# CERTIFICATION

## CERTIFICATION OF APPROVAL

**Solar adsorption cooling system using activated media for equatorial humid climate**

by

Helder Sitoi

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in partial fulfilment of the requirement for the
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**Approved by,**

Khairul Habib

**(DR. KHAIRUL HABIB)**

**UNIVERSITI TEKNOLOGI PETRONAS**

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# CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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**HELDER SITOI**

## ABSTRACT

Starting from the project background to its problem statement and objective, the writer explored and explained the basic theoretical information behind the topic aborted in this project (solar adsorption cooling system using activated media for equatorial humid climate), as well as the methodology to be used in order to accomplish the desired output. This project is about designing a solar powered adsorption cooling system that fits the needs and cooling requirements of a typical house under the equatorial humid climate. Kuala Lumpur, Malaysia was chosen and all the relevant data concerning the design of the refrigeration system shall take into account its climate properties. A few adsorbent candidates were compared using relevant criteria that suits for this current application, and final choice was the activated carbon for presenting better results among the other adsorbents. The same was done to select adsorbates and the final choice was the refrigerant R600 (N-butane). Adsorption analysis on this pair was done following the ideal cycle and based on the calculations and results obtained, could be noticed that the SCE of the system can go up to 27 KJ/Kg while the COP up to 0.169 (Optimum value). Under these results could be concluded that this system is capable to keep up with the house cooling load demand which presents a value of 6.03 KW.

# ACKNOWLEDGMENTS

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# NOMENCLATURE

$E_a$ - Activation energy, KJ/ kg

$R$ - Gas constant, KJ/Kg. K

$T$ - Temperature, K

$E$ - Characteristic energy, KJ/ kg

$n$ - Heterogeneity constant

$q$ - Instantaneous adsorption uptake, kg/kg

$q_o$ - Limiting adsorption uptake, kg/kg

$t$ - time, s

$Q_{st}$ – Isosteric heat of adsorption, KJ.Kg

$SCE$ – Specific cooling effect, KJ/Kg

$Q$ – Cooling load, KW

$P$ – Pressure, KPa

$C_p$ – Constant pressure specific heat, KJ/Kg.K

$h_{fg}$ – Enthalpy of evaporation, KJ/Kg

# SUBSCRIPTS

***ref*** - Refrigerant

***s,d*** – Start of desorption

***e,d*** – End of desorption

***s,a*** – Start of adsorption

***e,a*** – End of adsorption

***cond*** - Condenser

***ev*** - Evaporator

***adb*** - Adsorbent

***min*** – Minimum

***max*** - Maximum

***h*** – System

***N***- North

***S***- South

***E***- East

***W***- West

***T***- Total

# CHAPTER 1: INTRODUCTION

## 1.1 Background study

Global warming has become one of the major environmental issues nowadays. By definition global warming is the continuing rise in the average temperature of earth's atmosphere and oceans. There are many events responsible to the global warming of the planet and all of them contribute in the same way, the temperature increment due to the trapping of the heat and light from the sun by greenhouse gases, where this is the effect of the on-going destruction of the ozone layer that has been happening for a while now. The rapid growth of technology brought about new concepts and radical changes on various scientific fields on which many of the existing inventions are merely descendants from the past experiments, trials and errors.

The same way it was not possible in the past to reach long distances before the invention of the car, getting cold water, producing ice and ability to control the thermal comfort was practically impossible before the development of the refrigeration and air conditioning area. Nowadays, from industrial applications to simple house hold usage, the refrigeration and air conditioning topic is a crucial part on the human being lives, not only to provide thermal comfort but also indispensable in many other fields such as conservation of food, drugs (vaccines), and conservation of other products. However, the conventional refrigeration systems are units that need electricity to run and use a refrigerant to produce the cooling effect. These refrigerants used are made of Chloroflouroscarbons and HFC's which are substances that have been identified for being lethal to the ozone layer and global warming, for having high ozone depleting potential and high global warming potential values. [1]

Due to the advanced damage on the ozone layer the Montreal protocol, an international treaty, was signed in order to protect the ozone layer by phasing out products of a number of substances believed to be responsible for the ozone depletion. Among the other several substances included, some are highlighted here such as: CFC's, Halons, HCFCs, Carbon Tetrachloride, Hydrochloroflourocarbons, Trichloroethane, Methyl bromide and Bromochloromethane. Fig 1.1 is a basic representation on how the ozone depletion process takes place.

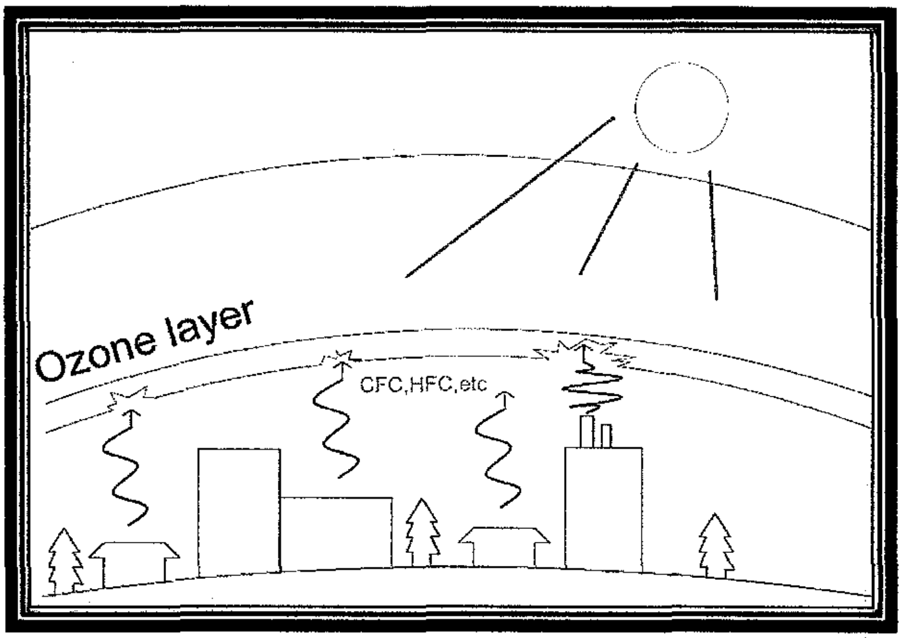


Figure 1.1: Ozone depletion process

So in order for the human lives continue benefiting from this magnificent inventions, a lot of studies have been done to find ways to replace the used refrigerants to finding alternative refrigeration cooling methods. In the meantime as we live in an age where a wiser energy management is required as the conventional fossil fuels are depleting with time, the researches under the refrigeration topic have not only been focused on the environmental point of view but at the same time should address the energy management too. This is where the adsorption cooling system has gained its reputation over the time for proving its usefulness in addressing today's current issues (environment and energy management).

The adsorption refrigeration system presents several advantages over the conventional refrigeration system, but that fact that it needs no electricity to run the system but waste heat or solar heat. Among the other advantages of the adsorption cooling systems we have the following: few moving components (Less maintenance), long life span (of at least 20 years), usage of heat instead of electricity as driving energy reducing $CO_2$ emissions, simple structure and very low or no electricity demand.

## 1.2 Problem statement

The current cooling systems being widely used in the market present several environmental problems related to $CO_2$, CFC and HFC emissions. Furthermore, with the depleting of the fossil fuels, a wiser management of energy resources became a must in our current world. The running out of our resources and the damaging of the ozone layer constitute a double problem and a great challenge under the refrigeration topic.

## 1.3 Objectives

To design an adsorption cooling system using activated media for a single storey house type exposed to equatorial humid climates. The design specifications will take into account Kuala Lumpur weather data as it will be the country reference for this current project. This project shall also study the feasibility of powering this adsorption system with thermal energy from the sun by using the conventional water heating system.

## 1.4 Scope of study

As this project is about designing a cooling system using the adsorption mechanism, starting from the selection of the adsorption pair to be used to the thermodynamic analysis of the system are points to be included. Furthermore, the integration with the solar thermal system reminds not forget that simulations in order to check if the Malaysian climate provides enough energy to power the system must also be checked.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Adsorption theory

In order to understand fully this phenomenon of adsorption, a lot of scientists have written many books and research papers. Adsorption is a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid (adsorbent), forming a molecular or atomic film (the adsorbate). It is different from *absorption*, in which a substance diffuses into a liquid or solid to form a solution. The term *sorption* encompasses both processes, while *desorption* is the reverse process. Fig 2.1 shows the surface adsorption process of gas molecules on solid adsorbents, in this case activated carbon (Maxorb III).

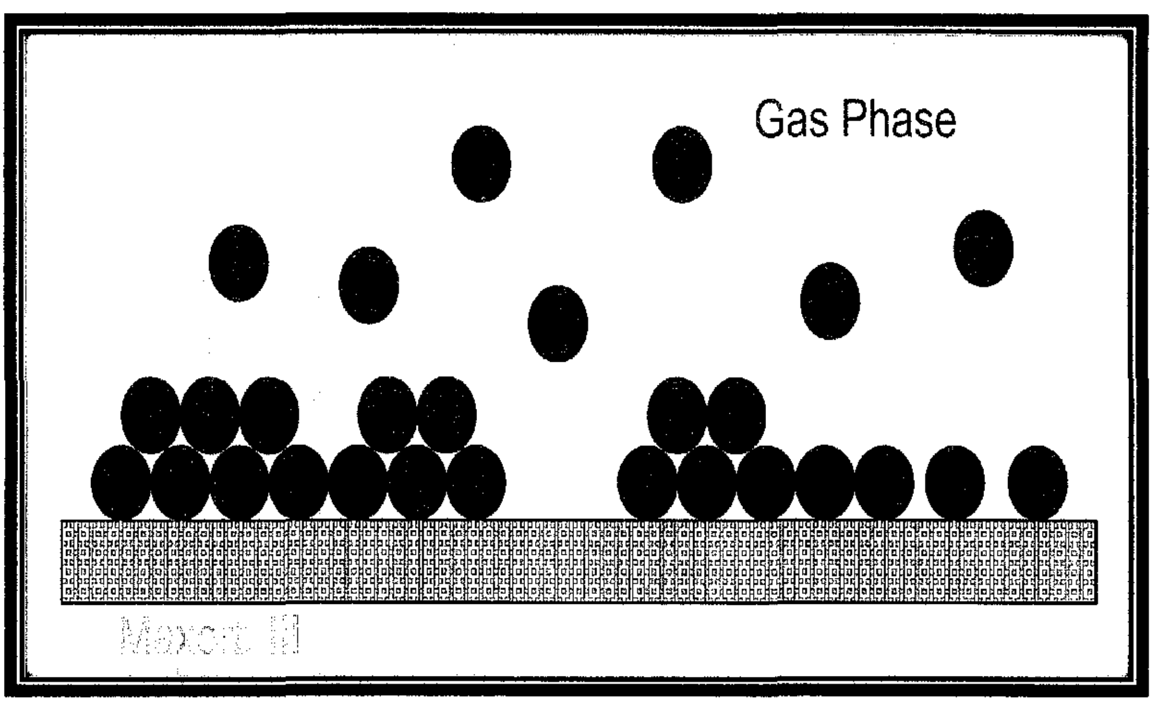


Figure 2.1: Surface adsorption process

## 2.2 Types of adsorption

Depending on the nature of attractive forces existing between the adsorbate and adsorbent, adsorption can be classified as physical adsorption or chemical adsorption.

- ***Physical adsorption:*** The forces of attraction between the molecules of the adsorbate and adsorbent are of weak van der Waals' type. Since the forces of attraction are weak, the process of physical adsorption can be easily reversed by heating or decreasing the pressure of the adsorbate in the surface.

- ***Chemical adsorption:*** The forces of attraction between the adsorbate and adsorbent are very strong. The molecules of the adsorbate form chemical bonds with the molecules of the adsorbent present in the surface.

## 2.3 Adsorption applications

Adsorption has wide known applications, from industrial to house hold applications, below are some of them currently used:

- Gas adsorption: Odor control, Industrial gas separation
- Water adsorption/desorption: Heat storage and solar refrigeration, desiccants
- Ion exchange: Water treatment, aquaculture, agriculture and horticulture

## 2.4 Adsorption cooling

Adsorption cooling is a thermally driven refrigeration system, which can be powered by solar energy as well as waste heat. The adsorption cooling system has been around for a while, from the old days it was invented until today, this system has suffered drastic changes and major improvements. Just like the normal refrigeration system, the adsorption system is also comprised of a condenser, expansion valve and evaporator. There is practically no mechanical work needed to make the system run as the compressor has been replaced by the adsorber bed which operates using heat instead of mechanical energy. The use of this thermal driven refrigeration system helps to reduce the carbon dioxide emission from combustion of fossil fuels in power plants. The adsorption system as compared to the conventional vapour compression system is a much more environmentally friendly has it uses natural working fluid which zero ozone depleting potential.

**Step 1 (Desorption)** – Drying of the adsorbent the adsorbent is dried by heat input. Refrigerant vapour is set free, flows in the condenser and is liquefied there under heat emission. When the material is dry, the heat input in the adsorber is stopped and the upper check valve closes.

**Step 2 (Adsorption)** – Refrigerant vapour is adsorbed at the surface of the adsorbent after a cool down phase the reverse reaction and the evaporation of the liquid condensate starts. The lower check valve to the evaporator opens and the dry adsorbent aspirates refrigerant vapour. In the evaporator, refrigerant evaporates and generates cold, which can be used for air-conditioning. During the adsorption process heat is rejected which has to be dissipated.

**Step 3** - Return of condensate in a final step, the liquid condensate is returned to the evaporator and the circuit is closed. In order to achieve a continuous cold production two adsorbers work in combination.

