



UNIVERSITI
TEKNOLOGI
PETRONAS

STUDY OF THERMALLY DRIVEN SORPTION CHILLER

by

Muhammad Hazwan Bin Zainudin

13234

SUPERVISOR: DR KHAIRUL HABIB

Dissertation submitted in partial fulfilment of
the requirements for the

Bachelor of Engineering (Hons)
(Mechanical Engineering)

December 2013

Universiti Teknologi PETRONAS
Bandar Seri Iskandar
31750 Tronoh
Perak Darul Ridzuan

CERTIFICATION OF APPROVAL

Study of Thermally Driven Sorption Chiller

By

Muhammad Hazwan Bin Zainudin

A project dissertation submitted to the
Mechanical Engineering Programme

Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the

BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

(Dr Khairul Habib)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
December 2013

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.

MUHAMMAD HAZWAN BIN ZAINUDIN

ABSTRACT

In this study, the dynamic behaviour of a 4 bed adsorption chiller was analysed employing silica gel as the adsorbent and water as the refrigerant. The simulated results in terms of heat transfer fluid temperatures cycle average cooling capacity and coefficient of performance (COP) were obtained numerically. With 47 kg of silica gel, the system is able to produce 14 kW of cooling power and 0.46 of COP at driving heat source temperature of 85°C which can be obtained from waste heat or solar energy. In particular, it can be powered by the waste heat from the internal combustion engine and therefore is suitable for automobile air-conditioning applications. Water is used as refrigerant as it has no harm to environment, it is a non-toxic substance, moreover, ethanol has comparatively higher vapour pressure even at low temperature. This innovative system utilizes effectively low-temperature waste heat sources of temperature between 60 and 95°C along with a coolant at 30°C.

ACKNOWLEDGEMENT

First and foremost, the author would like to express her highest gratitude to the supervisor, Dr. Khairul Habib, for all the motivation, knowledge and advices that has been shared. The help received from him have led the author to a clear path in overcoming numerous obstacles when conducting this project.

The author would like to thank another personnel which contributed in making this project succesful. The personnel mentioned is Dr Mohan as co supervisor, who has given help be it small or big for the author to complete the project.

Finally, the author would also like to express gratitude to Universiti Teknologi PETRONAS for providing the facilities either for doing the experimental work or researches in undertaking the project. Also personal thanks given to the family and friends whom gave constant support throughout.

TABLE OF CONTENTS

	Page
CERTIFICATION	
ABSTRACT	i
ACKNOWLEDGEMENT	iii
	iv

CHAPTER 1: INTRODUCTION

1.1 Background Study	3
1.2 Problem Statement	4
1.3 Objectives of Study	5

CHAPTER 2: LITERATURE REVIEW

2.1 Concept of adsorption	6
2.2 Project Overview	7
2.2.1 Adsorption Chiller	7
2.3 Operation of Single Stage Four Beds Chiller	9
2.4 Practical Adsorbent.....	13
2.4.1 Silica Gel.....	14

CHAPTER 3: METHODOLOGY

3.1 Project Flow Chart.....	16
3.2 Key Milestone.....	17
3.3 Gantt-Chart	18
3.3.1 Final Year Project 1.....	18
3.3.2 Final Year Project 2.....	19

CHAPTER 4: RESULT & DISCUSSION

4.1 Mathematical Modelling	21
4.1.1 Adsorption Isotherms	21
4.1.2 Adsorption and Desorption Energy Balance.....	22
4.1.3 Evaporator Energy Balance	23
4.1.4 Condenser Energy Balance	24
4.1.5 Mass Balance	25
4.1.6 Simulation Procedure.....	26
4.2 Critical Analysis	30
4.2.1 Chiller Transient Response	30
4.2.2 Adsorption/Desorption Cycle Time	32
4.2.3 Switching Time	33
4.2.4 Heat Source Temperature	34
4.2.5 Chilled Water Temperature	35
4.2.6 Heat Transfer Fluid Flow Rates	36
4.2.6.1 Hot Water Flow Rates.....	36
4.2.6.2 Chilled Water Flow Rates.....	37

CHAPTER 5: CONCLUSION AND FUTURE WORK **38**

REFERENCES **39**

LIST OF FIGURES	Page
Figure 2.1: Comparison of conventional chiller and adsorption chiller studied in the present study	8
Figure 2.2: Single Stage Operation Mode A	9
Figure 2.3: Single Stage Operation Mode C	10
Figure 2.4: Photograph of Silica Gel	14
Figure 2.5: SEM Photograph of Silica Gel	14
Figure 3.1: Project Flowchart	16
Figure 3.2: Key Milestone	17
Figure 3.3: Gantt Chart Final Year Project 1	18
Figure 3.4: Gantt Chart Final Year Project 2	19
Figure 4.1: Flow Chart of Simulation Program	27
Figure 4.2: Temperature profile for adsorption chiller	31
Figure 4.3: Outlet temperature variation	31
Figure 4.4: Adsorption/Desorption cycle time effect on COP and cooling capacity	32
Figure 4.5: Switching time effect on COP and cooling capacity	33
Figure 4.6: Heat source temperature effect on COP and cooling capacity	35
Figure 4.7: Chilled water temperature effect on COP and cooling capacity	36
Figure 4.8: Hot water flow rate effect on COP and cooling capacity	37
Figure 4.9: Chilled water flow rate effect on COP and cooling capacity	37

LIST OF TABLES

Table 2.1: Operation Schedule	10
Table 2.2: Properties of Silica Gel	15
Table 4.1: Values for the parameters used in model	20
Table 4.2: Standard Rated Condition	30

Nomenclature

A_0	coefficient [kg/kg of dry adsorbent]
A_1	coefficient [kg/kg of dry adsorbent K]
A_2	coefficient [kg/kg of dry adsorbent K ²]
A_3	coefficient [kg/kg of dry adsorbent K ³]
B_0	coefficient in the isotherm equation [-]
B_1	coefficient in the isotherm equation [K ⁻¹]
B_2	coefficient in the isotherm equation [K ⁻²]
B_3	coefficient in the isotherm equation [K ⁻³]
A	area [m ²]
COP	coefficient of performance [-]
C_p	specific heat capacity [J·mol ⁻¹ ·K ⁻¹]
D	exponential constant [K ⁻¹]
D_{so}	pre-exponential constant [m ² ·sec ⁻¹]
E_a	activation energy [J·mol ⁻¹]
h	enthalpy [J·mol ⁻¹]
m	mass [kg]
m'	mass flow rate [kg·sec ⁻¹]
P	pressure [bar]
P_s	saturation pressure [bar]
Q	power [W]
R	gas constant [J·mol ⁻¹ ·K ⁻¹]
R_p	fiber radius [m]
T	temperature [°C]
t_{cycle}	cycle time [sec]
t	time [sec]

U	overall heat transfer coefficient [$\text{W}\cdot\text{m}^{-2}\cdot\text{K}^{-1}$]
x	instantaneous uptake [$\text{kg}\cdot\text{kg}^{-1}$]
x^*	equilibrium uptake [$\text{kg}\cdot\text{kg}^{-1}$]
x_0	limiting uptake [$\text{kg}\cdot\text{kg}^{-1}$]
E	characteristic energy [$\text{J}\cdot\text{mol}^{-1}$]
n	heterogeneity constant [-]
Δh_{st}	isosteric heat of adsorption [$\text{J}\cdot\text{mol}^{-1}$]

Subscript

<i>ads</i>	adsorption
<i>des</i>	desorption
<i>chill</i>	chilled water f liquid phase
<i>g</i>	gaseous phase
<i>h</i>	hot water
<i>in</i>	inlet
<i>out</i>	outlet
<i>w</i>	water
<i>ads</i>	adsorber
<i>bed</i>	sorption heat exchanger
<i>cond</i>	condenser
<i>eva</i>	evaporator
<i>Hex</i>	heat exchanger
<i>des</i>	desorber
<i>sg</i>	silica gel
<i>ref</i>	refrigerant
<i>V</i>	valve
<i>SE</i>	sorption element
<i>SEM</i>	Scanning Electron Microscope

CHAPTER 1

INTRODUCTION

1.0 INTRODUCTION

1.1 Background Study

In the last few decades, thermally driven adsorption cooling cycles have drawn the attention of several countries due to the increasing awareness of ozone depletion potential (ODP) problems. Thermally powered adsorption cooling cycle has the potential to replace CFCs and HCFCs existing in traditional compression refrigeration. The attractive features of these systems are; they can operate at low temperature driving source typically below 100°C, thus makes it possible to use solar energy and industrial waste heat as the driving heat sources. The adsorption based cooling systems are environmental friendly and simple in design as they do not have moving parts, require low electricity usage and generates no noise of vibration.

1.2 Problem Statement

1) The demand of power source

On nowadays development, the demand for the power energy source is highly concerned. Should be aware that the resources of fossil fuels are started to decrease from time to time. Thermal adsorption energy is the interesting answer to solve this problem. This concept is generally applicable to run the cooling system without consuming electrical power supply.

2) Utilization of low temperature heat waste

Thermal adsorption chiller has been proven that it can utilizes effectively low-temperature waste heat sources of temperature within the range of between 60°C and 95°C along with a coolant at 30°C.

1.3 Objective of Study

- 1) Conduct the analysis of the four beds adsorption chiller by employed silica gel as the adsorbent and water as the refrigerant with cooling capacity and coefficient of performance (COP) as the performance indicator.
- 2) Mathematical modelling of 4 beds single stage thermal adsorption chiller by MATLAB.
- 3) Comparing the performance of the four beds adsorption chiller with the two beds adsorption chiller in term of cooling capacity and coefficient of performance (COP).

CHAPTER 2: LITERATURE REVIEW

CHAPTER 3: METHODOLOGY

CHAPTER 4: RESULT &DISCUSSION

CHAPTER 5: CONCLUSION AND FUTURE WORK

CHAPTER 2

LITERATURE REVIEW

2.0 LITERATURE REVIEW

2.1 Concept of Adsorption

The ability of porous solids to adsorb large volumes of vapour was recognized in eighteenth century and early experiments were carried out by Scheele and Fontana[2] but the practical application of this property to the large-scale separation and purification of industrial process streams is relatively recent. The application of adsorption as a means of separating mixtures into two or more streams, each enriched in a valuable component which is to be, is a more recent development. Understanding of engineering design methods of adsorption system is an important aspect of process engineering design not only in chemical industry but also in the fields of environmental pollution control and energy utilization. Moreover, adsorption is coming to be regarded as a practicable separation method for purification or bulk separation in newly developed material production processes [3].

