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.

____

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

First and foremost I would like to express my sincere gratitude to my supervisor, Dr. Khairul Habib for the finding time among the busy schedule and provide me full support with my final year project work. Your supervision and support is what truly helped the progression and smoothness of my work. The co-operation is much indeed appreciated.

Secondly I would like to thank Dr. Gilani for the consultation hours provided and also for helping me with my work and the useful advices regarding the project. I would like also to thank Mr Mohd Faizairi bin Mohd Nor, the FYP Coordinator for Mechanical Engineering Department. Without his contribution in organizing and coordinating the FYP proceedings, the project work would not have been able to proceed well.

My deepest gratitude goes also to my university, Universiti Teknologi PETRONAS, for giving me with the opportunity to pursue my higher education and complete my FYP. The university provided a lot of books and research material that were helpful for my work.

Last but not least, I would like also to thank all the people that have helped me complete this final year project and also for the support given. Without them it would be very difficult to find motivation and complete the project with the smoothness I had.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

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.

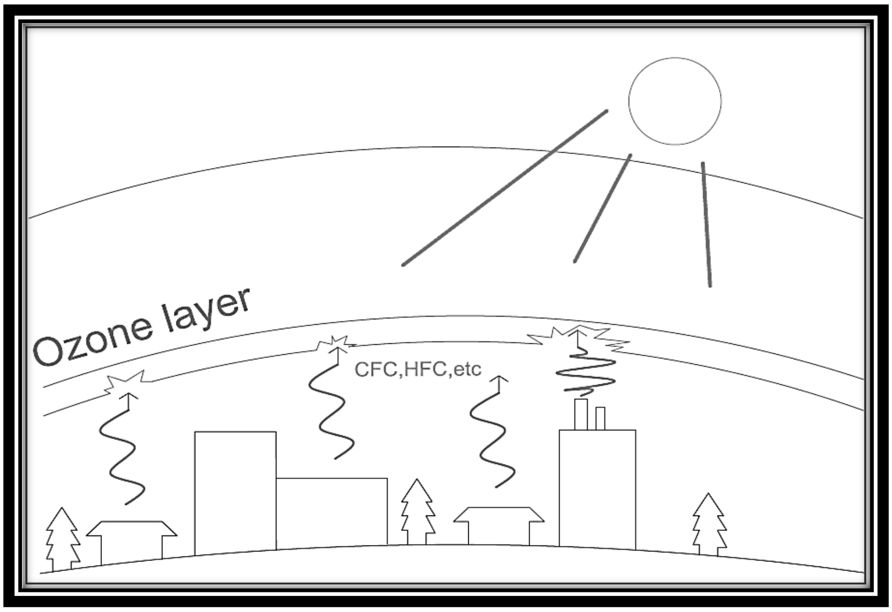


Figure 1.1: Ozone depletion process

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).

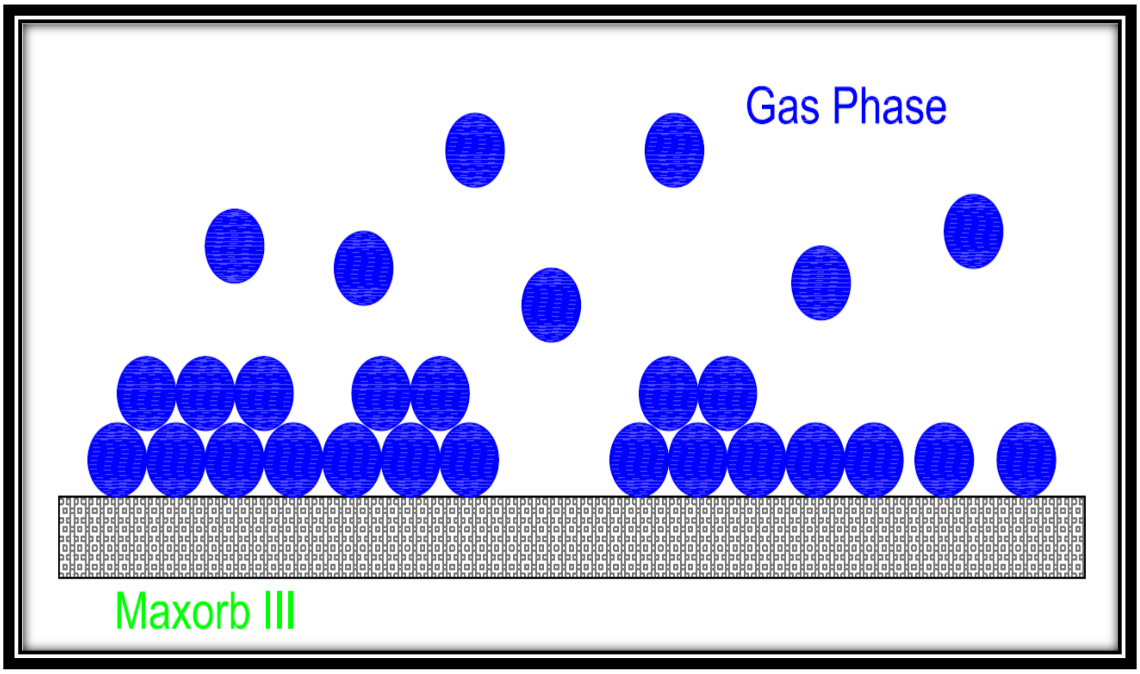


Figure 2.1: Surface adsorption process

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.

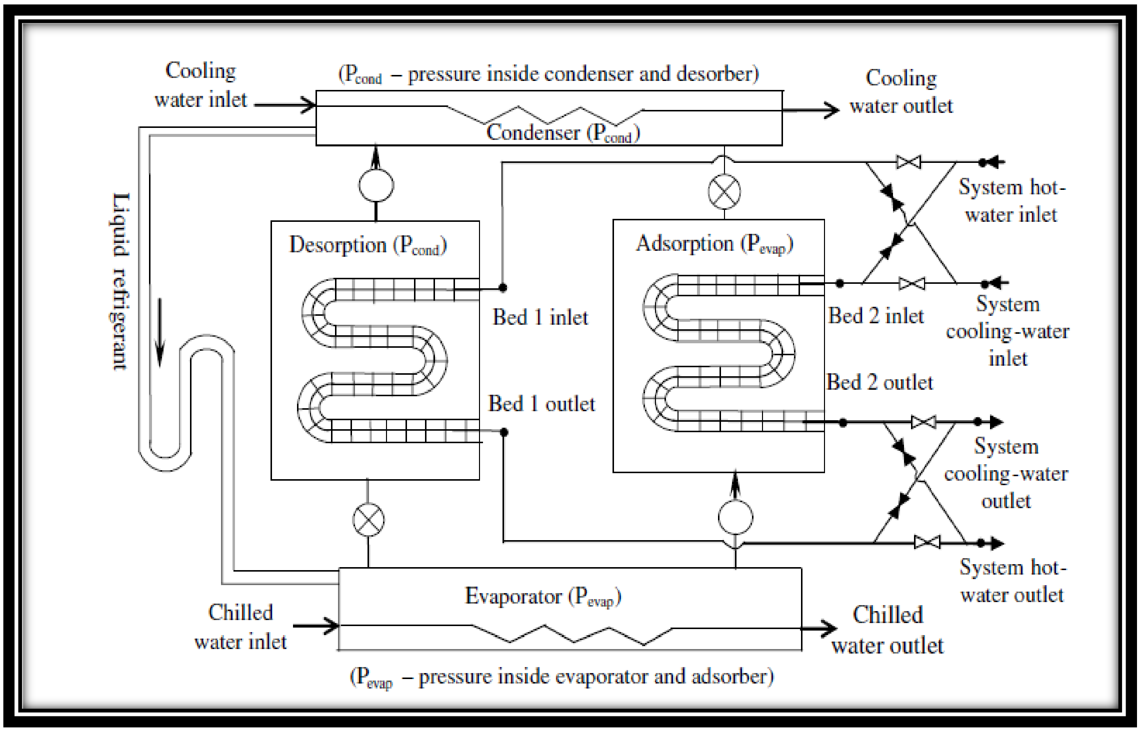


Figure 2.2: Schematic diagram of a two bed adsorption chiller [2]

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]

