2*TCV5-TCI5
011 TCF6=2*TCV6-TCI6:TPF=2*TPV-TPI
012 TTF=2*TTV-TTI:TGF=2*TGV-TGI:TDF1=2*TDV1-TDI1
013 TDF2=2*TDV2-TDI2:TDF3=2*TDV3-TDI3
014 TDF4=2*TDV4-TDI4:TDF5=2*TDV5-TDI5
015 HPGR=(TPF^2+TGF^2)*(TPF+TGF)
016 HPAR=(TPF^2+TA^2)*(TPF+TA)
017 HGAR=(TGF^2+TAS^2)*(TGF+TAS)
018 TMF=2*PI*GX*((RI+GX)*TCF1+(RI+2*GX)*TCF2+(RI+3*GX)*TCF3+(RI+4*GX)*TCF4+(RI+5
*GX)*TCF5+.5*(RO-.25*GX)*TCF6+.5*(RI+.25*GX)*TCF0)/(PI*(RO^2-RI^2))
019 XMF=1-TMF/512.6
020 PSMF=80.9*EXP((1-XMF)^-1*(-8.54796*XMF+.76982*XMF^1.5-3.1085*XMF^3+1.54481*X
MF^6))
021 PMF=937.911-.058267*TMF-.001495*TMF^2
022 IF P=P1 OR P=P2 THEN 895
023 S1=(1/D)*LOG((PMF*WO)/XMI):S2=S1^(1/N):PO=PSMF/EXP(1/TMF*S2)
024 P=PO
025 XF0=1-TCF0/512.6
026 PSF0=80.9*EXP((1-XF0)^-1*(-8.54796*XF0+.76982*XF0^1.5-3.1085*XF0^3+1.54481*X
F0^6))
027 PMF0=937.911-.058267*TCF0-.001495*TCF0^2
028 XO0=TCF0*LOG(PSF0/P):XP0=XO0^N:XCF0=PMF0*WO*EXP(-1*D*XP0)
029 HF01=6027.156-9935.651*XCF0:HF02=5681.649-4144.85*XCF0
030 HF03=5547.501-3104.39*XCF0
031 IF XCF0<.06 THEN HF04=HF01 ELSE HF04=HF02
032 IF XCF0>=.14 THEN HF0=HF03 ELSE HF0=HF04
033 HI01=6027.156-9935.651*XCI0:HI02=5681.649-4144.85*XCI0
034 HI03=5547.501-3104.39*XCI0
035 IF XCI0<.06 THEN HI04=HI01 ELSE HI04=HI02
036 IF XCI0>=.14 THEN HI0=HI03 ELSE HI0=HI04
037 HD0=(R/M)*(HF0+HI0)/2
038 CM0=(3.9924-.0158*TCV0+.0000364*TCV0^2)*1000
039 XF1=1-TCF1/512.6
040 PSF1=80.9*EXP((1-XF1)^-1*(-8.54796*XF1+.76982*XF1^1.5-3.1085*XF1^3+1.54481*X
F1^6))
041 PMF1=937.911-.058267*TCF1-.001495*TCF1^2
042 XO1=TCF1*LOG(PSF1/P):XP1=XO1^N:XCF1=PMF1*WO*EXP(-1*D*XP1)
043 HF11=6027.156-9935.651*XCF1:HF12=5681.649-4144.85*XCF1
044 HF13=5547.501-3104.39*XCF1
045 IF XCF1<.06 THEN HF14=HF11 ELSE HF14=HF12
046 IF XCF1>=.14 THEN HF1=HF13 ELSE HF1=HF14
047 HI11=6027.156-9935.651*XCI1:HI12=5681.649-4144.85*XCI1
048 HI13=5547.501-3104.39*XCI1
049 IF XCI1<.06 THEN HI14=HI11 ELSE HI14=HI12
050 IF XCI1>=.14 THEN HI1=HI13 ELSE HI1=HI14
051 HD1=(R/M)*(HF1+HI1)/2
052 CM1=(3.9924-.0158*TCV1+.0000364*TCV1^2)*1000
053 XF2=1-TCF2/512.6