Early examples include the Arosorb process for recovery of aromatic hydrocarbons [4] which was introduced in early 1950s and variety of processes, first introduced in the early 1960s, for the separation of linear paraffins from branched and cyclic isomers. During 1970s there has been a significant increase in both the range and scale of such process. However for an adsorption process to be developed on a commercial scale requires the availability of a suitable adsorbent in tonnage quantities at economic cost. This stimulated fundamental research in adsorption and led to the development of new adsorbents. The early adsorption processes used either activated carbon or silica gel adsorbents but the potential of adsorption as a separation process was greatly enhanced by the development of molecular sieve adsorbent, especially the synthetic zeolites, which first became available a commercial scale in the late 1950s [5].

2.2 Project Overview

2.2.1 Adsorption Chiller

Adsorption chiller consist of 2 pair of sorption elements, an evaporator and a condenser. Adsorption is a process that occurs when a gas or liquid solute accumulates on the surface of a solid or a liquid, which forming a molecular component while desorption opposite to the adsorption. The function of the sorption element is to link up refrigerant vapour from the evaporator to the condenser. Refrigerant will be heat up in evaporator and turn out to be refrigerant vapour. From there, refrigerant vapour is adsorbed to the sorption element, switching the pressure to reach equilibrium level to be desorbed to the condenser. The desorbed refrigerant vapour is condensed in the condenser at temperature certain temperature while cooling water removes the condensation heat. This condensed refrigerant comes back to the evaporator via the tube connecting condenser and evaporator to complete the cycle.

The thermal adsorption cooling system is environmental friendly system that provides the alternative solution to vapour-compression cooling system. However, this concept is constrained by its low performance even though it is widespread applied. Advance studies have been proposed by the various authors for the purpose of improving the performance. Shelton et al. [9] applied thermal wave cycle with adsorber/desorber heat recovery by which heat losses are reduced in fixed-bed cycles Saha et al. [10,11] deliver study of capability of the three beds silica gel-water based adsorption to lower down the chilled water temperature. In comparison to the two-bed system that using the same refrigerant adsorbent, it manage to recover the waste heat that boosted up 35% efficiency. Saha et al. [12] develop for silica gel-water for the cooling applications for the hybrid system.

Relatively high or medium temperature heat source needed as driving mechanism for the adsorption cooling cycle. However, many researchers such as Saha et al. [13], Boelman et al. [13], Saha et. al. [14] and Li et al. [15] reported that relatively low, near-ambient temperature can drive silica gel-water and activated-carbon (AC)/methanol adsorption cooling systems. That gives explanation the waste heat below 100°C can be recovered and used. Saha et al. [16,17] emphasized the analysis of an advance dual-mode adsorption chiller. There are 2 operation modes by using silica gel-water as sorption element. The first operation mode work as high efficient single stage, where the driving source temperature between 60°C and 95°C with coolant of 30°C. The three-stage adsorption chiller is used in the second operation where the available driving source temperature between 40°C and 60°C with combination of coolant at 30°C. The construction of the system is rather complicated than expected.

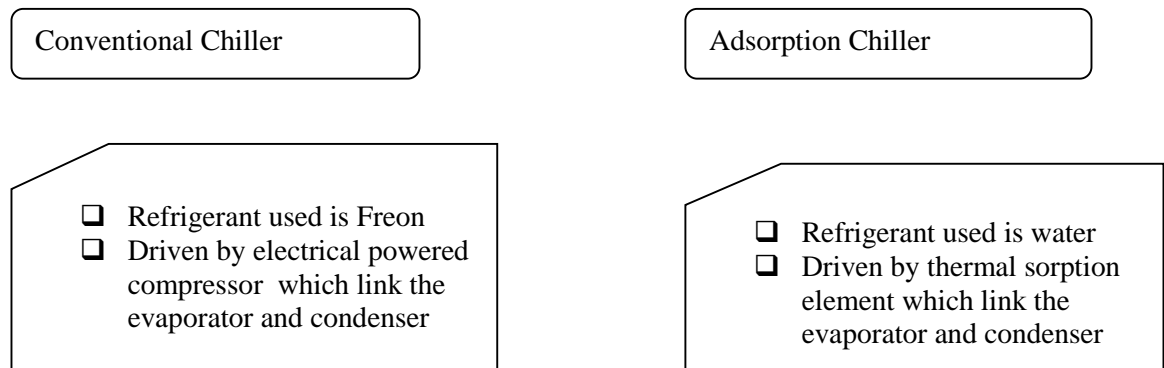


Figure 2.1: Comparison of conventional chiller and adsorption chiller studied in the present study

2.3 Operation of Single Stage four beds Adsorption Chiller

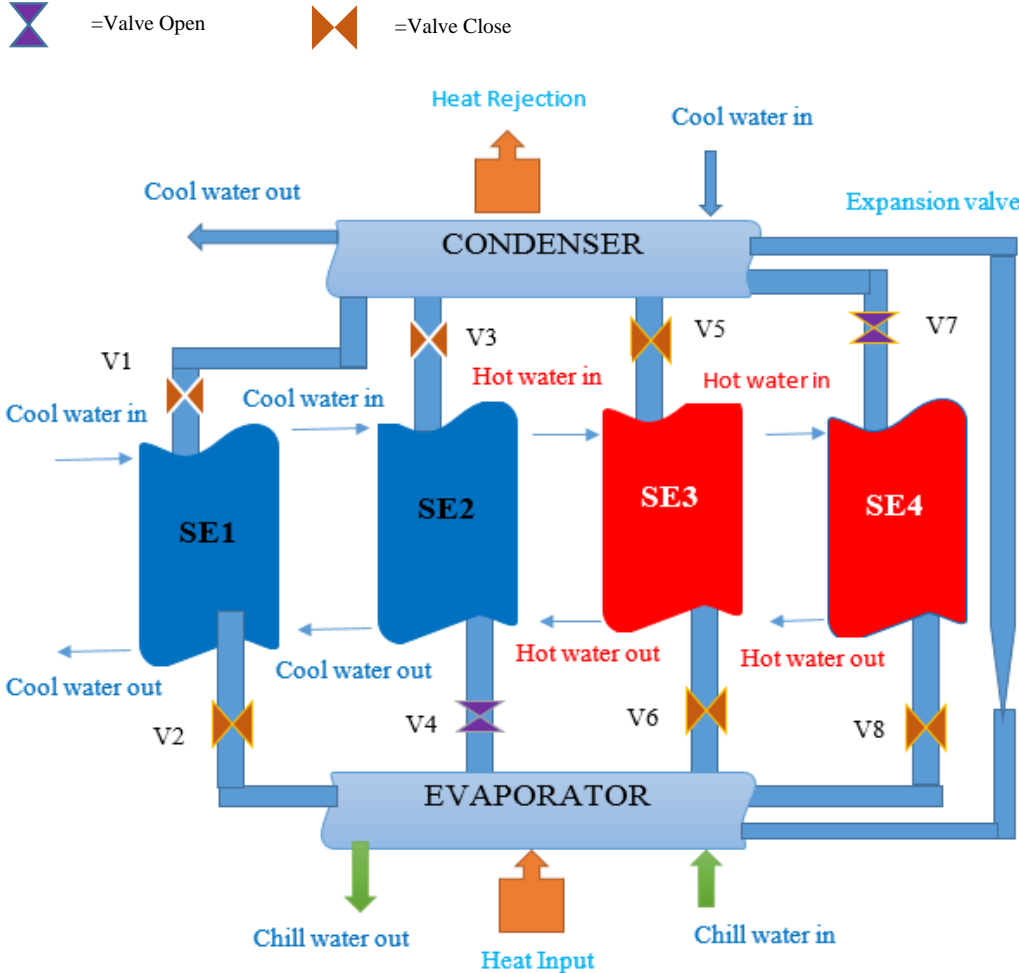


Figure 2.2: Single Stage Operation Mode A

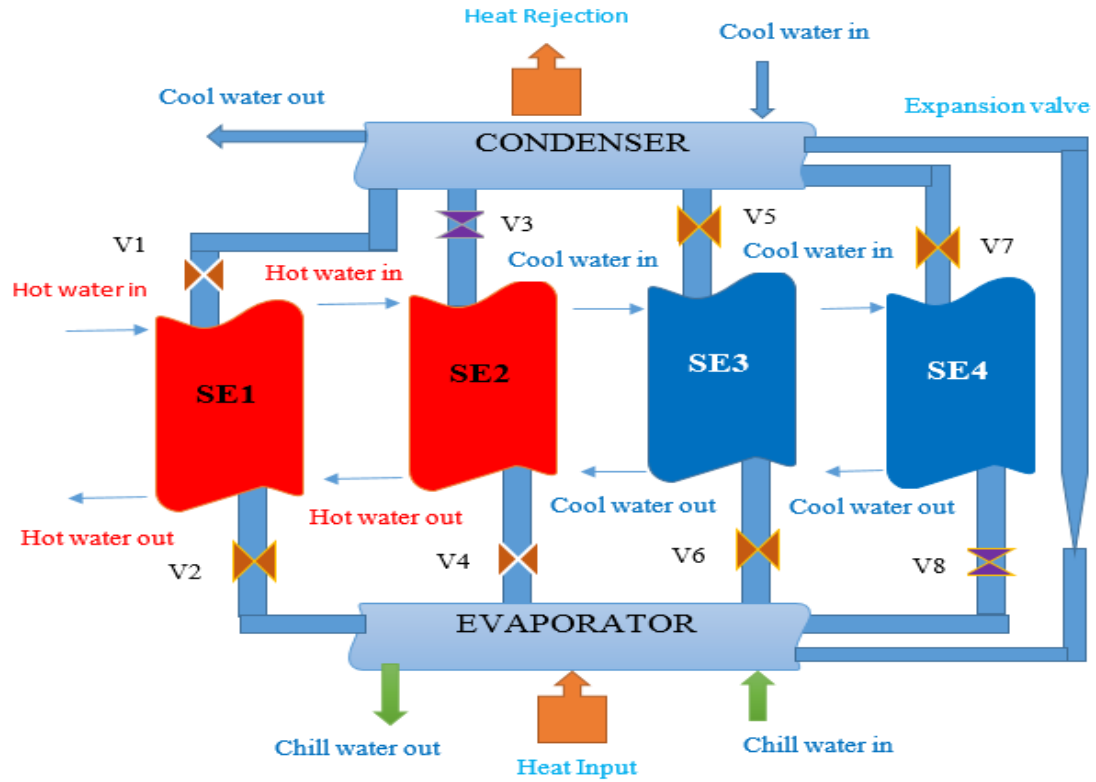


Figure 2.3: Single Stage Operation Mode C

Table 2.1: Operation Schedule

Cycle	Mode A	Mode B	Mode C	Mode D
SE 1	Pre Cooling V1 & V2 close	Adsorber V1 close & V2 open	Pre Heating V1 & V2 close	Desorber V1 open & V2 close
SE 2	Adsorber V3 close & V4 open	Pre Heating V3 & V4 close	Desorber V3 open & V4 close	Pre Cooling V3 & V4 close
SE 3	Pre Heating V5 & V6 close	Desorber V5 open & V6 close	Pre Cooling V5 & V6 close	Adsorber V5 close & V6 open
SE 4	Desorber V7 Open & V8 close	Pre Cooling V7 & V8 close	Adsorber V7 close & V8 open	Pre Heating V7 & V8 close

Figure 2.2 and 2.3 show the schematic diagram of the 4-bed adsorption cooling system which consists of a condenser, an evaporator, 4 sorption elements filled with silica gel as adsorbent. In this model, there are 4 modes to be considered to operate the thermal chiller which are called as Mode A, Mode B, Mode C, and Mode D. The cycle time allocated for the adsorber and desorber is 500 seconds while the period for pre heating and pre cooling is 30 seconds. All 4 sorption element will exchange their role on each specific period which are adsorber, desorber, pre heating and pre cooling.