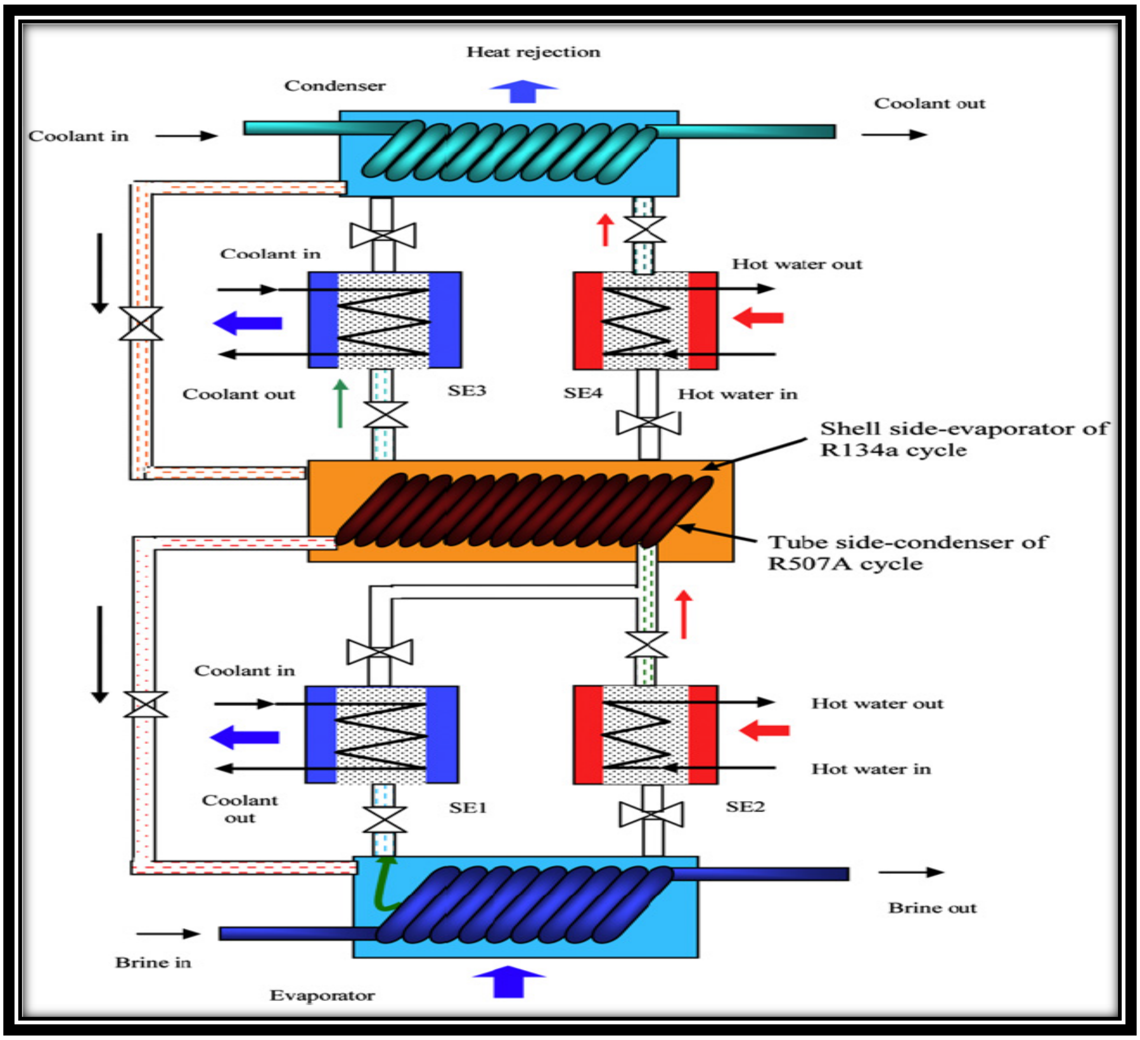


Figure 2.3: Combined adsorption refrigeration [4]

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.

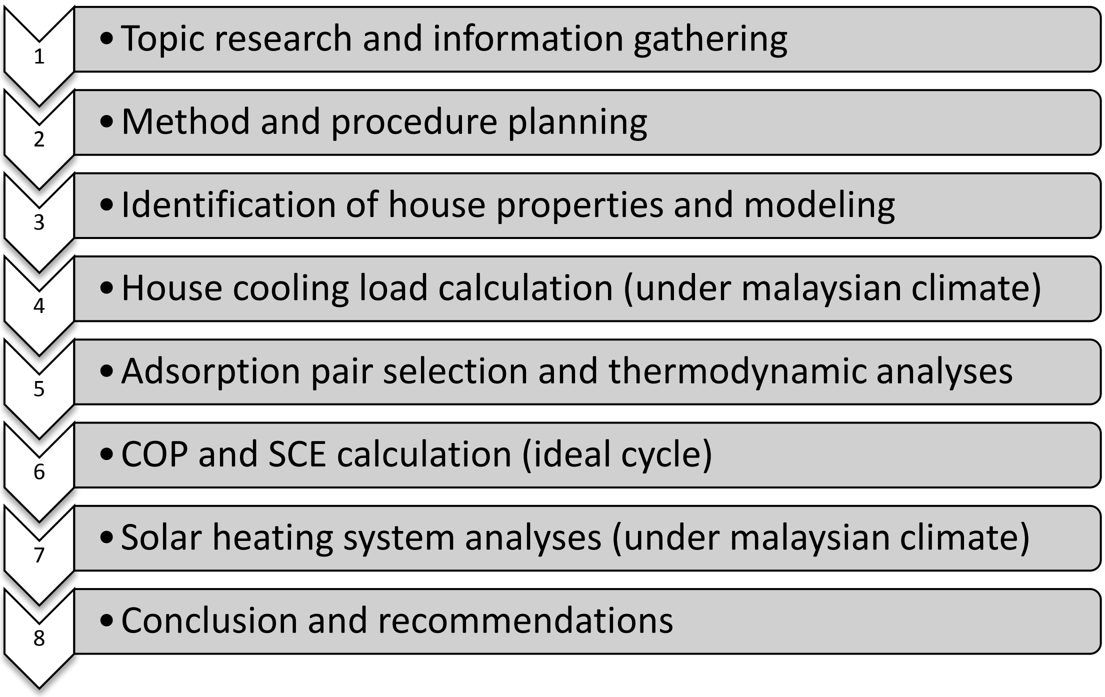


Figure 3.1: Project work flow

3.2 FYP 2 Gantt chart

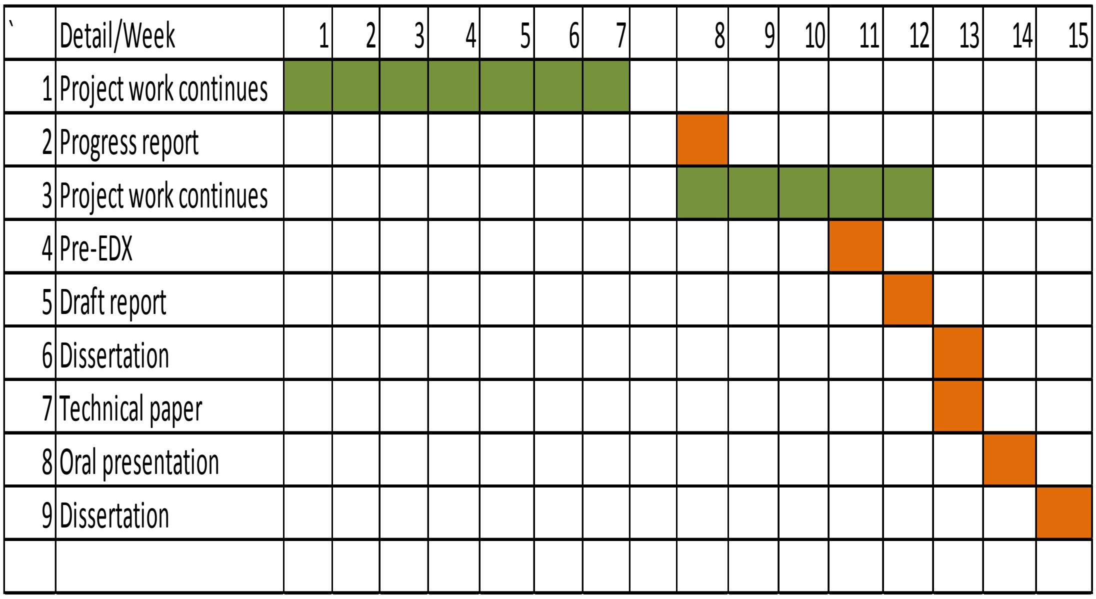


Figure 3.2: FYP2 Gantt chart

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 (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 (U = 2.6 W/m^{2}K, A = 2.6m^2).
Windows	Regular single glass with venetian blinds (U = 3.12 W/m^{2}K,).
Internal Loads	- People: 65W per person - Lights: 5W (40% fluorescent tube) - PC with color monitor: 230W/PC

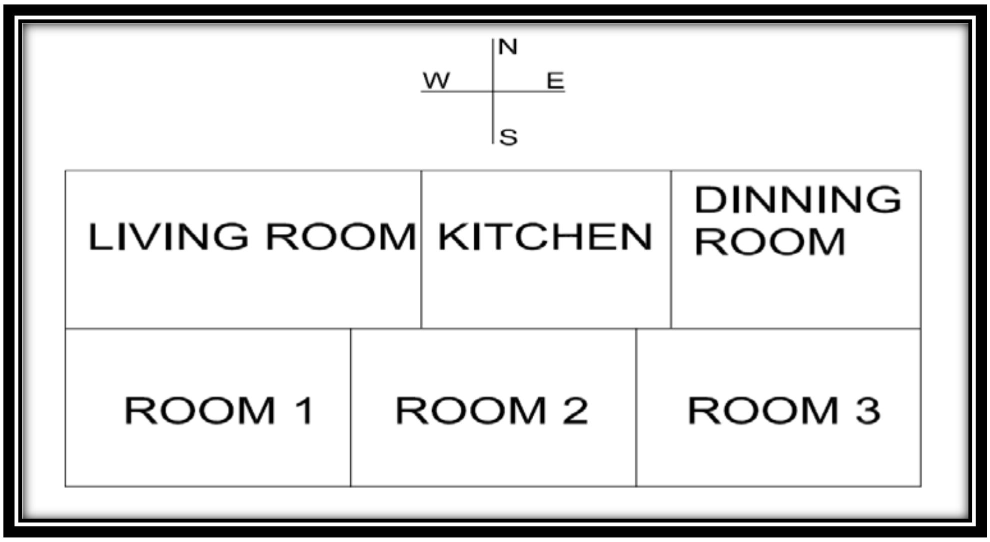


Figure 4.1: Layout of test house interior compartments

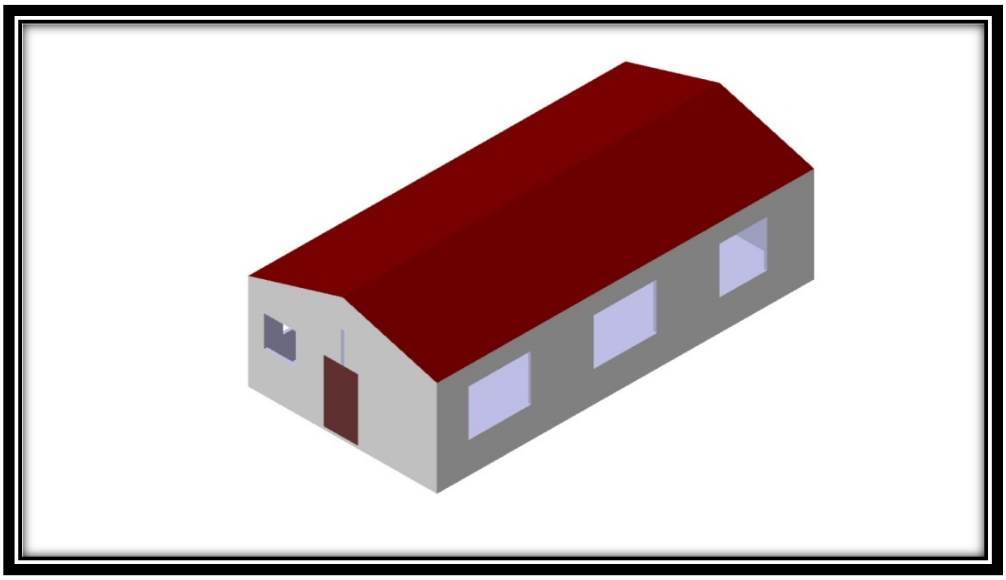


Figure 4.2: Isometric view of test house

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.

