KAUNAS UNIVERSITY OF TECHNOLOGY

FACULTY OF MECHANICAL ENGINEERING & DESIGN

Mihir Chaudhari

INVESTIGATION OF ADSORPTION CHILLERS CONNECTED IN SERIES

Final project for Master degree

Supervisor
Prof. Dr. Vytautas Grigas

KAUNAS, 2016

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Reviewer
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KAUNAS UNIVERSITY OF TECHNOLOGY

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Mechanical Engineering & Design (621H30001)

(Title and code of study programme)

INVESTIGATION OF ADSORPTION CHILLERS CONNECTED IN SERIES

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MASTER STUDIES FINAL PROJECT TASK ASSIGNMENT
Study programme MECHANICAL ENGINERING - 621H30001

Approved by the Dean's Order No.V25-11-7 of May 3rd, 2016 y

Assigned to the student

Mihir Chaudhari

(Name, Surname)

1. Title of the Project

Investigation of Adsorption Chillers connected in series

2. Aim of the project

To improve the Coefficient of Performance of the adsorption cooling process realized by two zeolite based adsorption chillers in series connection.

3. Tasks of the project

1. Analysis of thermal heat transfer process in zeolite based adsorption chiller.
2. Development based on the stratisorp concept in the adsorption cooling machinery & integration of the chillers in series to improve the cooling efficiency of the cycle.
3. Experiments with double adsorption and analysis of the results.
4. Experiments with advanced control strategies to maximize the potential of CCHP application.

4. Specific Requirements

1. CAD Design of the stratified storage tank with stratification rings based on the stratisorp concept.
2. Development of modified test setup with a heating & cooling module, 2 zeolite based adsorption chillers, cooling load unit and implementation of 4 way valve.
3. Mat Lab simulation of the experimental data for new test setup.

5. This task assignment is an integral part of the final project

6. Project submission deadline: 2016 May 20th

Task Assignment received Mihir Chaudhari

(*Name, Surname of the Student*) (*Signature, date*)

Supervisor Dr. Vytautas Grigas

(*Position, Name, Surname*) (*Signature, date)*

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Mihir Chaudhari

Nomenclatures

Abbreviations

COP	Coefficient of Performance
CHP	Combined Heat & Power
CCHP	Combined Cooling, Heating & Power

Symbols

Symbol	Units	Description
P	[mbar]	Pressure
T	[ºC]	Temperature
Q	[J]	Heat received / rejected
$R_1 ... R_6$		Stratification rings from 1 to 6
SW		Switching Valves
COP_{cool}		Coefficient of Performance for cooling
COP_{heat}		Coefficient of Performance for heating
Q_{cooler}	[J]	Heat rejected in the cooling module from the tank
Q_{heater}	[J]	Heat supplied by the heating module
$Q_{evaporator}$	[J]	Heat absorbed in the evaporator
$Q_{condenser}$	[J]	Heat rejected by condenser in the cooling module
V_h	[lph]	Heating module flow rate
V_c	[lph]	Cooling module rate circulating through the tank
$V_{c, tot}$	[lph]	Total flow rate of cooling module
V_{ad}	[lph]	Adsorber flow rate
V_{ev}	[lph]	Evaporator flow rate
V_{cond}	[lph]	Condenser flow rate
V_1 , V_2		3 way valves

$T_{ad,i}$, $T_{ad,o}$	[ºC]	Temperature of supply and return flow from adsorber
$T_{h,i}$, $T_{h,o}$	[ºC]	Temperature of supply and return flow from heater
$T_{c,i}$, $T_{c,o}$	[ºC]	Temperature of supply and return flow from cooler
$T_{ev,i}$, $T_{ev,o}$	[ºC]	Temperature of supply and return flow from evaporator
ΔT_{ad}	[K]	Temperature spread across the adsorption chiller
$Q_{cooling}$	[W]	Cooling Power
$Q_{heating}$	[W]	Heating Power
Q_{ads}	[J]	Adsorber power during adsorption half cycle
Q_{des}	[J]	Desorber power during desorption half cycle

Indices

Index	**Description**
ads	Adsorber
cond	Condenser
des	Desorber
ev	Evaporator
h	Heater
c	Cooler
i	Inlet
o	Outlet

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SUMMARY

Cooling is used in many aspects of human life. Adsorption chiller saves energy by using waste heat to address refrigeration and / or air conditioning needs. The end users includes food and beverage processors, universities, hospitals, chemical processors, other manufactures and large government facilities. The zeolite based adsorption chiller is an equipment that is used to provide the cooling effect in the cooling plants. These chillers can generate cold even at relatively low drive temperatures from 50 ºC and up. The zeolite based adsorption chillers are suitable for heat sources like waste heat due to lower regeneration temperature required.

The aim of the master‘s thesis is to improve the performance of the zeolite based adsorption chillers. One of the study is to investigate the adsorption cooling process that facilitates the operation of zeolite based adsorption chillers connected in series based on the stratisorp concept, by the use of the stratified thermal storage tank for the thermal heat recovery. According to the stratisorp concept of heat recovery, the heat of adsorption released during the adsorption half cycle is stored in a stratified thermal storage tank for later use in desorption half cycle thereby achieving internal heat recovery. The adsorber module is cooled and heated by extracting water from the stratified thermal storage tank. The existing setup consists of single adsorption chiller. The mixing taking place in the tank during the extraction and insertion of the fluid adversely affects the performance of the adsorption chiller cycle.