Mode A

On this mode, SE1 and SE3 undergo pre cooling and pre heating, while SE2 and SE4 undergo adsorber and desorber. During pre heating and pre cooling, the SE1 and SE3 are isolated which mean valve $V1$, $V2$, $V5$, and $V6$ are closed. Therefore no movement of refrigerant in and out from the SE1 and SE3. As shown in the Table 2.1, valve $V3$, $V8$ are closed while valve $V4$, $V7$ are opened. In the adsorption-evaporation process (SE2) which takes place at pressure (P_{eva}), refrigerant in the evaporator is evaporated at evaporation temperature, (T_{eva}) and seized heat, (Q_{chill}) from chilled water. The evaporated refrigerant is as adsorbed by silica gel which is in the SE2 and cooling water removes the adsorption heat (Q_{ads}).

The desorption-condensation process takes place at pressure (P_{cond}) where the desorber (SE4) is heated to the desorber temperature (T_{des}) which is provided by the driving heat source (Q_{des}). The resulting refrigerant vapor is cooled down to temperature (T_{cond}) in the condenser by cooling water, which removes condensation heat, (Q_{cond}) and the warm condensate is refluxed back to the evaporator through a pressure reduction valve to maintain pressure difference between the condenser and the evaporator.

Mode B

When the refrigerant concentrations in the SE2 (adsorber) and SE4 (desorber) are at or near their equilibrium levels, the cycle is continued by changing into a short durations (30 sec) for pre heating and pre cooling, where all refrigerant valves, V3, V4, V7, and V8 remain closed.

When the pressures of adsorber and desorber are nearly equal to the pressures of evaporator and condenser, respectively, then valve V2 and V5 are opened to allow the flow of refrigerant from SE3 to condenser and from evaporator to SE1. In this case, valve V1 and V6 are closed during this mode. SE1 and SE3 are changed to adsorber and desorber.

Mode C

On Mode C, the role of the SE1, SE2, SE3, and SE4 is opposite of what happen in Mode A, where they interchange each other as shown in Figure 4. SE1 and SE3 undergo pre heating and pre cooling, while SE2 and SE4 undergo desorber and adsorber. During pre heating and pre cooling, the SE1 and SE3 are isolated which mean valve V1, V2, V5, and V6 are closed. Therefore no movement of refrigerant in and out from the SE1 and SE3. As shown in the Table 2.1, valve V3, V8 are opened while valve V4, V7 are closed.

In the adsorption-evaporation process (SE4) which takes place at pressure (P_{eva}), refrigerant in the evaporator is evaporated at evaporation temperature, (T_{eva}) and seized heat, (Q_{chill}) from chilled water. The evaporated refrigerant is as adsorbed by silica gel which is in the SE4 and cooling water removes the adsorption heat (Q_{ads}). The desorption-condensation process takes place at pressure (P_{cond}) where the desorber (SE2) is heated to the desorber temperature (T_{des}) which is provided by the driving heat source (Q_{des}). The resulting refrigerant vapor is cooled down to temperature (T_{cond}) in the condenser by cooling water, which removes condensation heat, (Q_{cond}) and the warm condensate is refluxed back to the evaporator through a pressure reduction valve to maintain pressure difference between the condenser and the evaporator.

Mode D

On Mode C, the role of the SE1, SE2, SE3, and SE4 is opposite of what happen in Mode A, where they interchange each other as shown in Table 3.1. When the refrigerant concentrations in the SE2 (desorber) and SE4 (adsorber) are at or near their equilibrium levels, the cycle is continued by changing into a short durations (30 s) for pre heating and pre cooling, where all refrigerant valves, V3, V4, V7, and V8 remain closed.

When the pressures of adsorber and desorber are nearly equal to the pressures of evaporator and condenser, respectively, then valve V1 and V6 are opened to allow the flow of refrigerant from SE1 to condenser and from evaporator to SE3. In this case, valve V2 and V5 are closed during this mode. SE1 and SE3 are changed to desorber and adsorber.

2.4 Practical Adsorbents

The required for adequate adsorptive capacity restricts the choice of adsorbent for practical separation processes to microporous adsorbents with pore diameters ranging from a few Angstrom to a few tens of Angstroms. This includes both the traditional microporous adsorbents such as silica gel, activated alumina, and activated carbon as well as the more recently developed crystalline alumina silicates or zeolites. There is however a fundamental difference between these materials. In the traditional adsorbents there is a distribution of micropore size, and both the mean micropore diameter and the width of the distribution about this mean are controlled by the manufacturing process. By contrast, the micropore size of a zeolitic adsorbent is controlled by the crystal structure and there is virtually no distribution of pore size. This lead to significant differences in the adsorptive properties, and it is therefore convenient to consider the zeolities and other crystalline adsorbents such as the aluminium phosphate molecular sieves as a separate class of adsorbents. In this project, silica gel is selected to be the adsorbent.

2.4.1 Silica Gel

Silica gel is partially dehydrated form of polymeric colloidal silicic acid. The chemical composition can be expressed as $\text{SiO}_2 \cdot n\text{H}_2\text{O}$. The water content, which is present mainly in the form of chemically bound hydroxyl groups, amounts typically to about 5 wt.%. The material appears first to have been developed during the First World War for use in gas masks although in this service it proved inferior to activated carbon [6]. A variety of methods for the manufacture of silica gel have been described including the hydrolysis of soluble alkali metal silicates with acid[7] and the direct removal of sodium from sodium silicate solutions by ion exchange[8].



Figure 2.4: Photograph of silica gel

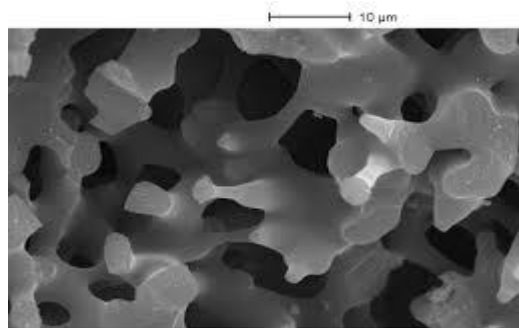


Figure 2.5: SEM Photograph of silica gel

Silica Gel is selected due the following reasons:

1. Provide the advantage in term of higher adsorption capacity due to the high internal pore volume.
2. Fast adsorption rate, high porosity and ease of handling

Table 2.2: Properties of Silica Gel

Physical and Chemical Properties	
Appearance	Transparent bead
Odour	None
Solubility	Insoluble
Boiling Point	2980°C
Melting Point	>1000°C
Bulk Density	400-900 kg/m ³
pH	Approximately 4
Stability and Reactivity	
Stability Data	Stable up to 823 °C. Above this temperature Amorphous Silica will transform into Crystalline Silica
Hazardous Decomposition Products	Fresh material: None anticipated Used material: In case of fire the adsorbed gases and vapours can be set free.
Polymerization	Will not occur
Incompatibility	This material is a desiccant and can absorb water or organic liquids and vapours with some generation of heat.
Polymerisation	None anticipated