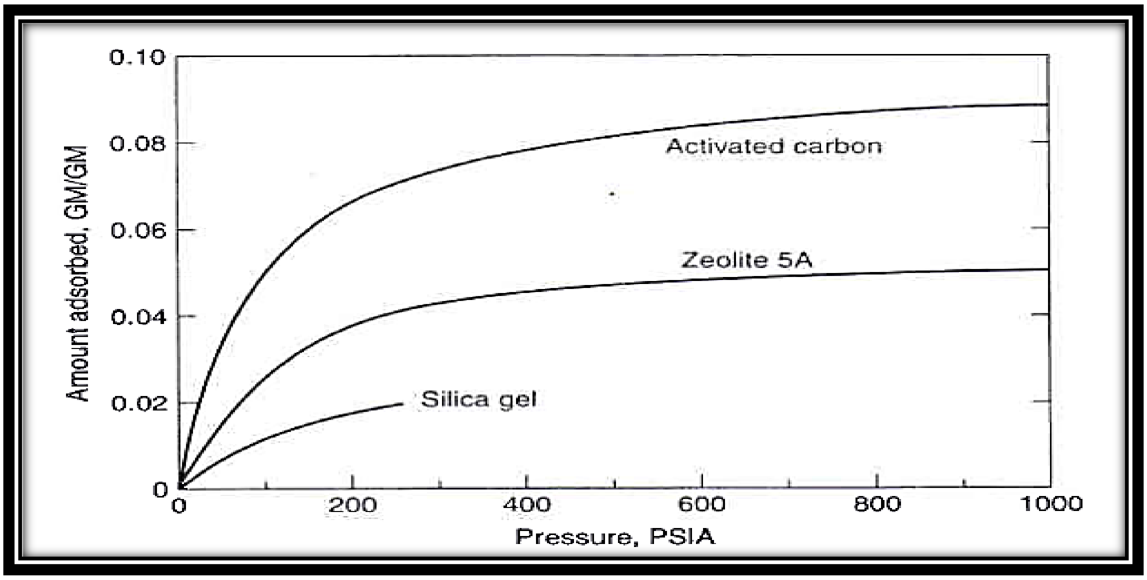


Figure 4.3: Adsorption capacity of adsorbents [9]

***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.

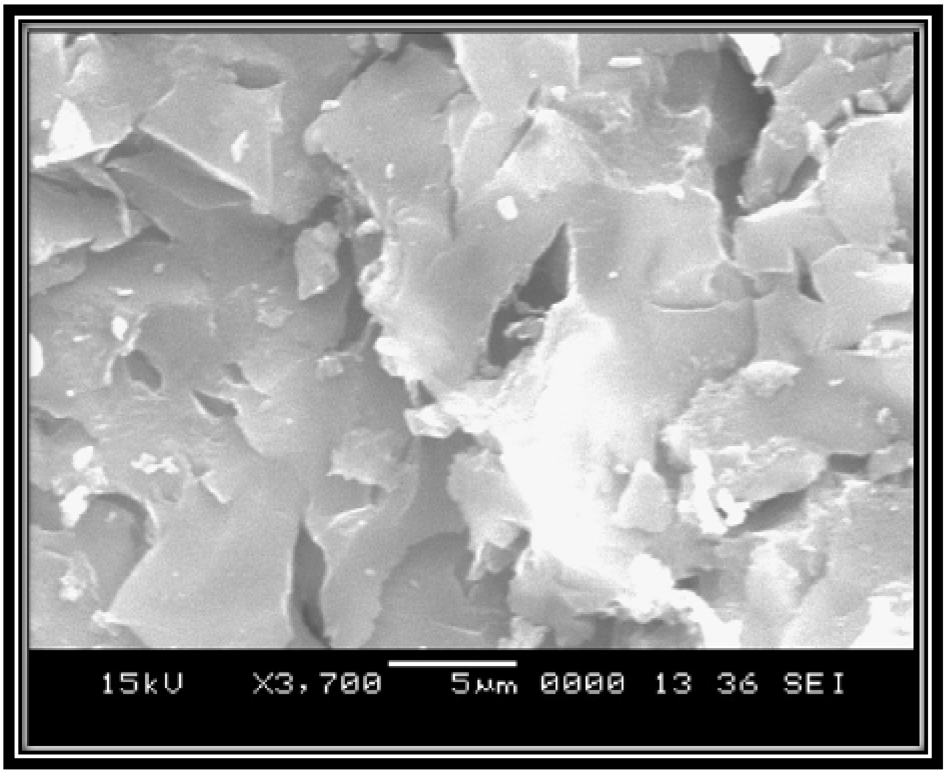


Figure 4.4: Maxorb III SEM picture [6]

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.