The key goal of this work is at improving the cooling COP of the zeolite based chillers to maximize the potential of the CCHP application using the stratisorp concept by integration of the second adsorption chiller in series. The work presents the practical study of the cycle efficiency, which may lead to improve the performance of the cooling process.

Keywords: *Zeolite based Adsorption chillers, Stratisorp concept, Thermal heat recovery.*

Chaudhari, M. Nuosekliai sujungtų adsorbcinių aušintuvų tyrimas. Mechanikos inžinerijos magistro baigiamasis projektas / vadovas prof. dr. Vytautas Grigas; Kauno Technologijos Universitetas, Mechanikos Inžinerijos ir dizaino fakultetas, Mechanikos inžinerijos katedra.

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SANTRAUKA

Aušinimas arba šaldymas yra svarbus daugelio įvairių techninių sistemų aspektas. Šaldymo ir/ar oro kondicionavimo sistemose naudojant adsorbcinius aušintuvus galima sumažinti šaldymui eikvojamos energijos sąnaudas panaudojant išmetamą šilumą. Tokio tipo įranga naudojama itin plačiai: maisto ir chemijos pramonės įmonėse, energetikoje, visuomeninėse, švietimo ir gydymo įstaigose ir kt. Daugelyje pramonės įmonių naudojami adsorbciniai aušintuvai su ceolito (Zeolite) užpildu. Jie gali generuoti šaltį net esant santykinai aukštoms temperatūroms (nuo 50 ºC ir daugiau). Ceolito Dėl mažesnės regeneravimui reikalingos temperatūros adsorbciniai aušintuvai su ceolitu ypač tinka siekiant panaudoti šilumos energiją, išsiskiriančią kaip šalutinis produktas veikiant įvairiems technologiniams įrenginiams ar šildymo/ventiliacijos sistemoms.

Šio magistro darbo tikslas – pagerinti adsorbcinių aušintuvų su ceolito užpildu šaldymo efektyvumą. Vienas svarbiausių tyrimo uždavinių yra ištirti adsorbcinius aušinimo procesus, vykstančius Stratisorp tipo adsorbciniuose aušintuvuose su ceolitu (įskaitant ir keleto nuosekliai sujungtų aušintuvų sistemas) kaip šilumos atgavimo įrenginius (rekuperatorius) panaudojant sluoksninio tipo šilumos energijos kaupiklius. Pagal šilumos atgavimo Stratisorp koncepciją adsorbcijos šiluma, išskiriama adsorbcinio ciklo metu, yra saugoma sluoksninio tipo šilumos energijos kaupiklyje ir vėliau panaudojama desorbcijos ciklo metu tokiu būdu atgaunant dalį vidinės šilumos energijos. Šiuo metu naudojamose sistemose yra tik vienas toks (adsorbcinis) aušintuvas. Adsorberių modulis yra šaldomas arba šildomas jį pripildant vandeniu arba išgaunant vandenį iš sluoksninio šilumos energijos kaupiklio. Šių procesų metu terpės maišosi, kas neigiamai veikia adsorbcinio aušinimo įrenginio su ceolito užpildu efektyvumą.

Jam padidinti (pagerinti naudingumo koeficientą) pasiūlyta aušinimo sistemoje nuosekliai įmontuoti antrą adsorbcinį aušintuvą. Tokio sprendimo efektyvumas patikrintas sukūrus eksperimentinio tyrimo stendą ir atlikus tyrimus bei patikrinamuosius skaičiavimus.

Raktininiai žodžiai: *adsorbciniai aušintuvai su ceolito užpildu; Stratisorp koncepcija; šilumos energijos kaupiklis.*

TABLE OF CONTENTS

INTRODUCTION

Global Warming is the primary problem of too much of carbon dioxide in the atmosphere, which acts as a blanket and traps the heat. The problem of global warming has been in serious discussion throughout the world and all social elements are becoming more and more concerned about solving it. As we burn fossil fuels like coal, oil and natural gas for energy, carbon gets accumulated and overloads the atmosphere [16]. Certain waste management practices aggravate the problem by releasing other potential global warming gases. In order to achieve the global goal of CO_2 emission reduction, energy efficiency must be strongly improved. One step in that direction is to reduce the dependence on primary energy sources such as fossil fuel energy and promote the use of renewable energy source.

The heat driven chillers offer a promising option in the light of world's global warming problem. The mechanical driven heat pump is the most commonly used and commercially feasible heat pump. Inside the heat pump, pressure of the refrigerant is increased with use of the compressor. Due to this increase in pressure, the condensation temperature increases. Most of the installations have an electric motor to drive the compressor. The mechanical heat pump that operates on electrical energy has poor primary energy efficiency. The mechanical moving parts (e.g. compressor) are prone to wear with time and hence regular maintenance becomes essential. As a consequence of these facts the thermally driven heat pumps have gained popularity in the recent years [17].