CHAPTER 3 METHODOLOGY

3.0 METHODOLOGY

3.1 Project Flow Chart

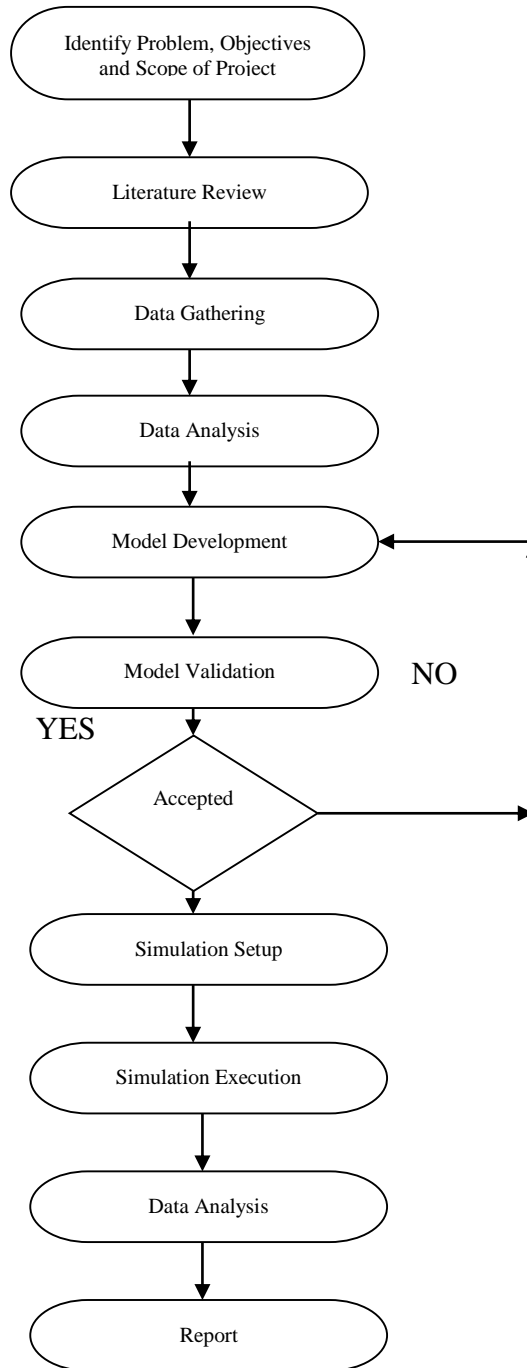


Figure 3.1: Project Flow Chart

3.2 Key Milestone

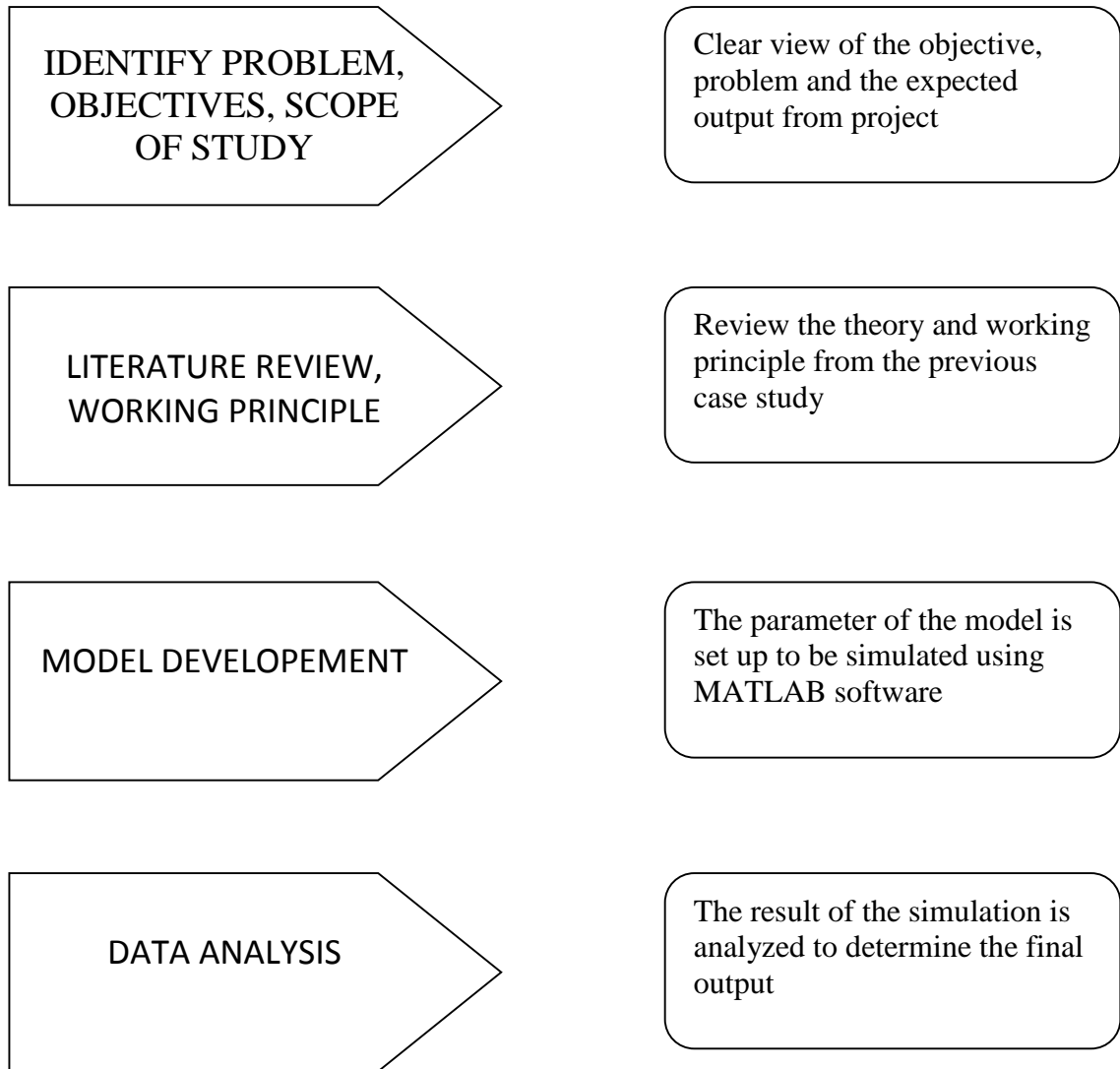


Figure 3.2: Key Milestone

3.3 Final Year Project Gantt Chart

3.3.1 Final Year Project 1

No	Detail	1	2	3	4	5	6	7		8	9	10	11	12	13	14	
1	Selection of Project Topic	█	█						Mid-Sem break								
2	Preliminary Research Work		█	█	█	█											
3	Submission of Extended Proposal						█										
4	Proposal Defense										█	█					
5	Project Work Continues												█	█	█		
6	Submission Interim Draft Report															█	
7	Submission Interim Report																█

Figure 3.3: Final Year Project 1 Gantt Chart

3.3.2 Final Year Project 2

No	Detail	1	2	3	4	5	6	7		8	9	10	11	12	13	14
1	Project Work Continues	■	■	■	■	■	■	■								
2	Submission of Progress Report									■						
3	Project Work Continues									■	■	■	■	■	■	
4	Pre-SEDEX											■				
5	Submission of Draft Report												■			
6	Submission of Dissertation (soft bound)													■		
7	Submission of Technical Paper													■		
8	Oral Presentation														■	
9	Submission of Dissertation (hard bound)															■

Figure 3.4 : Final Year Project 2 Gantt Chart

CHAPTER 4

RESULT & DISCUSSION

Table 4.1: Values Adopted in Simulation Cycle

Symbol	Value	Unit
D_{so}	2.5E-4	[m ² /s]
E_a	4.2E4	[J/mol]
R_p	1.7E-4	[m]
A_o	-6.5314	[kg/kg of dry adsorbent]
A_1	0.72452E-1	[kg/kg of dry adsorbent K]
A_2	-0.23951E-3	[kg/kg dry adsorbent K ²]
A_3	0.25493E-6	[kg/kg dry adsorbent K ³]
B_o	-15.587	[-]
B_1	0.15915	[K ⁻¹]
B_2	50612E ⁻²	[K ⁻²]
B_3	0.53290E-6	[K ⁻³]
$m_w',_{cooling}$	1.52	[kg/s]
$m_w',_{heating}$	1.28	[kg/s]
$m',_{chilled}$	0.71	[kg/s]
$m',_{cond}$	1.37	[kg/s]
$U_{cooling}$	1602.56	[W/m ² K]
$U_{heating}$	1724.14	[W/m ² K]
$U_{chilled}$	2557.54	[W/m ² K]
U_{cond}	4115.23	[W/m ² K]
A_{bed}	2.46	[m ²]
A_{eva}	1.91	[m ²]
A_{cond}	3.73	[m ²]
m_{sg}	47	[kg]
m_{hex}, C_p	77719.4	[kJ/K]
m_{eva}, C_p	4805.7	[kJ/K]
m_{cond}, C_p	9372.08	[kJ/K]

4.0 RESULT & DISCUSSION

4.1 Mathematical Modelling

4.1.1 Adsorption Isotherms

In the current chiller model, the rate of adsorption or desorption is governed by the linear driving force kinetic equation:

$$\frac{dx}{dt} = 15 \frac{D_{sO} e^{\frac{E_a}{RT}}}{R_p^2} (x' - x) \quad (4.1)$$

Where the coefficient are determined by Chirara and Suzuki, and x' is given by the following empirical isotherm equation which is based on the manufacturer's proprietary data which is shown below:

$$x' = A(T_{sg}) \left[\frac{P_{sat}(T_{ref})}{P_{sat}(T_{sg})} \right]^{B(T_{sg})} \quad (4.2)$$

Where

$$A(T_{sg}) = A_0 + A_1 T_{sg} + A_2 T_{sg}^2 + A_3 T_{sg}^3$$

$$B(T_{sg}) = B_0 + B_1 T_{sg} + B_2 T_{sg}^2 + B_3 T_{sg}^3$$

4.1.2 Adsorption and Desorption Energy Balance

The adsorption and desorption process which comprises silica gel, the heat exchanger fins and tubes, the energy balance equation is given by,

$$\begin{aligned} & \left[(m_{sg}C_{p,sg} + m_{sg}C_{p,ref} x) + (m_{hex}C_{p,Cu} + m_{hex}C_{p,Al}) \right] \frac{dT_{bed}}{dt} \\ & = \delta m_{sg}(\Delta h_{st}) \frac{dx_{bed}}{dt} - (\dot{m}_w C_{p,w})(T_{w,out} - T_{w,in}) \end{aligned} \quad (4.3)$$

The rate of change of internal energy is shown by the left hand side of adsorber/desorber energy balance equation Eq. (4.4) due to the thermal mass of adsorbents and the refrigerant (water) and adsorber/desorber heat exchanger during adsorption and desorption. During adsorption process or the input of desorption heat during desorption process, the heat release of adsorption or desorption process are represent by the first term on the right hand side of Eq. (4.4). The second term on the right hand side of Eq. (4.4) defines the total amount of heat released to the cooling water upon adsorption or provided by the hot water for desorption. The flag $\delta=0$ is for switching operation and $\delta=1$ represent the process during adsorption/desorption cycle operation.

For a small temperature difference across heating/cooling fluid such as water, the bed water outlet temperature can be modelled by the log mean temperature difference (LMTD) method and it is given by,

$$T_{w,out} = T_{bed} + (T_{w,in} - T_{bed}) \exp \left[\frac{-(UA)_{bed}}{(\dot{m}Cp)_w} \right] \quad (4.4)$$

4.1.3 Evaporator Energy Balance

The evaporator energy balance most likely involve with the interactions of the evaporator and adsorption bed. The properties of the mass, heat and liquid condensate coming from the evaporator need to be consider as well. The energy balance equation of the evaporator can be expressed as,

$$\begin{aligned}
 & [m_{ref,eva}C_{p,eva} + m_{eva}C_{p,Cu}] \frac{dT_{eva}}{dt} \\
 & = -\delta h_{fg,ads} m_{sg} \frac{dx_{ads}}{dt} - (\dot{m}_{chill} C_{p,chill})(T_{chill,out} - T_{chill,in}) \quad (4.5) \\
 & + \delta m_{sg} C_{p,ref} T_{cond} \frac{dx_{des}}{dt}
 \end{aligned}$$

The left hand side of Eq. (4.6) relates the interaction of sensible heat of liquid refrigerant and metal of the heat exchanger tubes that result in change of internal energy in the evaporator. On the right hand side, the first term is latent heat of evaporation for the amount of refrigerant adsorbed; the second term represents the cooling capacity of the evaporator. The last term shows the sensible heat required to cool down the incoming condensate from condensation temperature (T_{cond}) to evaporation temperature (T_{eva}). The chiller water outlet temperature can be modelled by the log mean temperature difference (LMTD) method and it is given by,

$$T_{chill,out} = T_{eva} + (T_{chill,in} - T_{eva}) \exp \left[\frac{-(UA)_{eva}}{(\dot{m}Cp)_w} \right] \quad (4.6)$$