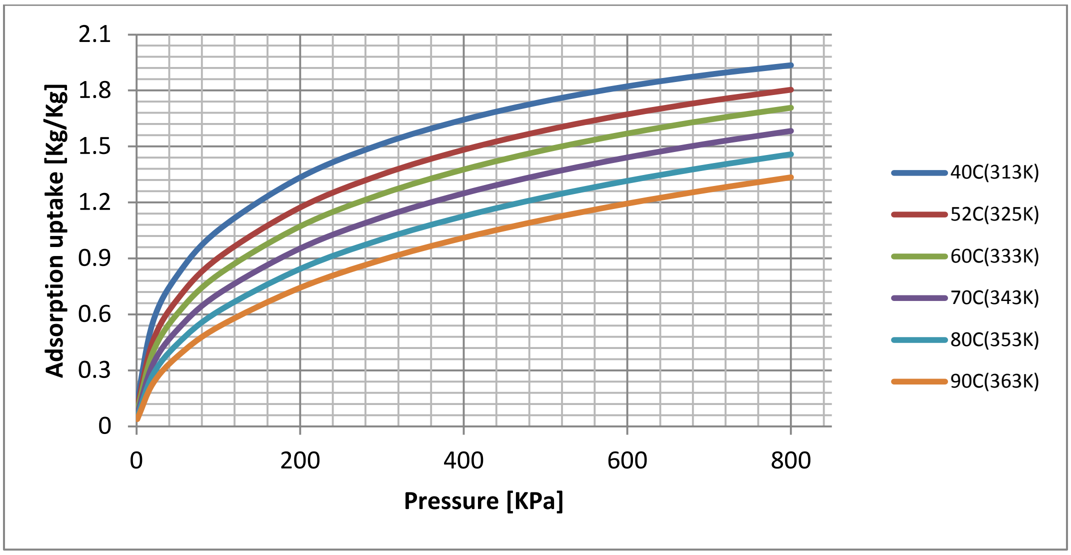


Figure 4.5: R134a adsorption isotherm

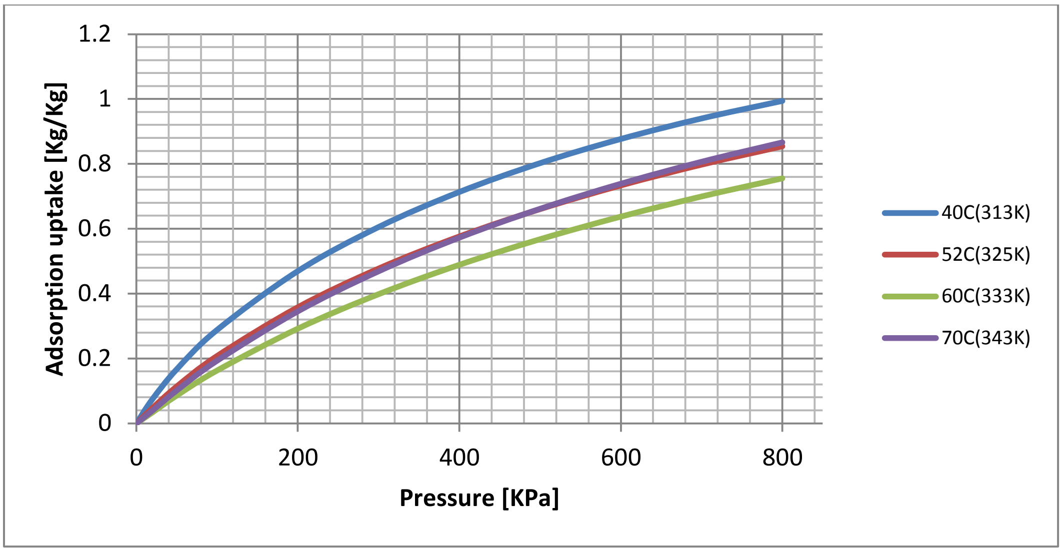


Figure 4.6: R507a adsorption isotherm

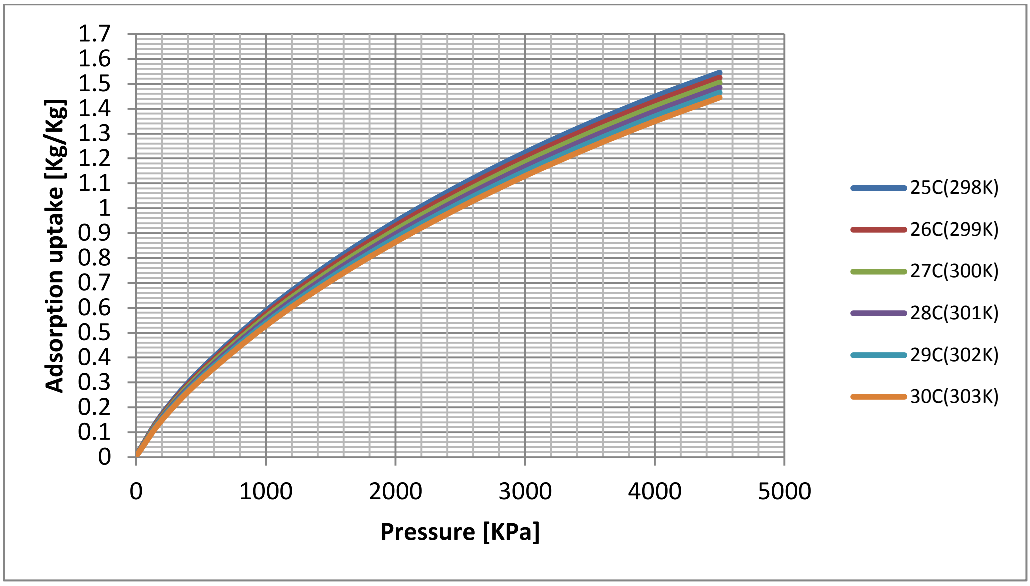


Figure 4.7: R744 adsorption isotherm

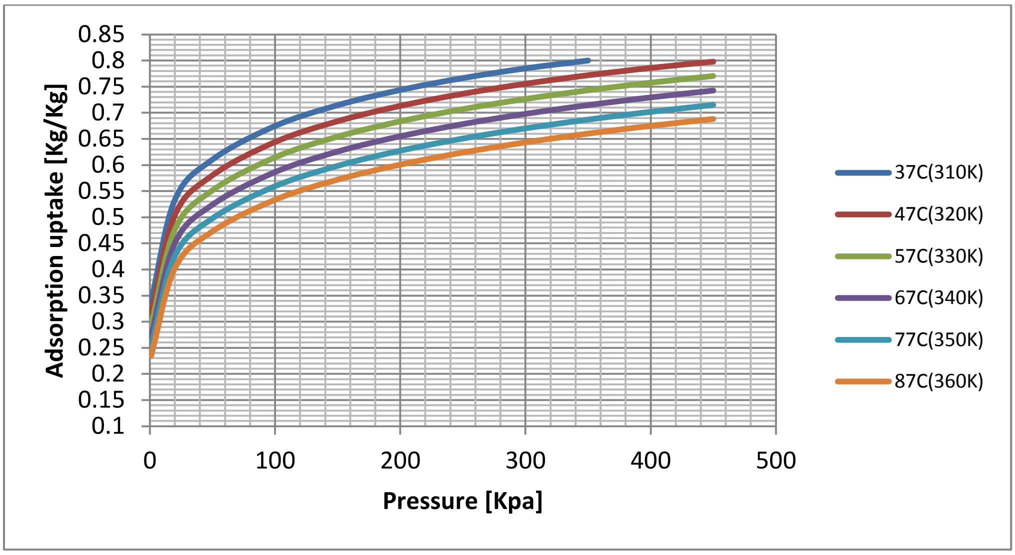


Figure 4.8: R600 adsorption isotherm

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

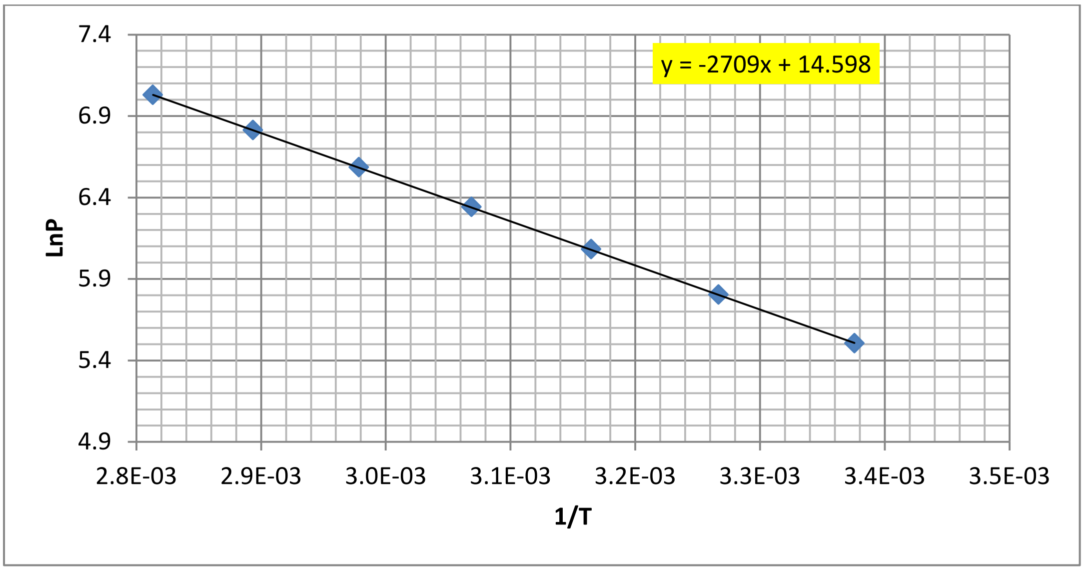


Figure 4.9: Pressure and temperature relation

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 (25^0C) and 358 Kelvin (85^0C), and the condenser temperatures will be respectively 302.4 Kelvin (29.4^0C) and 298 Kelvin (25^0C), with evaporator temperature equal to 279.7 Kelvin (6.7^0C).

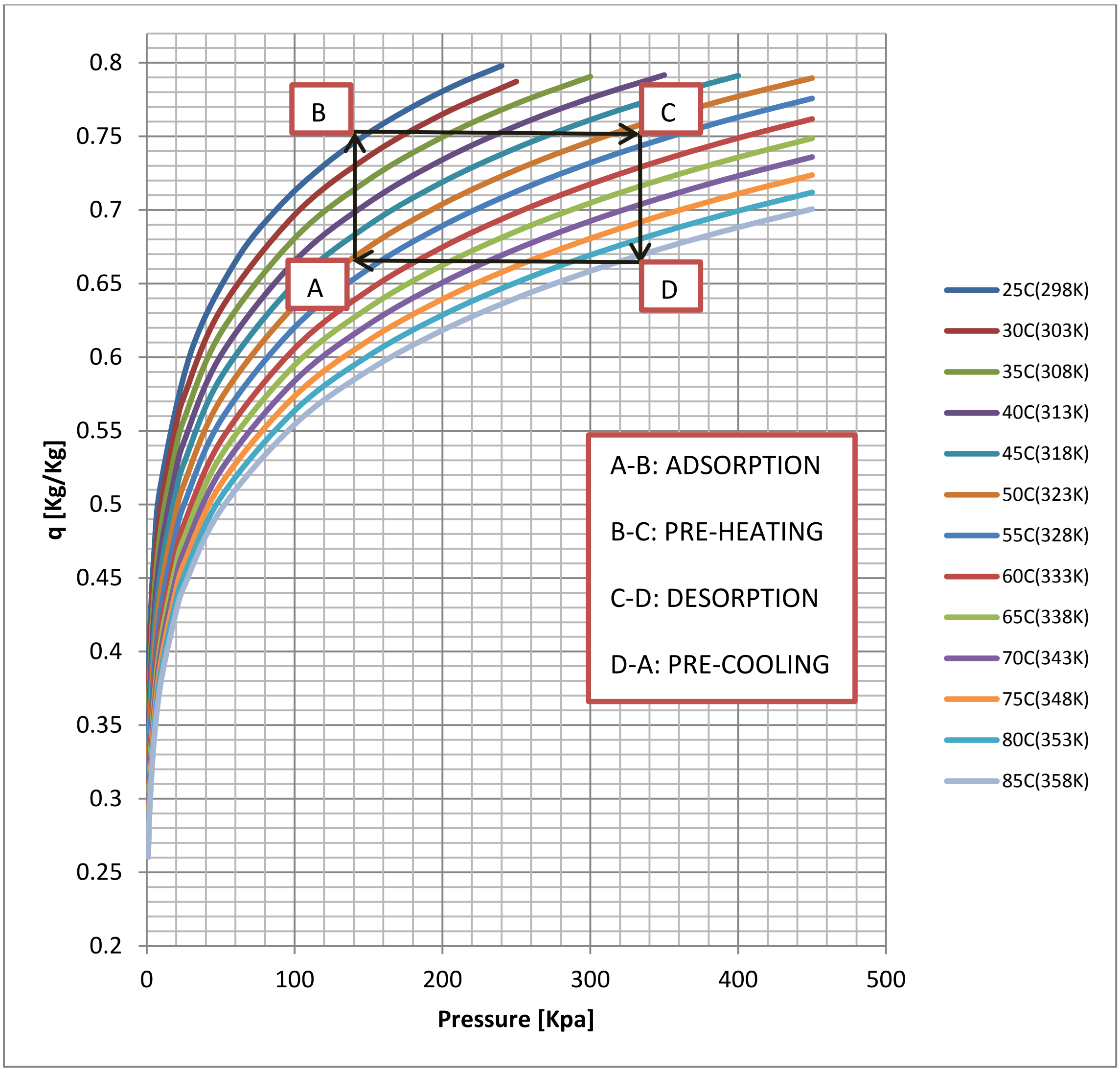


Figure 4.10: Ideal Cycle for N-butane in Maxorb III

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 24^0C(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)	Δq (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 24^0C(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)	Δq (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