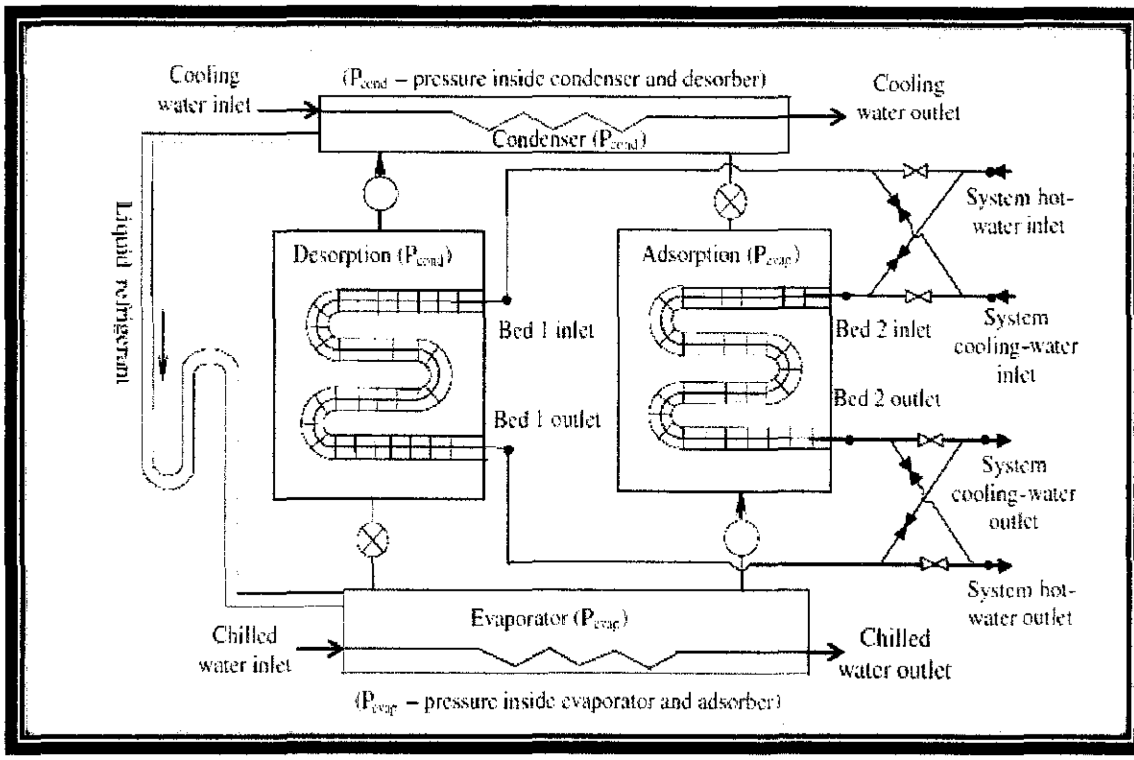


Figure 2.2: Schematic diagram of a two bed adsorption chiller [2]

Fig 2.2 shows a two bed adsorption chiller. The adsorber and desorber alternate functions so do the valves connecting them to the evaporator, condenser, heat and cooling source. While functioning as adsorber the bed connects to evaporator and cooling source and while functioning as desorber the bed connects to condenser and heat source.

## 2.5 Adsorption cooling previous studies

### 2.5.1 Hybrid solar-assisted adsorption cooling unit for vaccine storage

Solar powered vaccine storage using gas burner as second alternative for power supply in case they solar energy is not available in required quantities. The first adsorber is driven by a gas burner, Zeolite-13X while the second is driven by the solar energy and uses water to deliver the heat to the adsorption bed. Theoretical COP of this unit is about 0.28. [3]

### 2.5.2 Combined adsorption refrigeration

An adsorption cooling system integrating combined adsorption refrigeration cycles, where activated carbon (Maxorb III) is used as adsorbent, R134a and R507a as refrigerants. The top cycle is made of the pair AC-R507a and AC-R134a as the bottom cycle, delivering refrigeration at $-10^0$ C with heat source of $70^0$ C. Fig 2.3 is the graphical representation of the arrangement of the combined cycle adsorption system with the working flow of the entire refrigeration system. [4]

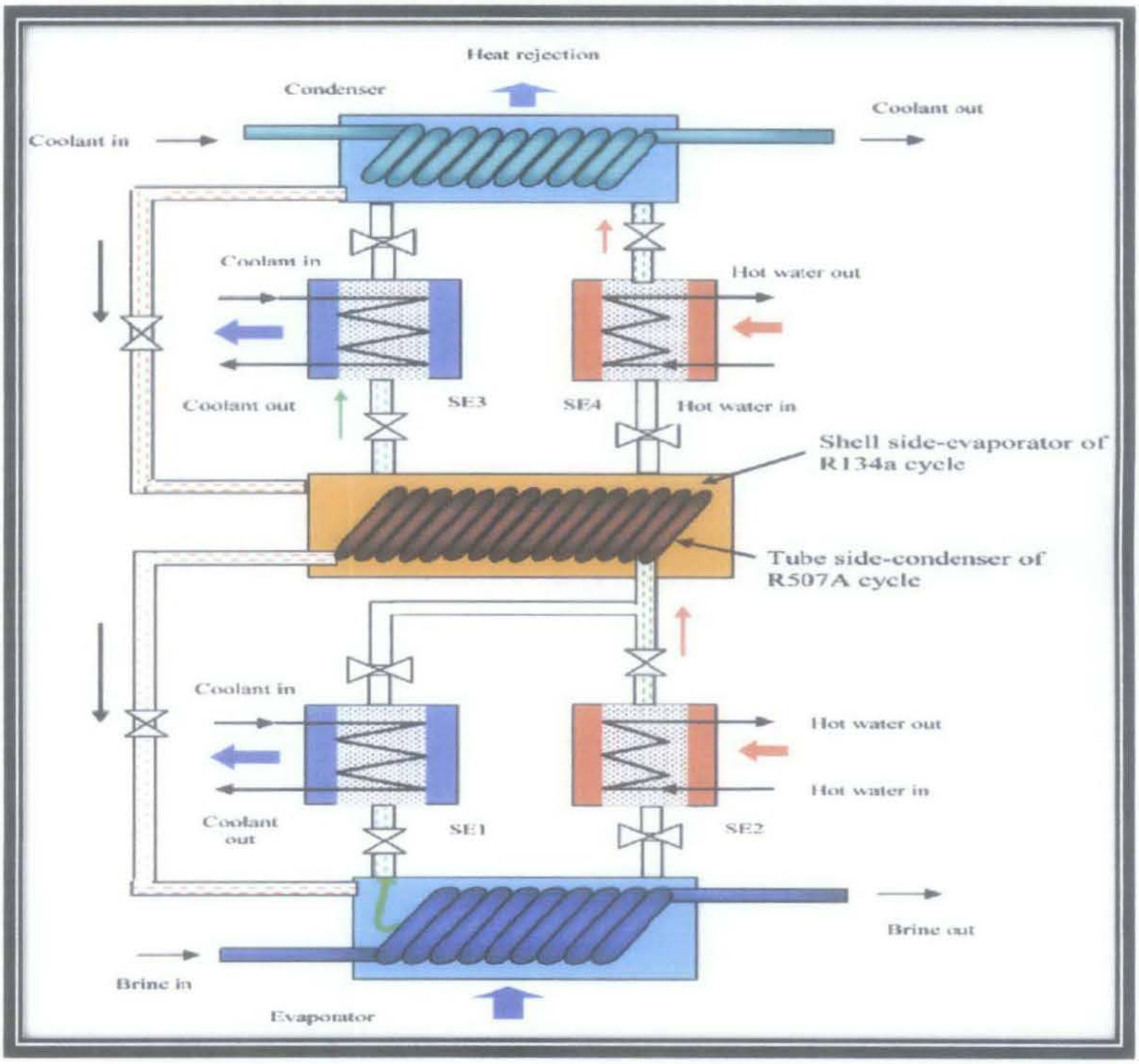


Figure 2.3: Combined adsorption refrigeration [4]

# CHAPTER 3: METHODOLOGY

## 3.1 Project work flow

This current project was conducted in several stages so a smooth organization and progress tracking could be implemented. Stage 1 and 2 were basically more focused on information gathering, familiarization with the topic and planning on the approaches to tackle the objectives of this current work. Stage 3 and 4 is where the design specifications for the house were defined in terms of dimensions, house type and then the calculation of the cooling load demand under Malaysian climate (Kuala Lumpur city). Stage 5 and 6 comprised all the adsorption analysis, from the selection of adsorption pairs to thermodynamic analysis on the selected pair and system performance. Stage 7 comprised analysis on the solar thermal system, checking if it can deliver the demanded water temperature for the adsorption process, and last stage the conclusion and recommendation. Fig 3.1 shows the project work flow.

1. Topic research and information gathering
2. Method and procedure planning
3. Identification of house properties and modeling
4. House cooling load calculation (under malaysian climate)
5. Adsorption pair selection and thermodynamic analyses
6. COP and SCE calculation (ideal cycle)
7. Solar heating system analyses (under malaysian climate)
8. Conclusion and recommendations

Figure 3.1: Project work flow

## 3.2 FYP 2 Gantt chart


Figure 3.2: FYP2 Gantt chart

## 3.3 Engineering tools used

There are basically two tools that were used to conduct this project, one for energy analysis (TRNSYS) and another for engineering drawings (CATIA). Table 3.1 show in details the function of each tool used in this project.

Table 3.1: Engineering tools used

| Tools | Details |
|---|---|
| **TRNSYS** | For simulating solar thermal system under Malaysian climate |
| **SIMULATION STUDIO (TRNSYS)** | to analyze the building energy behavior and the cooling load calculation |
| **CATIA (DASSAULT SYSTEMES)** | to reproduce the 3D model of the house |

# CHAPTER 4: RESULTS AND DISCUSSION

## 4.1 House cooling load calculation

### 4.1.1 House specifications

As mentioned before, the equatorial humid region that will be taken as base of this current study will be Malaysia, Kuala Lumpur city. Table 4.1 shows all the house specifications that were used in order to calculate the cooling load demand. The house is a single storey type habited by a family comprised of 4 people. Table 4.2 shows how the windows are placed along the walls of the house, their dimension and orientation. Fig 4.1 shows the internal divisions of the house as well as the wall orientation while fig 4.2 is the isometric view of the model house.

Table 4.1: House specifications

| | |
|---|---|
| **Location** | Kuala Lumpur, Malaysia |
| **Latitude & longitude** | 3°7'N 101°33'E |
| **Humidity** | 99% |
| **Outdoor air temperature** | 32 $^0$C |
| **Indoor air temperature** | 24 $^0$C |
| **Daily Temperature range** | 8K |
| **External dimensions** | 12m x 6m x 3m |
| **Walls** | Bricks<br>(U= 2.33 W/m$^2$K) |
| **Roof** | 2.5 inch wood with 1 inch insulation with suspended ceiling (U = 0.545 W/m$^2$K). |
| **Floor** | Negligible |
| **Doors** | 2 Inch wood<br>(U = 2.6 W/m$^2$K, A = 2.6m$^2$). |
| **Windows** | Regular single glass with venetian blinds<br>(U = 3.12 W/m$^2$K,). |
| **Internal Loads** | - People: 65W per person<br>- Lights: 5W (40% fluorescent tube)<br>- PC with color monitor: 230W/PC |

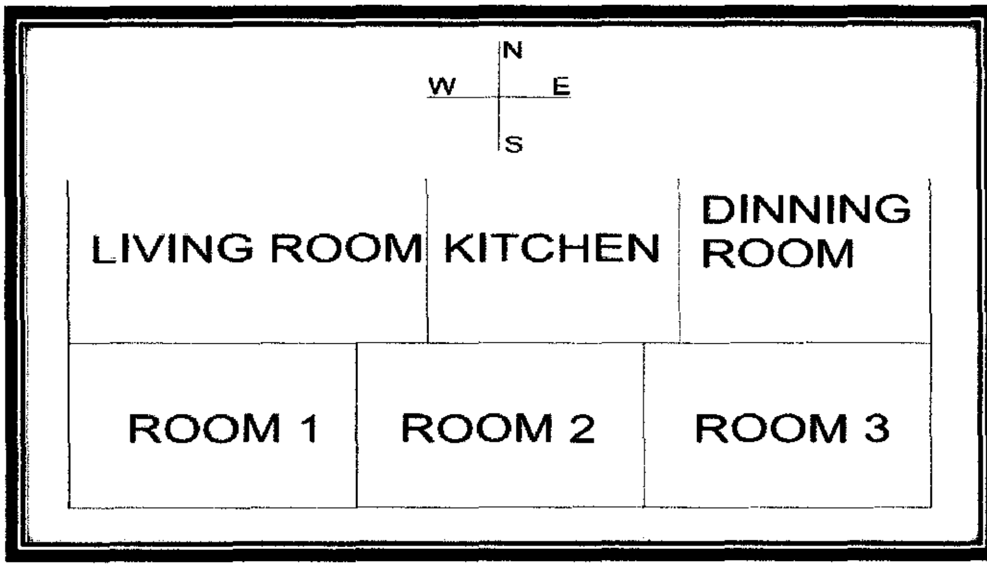


Figure 4.1: Layout of test house interior compartments

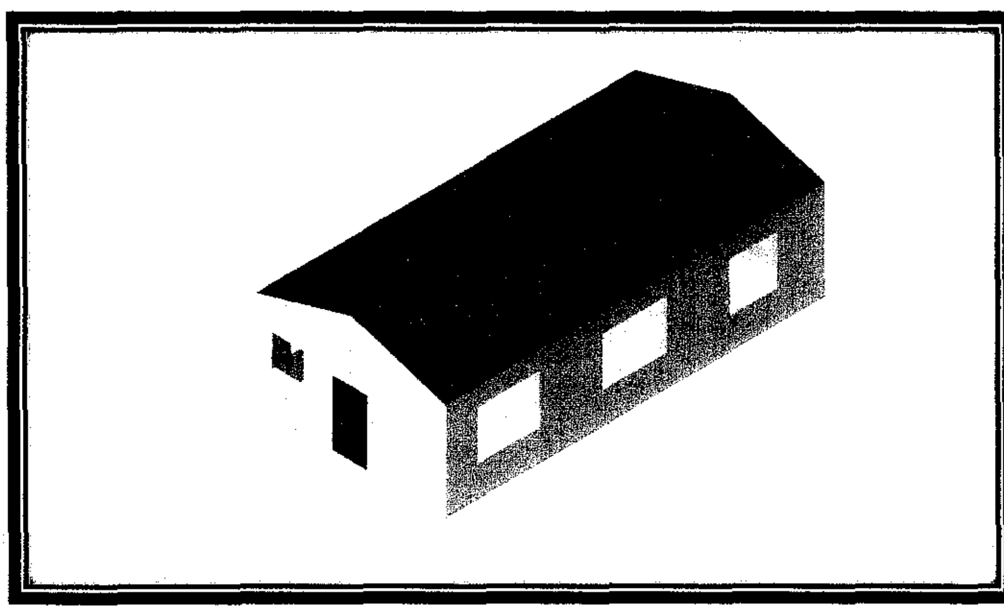

Figure 4.2: Isometric view of test house

Table 4.2: Window orientation and type

| | Living room | Room 1 | Room 2 | Room 3 |
|---|---|---|---|---|
| **Window** | North side ($3m^2$) West side ($1m^2$) | South side ($2.25m^2$) | South side ($2.25m^2$) | South side ($1m^2$) |
| **Type** | Single Glazing | Single Glazing | Single Glazing | Single Glazing |

### 4.1.2 Cooling load Calculation

#### 4.1.2.1 External Heat Gains:

- ***Conduction heat gains:***

$Q = A * U * CLTD$ (Wang S. [5])

Where: A – Area of the house, $m^2$
U- Heat transfer coefficient, $W/m^2.K$
CLTD- Cooling load temperature differences (see appendix C)

- Walls:
  - North: $A = (12 * 3) - 3 = 33\, m^2, CLTD = 7$
    $Q_N = 33 * 2.33 * 7 = 538.23\, W$
  - South: $A = (12 * 3) - 5.5 = 30.5\, m^2, CLTD = 9$
    $Q_S = 30.5 * 2.33 * 9 = 639.59\, W$
  - East: $A = 6 * 3 = 18\, m^2, CLTD = 13$
    $Q_E = 18 * 2.33 * 13 = 545.22\, W$
  - West: $A = (6 * 3) - 3.6 = 14.4\, m^2, CLTD = 13$
    $Q_W = 14.4 * 2.33 * 13 = 436.18\, W$

- Windows:
  - North: $CLTD = 7$
    $Q_N = 3 * 3.12 * 7 = 65.52\, W$
  - West: $CLTD = 13$
    $Q_W = 1 * 3.12 * 13 = 40.56\, W$
  - South: $CLTD = 9$
    $Q_S = 5.5 * 3.12 * 9 = 154.44\, W$

- Doors:
  - west: $CLTD = 13$
    $Q_W = 2.6 * 2.6 * 13 = 87.88\, W$

- Roof:
  - $CLTD = 44$
    $Q_R = 12 * 6 * 44 * 0.545 = 1726.56 W$

- ***Radiation heat gains:***

$Q = GLF * A$ (Wang S. [5])

Where: A – Area of the house, $m^2$
GLF- Glass load factor (see appendix C)

- Windows:
  - North: $GLF = 60$
    $Q_N = 60 * 3 = 180\ W$
  - South: $GLF = 88$
    $Q_S = 88 * 5.5 = 484\ W$
  - West: $GLF = 145$
    $Q_W = 145 * 1 = 145\ W$

**4.1.2.2 Internal Heat Gains:**

- People: $Q = 65W * 4 = 260\ W$
- Computers: $Q = 230W * 3 = 690\ W$
- Lights: $Q = 5W * 6 = 30\ W$

**4.1.2.3 Total heat gains**

- $Q_T = 538.23 + 639.59 + 549.22 + 436.18 + 65.52 + 40.56 + 154.44 + 87.88 + 1726.56 + 260+690+30+180+484+145$

$Q_T = 6.03KW$

The total cooling load calculation is the sum of all the external and internal cooling loads. The total cooling load demand of the model house proposed in this project is 6.03 KW.