4.1.4 Condenser Energy Balance

The condenser energy balance most likely involve with the interactions of the condenser and desorption bed. The desorber release the vapour refrigerant which liquefied by condenser. Moreover, the condenser will channel the condensate refrigerant to evaporator through pressure reduction valve. The energy balance of the condenser can be expressed as,

$$\begin{aligned}
 m_{cond}C_{p,Cu} \frac{dT_{cond}}{dt} &= \delta h_{fg,des} m \frac{dx_{des}}{dt} - \dot{m}_w C_{p,w} (T_{w,out} - T_{w,in}) \quad (4.7) \\
 &\quad - \delta m_{sg} C_{p,ref} T_{cond} \frac{dx_{des}}{dt}
 \end{aligned}$$

The left hand side of eq. (4.8) represents the rate of change of internal energy of the metallic tubes of the heat exchanger. Latent heat of vaporization is shown on the first term on right hand side eq. (4.8) when the refrigerant is desorbed during desorption. The second term gives the total amount of heat released to the cooling water. When the liquid condensate leaves the condenser for the evaporator, there will be amount of heat that carries away which is represents by the last term of eq. (4.8). The condenser water outlet temperature can be modelled by the log mean temperature difference (LMTD) method and it is given by,

$$T_{w,out} = T_{cond} + (T_{w,in} - T_{cond}) \exp \left[\frac{-(UA)_{cond}}{(\dot{m}Cp)_w} \right] \quad (4.8)$$

4.1.5 Mass Balance

The rate of change of mass of refrigerant is equal to the amount of refrigerant adsorbed and desorbed during adsorption and desorption process. The mass balance of refrigerant in the adsorption chiller is expressed by,

$$\frac{dm_{ref}}{dt} = -m_{sg} \left[\frac{dx_{bed,des}}{dt} + \frac{dx_{bed,ads}}{dt} \right] \quad (4.9)$$

The roles of beds (containing the adsorbent) are changed by switching which is performed by reversing the direction of the cooling and heating fluids to the designated sorption beds and similarly, the evaporator and condenser are switched to the respective adsorber and desorber. Should be noted that no mass transfer occurs between the hot bed and the condenser or the cold bed and the evaporator during the switching interval. The cycle average cooling capacity cycle chill Q_{chill}^{cycle} and COP are represent as,

$$Q_{chill}^{cycle} = \frac{1}{t_{cycle}} \int_0^{t_{cycle}} (\dot{m}C_p)_{chill} (T_{chill,in} - T_{chill,out}) dt \quad (4.10)$$

$$COP = \frac{\int_0^{t_{cycle}} (\dot{m}C_p)_{chill} (T_{chill,in} - T_{chill,out}) dt}{\int_0^{t_{cycle}} (\dot{m}C_p)_{chill} (T_{h,in} - T_{h,out}) dt} \quad (4.11)$$

Here t_{cycle} denotes total cycle time.

4.1.6 Simulation Procedure

The simulation procedure starts with the initialization of:

1. Constant (isotherm equation constants, kinetics constants and components' geometry)
2. Variables (hot, cooling and chilled water inlet temperatures and adsorption/desorption cycle times)
3. Estimated initial values of differential equation parameters (T_{bed1} , T_{bed2} , T_{bed3} , T_{bed4} , T_{eva} , T_{cond})

The system design constants and kinetics constants used in the simulation are furnished by the given parameter. The simulation of the system transient response is carried out with MATLAB and the solving of the differential equations is carried with the built in function ODE45 for solving ordinary differential equations. The key system variables are constantly computed and updated by numerical integration with time.

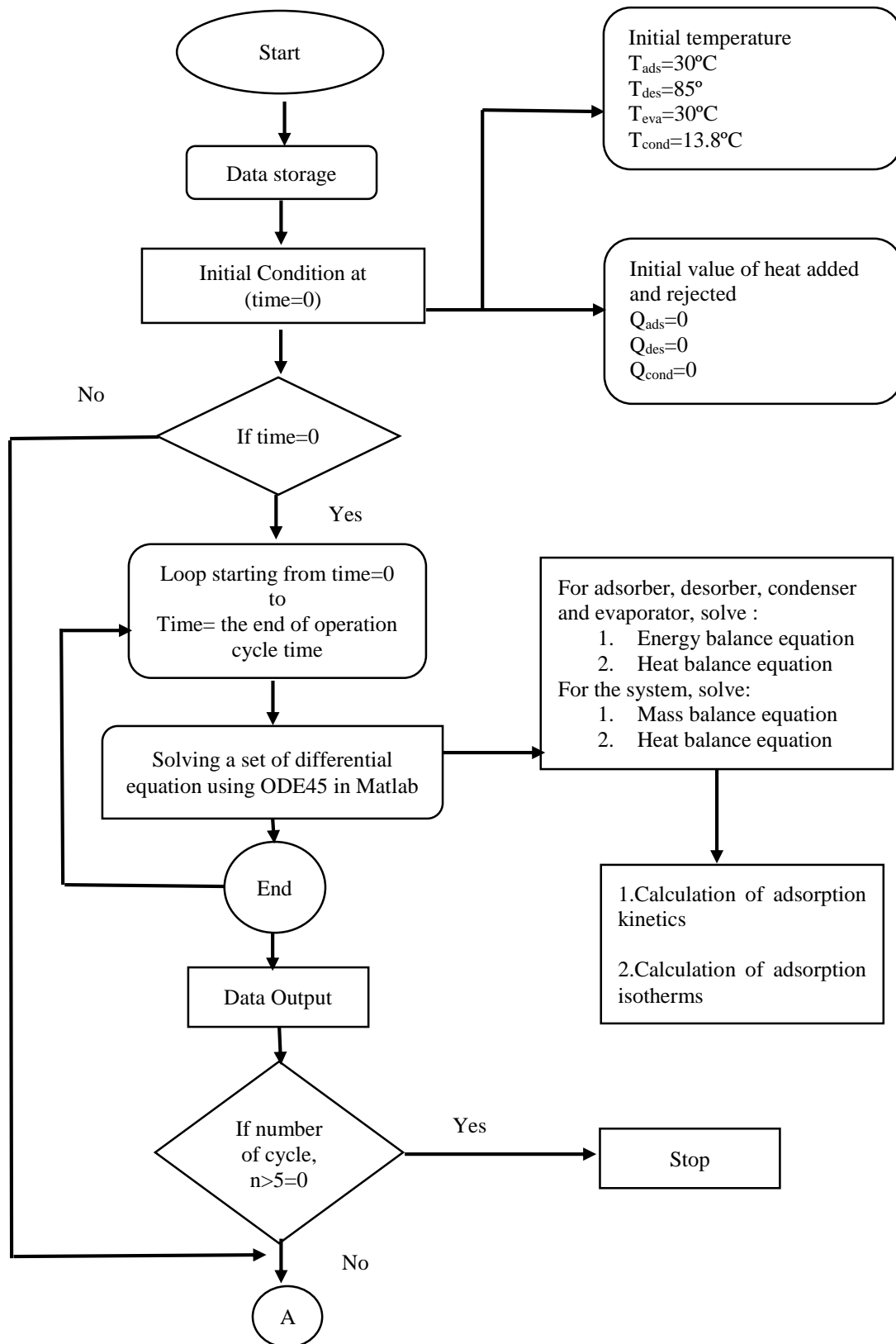


Figure 4.1: Flow Chart of Simulation Program

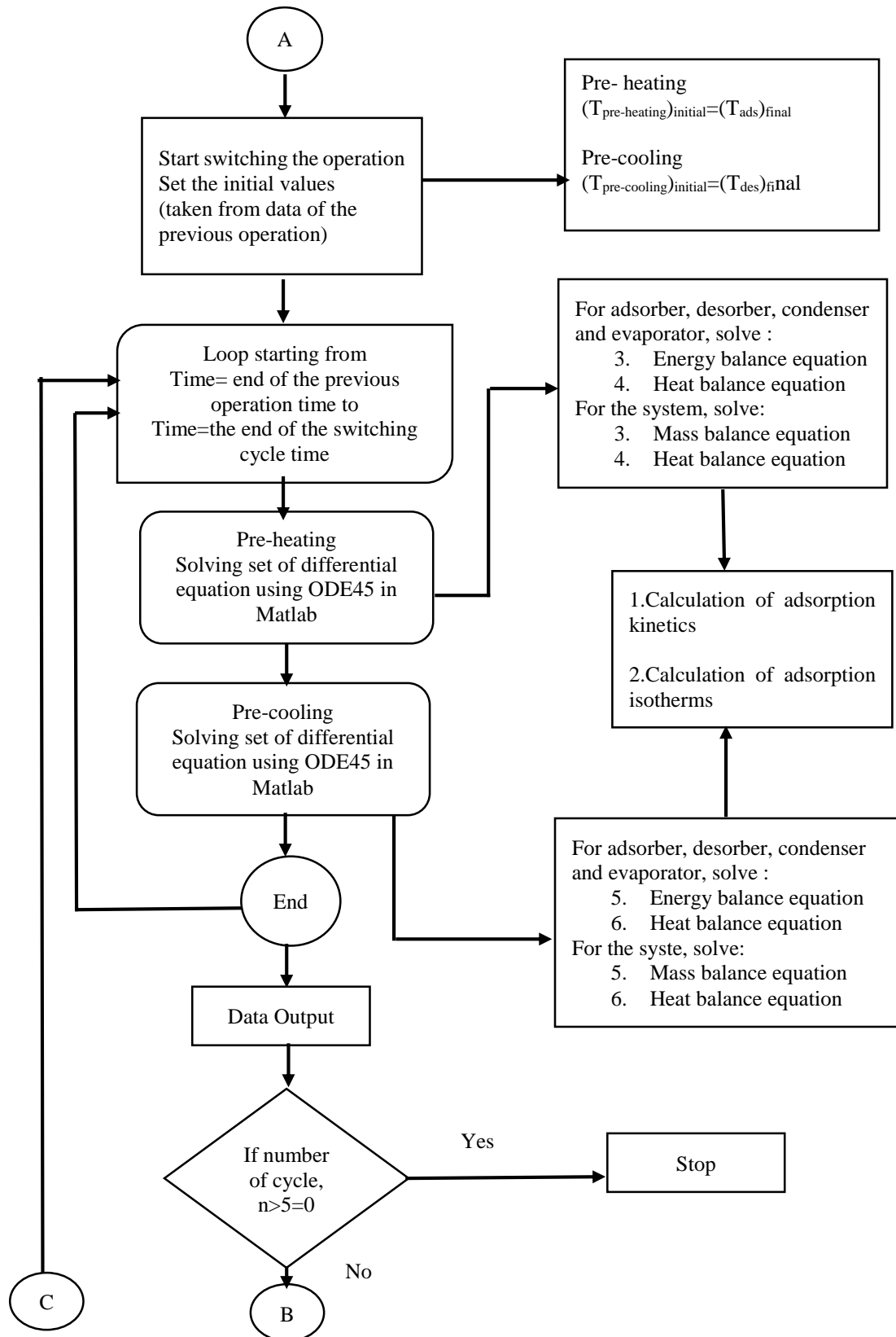


Figure 4.1 :Continued.