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1442 HP6=1-TCF6/511
1444 HP6=80.9*EXP((1-XP6)^-1*(-8.54796*XP6+.76982*XP6^1.5-3.1085*XP6^3+1.94481*
1446 HP6^4))
1448 HP6=937.911-.058267*TCF6-.001495*TCF6^2
1450 XH6=TCF6*LOG(PSP6/P):XP6=XH6^N: XCF6=HP6*WO*EXP(-1*D*XP6)
1452 HP61=4027.156-9935.651*XCF6:HP62=5681.649-4144.85*XCF6
1454 HP63=5547.501-3104.39*XCF6
1456 IF XCF6<.06 THEN HP64=HP61 ELSE HP64=HP62
1458 IF XCF6>=.14 THEN HP6=HP63 ELSE HP6=HP64
1460 HI61=4027.156-9935.651*XC16:HI62=5681.649-4144.85*XC16
1462 HI63=5547.501-3104.39*XC16
1464 IF XC16<.06 THEN HI64=HI61 ELSE HI64=HI62
1466 IF XC16>=.14 THEN HI6=HI63 ELSE HI6=HI64
1468 HD6=(R/M)*(HP6+HI6)/2
1470 CM6=(3.9924-.0158*TCV6+.0000364*TCV6^2)*1000
1474 RETURN
1480 REM PROGRAM FOR GAUSS-SIEDEL
1482 PFP=1
1484 GOSUB 615
1486 ET=MIT*CT*TTI/DT+2*PI*RI*L*NS*HPC*TCF0+4*PI*RI*LD*NS*KD*(1+DX/(2*RI))*(TDF1
/DT)
1488 ET3=MIT*CT/DT+2*PI*RI*L*NS*HPC+4*PI*RI*LD*NS*KD*(1+DX/(2*RI))/DX
1490 TTTF=WRS*ET/ET3+(1-WRS)*TTF
1492 ZU0=PC*CC*TC10/DT+PC*CM0*(XCF0+XC10)*TC10/(2*DT)+PC*HD0*(XCF0-XC10)/DT+2*HP
C*TTTF/DX+2*KC*TCF1/DX^2-HPC*TTTF/RI
1494 Z0=PC*CC/DT+(PC*CM0/DT)*(XCF0+XC10)/2+2*HPC/DX+2*KC/DX^2-HPC/RI
1496 TTCF0=WRS*ZU0/Z0+(1-WRS)*TCF0
1498 EU1=PC*CC*TC11/DT+PC*CM1*(XCF1+XC11)*TC11/(2*DT)+PC*HD1*(XCF1-XC11)/DT+KC*(
TTCF0+TCF2)/DX^2+KC/(RI+DX)*(TCF2-TTCF0)/(2*DX)
1500 Z1=PC*CC/DT+(PC*CM1/DT)*(XCF1+XC11)/2+2*KC/DX^2
1502 TTCF1=WRS*ZU1/Z1+(1-WRS)*TCF1
1504 EU2=PC*CC*TC12/DT+PC*CM2*(XCF2+XC12)*TC12/(2*DT)+PC*HD2*(XCF2-XC12)/DT+KC*(
TTCF1+TCF3)/DX^2+KC/(RI+2*DX)*(TCF3-TTCF1)/(2*DX)
1506 Z2=PC*CC/DT+(PC*CM2/DT)*(XCF2+XC12)/2+2*KC/DX^2
1508 TTCF2=WRS*ZU2/Z2+(1-WRS)*TCF2
1510 EU3=PC*CC*TC13/DT+PC*CM3*(XCF3+XC13)*TC13/(2*DT)+PC*HD3*(XCF3-XC13)/DT+KC*(
TTCF2+TCF4)/DX^2+KC/(RI+3*DX)*(TCF4-TTCF2)/(2*DX)
1512 Z3=PC*CC/DT+(PC*CM3/DT)*(XCF3+XC13)/2+2*KC/DX^2
1514 TTCF3=WRS*ZU3/Z3+(1-WRS)*TCF3
1516 EU4=PC*CC*TC14/DT+PC*CM4*(XCF4+XC14)*TC14/(2*DT)+PC*HD4*(XCF4-XC14)/DT+KC*(
TTCF3+TCF5)/DX^2+KC/(RI+4*DX)*(TCF5-TTCF3)/(2*DX)
1518 Z4=PC*CC/DT+(PC*CM4/DT)*(XCF4+XC14)/2+2*KC/DX^2
1520 TTCF4=WRS*ZU4/Z4+(1-WRS)*TCF4
1522 EU5=PC*CC*TC15/DT+PC*CM5*(XCF5+XC15)*TC15/(2*DT)+PC*HD5*(XCF5-XC15)/DT+KC*(
TTCF4+TCF6)/DX^2+KC/(RI+5*DX)*(TCF6-TTCF4)/(2*DX)
1524 Z5=PC*CC/DT+(PC*CM5/DT)*(XCF5+XC15)/2+2*KC/DX^2
1526 TTCF5=WRS*ZU5/Z5+(1-WRS)*TCF5
1528 EU6=PC*CC*TC16/DT+PC*CM6*(XCF6+XC16)*TC16/(2*DT)+PC*HD6*(XCF6-XC16)/DT+2*H
C*TPF/DX+2*KC*TTCF5/DX^2+(HPC/RO)*TPF
1530 Z6=PC*CC/DT+(PC*CM6/DT)*(XCF6+XC16)/2+2*HPC/DX+2*KC/DX^2+HPC/RO
1532 TTCF6=WRS*ZU6/Z6+(1-WRS)*TCF6
1534 EU7=PD*CD*TD11/DT+KD*(TTTF+TDF2)/DX^2+(KD/(RI+DX))*(TDF2-TTTF)/(2*DX)
1536 Z7=PD*CD/DT+2*KD/DX^2
1538 TTDF1=WRS*ZU7/Z7+(1-WRS)*TDF1
1540 EU8=PD*CD*TD12/DT+KD*(TTDF1+TDF3)/DX^2+(KD/(RI+2*DX))*(TDF3-TTDF1)/(2*DX)
1542 Z8=PD*CD/DT+2*KD/DX^2
1544 TTDF2=WRS*ZU8/Z8+(1-WRS)*TDF2
1546 EU9=PD*CD*TD13/DT+KD*(TTDF2+TDF4)/DX^2+(KD/(RI+3*DX))*(TDF4-TTDF2)/(2*DX)
1548 Z9=PD*CD/DT+2*KD/DX^2
1550 TTDF3=WRS*ZU9/Z9+(1-WRS)*TDF3