## 4.2 Adsorption cooling design

### 4.2.1 Adsorbent selection

There is a vast range of adsorbents used in different applications and for various purposes, where this in other words tells that choosing an effective adsorbent would imply comparison among the several choices available in the market. The most important attributes of an absorbent for any application are: Capacity, Selectivity, regenerability, Kinetics, Compatibility and cost. In this current analysis we will only focus the selection criteria for *adsorption capacity* and *pore size* distribution which are more relevant in the design of the current cooling system. The candidates to be compared are the following: Activated carbon (Maxorb III), Zeolite and Activated alumina. Table 4.3 shows basic properties of the adsorbent candidates.

Table 4.3: Properties of adsorbents

| Adsorbent | Apparent density ($Kg/m^3$) | BET Surface ($m^2/g$) | Pore volume ($m^3/Kg$) | Source |
|---|---|---|---|---|
| **Maxorb III** | 310 | 3140 | 0.00201 | B.B. Saha et al. [6] |
| **Zeolite 5A** | 680 | 571 | 0.000176 | Melissa magee. [7] |
| **Silica gel(A)** | 720 | 830 | 0.00042 | Barry C. & W. John Thomas. [8] |

***Adsorption capacity:*** adsorption capacity or "loading" is the most crucial characteristic of an adsorbent. In other words it is the amount of adsorbate taken up by the adsorbent per unit mass or volume of the adsorbent, so the bigger the uptake the better the performance of the adsorbent. Fig 4.3 shows the uptake capacity of each of the proposed candidates, and as we can see from the same, activated carbon presents a much bigger uptake as compared to the rest of the proposed candidates, followed by Zeolite 5A and last Silica gel.

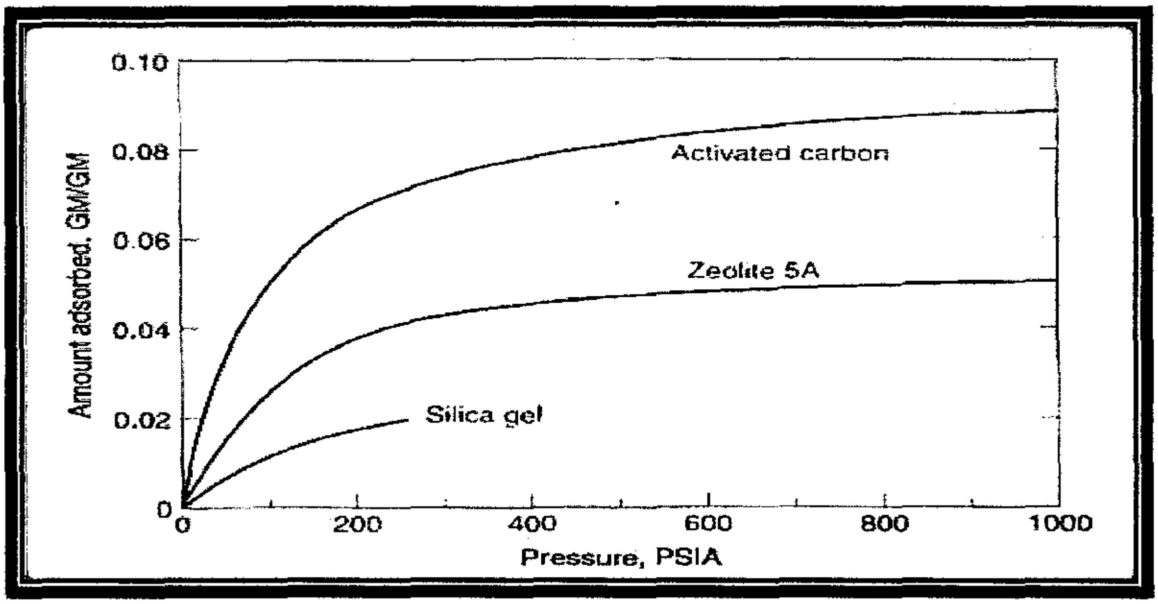


Figure 4.3: Adsorption capacity of adsorbents [9]

***Pore size distribution***: The property distribution is a related property that indicates the fraction of space occupied by micro-pores (dp < 20Å), meso-pores (20Å<=dp<500Å) and macro-pores (dp=>500Å). Pore dimensions are related to both kinetics and capacity of adsorbents. Activated carbon presents a wide range of pore diameters along its surface, followed by silica gel and last but not least zeolite 5A. This represents once again an advantage of activated carbon over the other candidates which are more likely to have limitations in adsorbing certain components whose pore sizes exceed or do not fall into the allowable range.

Among the various attributes of a good adsorbent already stated earlier in this section, we narrowed to only two of them (Kinetics and Capacity) which in terms of performance will determine the efficiency of our system and as well these two attributes automatically are interrelated to the rest. Activated carbon is the selection as the adsorbent to be used in the cooling system stated in this current project due to the above comparisons made on the capacity and pore-size distribution (kinetics related) which are basically the core attributes to decide how good or bad the performance of the adsorption process will be. Fig 4.4 shows the structure of Maxorb III from scanning electron microscope with 3700 magnifications.


Figure 4.4: Maxorb III SEM picture [6]

### 4.2.2 Adsorbate selection

In choosing the best adsorbate to be used in this current cooling system, criteria such as environmental constraints (ODP, DWP), Operating temperature and Adsorption Isotherm will be the main targets analysed and used in the selection process. Among the many possible candidates available, only a few of those will be analysed in this current project and they are the following: R134a, R507a, R600 (N-Butane), Ethanol and R744 ($CO_2$ liquid).

#### 4.2.2.1 Adsorption Isotherms

The process of Adsorption is usually studied through graphs known as adsorption isotherms. These isotherms are graphical representations of the amount of adsorbate adsorbed onto the surface of the adsorbent against pressure at constant temperature. Among the various tools and equations that can be used to analyse an isotherm of an adsorbate on a specific adsorbent, this current paper will make use of the famous Dubinin-Astakhov equation.

***Dubinin-Astakhov equation***

The Dubinin's theory of volume filling of micro-pores is applied to the evaluation of adsorption isotherms to characterize the capillary structure of micro-porous carbonaceous solids. This theory is frequently represented by the Dubinin-Astakhov (DA) equation (without volume correction for this case):

$$q = q_{o}.\ Exp\ [-(A/E)^{n}]$$

(Motoyuki Suzuki. [10])

Where:

$q$- Adsorption uptake in Kg/Kg

$q_o$ – Maximum uptake in Kg/Kg

$A\ [RTln\ (P/P_o)]$ - is the differential molar work of adsorption

$E$ -is the characteristic energy

***Adsorption parameters (D-A)***

The following are the adsorption parameters for the adsorbates. The parameters have been taken from previous researches and studies concerning the adsorption process, where tables 4.4, 4.5, 4.6 and 4.7 present the parameters for the refrigerants R134a, R507a, R744 and R600 consecutively.

Table 4.4: Adsorption parameters for R134a [4]

| **R134A** | | | | |
|---|---|---|---|---|
| Molar mass(g/mol) | $q_o$(Kg/Kg) | $E$(KJ/Kg) | $n$ | $R$(KJ/Kg.K) |
| 102.3 | 2.002 | 82.9 | 1.3 | 0.0814 |

Table 4.5: Adsorption parameters for R507a [4]

| **R507a** | | | | |
|---|---|---|---|---|
| Molar mass(g/mol) | $q_o$(Kg/Kg) | $E$(KJ/Kg) | $n$ | $R$(KJ/Kg.K) |
| 98.86 | 1.222 | 58.04 | 1.47 | 0.0841 |

Table 4.6: Adsorption parameters for R744 [11]

| **R744($CO_2$)** | | | | |
|---|---|---|---|---|
| Molar mass(g/mol) | $q_o$(Kg/Kg) | $E$(KJ/Kg) | $n$ | $R$(KJ/Kg.K) |
| 44.01 | 1.815 | 94.52 | 1.18 | 0.1889 |

Table 4.7: Adsorption parameters for R600 [6]

| **R600** | | | | |
|---|---|---|---|---|
| Molar mass(g/mol) | $q_o$(Kg/Kg) | $E$(KJ/Kg) | $n$ | $R$(KJ/Kg.K) |
| 58.12 | 0.8 | 300 | 1.05 | 0.1431 |

*Isotherm Plots*

Having identified all the adsorption parameters in our adsorbent activated carbon, we will proceed with plotting the adsorption behaviour of each adsorbate. Each adsorbate behaviour will be analysed under different temperatures not exceeding the adsorbate critical temperature.