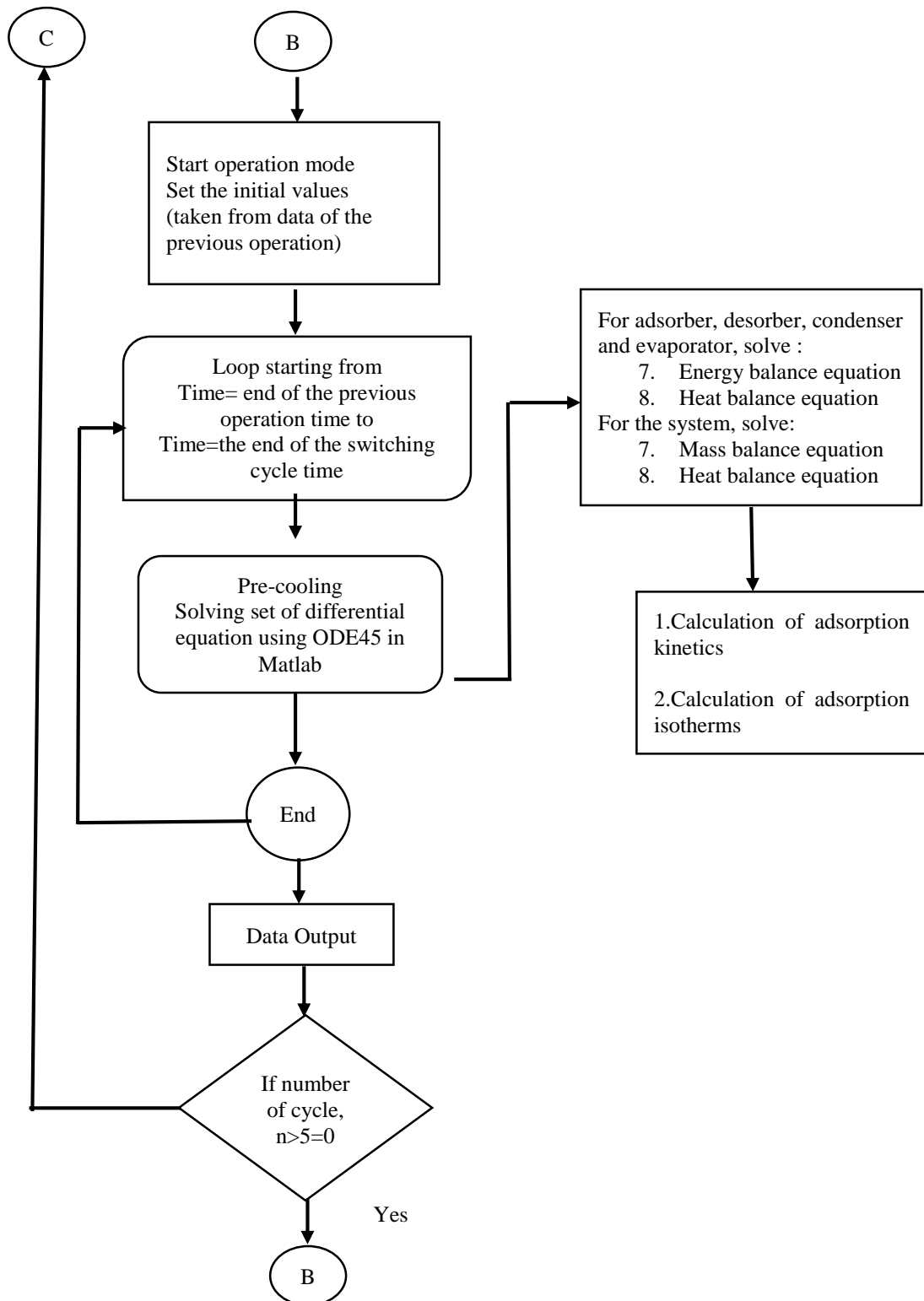


Figure 4.1 :Continued.

4.2 Critical Analysis

4.2.1 Chiller Transient Response

Figures 4.1 show the chiller response with the variation of temperature for the adsorber, desorber, condenser and evaporator for silica gel thermal sorption chiller systems by mathematical modelling, presented by Matlab Simulation. Table 4.1 depicts the standard conditions used for silica gel cycle by using water as the adsorbent. Hot and cooling water inlet temperatures for the systems are taken as 85 and 30°C, respectively. The chilled water inlet temperature has been taken as 13.8°C for the evaporator. From Figure 4.1, can be observed that the cycles are able to reach from transient to nearly steady state within three half cycles or 1800 s, where adsorption/desorption cycle time is taken as 600 s and switching time is taken as 30 s. Figure 4.2 depict the outlet temperature variation for heat transfer fluids for the cycle. The cooling water outlet temperature from the adsorber as shown in Figure 4.2 is about 1°C higher than the cooling water inlet temperature. It is can be observed from Figure 4.2 that the hot water outlet temperature from the desorber is about 2°C lower than the hot water inlet temperature.

Table 4.2: Standard Rated Condition

Refrigerant	Hot water inlet		Cooling water inlet		Chilled water inlet	
	Temperature (°C)	Flow rate (kg/sec)	Temperature (°C)	Flow rate (kg/sec)	Temperature (°C)	Flow rate (kg/sec)
Water	85	1.28	30	1.25	13.8	0.71
Adsorption/desorption cycle time : 600 sec			Switching time for both cycles : 30 sec			

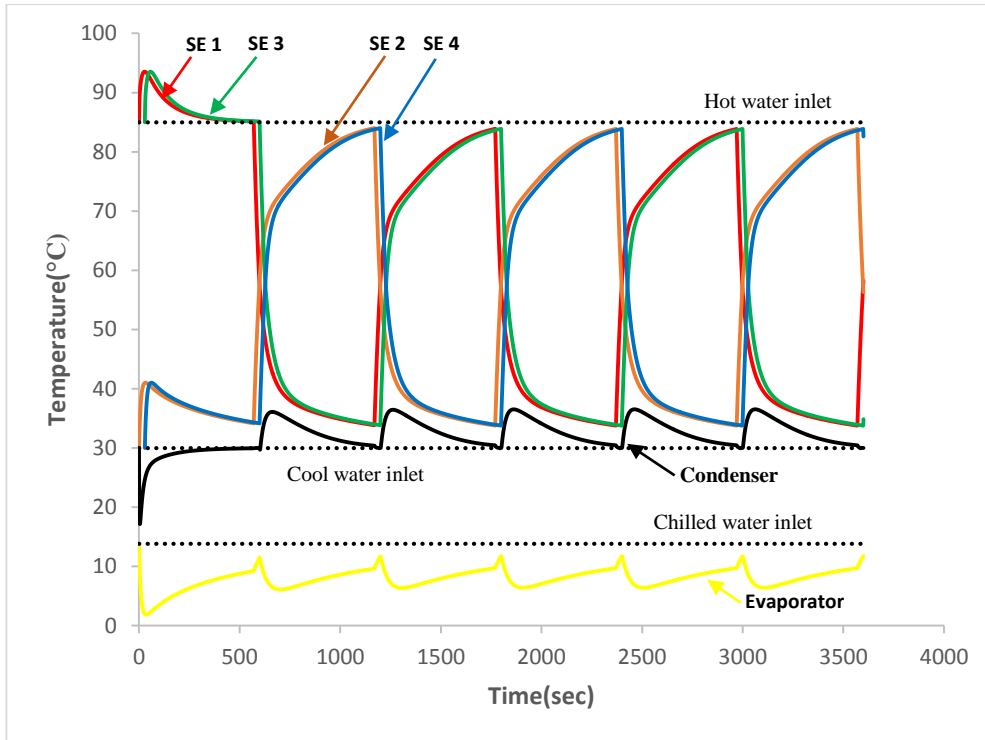


Figure 4.2: Temperature profile for adsorption chiller

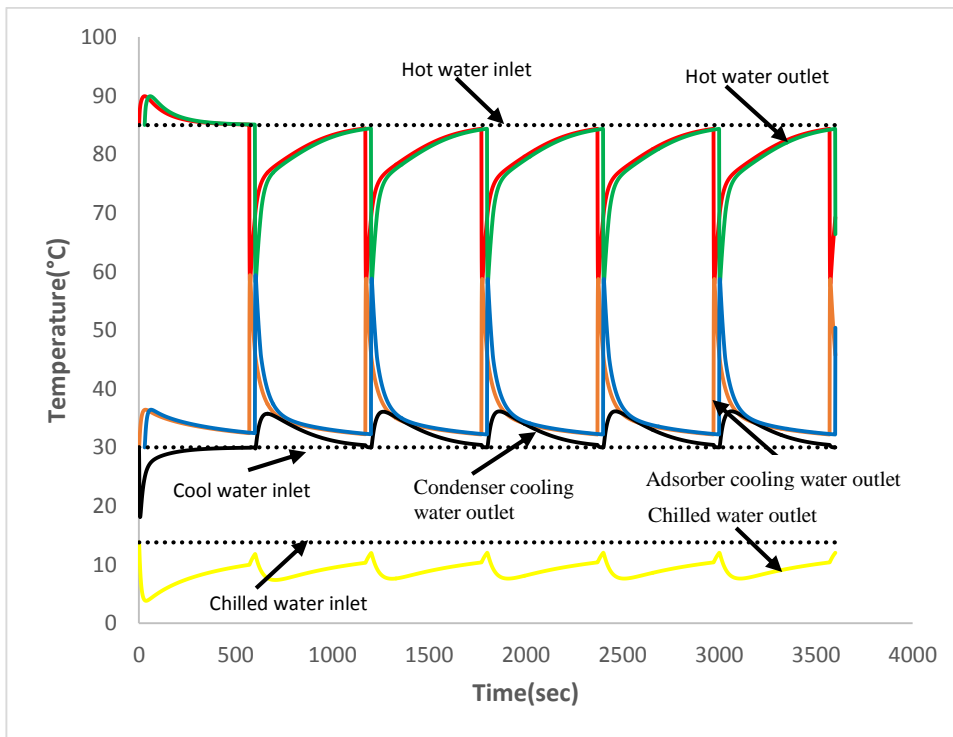


Figure 4.3: Outlet temperature variation

4.2.2. Adsorption/Desorption Cycle Time

Figure 4.3 shows the simulated result for the effect of the adsorption/desorption cycle on the cooling capacity and COP for this chiller system, for the standard operating conditions of heat transfer fluid temperatures and flow rates. As stated in Table 4.2, switching (pre-heating and pre-cooling) time is considered as 30 s. From the Fig. 4.3, it is observed that the highest cooling capacity is around 14kW, respectively for cycle times between 300 and 350 s. When the cycle times are shorter than 300 s, there is not enough time for adsorption/desorption to occur satisfactorily. As a results, the cooling capacity decreases abruptly. On the other hand, when cycle times are longer than 400 s, the cooling capacity decreases gradually due to the less intense of adsorption after the first 10 min as the adsorbent reaches towards equilibrium or near equilibrium. From the Figure 4.3, it is noted that the COP increases uniformly for both the systems with longer adsorption/desorption cycle time and after reaching a certain value (around 1100 s) it becomes steady. This is due to the fact that the lower consumption of driving heat allows longer duration cycles. The optimum value of COP is achieved for both the cycles when the adsorption/desorption cycle time is between 800 to 1000 s which is the value of COP is 0.5.