The thermally driven sorption pumps (absorption and adsorption) possess better primary energy efficiency and therefore in future will give a relevant contribution to save primary energy consumption and carbon dioxide emissions. Thermally driven heat pumps, due to their efficient energy use, are also able to contribute to reduce the environmental impact of heating and cooling. Besides eliminating the environmental problems caused by the conventionally used compression heat pumps, the biggest advantage of the thermally driven heat pumps reveals the fact that the provision of heating and cooling is predominantly drawn from ambient energy (using a low temperature driving energy). In addition to the heat recovery they also offer a cost effective operational system and advantages like lack of moving parts, lack of noise and vibrations and less maintenance. They also enable the use of waste heat originating from various processes. One of the most important thermally driven processes is adsorption cooling process. Worldwide the interest in the thermally driven heat pumps and cooling machines is continuously increasing. Improvement in the adsorption chiller's cooling *COP* has been a topic of research since many years [21].

Aim

The aim of the thesis is to improve the coefficient of performance of the adsorption cooling process realized by the zeolite based adsorption chillers in series connection.

Goal

The goal of this work is on the development of the adsorption cooling machinery based on the stratisorp concept in the thermal storage tank. To achieve the maximum cooling power by integration of double adsorption chillers in series.

Task

1. Analysis of thermal heat transfer process in zeolite based adsorption chiller.

2. Development based on the stratisorp concept in the adsorption cooling machinery & integration of the chillers in series to improve the cooling efficiency of the cycle.

3. Experiments with double adsorption and analysis of the results.

4. Experiments with advanced control strategies to maximize the potential of CCHP application.

Thesis Structure

Chapter 1 demonstrates the literature review at the preliminary stage which focus on the adsorption chillers, their industrial role and attributes.

Chapter 2 provides the thermodynamics of the thermally driven heat pump. The adsorption and desorption half cycles are explained in detail. The stratisorp concept developed by Schmidt is discussed. The role of a stratified thermal storage tank for thermal heat recovery is presented. The research study of the implementation of this concept in the experimental setup is the key point of this chapter.

Chapter 3 provides the experimental layout of the single adsorption chiller and modified test set up with double adsorption chillers connected in series. Various experiments are discussed in detail by explaining different components. Variation in the physical parameters are demonstrated and the cycle effects are discussed with the plots obtained from the simulation of the experimental data.

Chapter 4 discuss the variations in the control strategies implemented in the set up. Here the performance of the cycle along with the improvement in the cooling *COP* with the advanced control strategies from the test set up are documented.

1. LITERATURE SURVEY

Adsorption chillers are effective as a stand-alone system as an enhancement to the HVAC system or as a replacement technology to a current chiller system. By deploying these chillers previously unused process heat can be turned in to the cold in an efficient and energy saving manner. The equipment reaches very high level of effectiveness by utilizing existing heat, saving on electricity costs and the reduction of CO_2 emissions. The end users includes food and beverage processors, universities, hospitals, chemical processors, other manufactures and large government facilities.

Adsorption chiller attributes:

- Long life (more than 20 years)
- Use waste heat or solar thermal
- No replacement of adsorbent
- Simple mechanical construction

In the field of the cooling equipment adsorption cooling machinery are widely used with refrigerant as silica gel. The test facility of the cooling machinery consists of three main sections:

1. Adsorption chamber with pipings, where actual adsorption takes place.
2. Dosing chamber with piping, whose purpose is to provide a measurable amount of refrigerant to the adsorption chamber.
3. Evaporator chamber with piping.

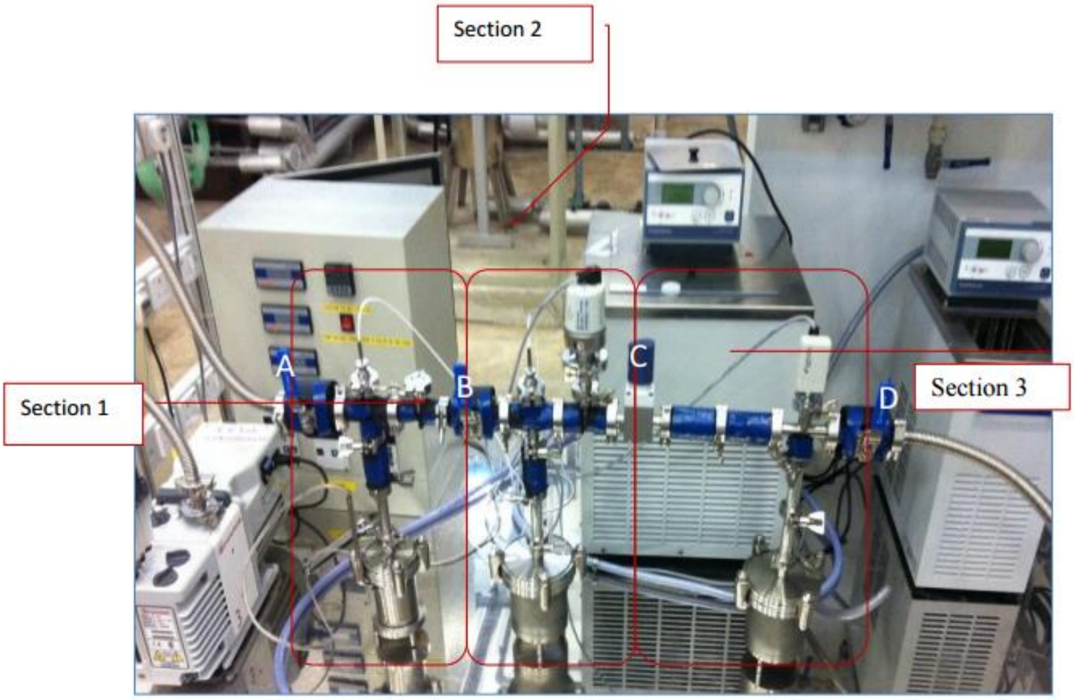

Figure 1.1: Adsorption cooling machinery with refrigerant [32]

1.1 Adsorption

Adsorption is the adhesion of atoms, ions or molecules from the gas, liquid or dissolved solid to the surface. This process creates a film of the adsorbate on the surface of the adsorbent. Adsorption is the surface based process. It is different from absorption in which a substance diffuses in to a liquid or a solid to form a solution. The term desorption is exactly opposite process to adsorption while sorption covers both adsorption and desorption [11].