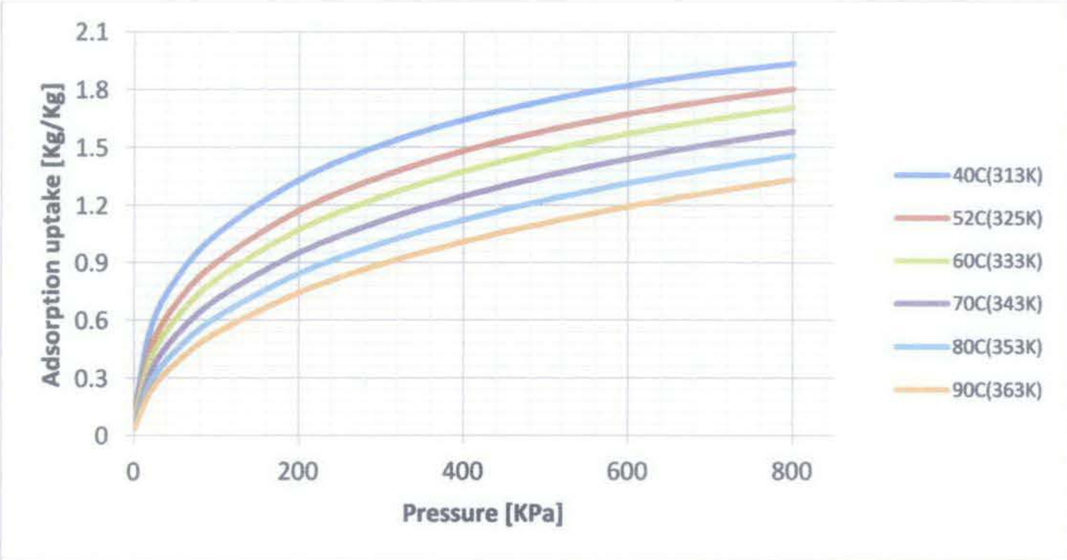


Figure 4.5: R134a adsorption isotherm

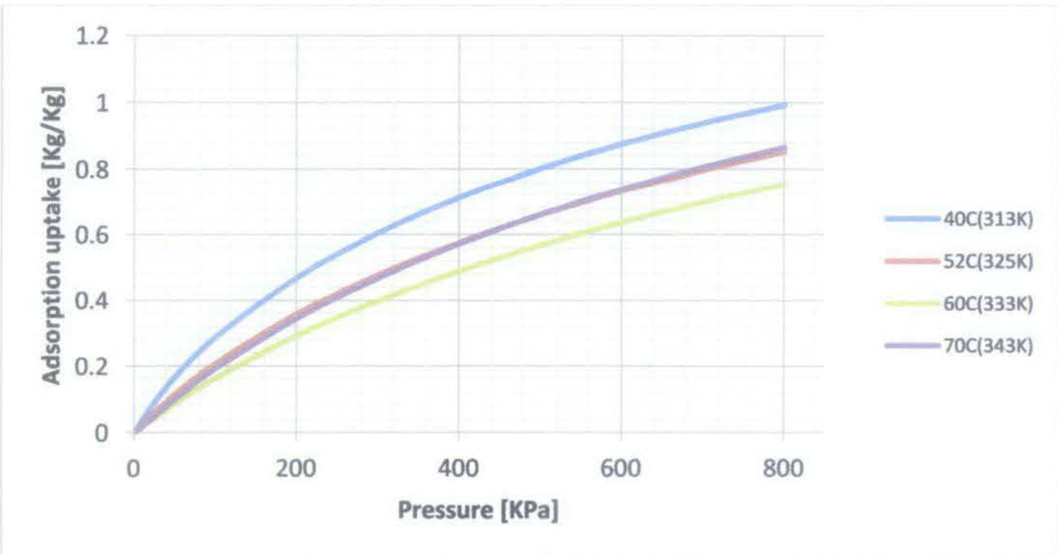


Figure 4.6: R507a adsorption isotherm

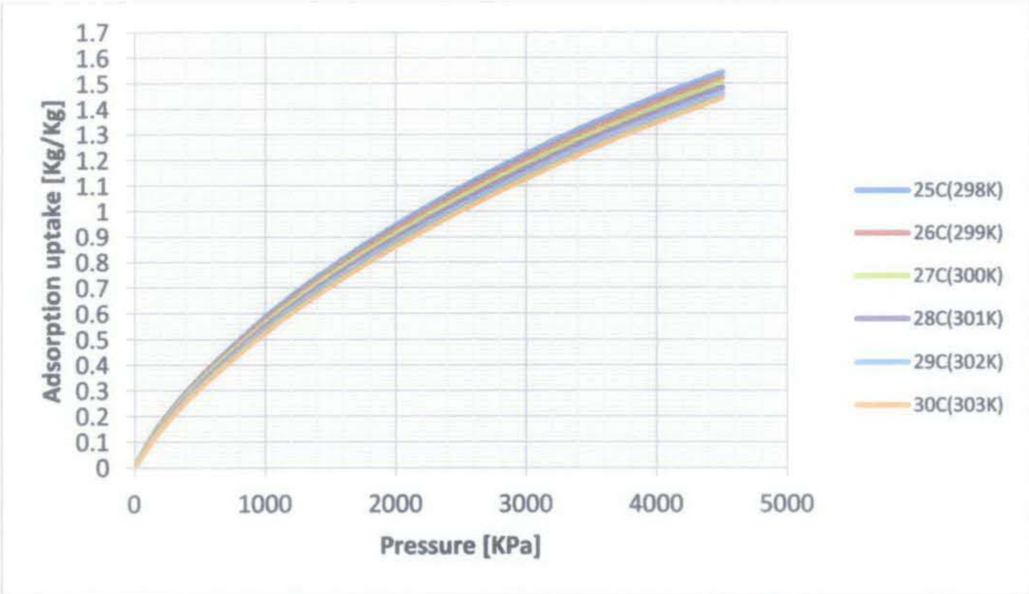


Figure 4.7: R744 adsorption isotherm

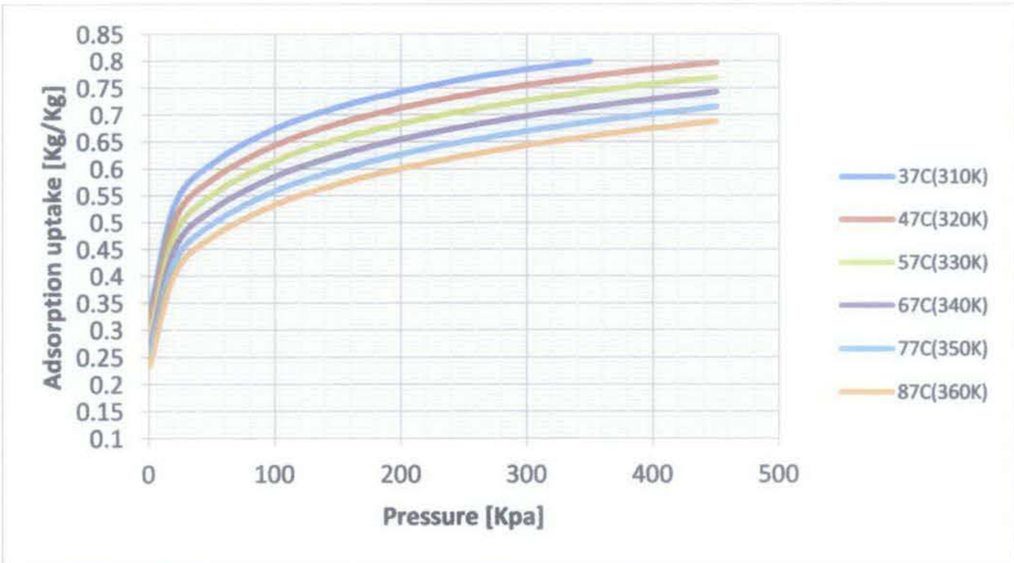


Figure 4.8: R600 adsorption isotherm

Fig 4.5 shows the adsorption behaviour of refrigerant R134a under different temperatures ranging from 313K to 363K, followed by fig 4.6 which represents the adsorption behaviour for refrigerant 507a, fig 4.7 and 4.8 shows the adsorption behaviour of refrigerants R744 and R600 consecutively. One thing common about the behaviour of each one of these components is that the adsorption uptake decreases with the increment of temperature; the increment of temperature is not the same for all components due to the fact that each of them has a critical temperature and the testing temperature must fall behind the critical value. The refrigerant R134a registered the highest uptake among the rest with a value of 1.9355 [Kg/Kg], followed by R744 with 1.5450 [Kg/Kg], R507a with 0.9940 [Kg/Kg] and last but not least R600 with 0.7999 [Kg/Kg]. As stated before the higher the uptake value the more favourable it is for the system, but since our system will be heat driven we can spot some problems with some of the refrigerants such as R507a and R744 which due to their critical temperatures that are very low. R134a and R600 in other hand do not present this limitation giving the two of them this big advantage over the other two refrigerants.

#### 4.2.2.2 Environmental constraints

This is another important point to be taken into account in the selection of adsorbates (refrigerants) to be used because one of the objectives of this project is to produce an environmental friendly cooling system. One of the major issues when it comes to using refrigerants for refrigeration purposes is the Ozone depletion potential and Global warming potential which tells how good a specific refrigerant is to the environment. Table 4.8 shows the values of ODP (Ozone depletion potential) and GWP (Global warming potential) for each refrigerant:

Table 4.8: GWP & ODP for different refrigerants [12]

| Refrigerants | GWP | ODP |
|---|---|---|
| R134a | 1300 | 0 |
| R744 | 1 | N/A |
| R507a | 3300 | 0 |
| R600 | 4 | 0 |

From the table 4.8 it can be seen that concerning the environmental point of view the refrigerant R134A and R507a totally fail for having a very high value of global warming potential. The other two refrigerants present acceptable values for both GWP and ODP, but since only the refrigerant R600 comply with this and the previous criteria, it is the choice to be used for this current refrigeration system. In this way the finalized pair will be of Activated carbon and R600 (N-butane).

## 4.3 Adsorption analysis on the finalized pair

### 4.3.1 Isosteric heat of adsorption

The isosteric heat is one of the thermodynamic properties that are of special relevance and importance when designing an adsorption system (Gas phase). The Clausius-Clapeyron equation, also known as the "van't Hoff" equation will be used to estimate the magnitude of this heat. The equation is expressed as:

$$Q_{st} = -R \frac{\partial lnP}{\partial(\frac{1}{T})}$$

(Cary T. Chiou. [13])

Where: $Q_{st}$ – Isosteric heat of adsorption

$R$ – Gas constant

$P$- Pressure at constant loading

$T$- Temperature at constant loading

Table 4.9 are the parameters found concerning the Pressure and temperature variation and other relevant variables needed for calculation of isosteric heat of adsorption:

Table 4.9: Isosteric heat data for R600

| *T(K)* | *P(KPa)* | *LnP* | *1/T* |
|---|---|---|---|
| 298 | 245.66 | 5.5039 | 0.00336 |
| 308 | 331.32 | 5.8031 | 0.00325 |
| 318 | 437.56 | 6.0812 | 0.00314 |
| 328 | 567.20 | 6.3407 | 0.00305 |
| 338 | 723.44 | 6.5840 | 0.00296 |
| 348 | 909.36 | 6.8127 | 0.00287 |
| 358 | 1128.20 | 7.0284 | 0.00279 |

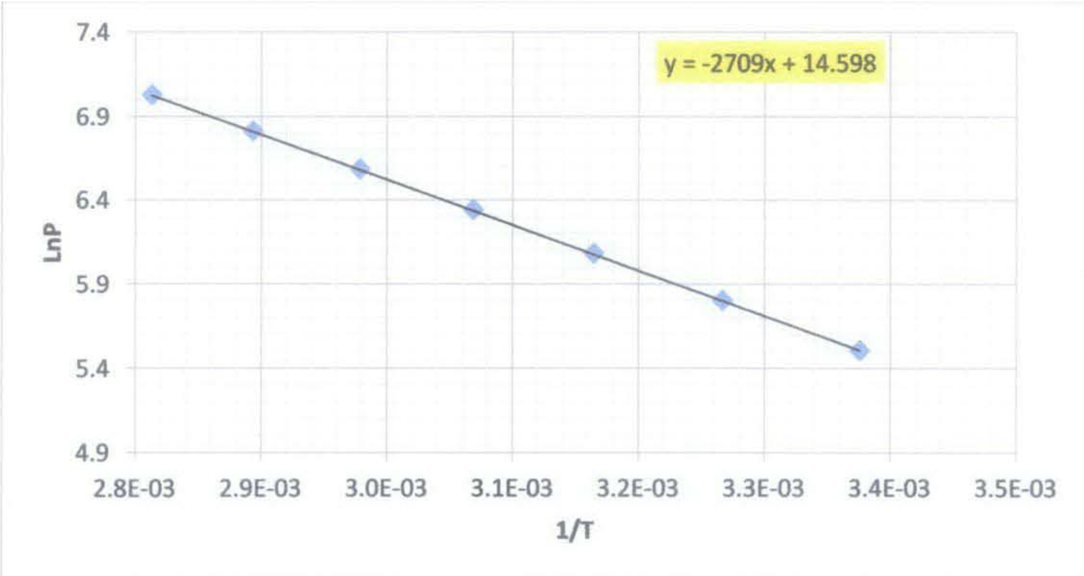


Figure 4.9: Pressure and temperature relation

From fig 4.9 the Isosteric heat of adsorption can be calculated by using the following equation:

$$Q_{st} / R = Slope$$

The Gas constant is known as well as the slope of the plot, and the values are 0.1431 and -2709.2 consecutively. The Isosteric heat of adsorption value is found to be equal to 387.66 KJ/Kg.

### 4.3.2 Ideal refrigeration Cycle

In this section we will analyse the performance of our system by calculating the theoretical COP and Specific Cooling Effect. Fig 4.10 represents the isotherms for different temperatures of N-butane on activated carbon (Maxorb III), and the arrows represent the ideal cycle in which we set the system to operate. The adsorption system will operate within temperatures of 298 Kelvin ($25^0$C) and 358 Kelvin ($85^0$C), and the condenser temperatures will be respectively 302.4 Kelvin ($29.4^0$C) and 298 Kelvin ($25^0$C), with evaporator temperature equal to 279.7 Kelvin ($6.7^0$C).

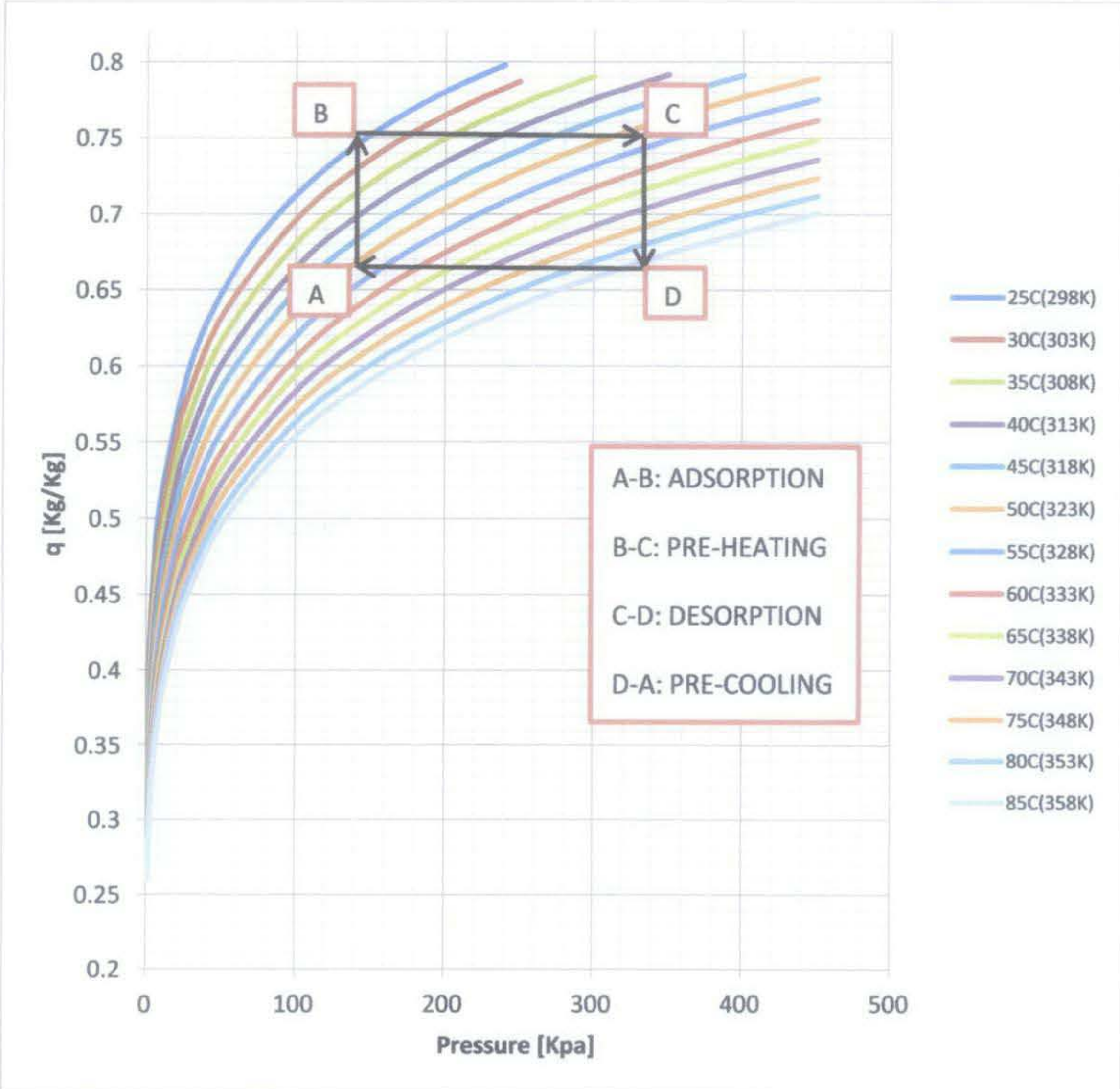


Figure 4.10: Ideal Cycle for N-butane in Maxorb III

***From fig 4.10:***

- $T_{e,d} = 358$ K
- $T_{s,d} = 323$ K
- $T_{e,a} = 298$ K
- $T_{s,a} = 323$ K
- $q_{max} = 0.750$ Kg/Kg
- $q_{min} = 0.665$ Kg/Kg
- $Q_{st} = 387.66$ KJ/Kg (Previously Calculated)
- $T_{cond} = 302.4$ K
- $T_{ev} = 279.7$ K

The *COP* of the system is defined by the specific cooling effect over the heat added to the system:

$$COP = SCE/Q_h$$

$$Q_h = Q_{adb} + Q_{ref}$$

$$Q_{adb} = \int_{Te,a}^{Te,d} Cp,adb\ dT$$

$$Q_{ref} = q_{max}\int_{Te,a}^{Ts,d} qCp,ref\ dT + \int_{Ts,d}^{Te,d} qCp,ref\ dT + \int_{qmin}^{qmax} Qst\ dq$$

$$SCE = (q_{max}-q_{min})[h_{fg} - \int_{Te}^{Tc} Cp,ref\ dT\ ]$$

(B.B. Saha et al [14])