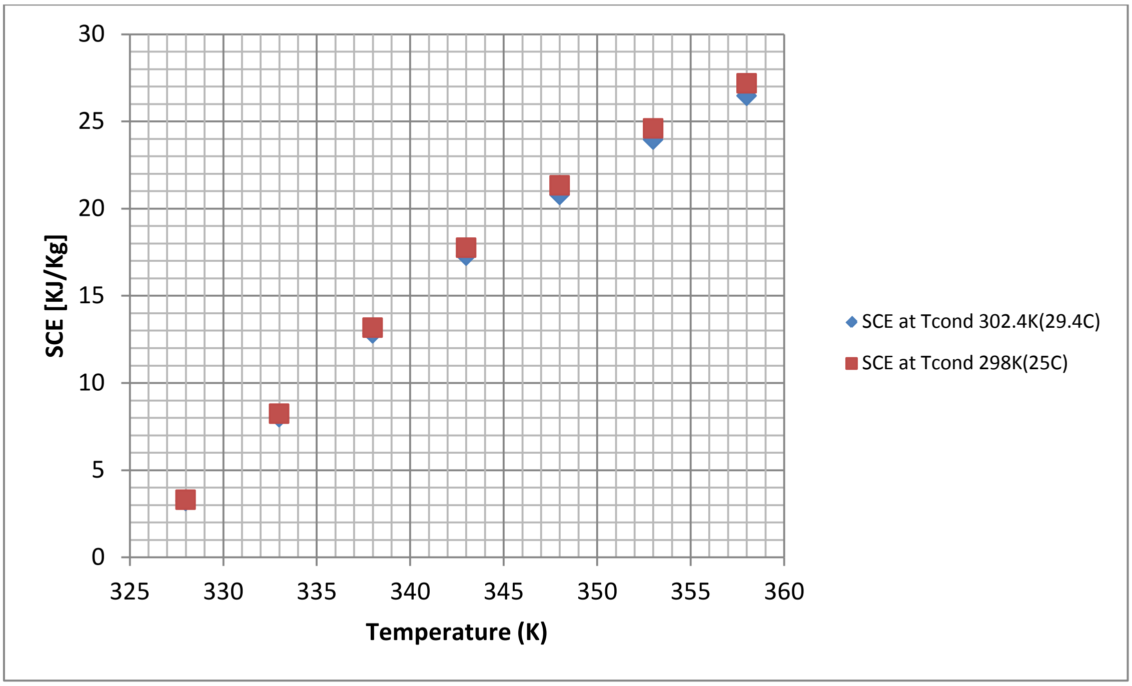


Figure 4.11: SCE and temperature relation

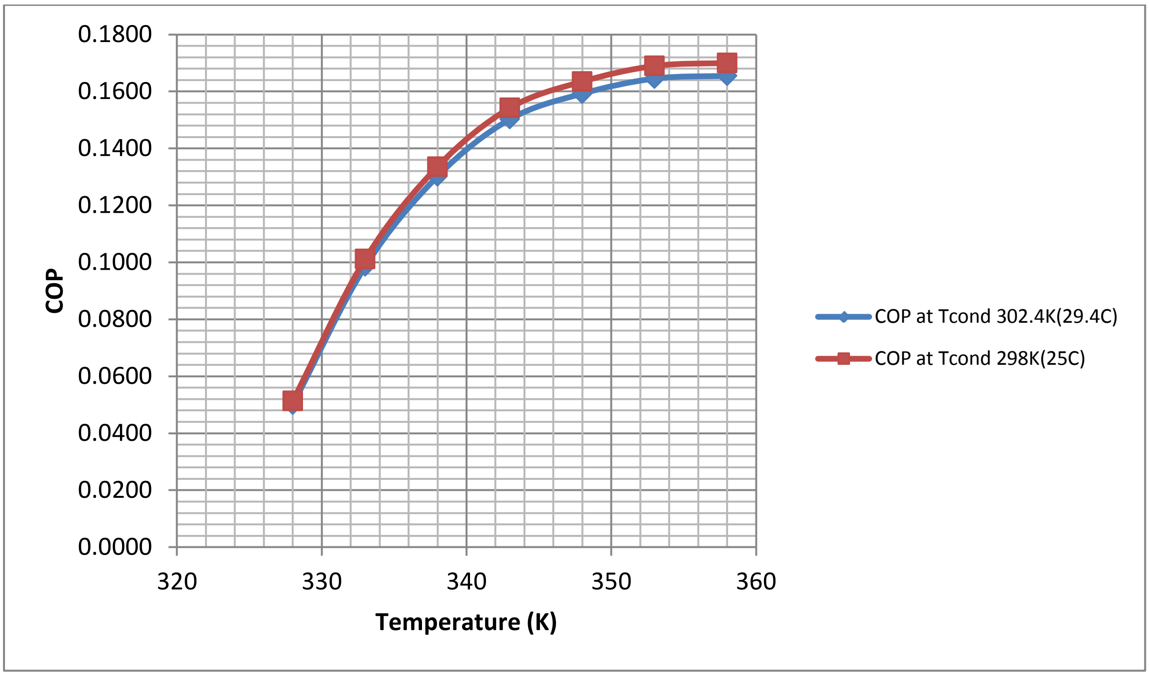


Figure 4.12: COP and temperature relation

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.

REFERENCES

1. R. Z. Wang & R. G. Oliveira, 2005, *Adsorption refrigeration – an efficient way to make good use of waste heat and solar energy,* International sorption heat pump conference.

2. H. T. Chua, K. C. Ng, W. Wang, C. Yap & X. L. Wang, 2004, *Transient modeling of a two-bed silica gel-water adsorption chiller,* International journal of heat and mass transfer, volume 47 (659-669).

3. B. Dawoud, 2006, *A hybrid solar-assisted adsorption cooling unit for vaccine storage* Renew Energy, volume 32 (947- 964).

4. K. Habib, B. B. Saha, A. Chakraborty, S. Koyama & K. Srinivasan, 2011, *Performance evaluation of combined adsorption refrigeration cycles,* International journal of refrigeration, volume 34 (129-137).

5. Wang, S, 2001, *Handbook of Air Conditioning and Refrigeration,* McGraw Hill, volume 2.

6. B. B. Saha , A. Chakraborty , S. Koyama, S. Y. Bisao Mochida, M. Kumja, C. Yap & K. Choon, 2008, *Isotherms and thermodynamics for the adsorption of n-butane on pitch based activated carbon,* International journal of heat and mass transfer, volume 51 (152-1589).

7. M. Magee, *Nitrogen gas adsorption in zeolites 13X and 5A,* Walla Wall university

8. Barry C. & W. J. Thomas, 1998, *Adsorption technology & design,* Butterworth-Heinemann.

9. R. T. Yang, *Adsorbents: Fundamentals and applications,* 2003, Wiley inter-science.

10. M. Suziki, 1990, *Adsorption engineering,* Kosasha LTD & Elsevier science publisher, volume 25.

11. B. B. Saha, S. Jribi, S. Koyama & I. El-Sharkawy, 2011, *Carbon Dioxide Adsorption Isotherms on Activated Carbons*, Journal of chemical and engineering data, (1980).

12. A. S. Runt and U. S. Wankhede, 2011, *Selection of the capillary tubes for retrofitting in refrigeration appliances,* International journal of engineering and science and technology (IJEST), volume 3 (1-7).

13. Cary T. Chiou, *Partition and adsorption of organic contaminants in environmental systems,* John wiley & sons, Inc. (2003).

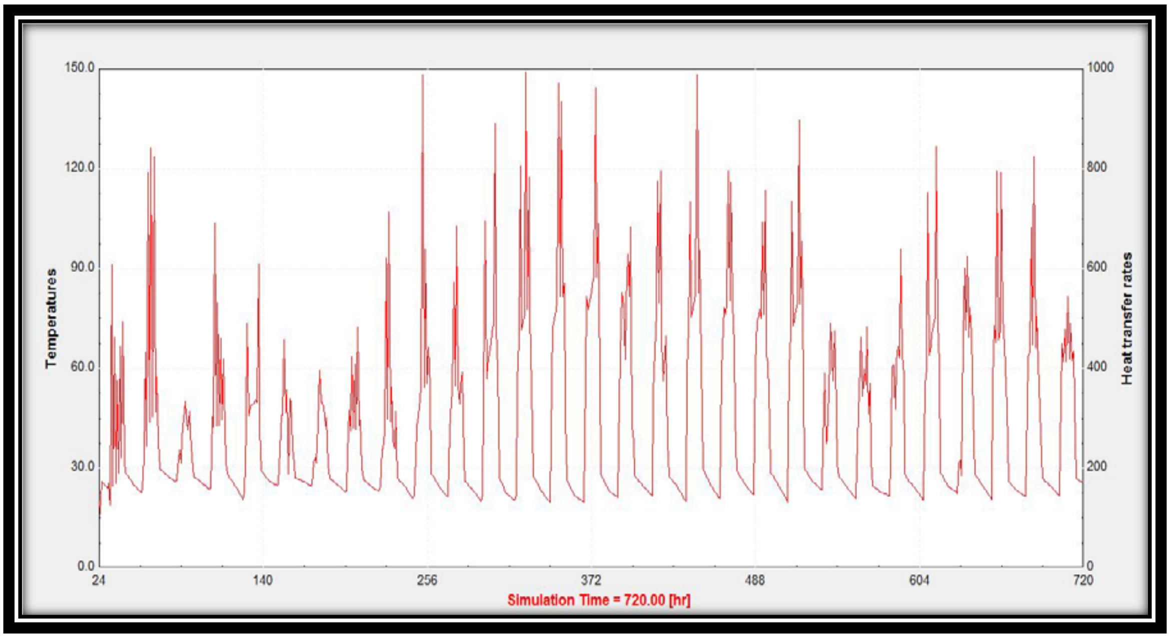
14. W.S. Loh, B. B. Saha, A. Chakrabortty, K. Choon NG and W. G. Chun, 2010, *Performance analysis of waste heat driven pressurized adsorption chiller* , Journal of thermal science and technology, volume 5 (2) (252-264).