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574 $TTCF6 = WRS * ZU6 / Z6 + (1 - WRS) * TCF6$
 576 $ZU5 = PC * CC * TCI5 / DT + PC * CM5 * (XCF5 + XCI5) * TCI5 / (2 * DT) + PC * HD5 * (XCF5 - XCI5) / DT + KC * ($
 $TCF6 - TTCF6) / DX^2 + KC / (RI + 5 * DX) * (TTCF6 - TCF4) / (2 * DX)$
 577 $Z5 = PC * CC / DT + (PC * CM5 / DT) * (XCF5 + XCI5) / 2 + 2 * KC / DX^2$
 578 $TTCF5 = WRS * ZU5 / Z5 + (1 - WRS) * TCF5$
 580 $ZU4 = PC * CC * TCI4 / DT + PC * CM4 * (XCF4 + XCI4) * TCI4 / (2 * DT) + PC * HD4 * (XCF4 - XCI4) / DT + KC * ($
 $TCF5 - TTCF5) / DX^2 + KC / (RI + 4 * DX) * (TTCF5 - TCF3) / (2 * DX)$
 581 $Z4 = PC * CC / DT + (PC * CM4 / DT) * (XCF4 + XCI4) / 2 + 2 * KC / DX^2$
 582 $TTCF4 = WRS * ZU4 / Z4 + (1 - WRS) * TCF4$
 584 $ZU3 = PC * CC * TCI3 / DT + PC * CM3 * (XCF3 + XCI3) * TCI3 / (2 * DT) + PC * HD3 * (XCF3 - XCI3) / DT + KC * ($
 $TCF4 - TTCF4) / DX^2 + KC / (RI + 3 * DX) * (TTCF4 - TCF2) / (2 * DX)$
 585 $Z3 = PC * CC / DT + (PC * CM3 / DT) * (XCF3 + XCI3) / 2 + 2 * KC / DX^2$
 586 $TTCF3 = WRS * ZU3 / Z3 + (1 - WRS) * TCF3$
 588 $ZU2 = PC * CC * TCI2 / DT + PC * CM2 * (XCF2 + XCI2) * TCI2 / (2 * DT) + PC * HD2 * (XCF2 - XCI2) / DT + KC * ($
 $TCF3 - TTCF3) / DX^2 + KC / (RI + 2 * DX) * (TTCF3 - TCF1) / (2 * DX)$
 589 $Z2 = PC * CC / DT + (PC * CM2 / DT) * (XCF2 + XCI2) / 2 + 2 * KC / DX^2$
 590 $TTCF2 = WRS * ZU2 / Z2 + (1 - WRS) * TCF2$
 592 $ZU1 = PC * CC * TCI1 / DT + PC * CM1 * (XCF1 + XCI1) * TCI1 / (2 * DT) + PC * HD1 * (XCF1 - XCI1) / DT + KC * ($
 $TCF2 - TTCF2) / DX^2 + KC / (RI + DX) * (TTCF2 - TCF0) / (2 * DX)$
 593 $Z1 = PC * CC / DT + (PC * CM1 / DT) * (XCF1 + XCI1) / 2 + 2 * KC / DX^2$
 594 $TTCF1 = WRS * ZU1 / Z1 + (1 - WRS) * TCF1$
 596 $ZU0 = PC * CC * TCI0 / DT + PC * CM0 * (XCF0 + XCI0) * TCI0 / (2 * DT) + PC * HD0 * (XCF0 - XCI0) / DT + 2 * HP$
 $C * TTF / DX + 2 * KC * TTCF1 / DX^2 - HPC * TTF / RI$
 597 $Z0 = PC * CC / DT + (PC * CM0 / DT) * (XCF0 + XCI0) / 2 + 2 * HPC / DX + 2 * KC / DX^2 - HPC / RI$
 598 $TTCF0 = WRS * ZU0 / Z0 + (1 - WRS) * TCF0$
 1600 $ZT = MIT * CT * TTI / DT + 2 * PI * RI * L * NS * HPC * TTCF0 + 4 * PI * RI * LD * NS * KD * (1 + DX / (2 * RI)) * (TTD$
 $F1 / DX)$
 1602 $ZT3 = MIT * CT / DT + 2 * PI * RI * L * NS * HPC + 4 * PI * RI * LD * NS * KD * (1 + DX / (2 * RI)) / DX$
 1604 $TTTF = WRS * ZT / ZT3 + (1 - WRS) * TTF$
 1606 $PPP = PPP + 1$
 1608 $RMS = ABS((TCF0 - TTCF0) + (TCF1 - TTCF1) + (TCF2 - TTCF2) + (TCF3 - TTCF3) + (TCF4 - TTCF4))$
 1609 $RMS = RMS + ABS((TCF5 - TTCF5) + (TCF6 - TTCF6) + (TDF1 - TTDF1) + (TDF2 - TTDF2) + (TDF3 - TTDF3)$
 $) + (TDF4 - TTDF4) + (TDF5 - TTDF5) + (TTF - TTTF) + (TPF - TTPF) + (TGF - TTGF))$
 1610 $RMS = RMS / 15$
 1618 $TCF0 = TTCF0 : TCF1 = TTCF1 : TCF2 = TTCF2 : TCF3 = TTCF3 : TCF4 = TTCF4 : TCF5 = TTCF5$
 1620 $TCF6 = TTCF6 : TDF1 = TTDF1 : TDF2 = TTDF2 : TDF3 = TTDF3 : TDF4 = TTDF4 : TDF5 = TTDF5$
 1622 $TTF = TTTF : TPF = TTPF : TGF = TTGF$
 1623 $IF TPF <= TA THEN TPF = TA : TS = TA$
 1624 $IF TGF <= TA THEN TGF = TA : TAS = TA$
 1626 $TCV0 = (TCF0 + TCI0) / 2 : TCV1 = (TCF1 + TCI1) / 2 : TCV2 = (TCF2 + TCI2) / 2 : TCV3 = (TCF3 + TCI3) / 2$
 1628 $TCV4 = (TCF4 + TCI4) / 2 : TCV5 = (TCF5 + TCI5) / 2 : TCV6 = (TCF6 + TCI6) / 2 : TPV = (TPF + TPI) / 2$
 1629 $TGV = (TGF + TGI) / 2 : TDV1 = (TDF1 + TDI1) / 2 : TDV2 = (TDF2 + TDI2) / 2 : TDV3 = (TDF3 + TDI3) / 2$
 1630 $TDV4 = (TDF4 + TDI4) / 2 : TDV5 = (TDF5 + TDI5) / 2 : TTV = (TTF + TTI) / 2$
 1632 $IF PPP <= 55 THEN 1455$
 1633 $ZVV4 = AC * SP - (BE * (TPF^4 - TGF^4) / (1 / EP + 1 / EG - 1) + NU * K1 * (TPF - TGF) / LS) * AC : ZVV5 = (KB * ($
 $TPF - TA) * DAY / LB + A * KE * (TPF - TA) / LE) * AC + 2 * PI * RO * L * NS * HPC * (TPF - TCF6)$
 1634 $UP1 = (RI + DX) * TCF1 + (RI + 2 * DX) * TCF2 + (RI + 3 * DX) * TCF3 + (RI + 4 * DX) * TCF4 + (RI + 5 * DX) * TCF$
 $5 + .5 * (RO - .25 * DX) * TCF6 + .5 * (RI + .25 * DX) * TCF0$
 1636 $TMF = 2 * PI * DX * UP1 / (PI * (RO^2 - RI^2))$
 1637 $ZVV6 = 4 * PI * RO * LD * NS * KD * (1 - DX / (2 * RO)) * (TPF - TDF5) / DX + (ET * BE * (TPF^4 - TS^4) + HB * ($
 $PF - TA)) * AC * NITE : KK41 = MOT * CT * (TPF - TPI) / DT : KK42 = ZVV4 - ZVV5 - ZVV6$
 1638 $TMI = 2 * PI * DX * ((RI + DX) * TCI1 + (RI + 2 * DX) * TCI2 + (RI + 3 * DX) * TCI3 + (RI + 4 * DX) * TCI4 + (RI$
 $5 * DX) * TCI5 + .5 * (RO - .25 * DX) * TCI6 + .5 * (RI + .25 * DX) * TCI0) / (PI * (RO^2 - RI^2))$
 1639 $KK51 = PD * CD * (TDF4 - TDI4) / DT : KK52 = KD * (TDF3 - 2 * TDF4 + TDF5) / DX^2 + (KD / (RI + 4 * DX)) * ($
 $Df5 - TDF3) / (2 * DX) : KK53 = 2 * PI * (RI + 4 * DX) * DX * LD : KK51 = KK51 * KK53 : KK52 = KK52 * KK53$
 1640 $UP2 = (RI + DX) * TDF1 + (RI + 2 * DX) * TDF2 + (RI + 3 * DX) * TDF3 + (RI + 4 * DX) * TDF4 + (RI + 5 * DX) * TD$
 $5 + .5 * (RO - .25 * DX) * TPF + .5 * (RI + .25 * DX) * TTF$
 1642 $TDMF = 2 * PI * DX * UP2 / (PI * (RO^2 - RI^2))$