Correlation to calculate $C_p$ of N-butane at any temperature ranging from 250 – 1100 Kelvin

$$C_p = 3.96 + 0.3715T - 18.34 \times 10^{-5}\ T^2 + 35 \times 10^{-9}\ T^3$$

(Yununs A.C, Michael A. B. [15])

***Heat added to the adsorbent ($Q_h$)***

$C_p$ for activated carbon (Maxorb III) = 930 J/Kg.K

$Q_{adb} = \int_{298}^{358} 930\, dT = 930\ (358 - 298) = 55.80\ KJ/Kg$

***Heat added to the refrigerant ($Q_{ref}$)***

$C_p$ for N-butane was calculated by using the correlation formula above stated, and the values are the following:

- At 328 Kelvin $C_p$ is equal 1.824 KJ/Kg.K
- At 358 Kelvin $C_p$ is equal 1.980 KJ/Kg.K

$Q_{ref} = q_{max} \int_{Te,a}^{Ts,d} qCp,ref\ dT + \int_{Ts,d}^{Te,d} qCp,ref\ dT + \int_{qmin}^{qmax} Qst\ dq$

$Q_{ref} = 0.750\text{x} \int_{298}^{323} 0.750x1.824\ dT + \int_{323}^{358} 0.665x1.980\ dT + \int_{0.620}^{0.706} 387.66dq$

$Q_{ref} = (25.65 + 46.08.01 + 32.95)\ KJ/Kg$

$Q_{ref} = 104.68\ KJ/Kg$

$Q_h = Q_{ref} + Q_{adb}$

$Q_h = 104.68\ KJ/Kg + 55.80\ KJ/Kg$

$Q_h = 160.48\ KJ/Kg$

#### 4.3.2.1 Specific cooling effect and COP

Table 4.10: Adsorption ideal cycle parameters (Tcondenser at 302.4 K)

| $Q_{st}$(KJ/Kg) | $T_{e,a}$(K) | $T_{s,d}$(K) | $T_c$(K) | $T_e$(K) | $h_{fg}$ @ cooling $24^0$C(KJ/Kg.K) |
|---|---|---|---|---|---|
| 387.66 | 298 | 323 | 302.4 | 279.7 | 363.64 |

Table 4.11: SCE & COP at condenser temperature 302.4 K

| $T_{e,d}$ (K) | $q_{max}$ (Kg/Kg) | $q_{min}$ (Kg/Kg) | $\Delta q$ (Kg/Kg) | $C_p$ (KJ/Kg.K) | SCE (KJ/Kg) | $Q_{adb}$ (KJ/Kg) | $Q_{ref}$ (KJ/Kg) | $Q_h$ (KJ/Kg) | COP |
|---|---|---|---|---|---|---|---|---|---|
| 328 | 0.750 | 0.740 | 0.010 | 1.846 | 3.2 | 27.90 | 36.36 | 64.26 | 0.0501 |
| 333 | 0.750 | 0.725 | 0.025 | 1.869 | 8.0 | 32.55 | 48.89 | 81.44 | 0.0986 |
| 338 | 0.750 | 0.710 | 0.040 | 1.891 | 12.8 | 37.20 | 61.30 | 98.50 | 0.1302 |
| 343 | 0.750 | 0.696 | 0.054 | 1.914 | 17.3 | 41.85 | 73.22 | 115.07 | 0.1503 |
| 348 | 0.750 | 0.685 | 0.065 | 1.936 | 20.8 | 46.50 | 84.00 | 130.50 | 0.1592 |
| 353 | 0.750 | 0.675 | 0.075 | 1.958 | 23.9 | 51.15 | 94.37 | 145.52 | 0.1645 |
| 358 | 0.750 | 0.667 | 0.083 | 1.980 | 26.5 | 55.80 | 104.04 | 159.84 | 0.1655 |

Table 4.12: Adsorption ideal cycle parameters (Tcondenser at 298 K)

| $Q_{st}$(KJ/Kg) | $T_{e,a}$(K) | $T_{s,d}$(K) | $T_c$(K) | $T_e$(K) | $h_{fg}$ @ cooling $24^0$C(KJ/Kg.K) |
|---|---|---|---|---|---|
| 387.66 | 298 | 323 | 298 | 279.7 | 363.64 |

Table 4.13: SCE and COP at condenser temperature 298 K

| $T_{e,d}$ (K) | $q_{max}$ (Kg/Kg) | $q_{min}$ (Kg/Kg) | $\Delta q$ (Kg/Kg) | $C_p$ (KJ/Kg.K) | SCE (KJ/Kg) | $Q_{adb}$ (KJ/Kg) | $Q_{ref}$ (KJ/Kg) | $Q_h$ (KJ/Kg) | COP |
|---|---|---|---|---|---|---|---|---|---|
| 328 | 0.750 | 0.740 | 0.010 | 1.846 | 3.3 | 27.90 | 36.36 | 64.26 | 0.0513 |
| 333 | 0.750 | 0.725 | 0.025 | 1.869 | 8.2 | 32.55 | 48.89 | 81.44 | 0.1011 |
| 338 | 0.750 | 0.710 | 0.040 | 1.891 | 13.2 | 37.20 | 61.30 | 98.50 | 0.1336 |
| 343 | 0.750 | 0.696 | 0.054 | 1.914 | 17.7 | 41.85 | 73.22 | 115.07 | 0.1542 |
| 348 | 0.750 | 0.685 | 0.065 | 1.936 | 21.3 | 46.50 | 84.00 | 130.50 | 0.1635 |
| 353 | 0.750 | 0.675 | 0.075 | 1.958 | 24.6 | 51.15 | 94.37 | 145.52 | 0.1690 |
| 358 | 0.750 | 0.667 | 0.083 | 1.980 | 27.2 | 55.80 | 104.04 | 159.84 | 0.1700 |

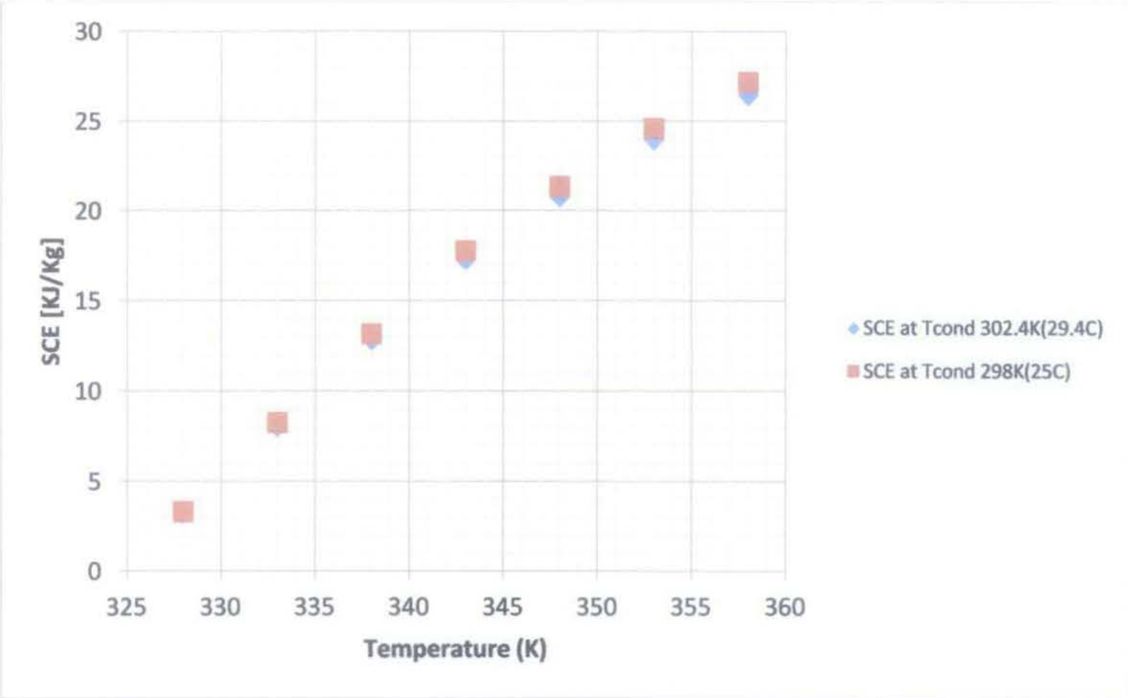


Figure 4.11: SCE and temperature relation

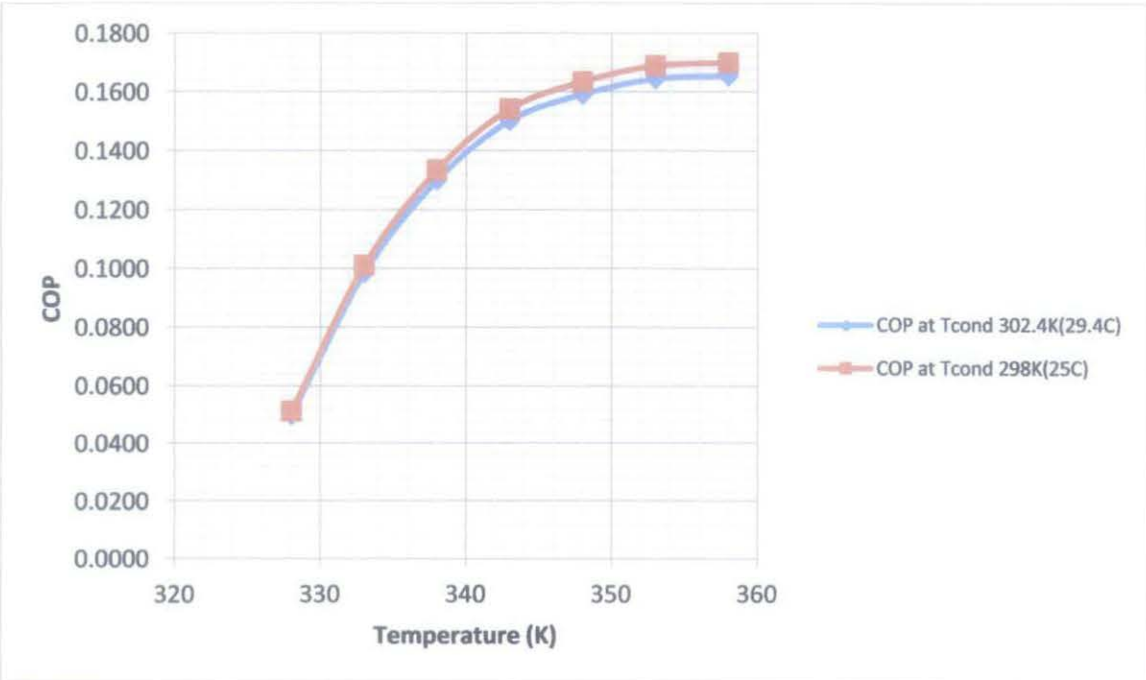


Figure 4.12: COP and temperature relation

Figure 4.11 shows the behaviour of SCE as the condenser temperature changes. Two condenser temperatures were used and the results show that it was moved from the first temperature (302.4K) to the second (298K) the SCE increases considerably. In conclusion these results show that even better results can be found if the condenser temperature decreases even further. From the results it can be seen that the SCE value goes up to 27 KJ/Kg. Figure 4.12 shows the behaviour of COP with respect to condenser temperature change once again, and the same could be observed that the lower the condenser temperature the higher is the COP, but up to a certain value which COP stops increasing. This value where the COP stops increasing with regeneration temperature is called optimum COP and based on our results is 0.1645 at 353 K for condenser temperature equal to 302.4K and 0.169 at 353K for condenser temperature equal to 298K.

## 4.4 Solar analysis

The current adsorption cooling system is to be powered by solar energy as it operates under Malaysian climate, Kuala Lumpur city. Malaysia has a favourable weather condition when it comes to implementation of solar technology as most of the days throughout the year are blessed with unlimited sunshine and solar radiation, reason why the country's average daily temperature can reach even up to $32^{o}$ C in most of the months. Malaysia has an average monthly radiation ranging from 4000-8000 $Wh/m^2$ with an average daily sunshine duration from 10 hours to 13.5 hours. [16]

The solar adsorption cooling system is intended to use a solar thermal system (heating system) that can provide heat through hot water at temperature of 85 $^{0}$ C ($358^{0}$ K). Thus in this section the feasibility of this project will be tested by means of a simulation under the Malaysian weather conditions. The simulation software used to conduct this simulation was TRNSYS SIMULATION STUDIO, where a basic solar thermal system using theoretical flat plate collector was set and analysed for a time corresponding of one year.

### 4.4.1 Simulation results

Based on the simulation results from TRNSYS SIMULATION STUDIO of the intended solar thermal system to be placed under Malaysian weather conditions, the results show that in terms of delivering the water at the required temperature for our designed adsorption system ($85^0$ C), should be no problem due to the fact that Malaysia has rich days of available solar energy throughout the entire year. The simulations were done for each and every month and can be noticed that the average yearly water temperature delivered to the thermal storage is about $90^0$ C, which is even above the requirement of $85^0$ C for the adsorption cooling.

# CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

The design of this current solar adsorption cooling systems was comprised in three stages which are: House cooling load calculation, Adsorption design and solar analysis. The system was successfully designed as it took into account several aspects from the model house cooling load requirements to the solar energy available in the selected country intended to install this system. The total cooling load for the house was found to be 6.03 KW, and for the cooling system, the specific cooling effect a maximum value of about 27 KJ/Kg which can handle the load requirements with no problems, and the COP of this refrigeration system presents an optimum value of 0.169 (at condenser temperature 298K). Having proved that the designed adsorption system can handle the model house cooling load, the last step was to determine the feasibility of powering this system with heat coming from the sun. The adsorption system required a water temperature at $85^0$ C (for desorption process) to be powered which was once again well matched with the Malaysian available solar energy throughout the entire months of a year. However, as this simulation and calculations are based on the ideal cycle operation of the system, not all the data and figures may reflect a full accuracy as a transient system would.

## 5.2 Recommendations

In order to obtain more accurate results, a full simulation should be done on the transient system and not only ideal which lacks many important points as assumptions have to be considered. A transient system would not only show the performance of the adsorption system but also the detailed information of the adsorption process such as cycle time and switching time.

Another important point is the fact that this system could also be tested and designed for bigger houses such as double storey or even buildings so wider applications on the adsorption cooling could be available.