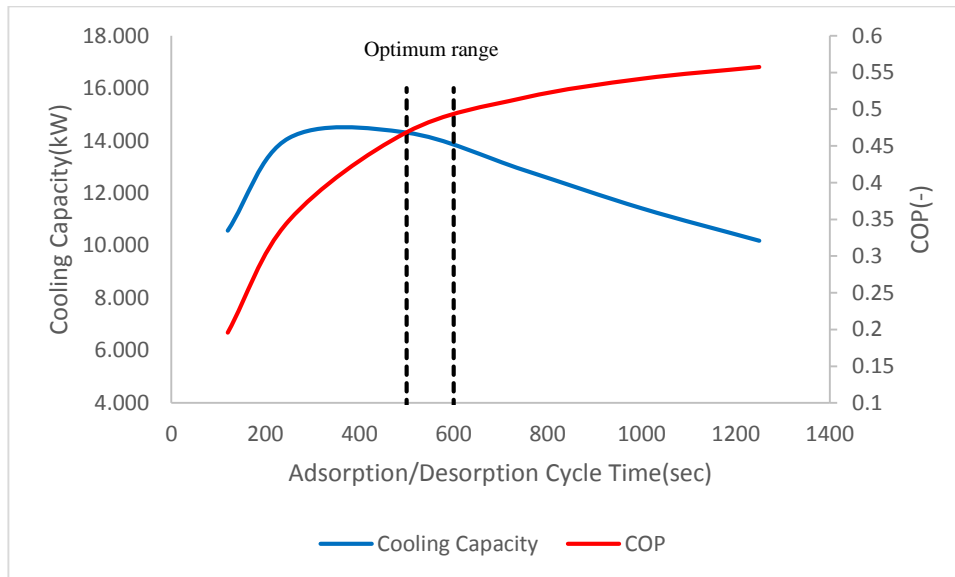


Figure 4.4: Adsorption/Desorption cycle time effect on COP and cooling capacity

4.2.3. Switching Time

The switching time has always been an integral part of adsorption chiller operation. But rather than immediately connect the saturated cold bed to the condenser, and the regenerated hot bed to the evaporator, a period of isolated, near-isosteric thermal swing is necessary. The condensing will not be hampered if the saturated cold bed is immediately connected to the condenser as the condensate in the condenser can evaporate and easily maintain the saturated pressure. But a premature connection between the regenerated hot bed and the evaporator would translate into momentary desorption of adsorbed refrigerant and undesirable reduction in instantaneous cooling power. Figure 4.4 shown the effects of switching time on cooling capacity and COP for this model. As it can be seen from Figure 4.4, the cooling capacity increases with the increase of switching time from 10 s to 28 s with maximum cooling capacity of 13.77kW. However started from 28 s, the gradient of graph is decreasing with respect to the time afterward. In Figure 4.4 the COP increases moderately during the switching time from 10 s to 32 s and after reaching optimum range at 32 s of 0.4914, the COP for the cycle started to decrease. The optimum value of switching time for the cycle is around 30 s.

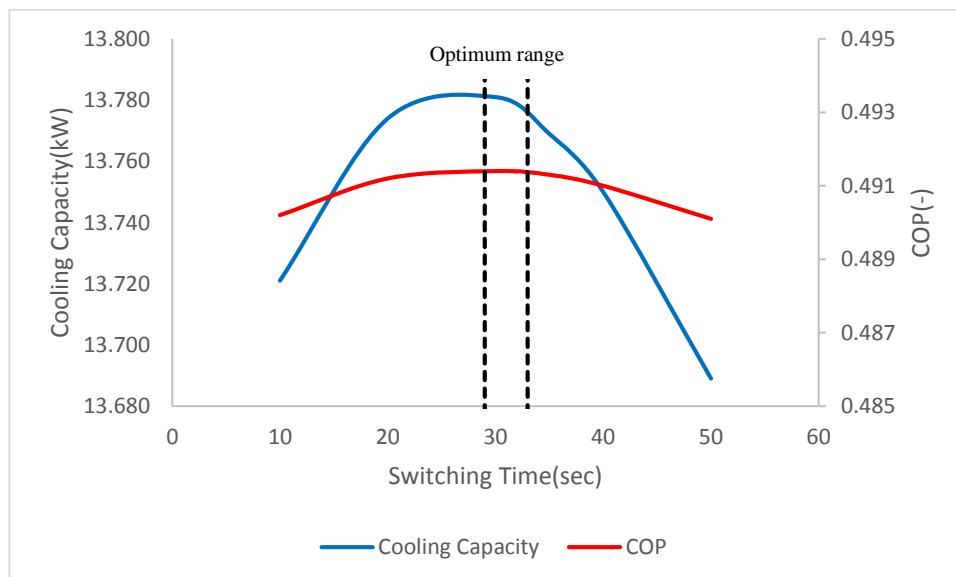


Figure 4.5: Switching time effect on COP and cooling capacity

4.2.4. Heat Source Temperature

The effect of the operating temperature on the cooling capacity and COP for both 4 beds and 2 beds are demonstrated in the Figure 4.5 with fixed cooling water and chilled water inlet temperatures. Heat transfer fluid flow rates and cycle times are taken as the rated values as shown in Table 4.2. From Figure 4.5, it is noticeable that the cooling capacity for both cycles increases linearly from 8kW to 14kW with the range of operating temperature of 65°C to 95°C as manipulated variable. This is due to the fact that the amount of refrigerant circulation increases when the amount of desorbed refrigerant increases with the higher driving heat source temperature. There are not much difference in term cooling capacity for both cycle. For the 2 beds cycle, it is noted that after 80 s, the gradient of the cooling capacity decrease and become steady. For 4 beds cycle, the gradient of the graph is constant until 85 s indicate that 4 beds cycle has higher cooling capacity compare to 2 beds cycle.

The simulated COP values of the system is also shown in the Figure 4.5 on secondary axis, rises with the different operating temperature and it reaches a peak value of 0.495 between 70°C to 80°C. After the temperature of 80°C, the COP value is decreasing. The lower value of COP for operating temperature is at 55°C which also indicates lower cooling capacity. For 2 beds cycle, it reaches the peak of 0.47 at the temperature of 80°C, then after that started to decrease. The COP of 2 beds is lower compare to 4 beds is due to the low capacity of adsorbent being injected to the system for the purpose of heat transfer. The optimum value for both COP and cooling capacity acquired when the operating temperature is between 70 to 80°C in combination with the coolant inlet temperature at 30°C.

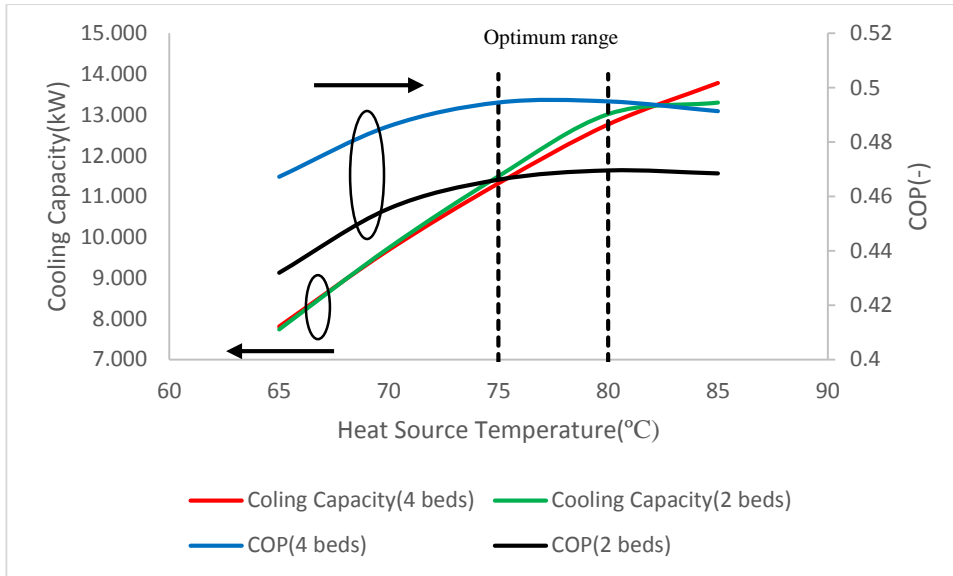


Figure 4.6: Heat source temperature effect on COP and cooling capacity

4.2.5. Chilled Water Temperature

The effects of chilled water inlet temperature for the cycle is shown in Figure 4.6, with fixed hot and cooling water inlet temperatures. It is observable from Figure 4.6 that the cooling capacity increase with the rise of chilled water inlet temperature where the chilled water inlet temperature is varying from 5 to 30°C. It is also observable that the COP also increases with the increase of chilled water inlet temperature from 5 to 30°C. At 30°C, the maximum cooling capacity and COP are achieved with 26kW and 0.6.