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732 IF XMI<.06 THEN HMI4=HMI1 ELSE HMI4=HMI2
734 IF XMI>=.14 THEN HMI=HMI3 ELSE HMI=HMI4
736 HDM=R*(HMF+HMI)/(M*2)
738 TMV=(TMF+TMI)/2
740 CM=(3.9924-.0158*TMV+.0000364*TMV^2)*1000
742 IF IT=0 THEN EFFP=0 :GOTO 1750
744 DE1=MC*CC*(TMF-TMI)/DT+MC*CM*(XMFF+XMI)*(TMF-TMI)/(2*DT)+MOT*CT*1*(TPF-TPI)
DT
746 DE2=MC*HDM*(XMI-XMFF)/DT+MIT*CT*(TTF-TTI)/DT+MDT*CD*(TDMF-TDMI)/DT
748 EFFP=(DE1+DE2)/(IT*AC)
750 IF EFFP>0 THEN EFF=EFFP ELSE EFF=0
751 QC=EFF*IT*AC
752 ITT=ITI+IT:QCF=QCI+QC
753 HFCD=95.8734+.86247*TCD+.0027778*TCD^2
754 HFEV=95.8734+.86247*TEV+.0027778*TEV^2
755 HFGEV=1038.1395#+2.4329*TEV-.006665*TEV^2
760 ITPF=TPF-273.15:TDF=TDMF-273.15:TCF=TMF-273.15
764 ITGF=TGF-273.15:ITTF=TTF-273.15:TAMB=TA-273.15
1770 RETURN
1800 REM PROGRAM FOR TC4
1804 TC4=TMF
1805 TC4=TC4+.01
1808 XC4=1-TC4/512.6
1809 IF XMIN=0 THEN 1825
1810 PSC4=80.9*EXP((1-XC4)^-1*(-8.54796*XC4+.76982*XC4^1.5-3.1085*XC4^3+1.54481*XC4^6))
1812 PC4=937.911-.058267*TC4-.001495*TC4^2
1818 SS3=(1/D)*LOG((PC4*WO)/XMIN):SS4=SS3^(1/N):PCC4=PSC4/EXP(1/TC4*SS4)
1820 IF PCC4<P1 THEN 1805
1825 RETURN
1900 COP=(XMMI-XMIN)*MC*(HFGEV+HFEV-HFCD)*1000/(3600*ITT*AC)
1902 QE=(XMMI-XMIN)*MC*(HFGEV+HFEV-HFCD)*1000
1904 EFFCY=QCF/(ITT*AC)
1906 TCD=TCD-273.15:TEV=TEV-273.15:TC2=TC2-273.15:TC4=TC4-273.15:TC3=TC3-273.15:
TI=TI-273.15:TE=TE-273.15:TC1=TC1-273.15
1907 PRINT #2,TAB(60);"
1908 PRINT #2,TAB(6);"OVERALL COL. EFFCY =";EFFCY;" OVERALL COP =";COP;" TEV =
";TEV;" TCD =";TCD;" TI =";TI;" TE =";TE;" QE =";QE
1910 PRINT #2,TAB(6);"TC1 =";TC1;" TC2 =";TC2;" TC3 =";TC3;" TC4 =";TC4;" S
=";S;" DC/L =";DC;"/";LCI;" DR/L =";DR;"/";LRI;" ITT =";ITT
1912 CLOSE
1916 IF ABUT=2 THEN 2220
2000 ETC=.13:DC=.0254*DCY:DR=.0254*DRI:VOL=(DC^2*LCI+DR^2*LRI)*PI/4:RIC=((DC^2*L
CI+DR^2*LRI)*3/16)^(1/3):ROC=((3*S^3)/(4*PI))^(1/3)
2001 AI=PI*(DC*LCI+DR*LRI)+(DR^2-DC^2)*PI/2:HRR3=HRR2-HRR1:HR=HRR3+1
2002 MO=MC*(XMMI-XMIN)/(3600*HR):TSAT=TAFN+3:TI=TAFN+1.5:TE=TAFN+1
2003 TVF=TSAT
2004 TVI=(TC3+TC2)/2:TFM=(TSAT+TI)/2:TV=(TVI+TVF)/2
2006 CPL=(3.9924-.0158*TFM+.0000364*TFM^2)*1000
2008 PL=937.911-.058267*TFM-.001495*TFM^2
2010 KL=.3225-.0004785*TFM+1.168E-07*TFM^2
2011 KV=-.007797+4.167E-05*TV+1.214E-07*TV^2-5.184E-11*TV^3
2012 UL=(EXP(-39.35+4826/TFM+.1091*TFM-.0001127*TFM^2))*0.001
2014 HFG=(1038.1395#+2.4329*TSAT-.006665*TSAT^2)*1000
2016 HEFG=HFG+(3/8)*CPL*(TSAT-TI)
2018 TC=512.6:ZRA=.2334:WY=.556:ZS=.9949
2020 X=1-TSAT/512.6
2022 PS=80.9*EXP((1-X)^-1*(-8.54796*X+.76982*X^1.5-3.1085*X^3+1.54481*X^6))
2024 FW=.48+1.574*WY-.176*WY^2:TR=TSAT/TC