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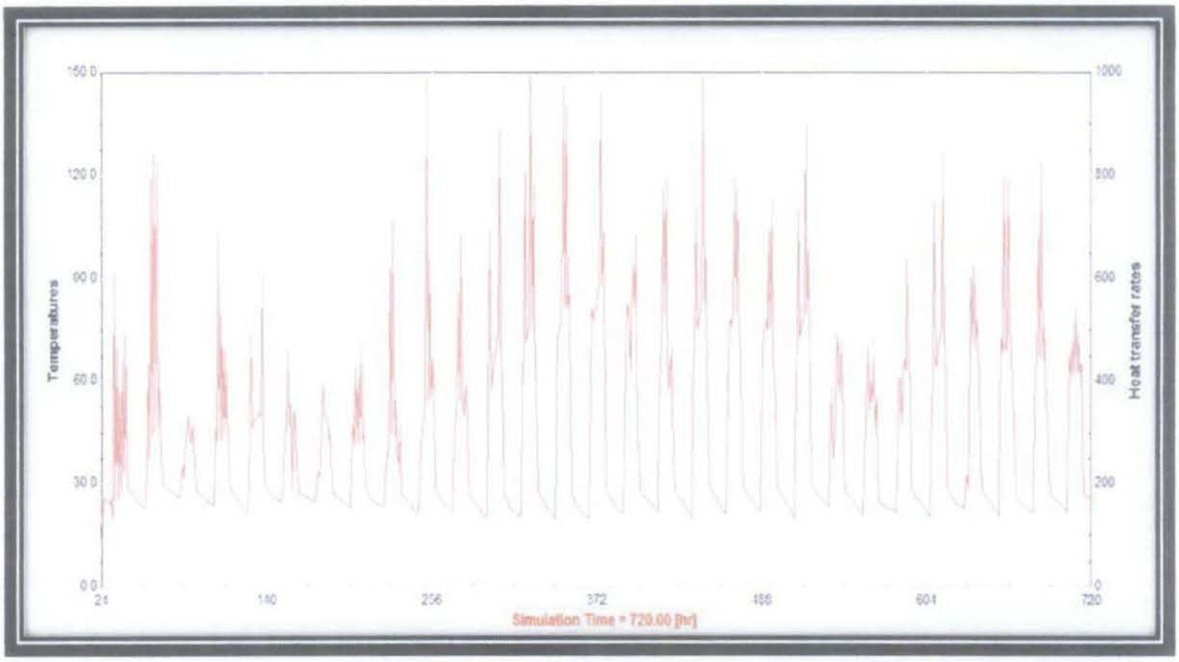
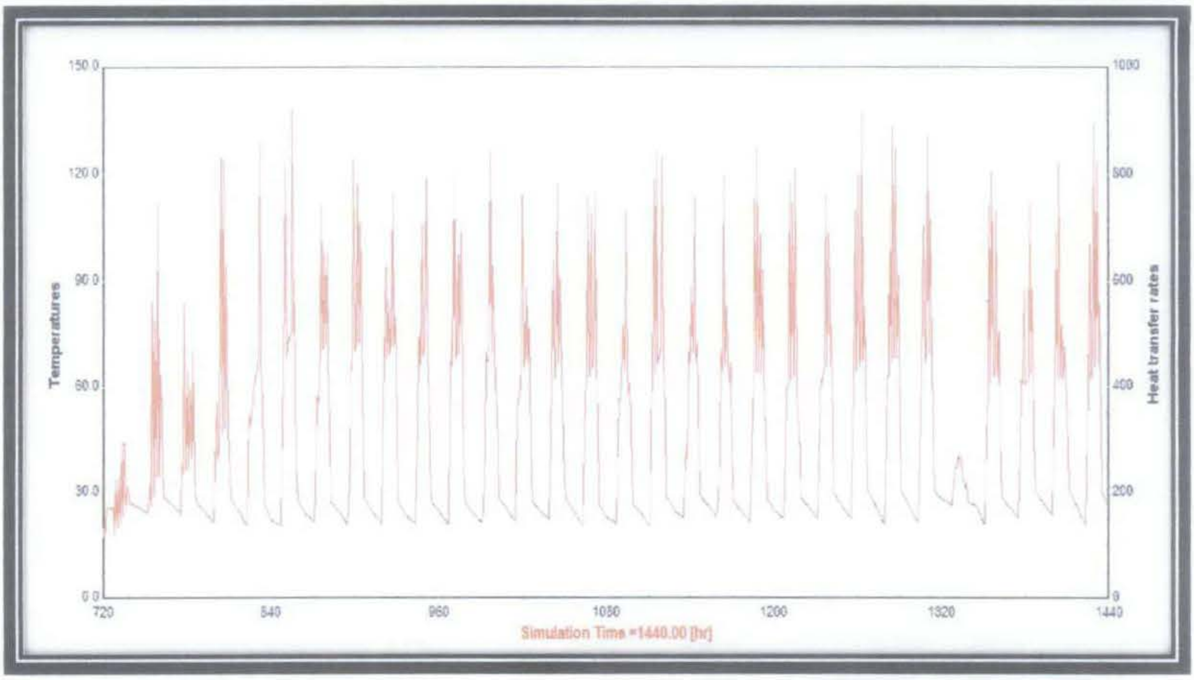
# APPENDICES

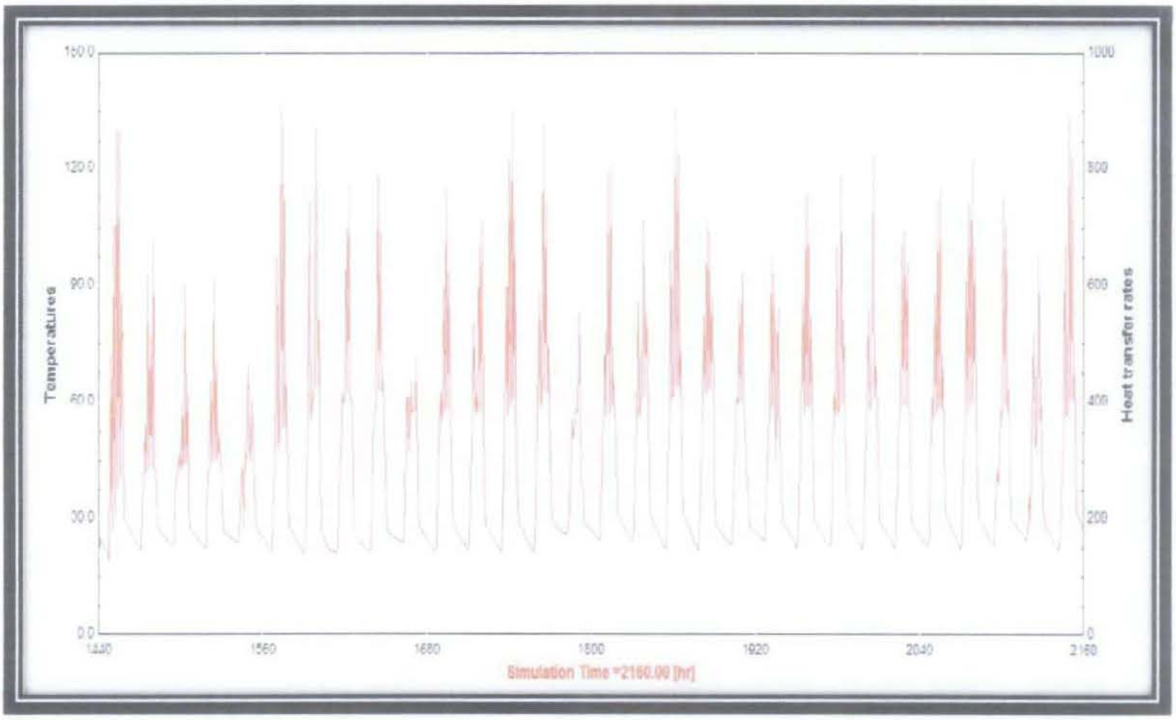
# Appendix A: TRNSYS SOLAR SIMULATION RESULTS



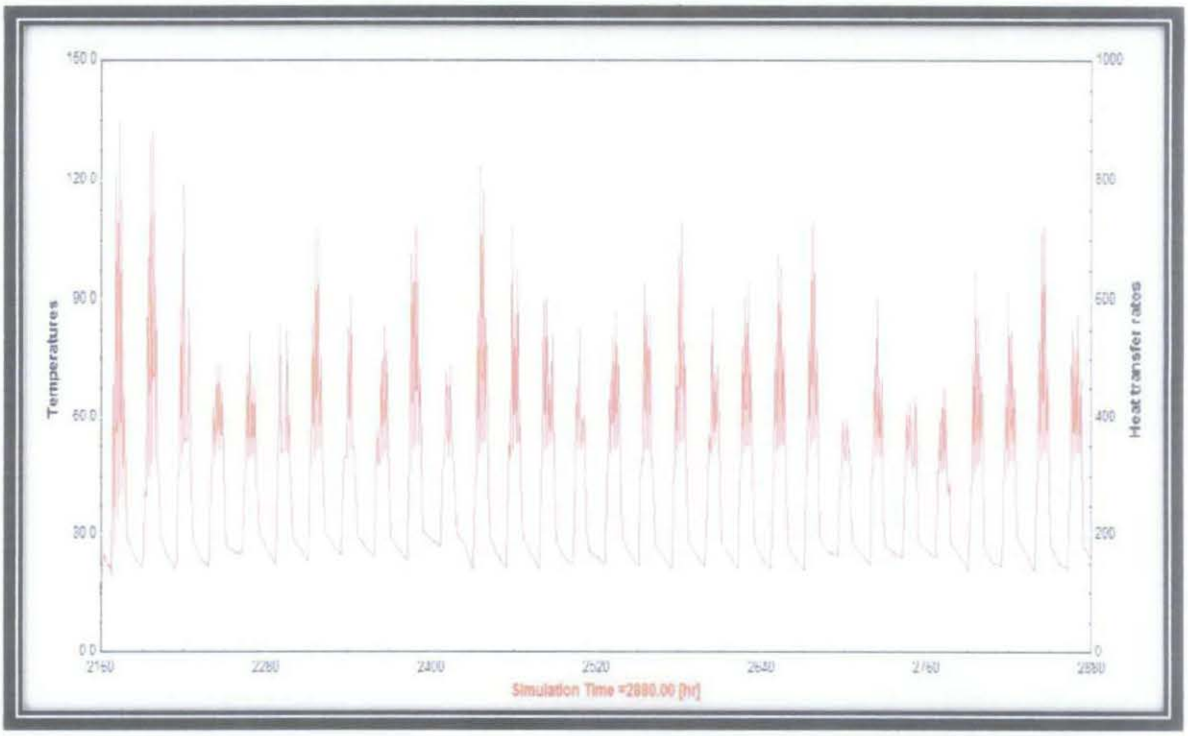

Appendix A-1: Water temperature from solar collector (January)



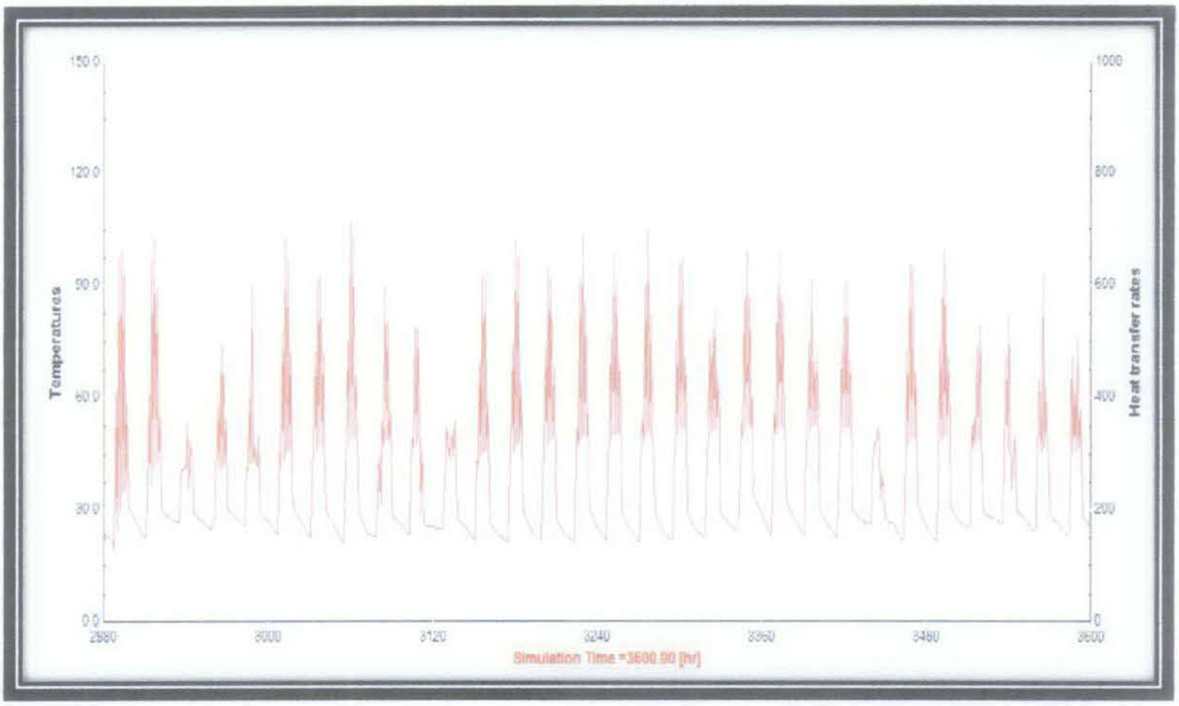

Appendix A-2: Water temperature from solar collector (February)



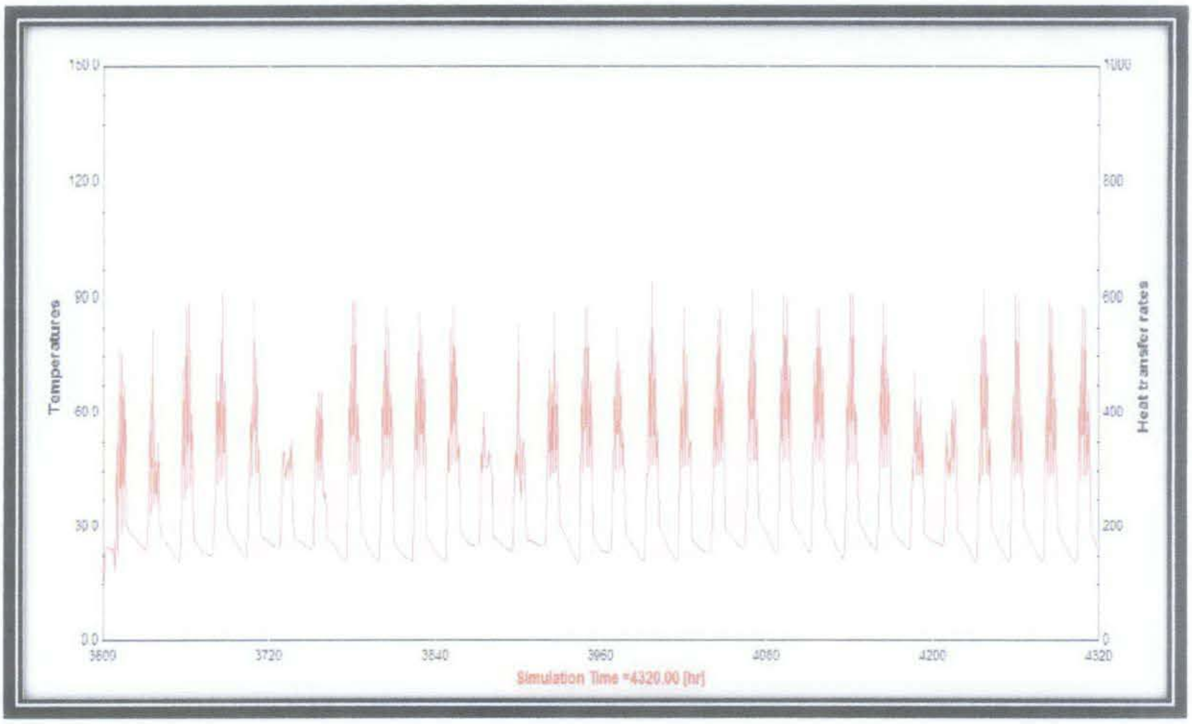

Appendix A-3: Water temperature from solar collector (March)