15. Yunus A. C, Michael A. B, 2007, *Thermodynamics, an engineering approach*, Mc. Graw Hill, volume 2.

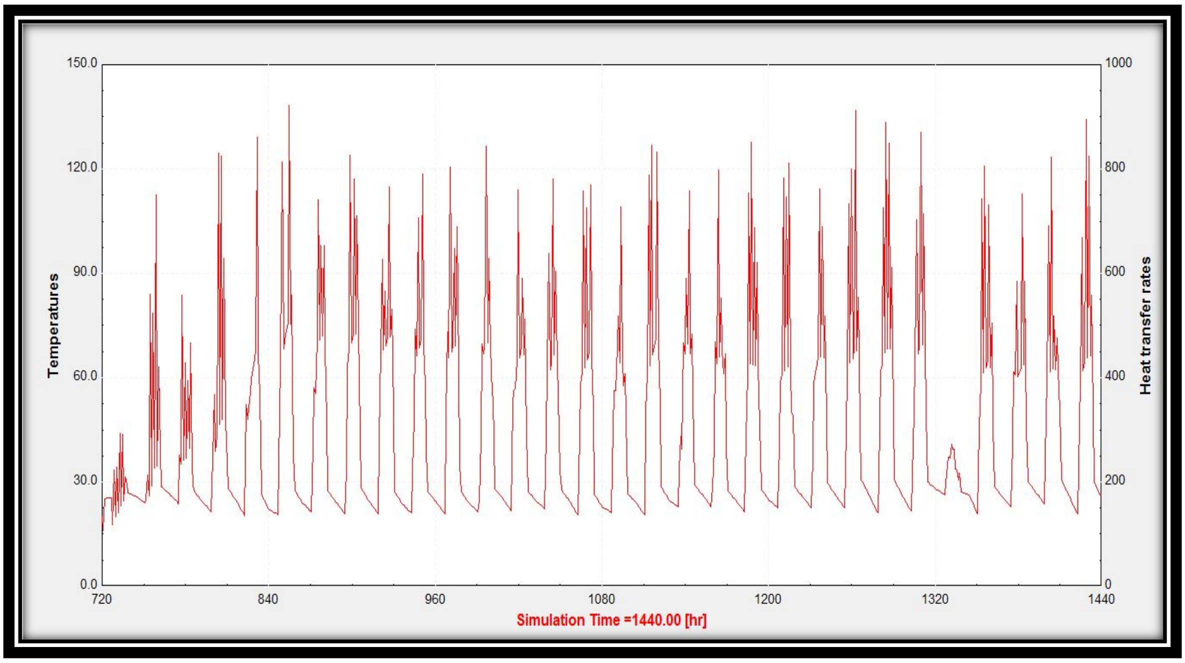
16. M. H. Ahmad, D. R. Ossen & C. S. Ling, 2004, *Impact of solar radiation on high-rise built form tropical climate*, Department of architecture, faculty of built environment, university of technology Malaysia.

APPENDICES

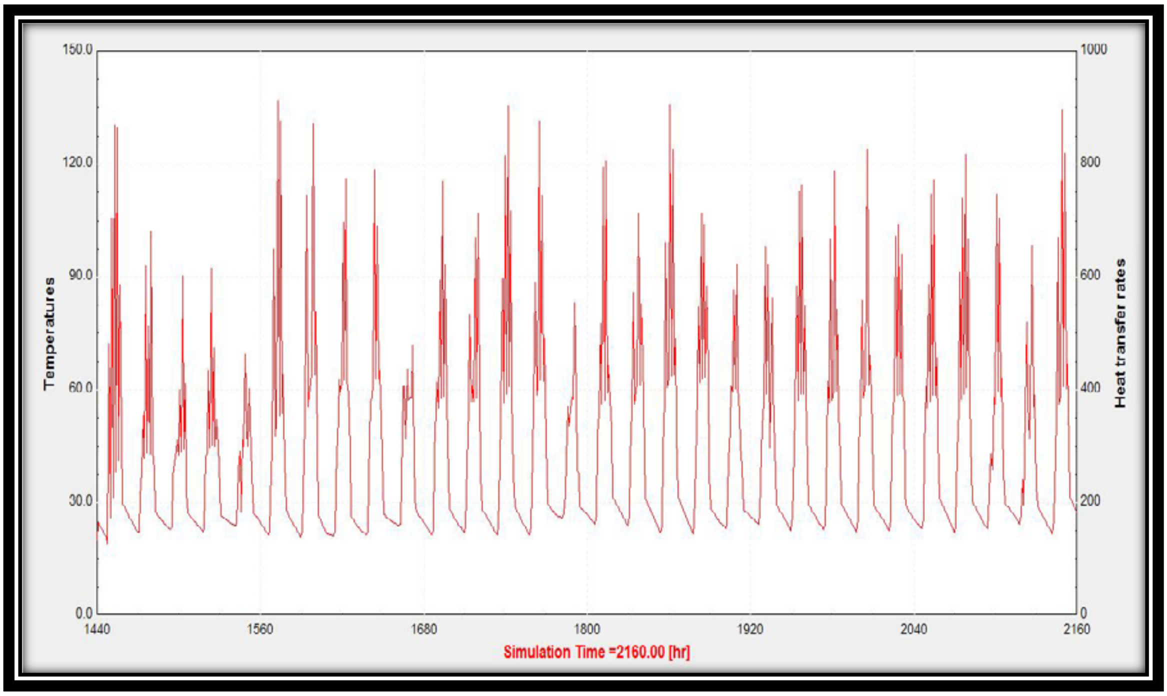
Appendix A: TRNSYS SOLAR SIMULATION RESULTS



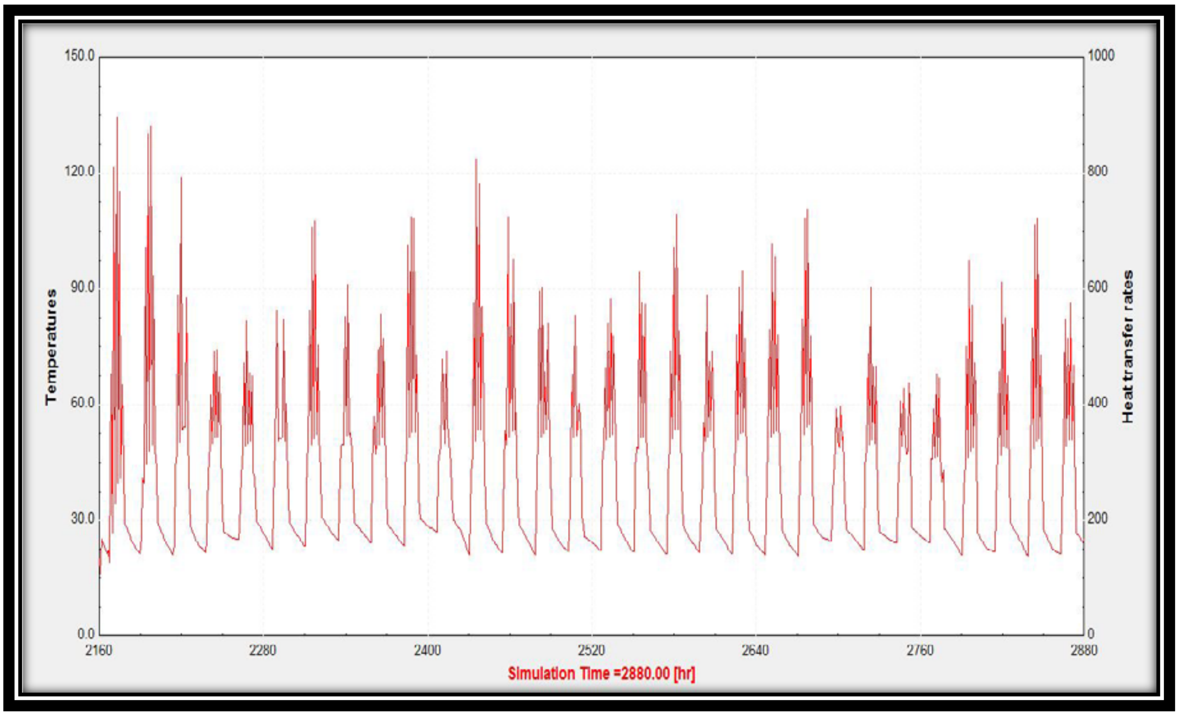
Appendix A-1: Water temperature from solar collector (January)