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EVAPORATOR BOX DESIGN PROGRAMME

written by Francis E. Quagraine

Mc, Xmax, Xmin, Tsat, Tm1, Tev, Tad(Tad1 and Tad2), Tan, Tai, t1, t2, t3, Lli, Lbi, Lhi, tk, tkb, tkc, tke, Ae and U (average wind velocity) are variables and the values are to be supplied for the programme to run.

$$\sigma := 5.6697 \cdot 10^{-8} \quad g := 9.81 \quad C_{per} := 380 \quad C_{pcw} := 963 \quad C_{pb} := 434 \quad C_{pw} := 4190 \quad C_{pi} := 2040$$

$$dsc := 2702 \quad dse := 8530 \quad dsi := 100 \quad dsb := 7854 \quad Et := 0.9 \quad Ew := 0.45 \quad kw := 0.05 \quad ki := kw$$

$$C_{pgt} := 3980$$

$$Mc := 19.432 \quad U := 1.44 \quad Lli := 0.3 \quad Lbi := 0.3 \quad Lhi := 0.45 \quad tk := 0.05 \quad tkb := \frac{1}{16} \quad tkc := \frac{1}{16}$$

$$tke := \frac{1}{16} \quad Ae := 2106.0595 \cdot 10^{-4} \quad Tsat := 301.49 \quad Xmax := 0.16 \quad Xmin := 0.08876393 \quad Tcd := Tsat$$

$$Ll := Lli + 2 \cdot tk \quad Lb := Lbi + 2 \cdot tk \quad Lh := Lhi + 2 \cdot tk$$

$$Vo := Ll \cdot Lb \cdot Lh \quad Vi := Lli \cdot Lbi \cdot Lhi$$

$$Ab := 2 \cdot (Ll \cdot Lb + Ll \cdot Lh + Lb \cdot Lh) \quad Ar := 2 \cdot (Lli \cdot Lbi + Lli \cdot Lhi + Lbi \cdot Lhi)$$

$$Ro := \left(\frac{3 \cdot Vo}{4 \cdot \pi} \right)^{\frac{1}{3}} \quad Ri := \left(\frac{3 \cdot Vi}{4 \cdot \pi} \right)^{\frac{1}{3}} \quad s := \frac{4 \cdot Ll \cdot Lb}{2 \cdot (Ll + Lb)}$$

$$i := 0, 1 \dots 4$$

$vJ_i :=$	$vp_i :=$	$v\mu a_i :=$	$vka_i :=$	$v\alpha_i :=$
293.15	1.204	$1.81 \cdot 10^{-5}$	0.0257	$2.12 \cdot 10^{-5}$
313.15	1.127	$1.90 \cdot 10^{-5}$	0.0272	$2.40 \cdot 10^{-5}$
333.15	1.059	$1.99 \cdot 10^{-5}$	0.0287	$2.69 \cdot 10^{-5}$
353.15	0.999	$2.09 \cdot 10^{-5}$	0.0302	$3.00 \cdot 10^{-5}$
373.15	0.946	$2.18 \cdot 10^{-5}$	0.0318	$3.32 \cdot 10^{-5}$