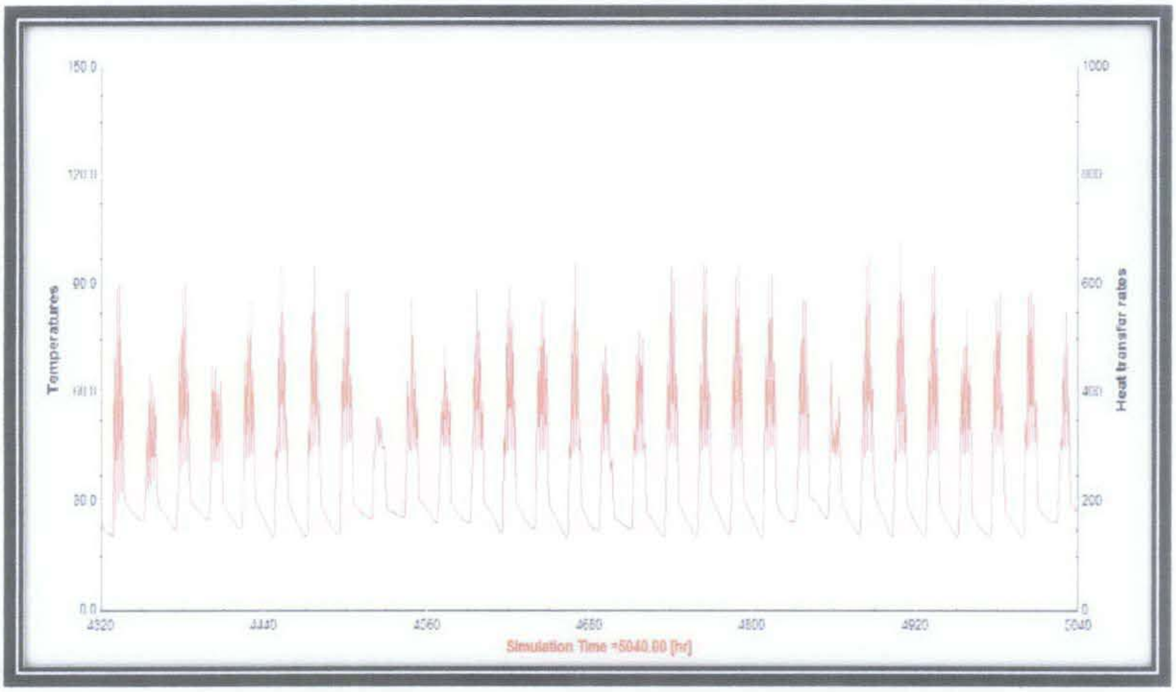

Appendix A-4: Water temperature from solar collector (April)



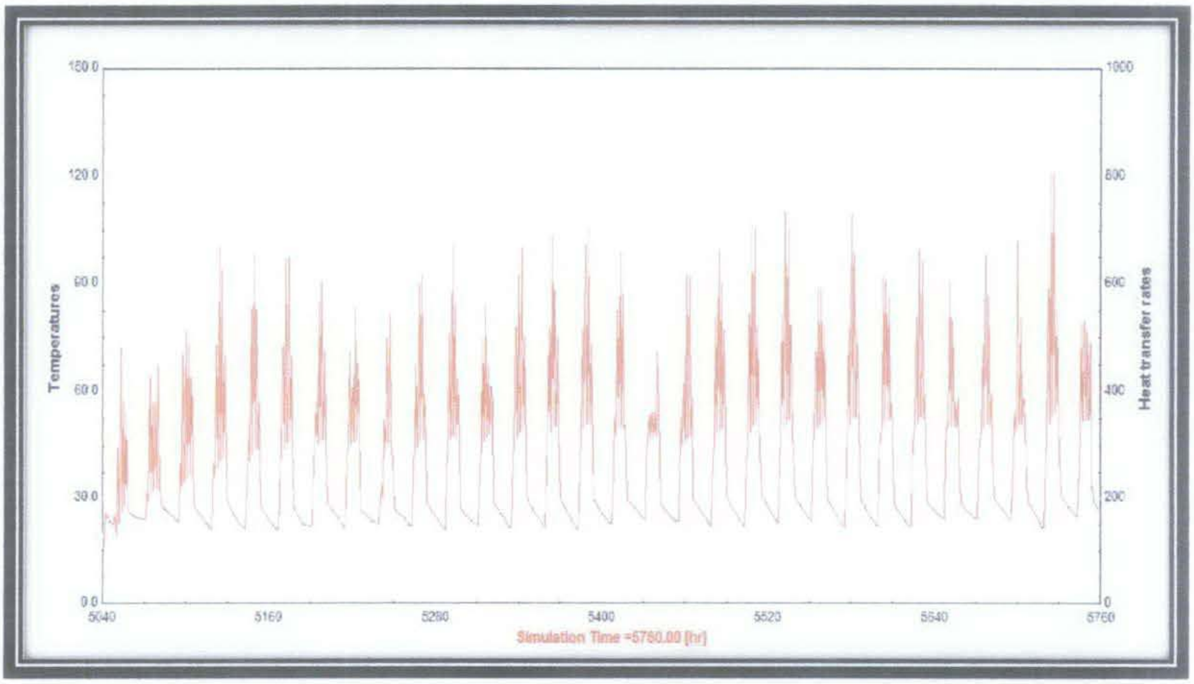

Appendix A-5: Water temperature from solar collector (May)



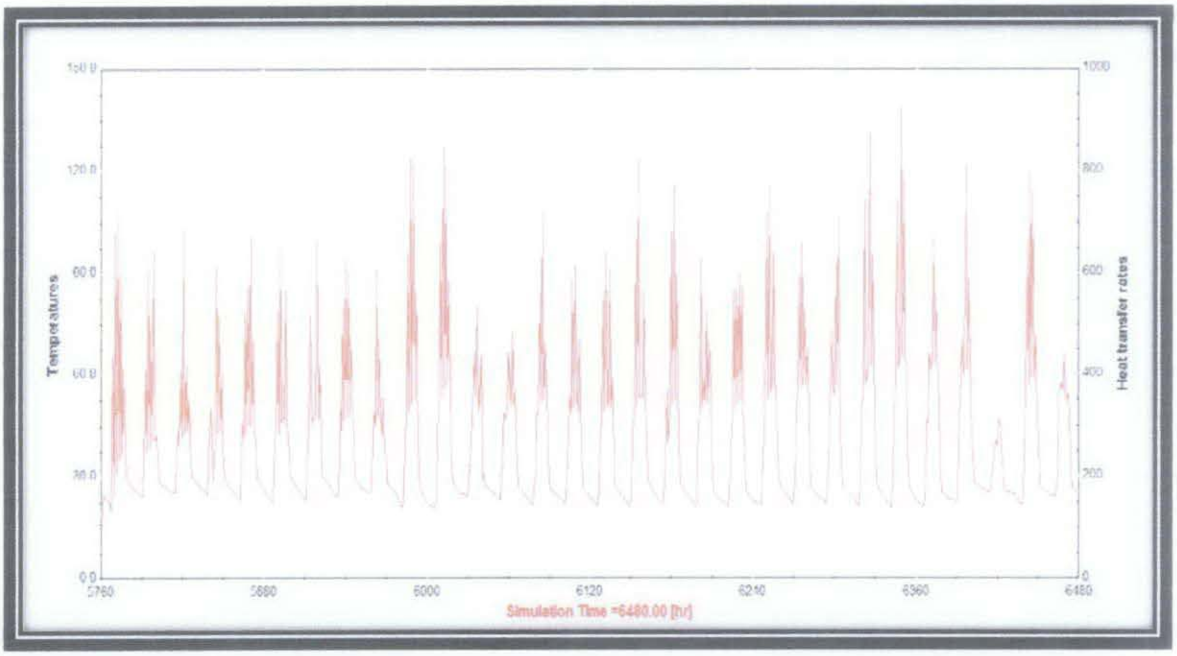

Appendix A-6: Water temperature from solar collector (June)



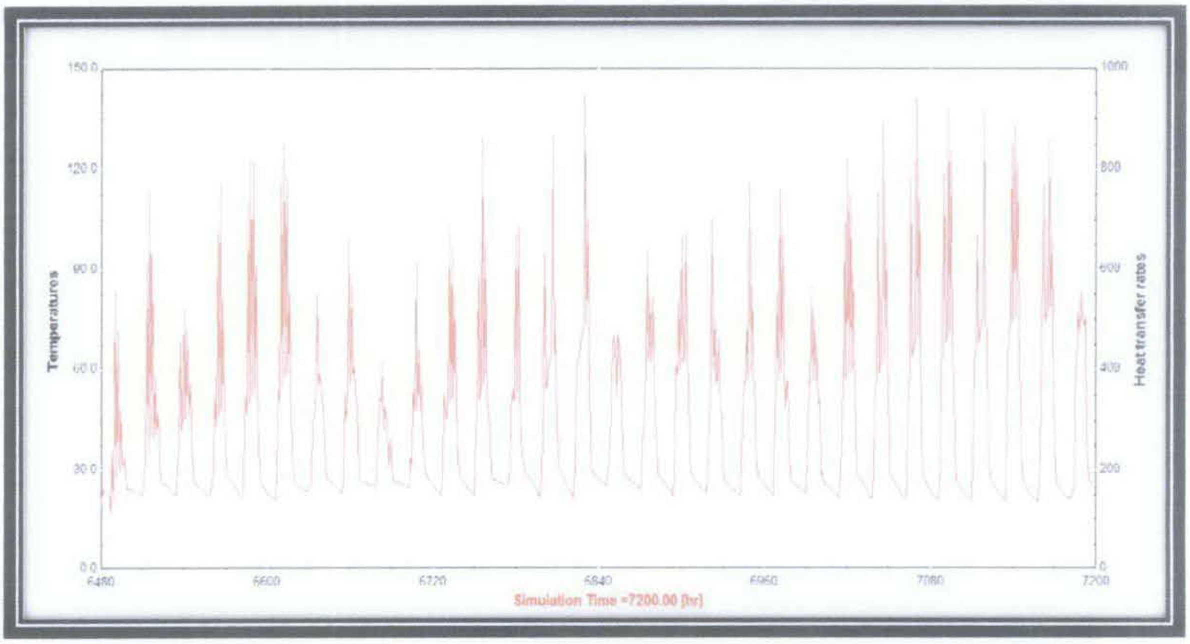

Appendix A-7: Water temperature from solar collector (July)



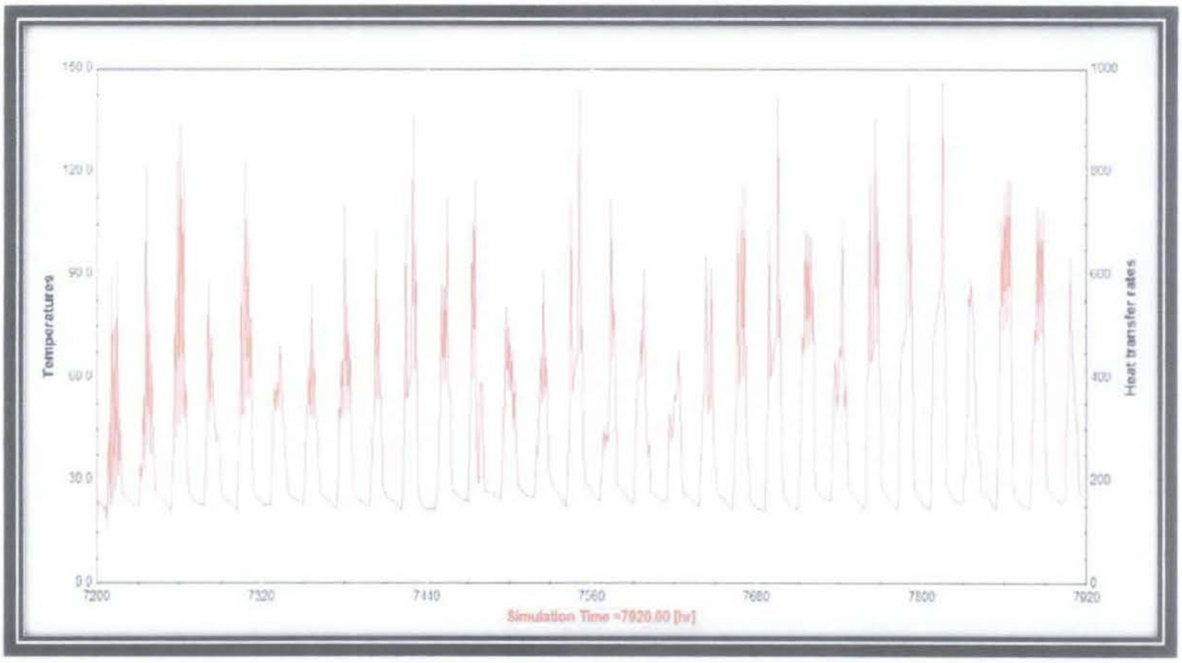

Appendix A-8: Water temperature from solar collector (August)