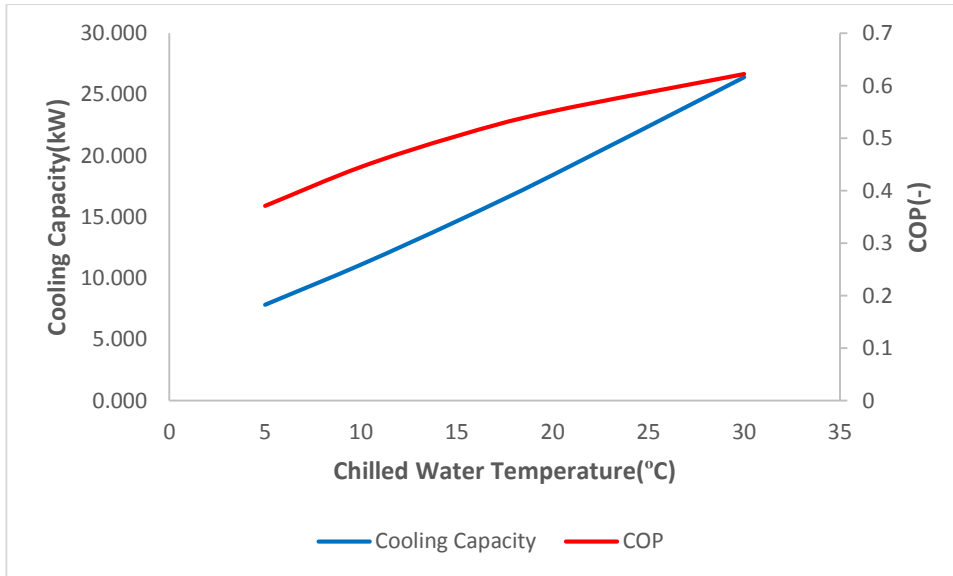


Figure 4.7: Chilled water temperature effect on COP and cooling capacity

4.2.6. Heat Transfer Fluid Flow Rates

4.2.6.1 Hot Water Flow Rates

The effects of hot water flow rate on cooling capacity and COP for the cycle is shown in Figure 4.7. It is noticeable that the cooling capacity for the cycle increases when the flow rate of hot water increase until 1.5 kg/sec with cooling capacity of 13.8kW. After that, with the increase of hot water flow rate, the cooling capacity becomes steady with slightly increase the value of cooling capacity. It is visible from Figure 4.7 that the COP for the cycle decrease when the flow rate of the hot water increase from 0.5 kg/sec to 2.5 kg/sec.

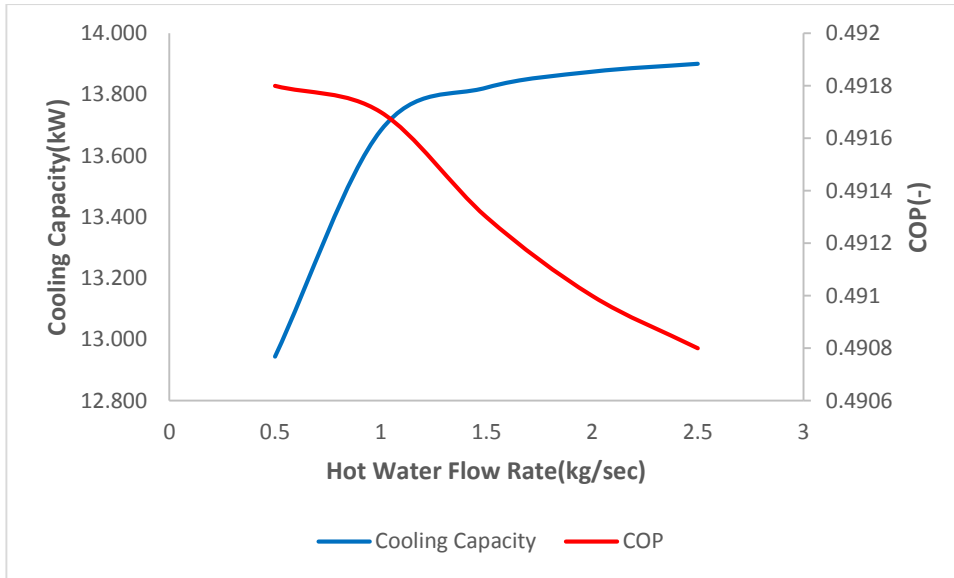


Figure 4.8: Hot water flow rate effect on COP and cooling capacity

4.2.6.2 Chilled Water Flow Rates

The chilled water effect on cooling capacity and COP for the cycle is shown in Figure 4.8. The cooling capacity for the system is increase with the increase of chilled water flow rates until it reaches the peak value of 15 kW at flow rate of 1 kg/sec. After that, with the increase of chill water flow rate, the cooling capacity becomes steady. It is visible from Figure 4.8 that the COP also increases with the rise of chilled water inlet temperature until it reaches the peak value of 0.5 at flow rate of 1 kg/sec. After that, with the increase of chill water flow rate, the cooling capacity becomes steady.

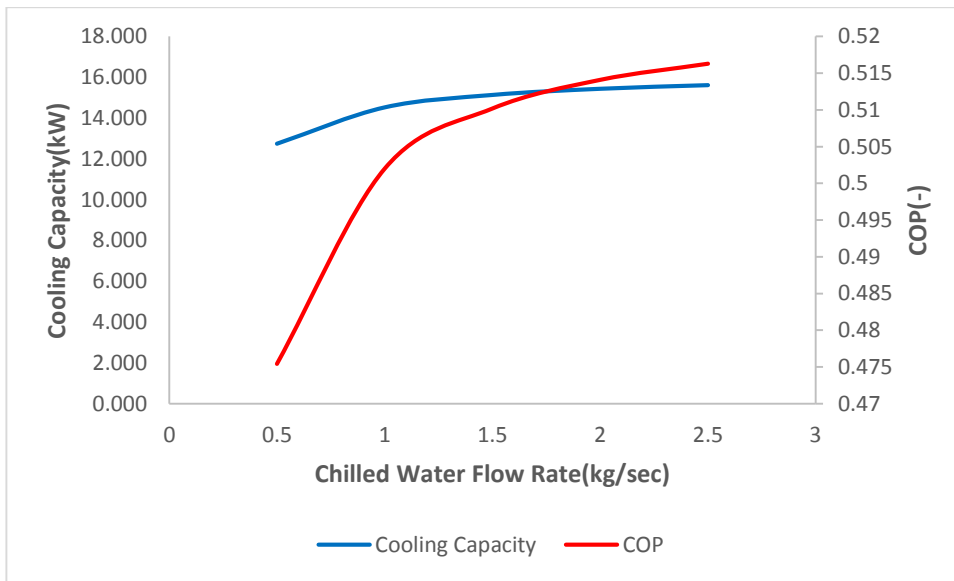


Figure 4.9: Chilled water flow rate effect on COP and cooling capacity

CHAPTER 5

CONCLUSION & RECOMMENDATIONS

After spending nearly eight months with the final year project, finally the project is successfully done. Most of the time in final year project is allocated with the project research and software simulation to make sure that the desired model meet the requirement and improvised from the previous model. Finally, the project is successfully done and the objective is achieved. The project was initiated from a problem statement which arises from the incomplete function of the single stage 2 beds thermally sorption chiller which to increase the performance and efficiency. With the objectives as explained in the introduction part, this research is relevance to be carried out. Previous research papers have been done on evaluating the performance and simulation of the single stage thermally sorption chiller.

As the performance of the previous study thermal chiller rise up with uncertainties in seasonal restriction, a method of improving the performance in its constraints should be developed. Therefore the single stage 4 beds mode sorption developed from this project is the perfect solution to enhance the performance of thermally driven sorption chiller.

In order to improve the project execution and simulation result, there are several recommendations that need to be considered which are:

1. Application of other software other than Matlab, such as Prosper. The results from both software can be compared for further analysis.
2. Hypothetical data can be obtained from previous studies or technical books related to drilling fluid design to improve the result of the research.
3. The coding of the simulation can be develop based on previous design to saves time constructing the simulation and enable better analysis of the result.

The main advantage in the thermally adsorption cycle is its ability to utilize effectively low-temperature waste heat sources. This innovative project has a significant market potential as it can be used as the bottoming cycle of existing power generation cycles. From the above perspectives, the use of unexploited low-temperature waste heat may offer an attractive possibility for improving energy efficiency.

REFERENCES

- [1] Retrieved from <http://www.grace.com/engineeredmaterials/MaterialSciences/SilicaGel/SilicaGelTypes/SilicaGelTypeAdsorption.aspx>
- [2] J. W. McBain, The Sorption of Gases and Vapours by Solids, 1932, Chap.5.
- [3] Motoyuki Suzuki, Adsorption Engineering, "Introduction", (1989), 1-2.
- [4] W.H. Davis, J.I. Harper, and E.R. Weatherly, "Petroleum Refiner 31".
- [5] Motoyuki Suzuki, Adsorption Engineering, "Porous Adsorbents", (1989), 23-25
- [6] Motoyuki Suzuki, Adsorption Engineering, "Porous Adsorbents", (1989), 26-30
- [7] C.L. Mantell, Adsorption. McGraw-Hill, New York, (1951), Chap. 9.
- [8] V. Ponc, Z.Knor, and S.Cerny, Adsorption on Solids, Butterworth and Co-, London, (1974), Chap. 14.
- [9] S.V. Shelton, W.J. Wepfer, D.J. Miles, Square wave analysis of the solid evaporation adsorption heat pump, "Heat Recovery Systems and CHP", (1989) 223-247.
- [10] B.B. Saha, S. Koyama, J.B. Lee, K. Kuwahara, K.C.A. Alam, Y. Hamamoto, A. Akisawa, T. Kashiwagi, Performance evaluation of a low-temperature waste heat driven multi-bed adsorption chiller, International Journal of Multiphase Flow 29 (8), (2003) 1249-1263.
- [11] B.B. Saha, I.I. El-Sharkawy, S. Koyama, J.B. Lee, K. Kuwahara, Waste heat driven multi-bed adsorption chiller: heat exchangers overall thermal conductance on chiller performance, "Heat Transfer Engineering", 27 (5) (2006) 80-87.

[12] B.B. Saha, A. Chakraborty, S. Koyama, K.C. Ng, M.A. Sai, Performance modelling of an electro-adsorption chiller, "Philosophical Magazine", 86 (23) (2006) 3613-3632.

[13] Boelman, E., Saha, B.B. and Kashiwagi, T., "Experimental Investigation of a Silica Gel Water Adsorption Refrigeration Cycle, "The Influence of Operating Conditions on Cooling Output and COP", ASHRAE Transactions: Research, Vol. (101)(1995)358-366.

[14] Saha, B.B., Akisawa, A. and Koyama, S., (Editors), Thermally Powered Sorption Technology, (2003).

[15] Li, M., Huang, H.B., Wang, R.Z., Wang, L.L., Cai, W.D. and Yang, W.M., "Experimental Study on Adsorbent of Activated Carbon with Refrigerant of Methanol and Ethanol for Solar Ice Maker", Renewable Energy, Vol. 29(2004) 2235-2244.

[16] B.B. Saha, S. Koyama, T. Kashiwagi, A. Akisawa, K.C. Ng, H.T. Chua, Waste heat driven dual-mode, multi-stage, multibed regenerative adsorption system, International Journal of Refrigeration 26 (7) (2003) 749-757.

[17] B.B. Saha, S. Koyama, K.C. Ng, Y. Hamamoto, A. Akisawa, T. Kashiwagi, Study on a dual-mode, multi-stage, multi-bed regenerative adsorption chiller, "Renewable Energy 31", (13) (2006) 2076-2090