$$Tvd := \frac{Tbd + Tad}{2}$$

$$Tvn := \frac{Tbn + Tan}{2}$$

$$pd1 := \text{linterp}(vJ, vp, Tvd)$$

$$pn1 := \text{linterp}(vJ, vp, Tvn)$$

$$\mu d1 := \text{linterp}(vJ, v\mu a, Tvd)$$

$$\mu n1 := \text{linterp}(vJ, v\mu a, Tvn)$$

$$vd1 := \frac{\mu d1}{pd1}$$

$$vn1 := \frac{\mu n1}{pn1}$$

$$\alpha d1 := \text{linterp}(vJ, v\alpha, Tvd)$$

$$\alpha n1 := \text{linterp}(vJ, v\alpha, Tvn)$$

$$kd1 := \text{linterp}(vJ, vka, Tvd)$$

$$kn1 := \text{linterp}(vJ, vka, Tvn)$$

$$Prd := \frac{vd1}{\alpha d1}$$

$$Prn := \frac{vn1}{\alpha n1}$$

$$\beta_{d1} := \frac{2}{T_{bd} + T_{ad}}$$

$$\beta_{n1} := \frac{2}{T_{bn} + T_{an}}$$

$$Ra_{vd} := \frac{g \cdot \beta_{d1} \cdot (T_{ad} - T_{bd}) \cdot L_h^3}{\nu_{d1} \cdot \alpha_{d1}}$$

$$Ra_{vn} := \frac{g \cdot \beta_{n1} \cdot (T_{an} - T_{bn}) \cdot L_h^3}{\nu_{n1} \cdot \alpha_{n1}}$$

$$Nu_{vd1} := \left[0.825 + \frac{0.387 \cdot Ra_{vd}^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr_d} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

$$Nu_{vd2} := 0.68 + \frac{0.670 \cdot Ra_{vd}^{\frac{1}{4}}}{\left[1 + \left(\frac{0.492}{Pr_d} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}}$$

$$Nu_{vn1} := \left[0.825 + \frac{0.387 \cdot Ra_{vn}^{\frac{1}{6}}}{\left[1 + \left(\frac{0.492}{Pr_n} \right)^{\frac{9}{16}} \right]^{\frac{8}{27}}} \right]^2$$

$$Nu_{vn2} := 0.68 + \frac{0.670 \cdot Ra_{vn}^{\frac{1}{4}}}{\left[1 + \left(\frac{0.492}{Pr_n} \right)^{\frac{9}{16}} \right]^{\frac{4}{9}}}$$

$$Nu_{vd} := \text{if}(Ra_{vd} < 10^9, Nu_{vd2}, Nu_{vd1})$$

$$Nu_{vn} := \text{if}(Ra_{vn} < 10^9, Nu_{vn2}, Nu_{vn1})$$

$$h_{vd} := Nu_{vd} \cdot \frac{k_{d1}}{L_h}$$

$$h_{vn} := Nu_{vn} \cdot \frac{k_{n1}}{L_h}$$

$$Re_d := \frac{U \cdot s}{\nu_{d1}}$$

$$Re_n := \frac{U \cdot s}{\nu_{n1}}$$

$$Nu_{wd} := 0.86 \cdot Re_d^{\frac{1}{2}} \cdot Pr_d^{\frac{1}{3}} \quad h_{wd} := Nu_{wd} \cdot \frac{k_{d1}}{s}$$

$$Nu_{wn} := 0.86 \cdot Re_n^{\frac{1}{2}} \cdot Pr_n^{\frac{1}{3}} \quad h_{wn} := Nu_{wn} \cdot \frac{k_{n1}}{s}$$

$$Ra_{hd} := \frac{g \cdot \beta_{d1} \cdot (T_{ad} - T_{bd}) \cdot \left(\frac{s}{4} \right)^3}{\nu_{d1} \cdot \alpha_{d1}}$$

$$Ra_{hn} := \frac{g \cdot \beta_{n1} \cdot (T_{an} - T_{bn}) \cdot \left(\frac{s}{4} \right)^3}{\nu_{n1} \cdot \alpha_{n1}}$$

$$Nu_{bd} := 0.27 \cdot Ra_{hd}^{\frac{1}{4}} \quad h_{bcd} := 4 \cdot Nu_{bd} \cdot \frac{k_{d1}}{s}$$

$$Nu_{bn} := 0.27 \cdot Ra_{hn}^{\frac{1}{4}} \quad h_{bcn} := 4 \cdot Nu_{bn} \cdot \frac{k_{n1}}{s}$$

$$h_{bd} := \text{if}(h_{wd} < h_{bcd}, h_{bcd}, h_{wd})$$

$$h_{bn} := \text{if}(h_{wn} < h_{bcn}, h_{bcn}, h_{wn})$$

$$\text{Nutd1} := 0.54 \cdot \text{Rahd}^{\frac{1}{4}} \quad \text{Nutd2} := 0.15 \cdot \text{Rahd}^{\frac{1}{3}}$$

$$\text{Nutn1} := 0.54 \cdot \text{Rahn}^{\frac{1}{4}} \quad \text{Nutn2} := 0.15 \cdot \text{Rahn}^{\frac{1}{3}}$$

$$\text{Nutd} := \text{if}(\text{Rahd} < 10^7, \text{Nutd1}, \text{Nutd2})$$

$$\text{Nutn} := \text{if}(\text{Rahn} < 10^7, \text{Nutn1}, \text{Nutn2})$$

$$\text{htcd} := 4 \cdot \text{Nutd} \cdot \frac{\text{kd1}}{\text{s}}$$

$$\text{htcn} := 4 \cdot \text{Nutn} \cdot \frac{\text{kn1}}{\text{s}}$$

$$\text{htd} := \text{if}(\text{hwd} < \text{htcd}, \text{htcd}, \text{hwd})$$

$$\text{htn} := \text{if}(\text{hwn} < \text{htcn}, \text{htcn}, \text{hwn})$$

$$\text{Tme} := \frac{\text{Tm1} + \text{Tev}}{2}$$

$$\text{Tchn} := \frac{273.15 + \text{Tai}}{2}$$

$$\text{Tch1} := \frac{273.15 + \text{Tm3}}{2}$$

$$\text{hfm1} := (95.8734 + 0.86247 \cdot \text{Tm1} + 0.0027778 \cdot \text{Tm1}^2) \cdot 1000$$