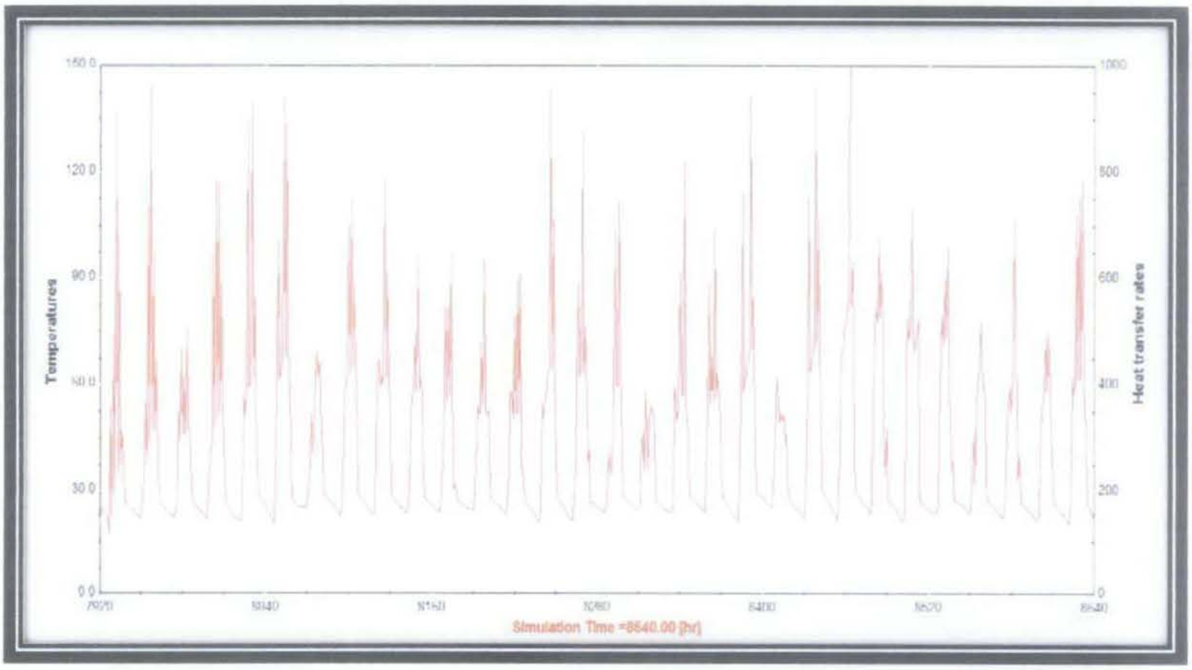

Appendix A-9: Water temperature from solar collector (September)




Appendix A-10: Water temperature from solar collector (October)




Appendix A-11: Water temperature from solar collector (November)




Appendix A-12: Water temperature from solar collector (December)

# Appendix B: HEAT TRANSFER COEFFICIENTS

| | Building Element | Heat-Transfer Coefficient (Btu/hr ft$^2$ $^oF$) | (W/m$^2$K) |
|---|---|---|---|
| Doors | Single sheet - metal | 1.2 | 6.8 |
| | 1 inch - wood | 0.65 | 3.7 |
| | 2 inches - wood | 0.45 | 2.6 |
| Roofing | Corrugated metal - uninsulated | 1.5 | 8.5 |
| | 1 inch wood - uninsulated | 0.5 | 2.8 |
| | 2 inches wood - un-insulated | 0.3 | 1.7 |
| | 1 inch wood - 1 inch insulation | 0.2 | 1.1 |
| | 2 inch wood - 1 inch insulation | 0.15 | 0.9 |
| | 2 inches - concrete slab | 0.3 | 1.7 |
| | 2 inches - concrete slab - 1 inch insulation | 0.15 | 0.9 |
| Windows | Vertical single glazed window in metal frame | | 5.8 |
| | Vertical single glazed window in wooden frame | | 4.7 |
| | Vertical double glazed window, distance between glasses 30 - 60 mm | | 2.8 |
| | Vertical tripple glazed window, distance between glasses 30 - 60 mm | | 1.85 |
| | Vertical sealed double glazed window, distance between glasses 20 mm | | 3.0 |
| | Vertical sealed triple glazed window, distance between glasses 20 mm | | 1.9 |
| | Vertical sealed double glazed window with "Low-E" coatings | 0.32 | 1.8 |
| | Vertical double glazed window with "Low-E" coatings and heavy gas filling | 0.27 | 1.5 |
| | Vertical double glazed window with 3 plastic films ("Low-E" coated) and heavy gas filling | 0.06 | 0.35 |
| | Horizontal single glass | 1.4 | 7.9 |
| Walls | 8 inches - poured concrete 80 lb/ft$^3$ | 1.5 | 8.9 |
| | 12 inches - poured concrete 80 lb/ft$^3$ | 1.1 | 5.9 |

Appendix B-1: Heat transfer coefficients

# Appendix C: CLTD AND GLF VALUES

## CLTD Values for Single-Family Detached Residences

| Daily Temperature Range[b] | Design Temperature, °C | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 29 | | 32 | | | 35 | | | 38 | | 41 | 43 |
| | L | M | L | M | H | L | M | H | M | H | M | H |
| *All walls and doors* | | | | | | | | | | | | |
| North | 4 | 2 | 7 | 4 | 2 | 10 | 7 | 4 | 10 | 7 | 10 | 13 |
| NE and NW | 8 | 5 | 11 | 8 | 5 | 13 | 11 | 8 | 13 | 11 | 13 | 16 |
| East and West | 10 | 7 | 13 | 10 | 7 | 16 | 13 | 10 | 16 | 13 | 16 | 18 |
| SE and SW | 9 | 6 | 12 | 9 | 6 | 14 | 12 | 9 | 14 | 12 | 14 | 17 |
| South | 6 | 3 | 9 | 6 | 3 | 12 | 9 | 6 | 12 | 9 | 12 | 14 |
| *Roofs and ceilings* | | | | | | | | | | | | |
| Attic or flat built-up | 23 | 21 | 26 | 23 | 21 | 28 | 26 | 23 | 28 | 26 | 28 | 31 |
| *Floors and ceilings* | | | | | | | | | | | | |
| Under conditioned space, over unconditioned room, or over crawl space | 5 | 2 | 7 | 5 | 2 | 8 | 7 | 5 | 8 | 7 | 8 | 11 |
| *Partitions* | | | | | | | | | | | | |
| Inside or shaded | 5 | 2 | 7 | 5 | 2 | 8 | 7 | 5 | 8 | 7 | 8 | 11 |

[a] Cooling load temperature differences (CLTDs) for single-family detached houses, duplexes, or multifamily, with both east and west exposed walls or only north and south exposed walls, K.

[b] L denotes low daily range, less than 9 K; M denotes medium daily range, 9 to 14 K; and H denotes high daily range, greater than 14 K.

Appendix C-1: CLTD values for single-family detached residences [5]

| Description of construction | Weight, lb/ft² | U-value, Btu/h·ft²·F | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 | Hours of maximum (CLTD) | Minimum (CLTD) | Maximum (CLTD) | Difference in CLTD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | Solar time, h | | | | | | | | | | | | | |
| **Without suspended ceiling** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 2.5-in. wood with 2-in. insulation | 13 | 0.093 | 30 | 26 | 23 | 19 | 16 | 13 | 10 | 9 | 8 | 9 | 13 | 17 | 23 | 29 | 36 | 41 | 46 | 49 | 51 | 50 | 47 | 43 | 39 | 35 | 19 | 8 | 51 | 43 |
| 4-in. wood with 2-in. insulation | 18 | 0.078 | 38 | 36 | 33 | 30 | 28 | 25 | 22 | 20 | 18 | 17 | 16 | 17 | 18 | 21 | 24 | 28 | 32 | 36 | 39 | 41 | 43 | 43 | 42 | 40 | 22 | 16 | 43 | 27 |
| **With suspended ceiling** | | | | | | | | | | | | | | | | | | | | | | | | | | | | | | |
| 1-in. wood with 2-in. insulation | 10 | 0.083 | 25 | 20 | 16 | 13 | 10 | 7 | 5 | 5 | 7 | 12 | 18 | 25 | 33 | 41 | 48 | 53 | 57 | 57 | 56 | 52 | 46 | 40 | 34 | 29 | 18 | 5 | 57 | 52 |
| 2.5-in. wood with 1-in. insulation | 15 | 0.096 | 34 | 31 | 29 | 26 | 23 | 21 | 18 | 16 | 15 | 15 | 16 | 18 | 21 | 25 | 30 | 34 | 38 | 41 | 43 | 44 | 44 | 42 | 40 | 37 | 21 | 15 | 44 | 29 |
| 8-in. lightweight concrete | 33 | 0.093 | 39 | 36 | 33 | 29 | 26 | 23 | 20 | 18 | 15 | 14 | 14 | 15 | 17 | 20 | 25 | 29 | 34 | 38 | 42 | 45 | 46 | 45 | 44 | 42 | 21 | 14 | 46 | 32 |
| 4-in. heavyweight concrete with 2-in. insulation | 53 | 0.090 | 30 | 29 | 27 | 26 | 24 | 22 | 21 | 20 | 20 | 21 | 22 | 24 | 27 | 29 | 32 | 34 | 36 | 38 | 38 | 38 | 37 | 36 | 34 | 33 | 19 | 20 | 38 | 18 |
| 2.5-in. wood with 2-in. insulation | 15 | 0.072 | 35 | 33 | 30 | 28 | 26 | 24 | 22 | 20 | 18 | 18 | 18 | 20 | 22 | 25 | 28 | 32 | 35 | 38 | 40 | 41 | 41 | 40 | 39 | 37 | 21 | 18 | 41 | 23 |
| Roof terrace system | 77 | 0.082 | 30 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 22 | 22 | 23 | 23 | 25 | 26 | 28 | 29 | 31 | 32 | 33 | 33 | 33 | 33 | 32 | 22 | 22 | 33 | 11 |
| 6-in. heavyweight concrete with 2-in. insulation | 77 | 0.088 | 29 | 28 | 27 | 26 | 25 | 24 | 23 | 22 | 21 | 21 | 22 | 23 | 25 | 26 | 28 | 30 | 32 | 33 | 34 | 34 | 34 | 33 | 32 | 31 | 20 | 21 | 34 | 13 |
| 4-in. wood with 2-in. insulation | 19<br>20 | 0.082<br>0.064 | 35 | 34 | 33 | 32 | 31 | 29 | 27 | 26 | 24 | 23 | 22 | 21 | 22 | 22 | 24 | 25 | 27 | 30 | 32 | 34 | 35 | 36 | 37 | 36 | 23 | 21 | 37 | 16 |

Conditions of direct application and adjustments are stated in the text.

*Source:* Abridged with permission from *ASHRAE Handbook 1989, Fundamentals.*

**Appendix C-2: CLTD values for calculating loads from roofs [5]**

## Window Glass Load Factors (GLFs) for Single-Family Detached Residences

| Design Temperature, °C | Regular Single Glass | | | | | | Regular Double Glass | | | | | | Heat-Absorbing Double Glass | | | | | | Clear Triple Glass | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 29 | 32 | 35 | 38 | 41 | 43 | 29 | 32 | 35 | 38 | 41 | 43 | 29 | 32 | 35 | 38 | 41 | 43 | 29 | 32 | 35 |
| *No inside shading* | | | | | | | | | | | | | | | | | | | | | |
| North | 107 | 114 | 129 | 148 | 151 | 158 | 95 | 95 | 107 | 117 | 120 | 129 | 63 | 63 | 73 | 79 | 82 | 88 | 85 | 85 | 95 |
| NE and NW | 199 | 205 | 221 | 237 | 243 | 262 | 173 | 177 | 186 | 196 | 194 | 208 | 114 | 117 | 123 | 132 | 139 | 139 | 158 | 158 | 167 |
| East and West | 278 | 284 | 300 | 315 | 322 | 337 | 243 | 246 | 255 | 265 | 268 | 278 | 161 | 161 | 170 | 177 | 186 | 186 | 221 | 221 | 230 |
| SE and SW[b] | 249 | 255 | 271 | 287 | 290 | 309 | 218 | 221 | 230 | 240 | 243 | 252 | 142 | 145 | 155 | 161 | 170 | 170 | 196 | 199 | 205 |
| South[b] | 167 | 173 | 189 | 205 | 211 | 227 | 145 | 148 | 158 | 167 | 170 | 180 | 98 | 98 | 107 | 114 | 125 | 125 | 132 | 132 | 142 |
| Horizontal skylight | 492 | 492 | 508 | 524 | 527 | 539 | 432 | 435 | 442 | 451 | 454 | 464 | 284 | 287 | 293 | 300 | 303 | 309 | 391 | 394 | 401 |
| *Draperies, venetian blinds, translucent roller shades, fully drawn* | | | | | | | | | | | | | | | | | | | | | |
| North | 57 | 66 | 73 | 85 | 91 | 104 | 50 | 50 | 60 | 69 | 73 | 82 | 41 | 44 | 50 | 57 | 60 | 66 | 47 | 50 | 57 |
| NE and NW | 101 | 104 | 120 | 132 | 136 | 148 | 91 | 95 | 101 | 110 | 114 | 123 | 76 | 76 | 85 | 91 | 91 | 101 | 88 | 88 | 95 |
| East and West | 112 | 145 | 158 | 170 | 173 | 186 | 126 | 129 | 139 | 145 | 148 | 158 | 104 | 104 | 114 | 120 | 120 | 129 | 123 | 123 | 129 |
| SE and SW[b] | 126 | 129 | 145 | 155 | 161 | 173 | 114 | 117 | 123 | 132 | 136 | 145 | 91 | 95 | 101 | 107 | 110 | 117 | 110 | 114 | 120 |
| South[b] | 85 | 88 | 104 | 117 | 120 | 132 | 76 | 79 | 88 | 98 | 98 | 107 | 63 | 66 | 73 | 79 | 82 | 88 | 73 | 76 | 82 |
| Horizontal skylight | 246 | 249 | 262 | 271 | 274 | 284 | 224 | 224 | 233 | 240 | 243 | 249 | 183 | 186 | 192 | 199 | 199 | 205 | 218 | 218 | 224 |
| *Opaque roller shades, fully drawn* | | | | | | | | | | | | | | | | | | | | | |
| North | 44 | 47 | 63 | 73 | 79 | 91 | 41 | 44 | 54 | 60 | 63 | 72 | 38 | 38 | 47 | 54 | 54 | 63 | 41 | 41 | 47 |
| NE and NW | 79 | 82 | 98 | 107 | 114 | 126 | 73 | 76 | 85 | 95 | 95 | 104 | 66 | 69 | 76 | 82 | 85 | 91 | 73 | 73 | 82 |
| East and West | 107 | 111 | 126 | 139 | 142 | 155 | 101 | 104 | 114 | 120 | 123 | 132 | 91 | 95 | 101 | 107 | 110 | 117 | 101 | 101 | 110 |
| SE and SW[b] | 98 | 101 | 114 | 126 | 132 | 145 | 91 | 95 | 104 | 110 | 114 | 123 | 82 | 85 | 91 | 98 | 101 | 107 | 91 | 91 | 98 |
| South[b] | 66 | 69 | 85 | 95 | 101 | 114 | 63 | 63 | 73 | 82 | 85 | 95 | 57 | 60 | 66 | 73 | 76 | 82 | 60 | 63 | 69 |
| Horizontal skylight | 189 | 192 | 202 | 214 | 218 | 227 | 180 | 180 | 189 | 196 | 199 | 205 | 164 | 164 | 173 | 180 | 180 | 186 | 177 | 180 | 186 |

Appendix C-3: Glass load factor for single-family detached residence [5]