Adsorbent: The process of adsorption involves separation of a substance from one phase accompanied by its accumulation or concentration at the surface of another. The separating agent used here is called as the adsorbent. Most commonly used adsorbents used are Alumina, Silica Gel, Zeolite (4A), Zeolite X and Y, Active carbon, Carbon molecular sieves, etc.

Adsorbate: During adsorption, the substance, which gets adsorbed by the adsorbent, is called the adsorbate. Thus the adsorbent holds the molecules of the adsorbate, which is essentially al liquid or a solid substance.

In adsorption heat pump process useful heat is produced by the condensation of the refrigerant. Before this process, the refrigerant in the evaporator is evaporated at lower pressure using low temperature heat source [9].

The adsorber element is a copper tube with zeolite foil stuck on its outer surface as adsorbent. The adsorber element is placed inside the vacuum chamber. Zeolite is a porous ceramic material that is produced synthetically and via the composition and the porous structure it is possible to widely adjust the adsorption properties of a zeolite molecule [2].

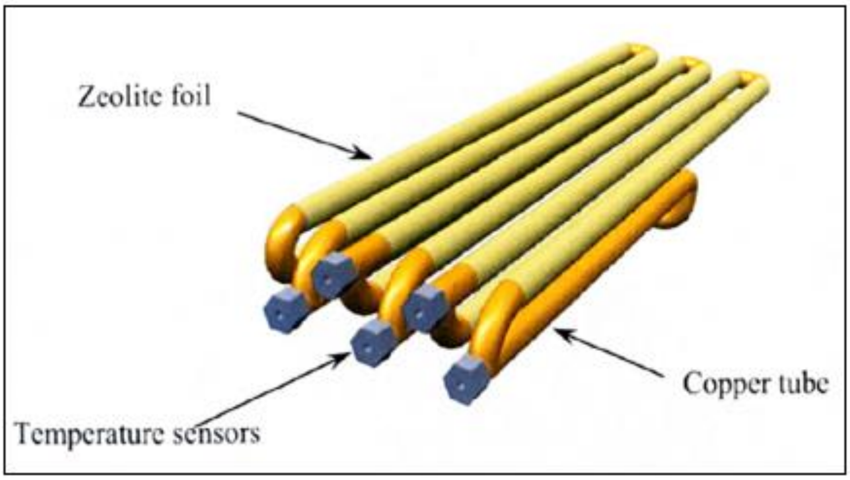

Figure 1.2: Adsorber (chiller tubes with zeolite foil)

The adsorption process is a combination of heat and mass transfer processes. When the adsorbate is adsorbed by the adsorbent the heat of adsorption is released. This increases the temperature of zeolite particles and at the same time, due to the porous structure of zeolite, the water molecules diffuse inside it. The figure 1.2 shows the cross section of a copper tube with zeolite layer on it and the direction of heat transfer. The heat released during adsorption is conducted through the zeolite layer and through the copper tube wall.

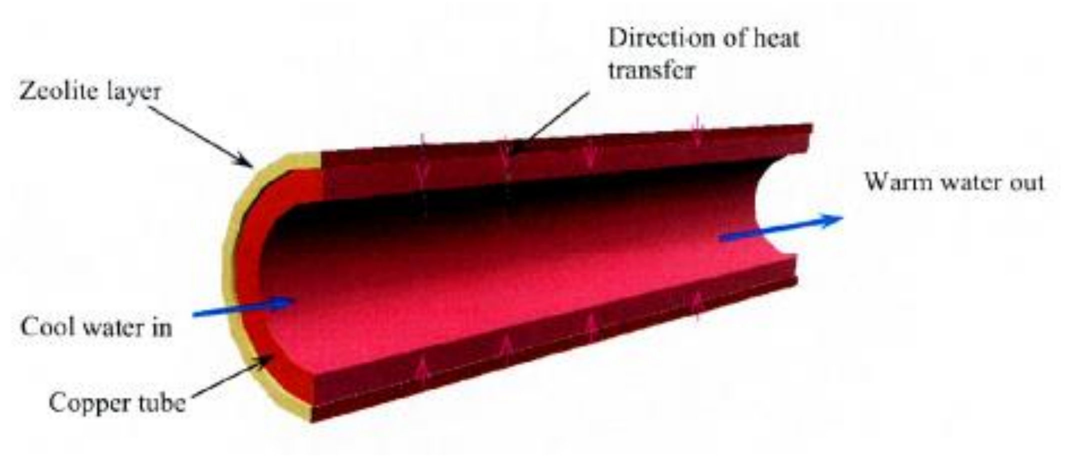

Figure 1.3: Heat transfer flow during adsorption phenomenon

On the other hand, for desorption of this adsorbed water vapour, hot water is sent through the pipe. The heat is transferred by convection to the tube wall and from there by conduction to the zeolite layer. This is heat utilised to desorb the water so that the adsorbate could be regenerated after condensation in the condenser. The figure shows the direction of the heat transfer during desorption.