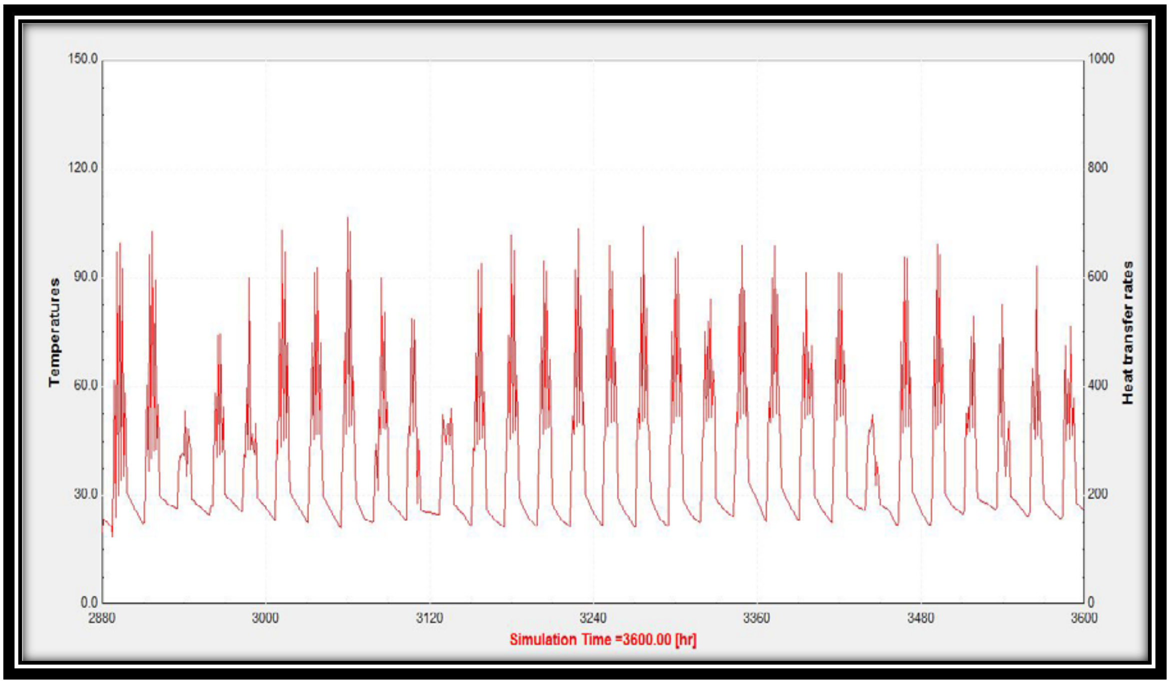
Appendix A-2: Water temperature from solar collector (February)



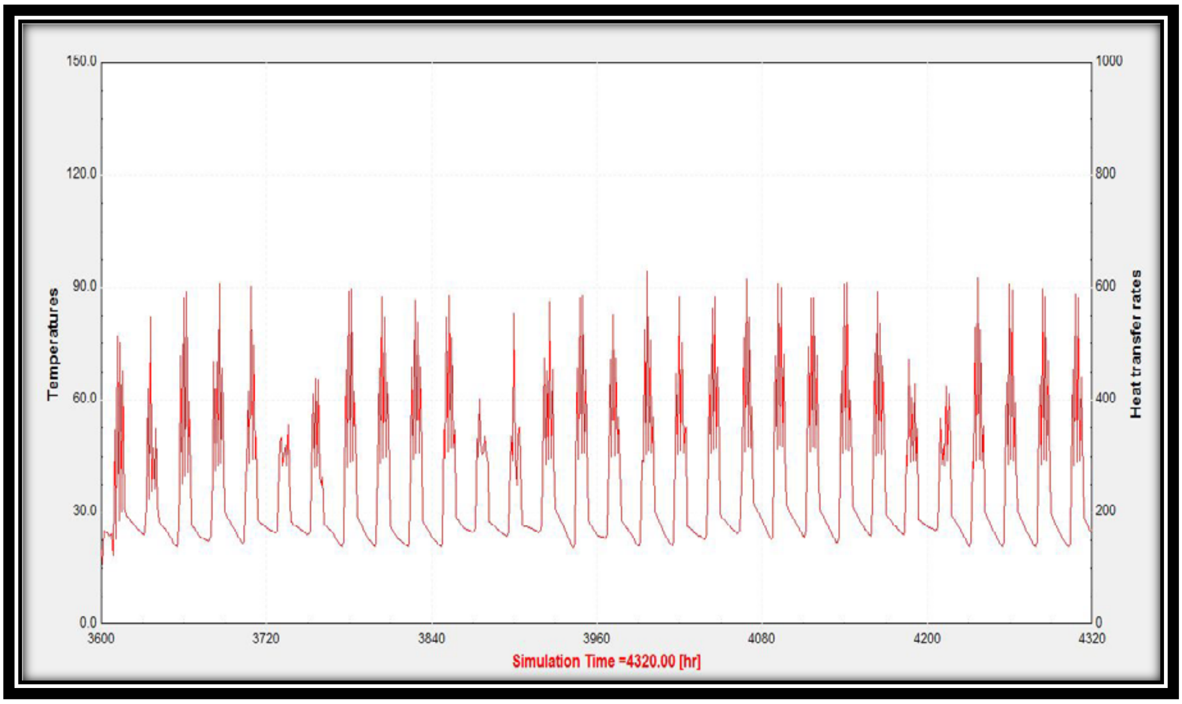
Appendix A-3: Water temperature from solar collector (March)



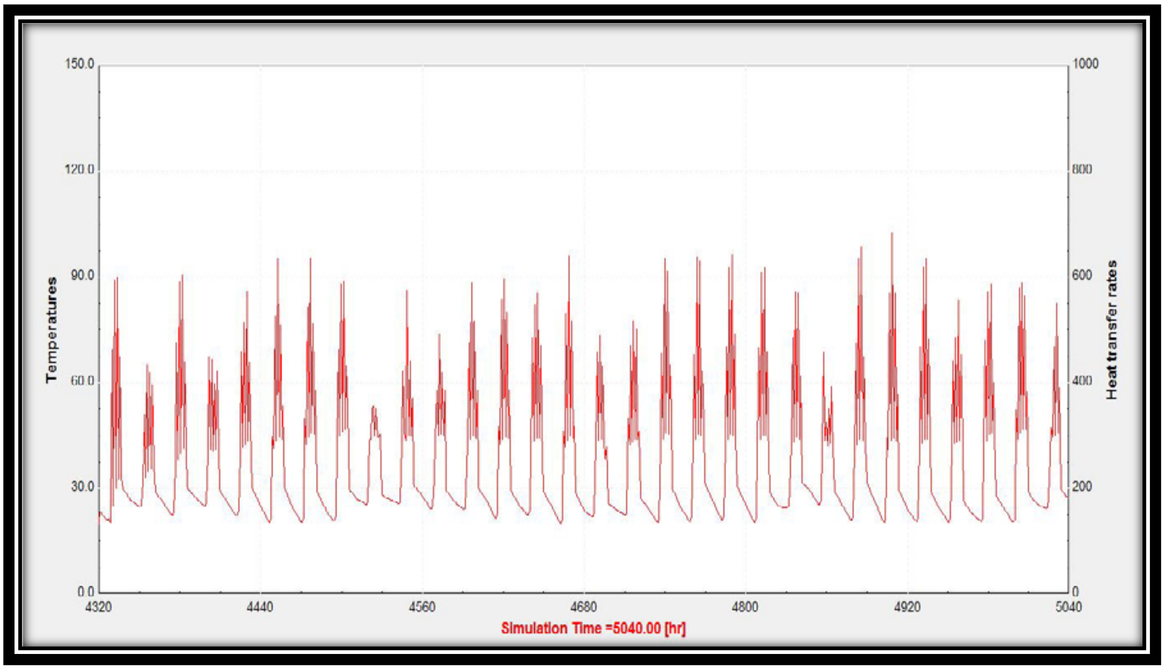
Appendix A-4: Water temperature from solar collector (April)



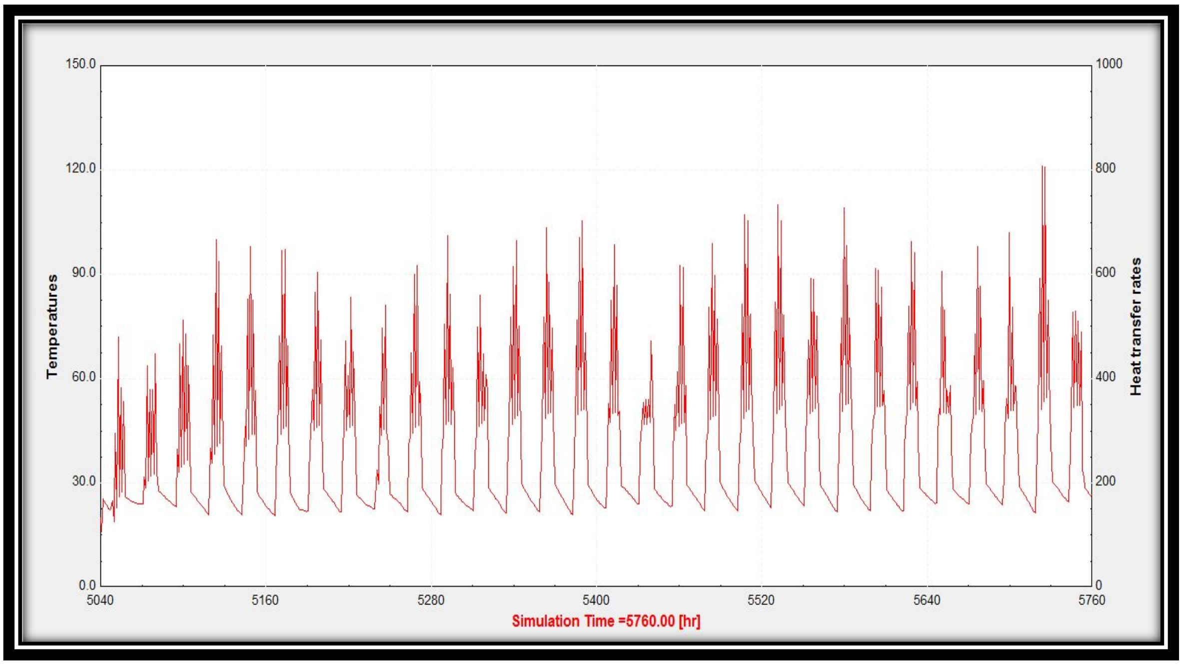
Appendix A-5: Water temperature from solar collector (May)