$$\text{hfm4} := (95.8734 + 0.86247 \cdot \text{Tm4} + 0.0027778 \cdot \text{Tm4}^2) \cdot 1000$$

$$\text{hfcd} := (95.8734 + 0.86247 \cdot \text{Tcd} + 0.0027778 \cdot \text{Tcd}^2) \cdot 1000$$

$$\text{hfgev} := (95.8734 + 0.86247 \cdot \text{Tev} + 0.0027778 \cdot \text{Tev}^2) \cdot 1000$$

$$\text{hfgme} := (1038.1395 + 2.4329 \cdot \text{Tme} - 0.006665 \cdot \text{Tme}^2) \cdot 1000$$

$$\text{hfgev} := (1038.1395 + 2.4329 \cdot \text{Tev} - 0.006665 \cdot \text{Tev}^2) \cdot 1000$$

$$\text{x} := \frac{\text{hfm1} - \text{hfgev}}{\text{hfgme}}$$

$$\text{y} := \frac{\text{hfm1} - \text{hfgev}}{\text{hfgev}}$$

$$\text{z} := \frac{\text{hfcd} - \text{hfgev}}{\text{hfgev}}$$

$$\text{mo} := \text{Mc} \cdot (\text{Xmax} - \text{Xmin})$$

$$\text{qtx1} := \text{mo} \cdot (1 - \text{x}) \cdot \text{hfgev}$$

$$\text{qty1} := \text{mo} \cdot (1 - \text{y}) \cdot \text{hfgev}$$

$$\text{qtz1} := \text{mo} \cdot (1 - \text{z}) \cdot \text{hfgev}$$

$$\text{qtx2} := \text{mo} \cdot (\text{hfcd} - \text{hfm1})$$

$$\text{qty2} := \text{mo} \cdot (\text{hfcd} - \text{hfm1})$$

$$\text{qtz2} := 0$$

$$\text{qtu2} := \text{mo} \cdot (\text{hfcd} - \text{hfm4})$$

$$\text{r} := \text{y}$$

$$\text{qt} := \text{qtu2}$$

$$\text{Mi} := (\text{Vo} - \text{Vi}) \cdot \text{dsi}$$

$$\text{Do} := 2 \cdot \text{Ro}$$

$$\text{Di} := 2 \cdot \text{Ri}$$

$$\text{NuL} := 1$$

$$\text{so} := \text{Vo}^{\frac{1}{3}}$$

$$\text{si} := \text{Vi}^{\frac{1}{3}}$$

$$\text{Mer} := \text{Ae} \cdot \text{tke} \cdot 0.0254 \cdot \text{dse}$$

$$\text{Mcw} := \text{Ar} \cdot \text{tkc} \cdot 0.0254 \cdot \text{dsc}$$

$$\text{Mb} := \text{Ab} \cdot \text{tkb} \cdot 0.0254 \cdot \text{dsb}$$

Ice Production

The two equations below are solved for Tbn and either Mgt (tomato storage) or MilL (ice production). Tm1 below stands for Tsat. The actual Tm1 is taken as Tai

Given

$$3600 \cdot t1 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} - mo \cdot (1 - r) \cdot hfgev = (Mer \cdot Cper + Mcw \cdot Cpcw + Mgt \cdot Cpgt + MilL \cdot Cpw) \cdot (273.15 - Tai) - 333500 \cdot MilL$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} = (2 \cdot hvn \cdot Ll \cdot Lh + 2 \cdot hvn \cdot Lb \cdot Lh + hbcn \cdot Ll \cdot Lb + htcn \cdot Ll \cdot Lb) \cdot (Tan - Tbn) + Et \cdot \sigma \cdot (Tan^4 - Tbn^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbn, MilL) = \left(\frac{296.048}{2.735} \right) \quad ERR = 5.151 \cdot 10^{-14}$$

Ro - Ri = 0.063	Tan = 296.75	Tai = 299.35	t1 = 12	Tev = 270.21
qty1 = 1.567 · 10 ⁶	Mgt = 0	MiL = 2.735	Tbn = 296.048	Tm1 = 301.49
mo = 1.384				

Tomato Storage

The two equations below are solved for Tbn and either Mgt (tomato storage) or MiL (ice production). Tm1 below stands for Tsat. The actual Tm1 is taken as Tai

Given

$$3600 \cdot t1 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} - mo \cdot (1 - r) \cdot hfgev = (Mer \cdot Cper + Mcw \cdot Cpcw + Mgt \cdot Cpgt + MiL \cdot Cpw) \cdot (273.15 - Tai) - 333500 \cdot MiL$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} = (2 \cdot hvn \cdot Ll \cdot Lh + 2 \cdot hvn \cdot Lb \cdot Lh + hbcn \cdot Ll \cdot Lb + htcn \cdot Ll \cdot Lb) \cdot (Tan - Tbn) + Et \cdot \sigma \cdot (Tan^4 - Tbn^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbn, Mgt) = \begin{pmatrix} 296.048 \\ 11.627 \end{pmatrix} \quad ERR = 2.328 \cdot 10^{-10}$$