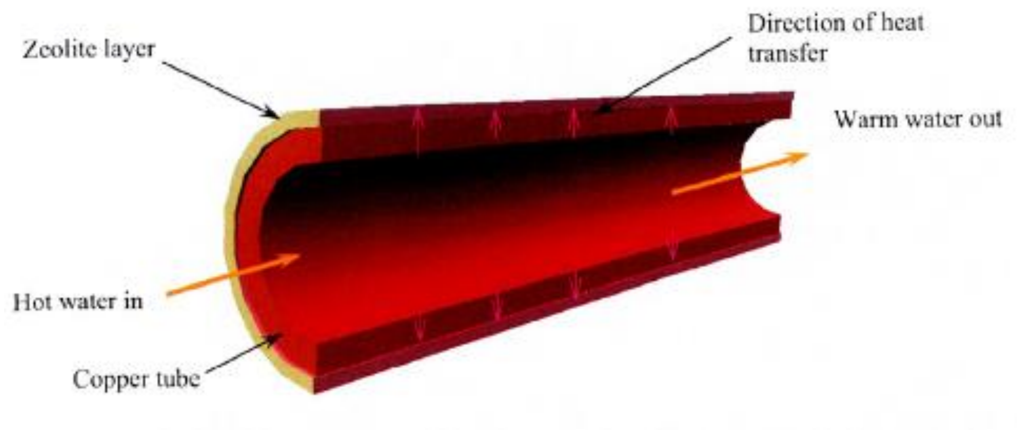

Figure 1.4: Heat transfer flow during desorption phenomenon

Absorption heat pump: An absorption heat pump is driven by thermal energy. They are used in the situation where both heating and cooling is required. The principle of operation of an adsorption heat pump is based on absorption and evaporation of a refrigerant. An absorption medium as well as refrigerant has to be chosen. The well-known pair is: ammonia and water, with ammonia as the refrigerant and water as absorption medium.

Adsorption heat pump: The operation principle of adsorption heat pump is same as that of absorption heat pump. The adsorption heat pump uses solid sorption instead of liquid sorption that is used in absorption systems. The material pair usually applied in adsorption heat pump is zeolite – water pair. The adsorption principle is more used in small heat pump systems (70-150 KW), that are mainly used for cooling applications. The adsorber is the heart of the cycle that has to be experimentally modelled and simulated so that energy efficient heat pump could be built. The key element of the adsorption system is the adsorber, a heat exchanger which is in contact with the adsorbent material. The adsorption heat pumps, for heating and cooling applications, can be operated using a lower temperature which utilises heat energy as driving power (example solar energy, natural gas, waste heat recovery) [4].

1.2 Adsorption cooling process

The basic principle behind the thermal cooling process of the sorption: a liquid or gaseous substance is either attached to solid, porous material (adsorption) or is taken in by a liquid or solid material (absorption). The principle followed in this process is that water molecules bind more efficiently to certain sorbent materials than to other water molecules. Consider two separate bowls one containing water and the other containing a sorbent that are placed into a closed space, the water will evaporate that means the sorbent which absorbs or adsorbs the water. If the closed space is considered to be a vacuum, the water will start boiling and vapours are produced which are sorbed [11].

Boiling water requires a lot of energy. If the energy is not supplied from outside the system it will be taken from the water itself, which, as a consequence, gets colder. In essence the evaporation process transports heat from the water to the sorbent. The temperature difference increases until the sorbent is no longer able to take more water.

A cooling cycle can be performed if the chilled water is used to provide air conditioning and the sorbed water is liberated from the sorbent by boiling it out with the externally driven heat. The heat that is transferred to the sorbent also needs to be removed either with a wet or dry cooling tower.

The adsorption chiller used in the figure 1.4 consists of water as the refrigerant and zeolite as an adsorbent. The adsorption chiller consists of four major components:

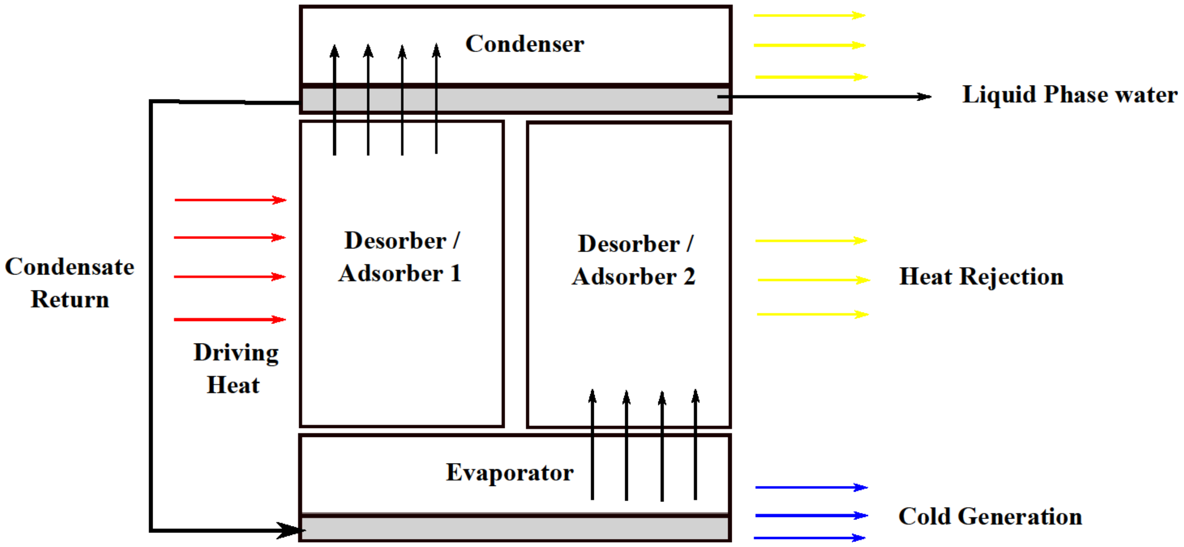

Figure 1.5: Adsorption cooling phenomenon [7]

Desorber / Adsorber 1: The adsorber is dried out by applying external driving heat. Vapours are generated and flow in to the condenser. As soon as the material is dried out, heat input to the adsorbing chamber stops.

Condenser: Water vapour is condensed in the condenser where it rejects excess amount of heat to the cooling tower. The resulting liquid water flows in to the evaporator.

Evaporator: In the low pressure evaporator water is induced to boil by the attraction of the adsorbent in to the second adsorption chamber. This further cools the water in to the evaporator which is used to provide chilled water for the air conditioning purpose.

Desorber / Adsorber 2: The water vapour from the evaporator is adsorbed in the second adsorbing chamber. During the adsorption process the heat is being generated which later has to be removed by the cooling tower. A continuous cooling cycle is created by using two adsorbing/desorbing chambers so that while one chamber is adsorbing water vapour the other one is desorbing water vapour.

1.3 Working principle – Adsorption Chiller

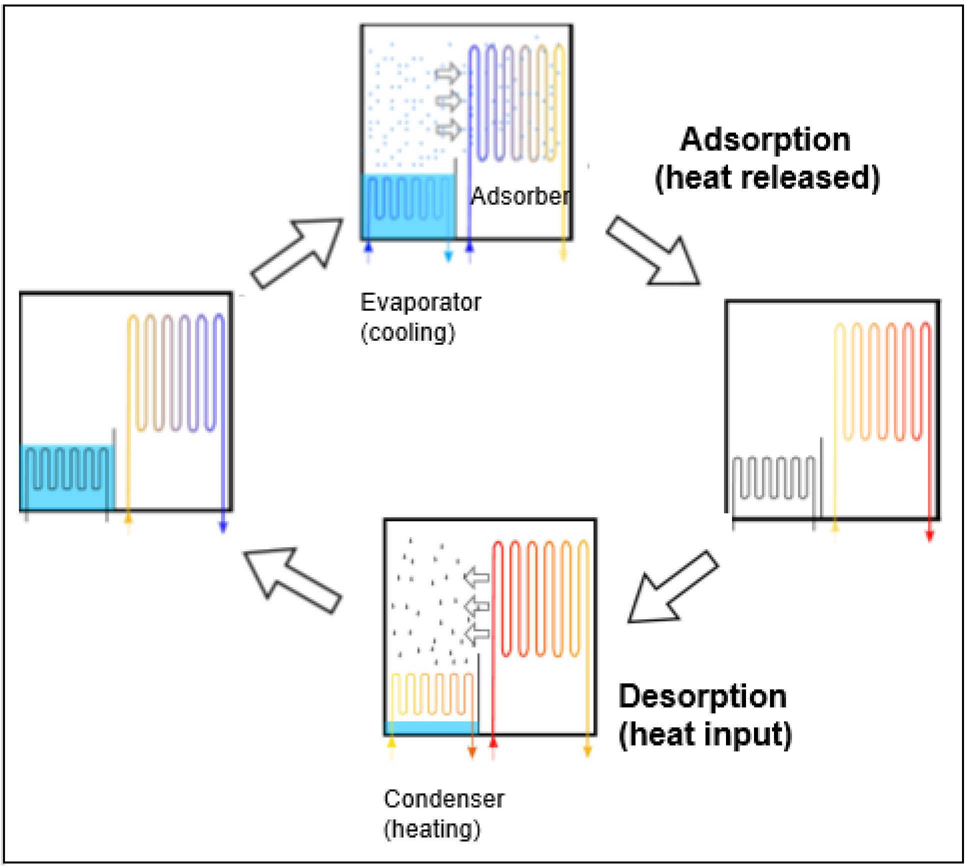

Figure 1.6: Working principle of the adsorption chiller [4]

During the adsorption cycle, the heat released by the evaporator is adsorbed by the adsorber chiller and the heat is stored in to the adsorber. This heat is captured by the incoming cool water flowing through the adsorber chiller tubes and thus gets heated up, which results in cooling of the adsorber. The outcoming heated water flows in to the thermal storage tank. The cooler water is continuously extracted from the decresing height of the thermal storage tank and the inlet to the tank from the adsorber is heated up water that gets stored from top to bottom of the tank.