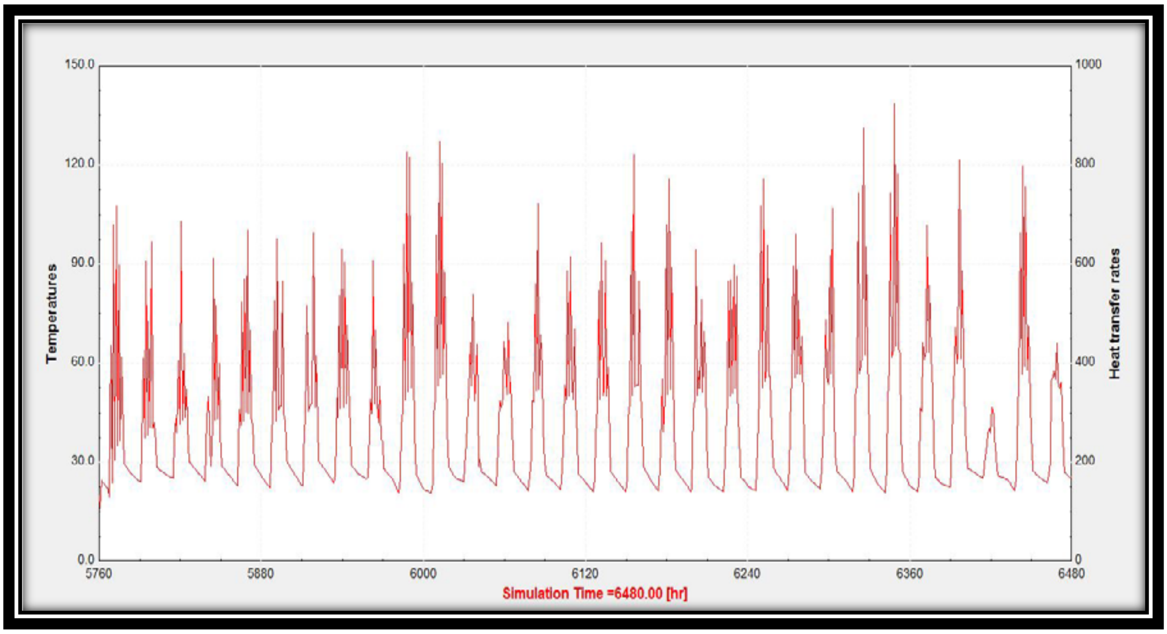
Appendix A-6: Water temperature from solar collector (June)



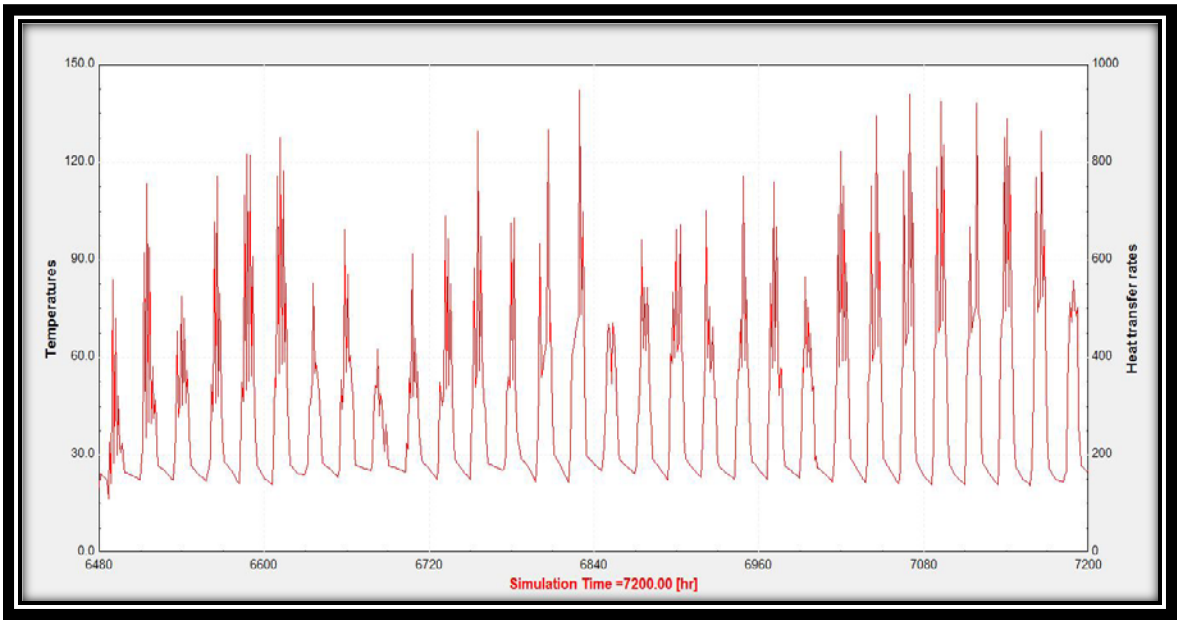
Appendix A-7: Water temperature from solar collector (July)



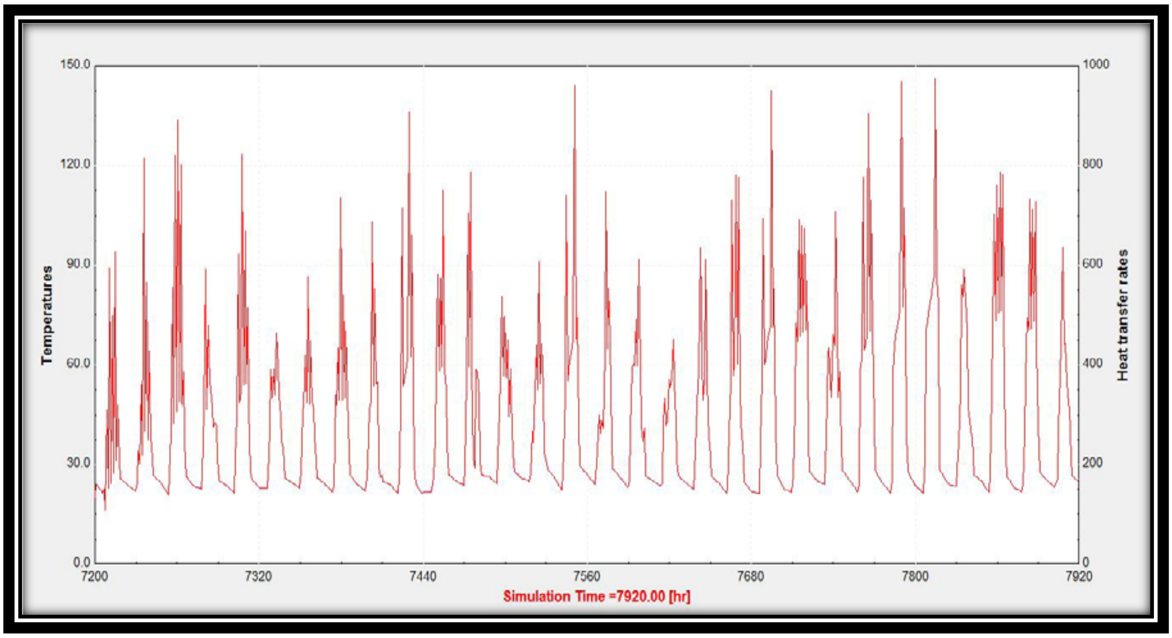
Appendix A-8: Water temperature from solar collector (August)



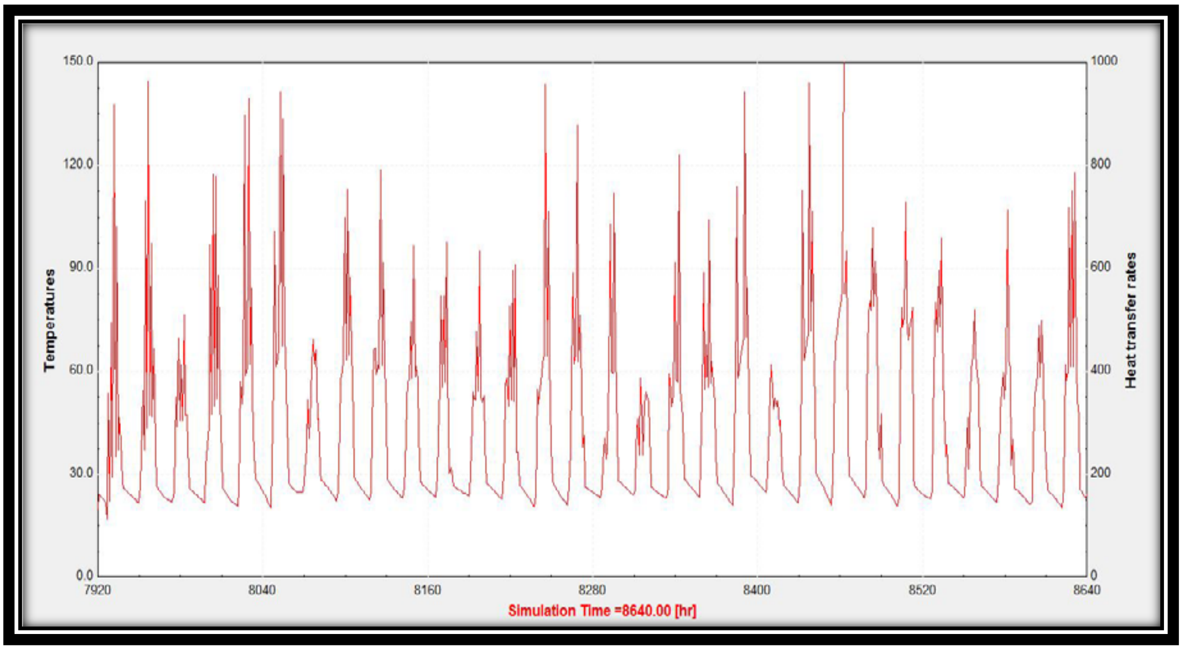
Appendix A-9: Water temperature from solar collector (September)



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 ft² °F)	(W/m²K)
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/ft³	1.5	8.9
	12 inches - poured concrete 80 lb/ft³	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	Solar time, h: 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
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	54	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	33	22	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 20	0.082 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	Regular Single Glass						Regular Double Glass						Heat-Absorbing Double Glass						Clear Triple Glass		
Temperature, °C	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	199	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	123	123	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	60	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	142	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	73	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	114	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[a]	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]