$$Tan = 296.75 \quad Tai = 299.35 \quad t1 = 12 \quad Tev = 270.21$$

$$Mgt = 11.627 \quad MiL = 0 \quad Tbn = 296.048 \quad Tm1 = 301.49$$

$$Ro - Ri = 0.063$$

$$qty1 = 1.567 \cdot 10^6$$

$$mo = 1.384$$

Given

$$3600 \cdot t2 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd1 - Tch1}{(Ro - Ri)} = (Mer \cdot Cper + Mcw \cdot Cpcw + Mgt \cdot Cpgt) \cdot (Tm3 - 273.15)$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd1 - Tch1}{(Ro - Ri)} = (2 \cdot hvd \cdot Ll \cdot Lh + 2 \cdot hvd \cdot Lb \cdot Lh + hbcd \cdot Ll \cdot Lb + hbcd \cdot Ll \cdot Lb + htcd \cdot Ll \cdot Lb) \cdot (Tad1 - Tbd1) + Et \cdot \sigma \cdot (Tad1^4 - Tbd1^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbd1, Tm3) = \left(\frac{298.256}{281.132} \right) \quad ERR = 1.222 \cdot 10^{-9}$$

$$Mcw = 3.088$$

$$Mer = 2.852$$

$$Mb = 14.962$$

$$Mi = 4.75$$

$$Tad1 = 299.68 \quad Tbd1 = 298.256 \quad Tm3 = 281.132$$

$$Tch2 = \frac{Tm4 + Tm3}{2}$$

Given

$$3600 \cdot t3 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd2 - Tch2}{(Ro - Ri)} + qt = (Mer \cdot Cper + Mcw \cdot Cpcw + Mgt \cdot Cpgt) \cdot (Tm4 - Tm3)$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd2 - Tch2}{(Ro - Ri)} = (2 \cdot hvd \cdot Ll \cdot Lh + 2 \cdot hvd \cdot Lb \cdot Lh + hbcd \cdot Ll \cdot Lb + hbcd \cdot Ll \cdot Lb + htcd \cdot Ll \cdot Lb) \cdot (Tad2 - Tbd2) + Et \cdot \sigma \cdot (Tad2^4 - Tbd2^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbd2, Tm4) = \left(\frac{298.61}{284.31} \right) \quad ERR = 5.53 \cdot 10^{-10}$$

$$Tad2 = 299.68 \quad Tbd2 = 298.61 \quad Tm4 = 284.311$$

$$t3 = 3$$

Given

$$3600 \cdot t1 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} - mo \cdot (1 - r) \cdot hfgev = (Mer \cdot Cper + Mcw \cdot Cpcw + Mgtc \cdot Cpgt) \cdot (273.15 - Tm1) + Mgtf \cdot Cpgt \cdot (273.15 - Tai)$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbn - Tchn}{(Ro - Ri)} = (2 \cdot hvn \cdot Ll \cdot Lh + 2 \cdot hvn \cdot Lb \cdot Lh + hbcn \cdot Ll \cdot Lb + htcn \cdot Ll \cdot Lb) \cdot (Tan - Tbn) + Et \cdot \sigma \cdot (Tan^4 - Tbn^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbn, Mgtf) = \left(\frac{295.577}{6.112} \right) \quad ERR = 6.04 \cdot 10^{-14}$$

$$Tan = 296.75 \quad Tai = 299.35 \quad t1 = 12 \quad Tev = 270.21$$

$$qty1 = 1.627 \cdot 10^6$$

$$Mgtf = 6.112 \quad Mgtc = 11.627 \quad Tbn = 295.577 \quad Tm1 = 284.311$$

Given

$$3600 \cdot t2 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd1 - Tch1}{(Ro - Ri)} = Mer \cdot Cper \cdot (Tm3 - 273.15) + (Mcw \cdot Cpcw + Mgtf \cdot Cpgt + Mgtc \cdot Cpgt) \cdot (Tm3 - 273.15)$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd1 - Tch1}{(Ro - Ri)} = (2 \cdot hvd \cdot Ll \cdot Lh + 2 \cdot hvd \cdot Lb \cdot Lh + hbcd \cdot Ll \cdot Lb + htcd \cdot Ll \cdot Lb) \cdot (Tad1 - Tbd1) + Et \cdot \sigma \cdot (Tad1^4 - Tbd1^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Lb)$$

$$Minerr(Tbd1, Tm3) = \left(\frac{298.187}{278.81} \right) \quad ERR = 1.746 \cdot 10^{-10}$$

$$t2 = 9 \quad Tad1 = 299.68 \quad Tbd1 = 298.186 \quad Tm3 = 278.81$$

$$Tad = Tad1 \quad Tbd = Tbd1$$

Tomato storage

$$Tch2 := \frac{Tm4 + Tm3}{2}$$

Given

$$3600 \cdot t3 \cdot NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd2 - Tch2}{(Ro - Ri)} + qt = Mer \cdot Cper \cdot (Tm4 - Tm3) + (Mcw \cdot Cpcw + Mgtf \cdot Cpgt + Mgtc \cdot Cpgt) \cdot (Tm4 - Tm3)$$

$$NuL \cdot kw \cdot \pi \cdot Do \cdot Di \cdot \frac{Tbd2 - Tch2}{(Ro - Ri)} = (2 \cdot hvd \cdot Ll \cdot Lh + 2 \cdot hvd \cdot Lb \cdot Lh + hbcd \cdot Ll \cdot Lb + htcd \cdot Ll \cdot Lb) \cdot (Tad2 - Tbd2) + Et \cdot \sigma \cdot (Tad2^4 - Tbd2^4) \cdot (2 \cdot Ll \cdot Lh + 2 \cdot Lb \cdot Lh + 2 \cdot Ll \cdot Ll$$

$$Minerr(Tbd2, Tm4) = \left(\frac{298.444}{281.301} \right) \qquad ERR = 1.572 \cdot 10^{-9}$$

$$t3 \approx 3 \qquad Tad2 \approx 299.68 \qquad Tbd2 \approx 298.444 \qquad Tm4 \approx 281.301$$