During the desorption cycle, the reverse action takes place. The heat of adsorption released during the adsorption half cycle is stored in the tank which is later used in desorption half cycle. Here the chiller acts as desorber.The hot water is extracted from the upper level in the tank, passes through the chiller where it releases its heat and the released heat is condensed in to the condenser. The outcoming cool water from the desorber is passed to the tank. The inlet to the tank is cold water where its storage takes place from bottom to the top of the tank. During this process the major part of the heat recovery is achieved. This ultimately reduces the intake energy from the heater to drive the cycle.

1.4 Cycle basics of the adsorption chiller

Heat pumps are the devices that extract the energy in the form of heat from the low temperature level (T_L) and release this heat at the high temperature level (T_C or T_A). In the case of zeolite based adsorption chiller the heat is extracted from the low temperature region (cooling load unit). As per the second law of thermodynamics the heat transfer from a low temperature to a high temperature takes place only with the existence of the external energy source, which may be available in the form of mechanical / electrical or in the form of heat as in the case of thermally driven sorption (adsorption and absorption) heat pump [30].

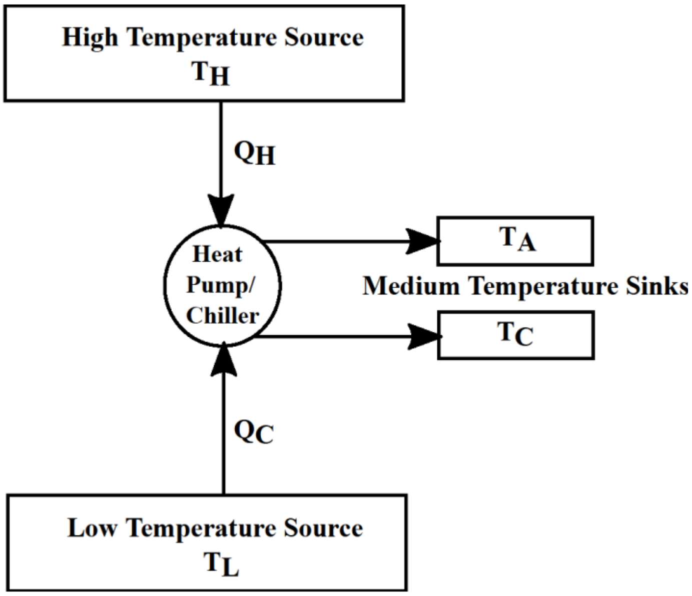

Figure 1.7: Thermodynamic cycle basics of the adsorption chiller [14]

Thermal driven heat pump works at three different temperature levels. The driving heat (T_H) is supplied at high temperature level and useful cold or low temperature heat is supplied at low temperature level (T_L). The heat that is released at medium temperature level can be used as useful heat further in the heating operation. The medium and low temperature heat can be further used for heating and cooling operations.

2. ADSORPTION BASED ON STRATISORP CONCEPT

Stratisorp concept gives the competitive alternative to state of the art heat recovery technologies as other heat sources (e.g. waste heat, solar thermal energy) can be incorporated in to the system. The concept provides with the experimental proof of the internal heat recovery using the stratified thermal storage tank. The concept was originally proposed by Schmidt and was demonstrated with a silica gel adsorption chiller for the internal heat recovery using the stratified thermal storage [1].

2.1 Layout of the stratisorp system

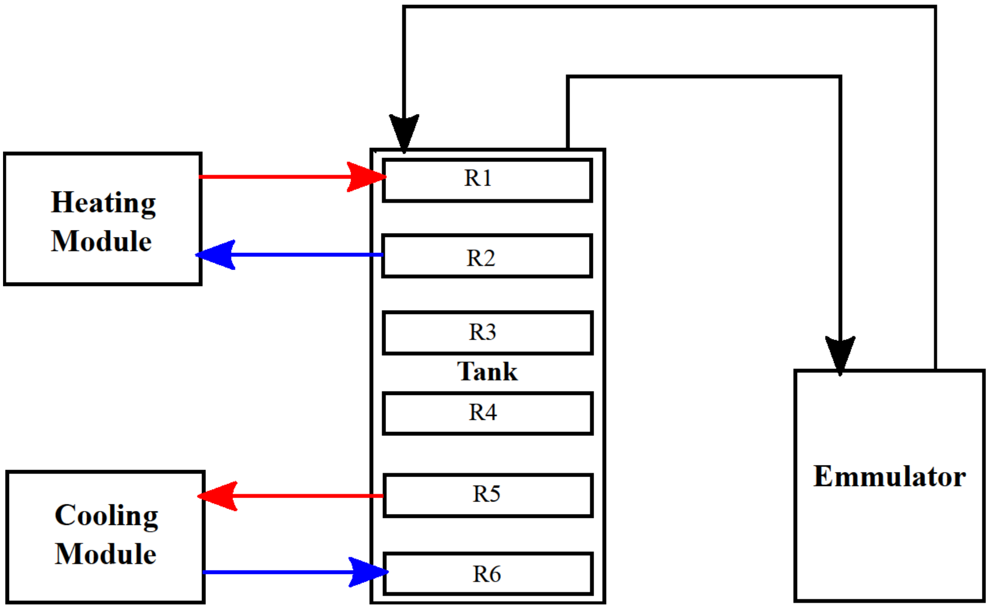

Figure 2.1: Schematic layout of the stratisorp system

The above figure shows the schematic layout of the stratisorp system based on which the adsorption and desorption half cycles are carried out. A stratified thermal storage is capable of recovering a part of the adsorptive heat released during adsorption half cycle. For demonstration of the potential of the thermally stratified storage as an agent for internal heat recovery and its effect on the performance of the adsorption heat chiller's cycle, an experimental set-up was designed and built during this work. This set-up consists of the following essential components:

1. Heating module (Heat source)

2. Cooling module (Heat sink)

3. Cooling Load Unit (Emulator)

4. Stratified thermal storage tank with stratification rings

5. Zeolite based adsorption chillers

For one complete cycle:

Q_{heater} = Heat energy received by the tank from heater

Q_{cooler} = Heat rejected by the tank to cooler

Let, $Q_{adsorption}$ be the heat of adsorption stored by an adsorber during the adsorption half cycle in to the thermal storage tank and $Q_{desorption}$ be heat of desorption supplied by the tank to the adsorber during desorption half cycle. Due to the difference of these energy exchanges with the tank during each cycle, net energy is stored in to the tank. Thus the energy which is stored in to the tank assist the adsorption heat pump cycle by reducing the demand for the total driving energy required.

$Q_{tank\ (end)}$ = energy contained in to the tank at the end of the adsorption cycle

$Q_{tank\ (start)}$ = energy contained in to the tank at the start of the adsorption cycle

Total change in the energy contained in to the tank is given as:

$$\Delta Q_{tank} = Q_{tank\ (end)} - Q_{tank\ (start)}$$

COP Estimation:

$$COP_{cool} = \frac{Qevaporator}{Qheater - \Delta Qtank}$$

$$COP_{heat} = \frac{Qcondenser + Qcooler}{Qheater - \Delta Qtank}$$

The above equations serves as an estimate for *COP* of the stationary stratisorp cycle. The cycle can be termed as stationary only when the energy content of the tank at the start and at the end of the cycle is exactly equal ($\Delta Q_{tank} = 0$)

2.2 Heat recovery based on stratisorp cycle

The idea behind the heat recovery for adsorption heat pump is to utilize the heat released during the adsorption half cycle for desorption half cycle of the same or another adsorber. This reduces the heat input to the adsorber during desorption and thereby improves the *COP* of the cycle. Recovery of heat plays an important role in overall cycle efficiency. Heat recovery of adsorption refrigeration system can be realized through stratified system, for there is an overlap between adsorption and desorption differential heat curves [8]. The figure 2.2 represents the differential heat curves for the adsorption and desorption for the zeolite adsorption chiller with the cycle conditions 200/38/15 ºC. A large amount of heat is released during the adsorption half cycle being an exothermic process. Additionally, some energy is available due to sensible cooling of the adsorber. The energy released during the first half cycle is plotted under the dotted blue line. This energy also equals to the energy demand of the adsorber during desorption half cycle under the plotted curve bounded by red line. The two plots have an overlap (green points). This indicates that large fraction of the heat of adsorption can be utilized in desorption half cycle and thus heat recovery can be achieved. The remaining heat is additionally covered by use of external heat source. The heat which is not recovered needs to be rejected to the recooler. Therefore a heater and a cooler are composed to be an integral part of the system.

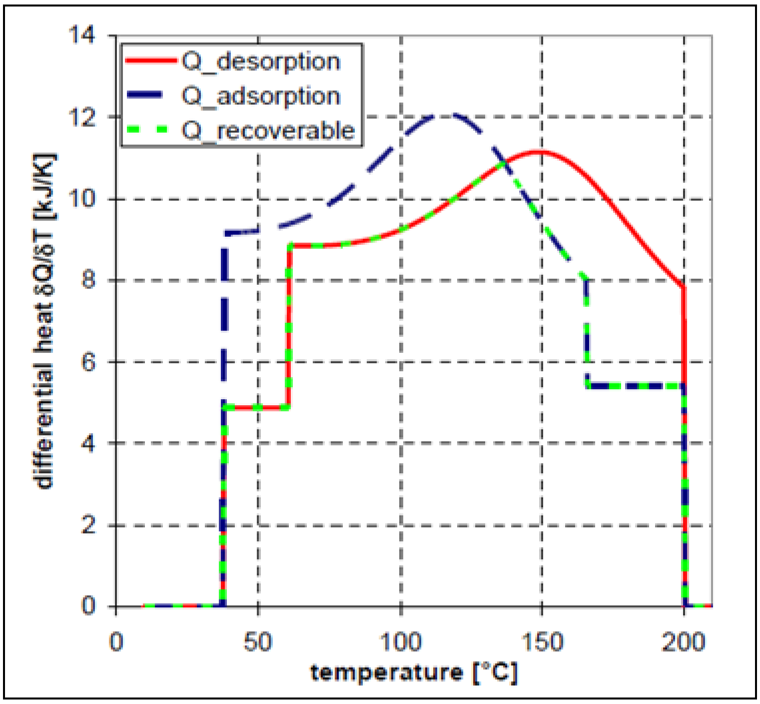

Figure 2.2: Differential heat curve with temperature [5]

This ultimately reduces the intake energy from the heater to drive the cycle. Thus the stratified storage tank plays a very vital role in the performance improvement. A stratified tank makes sure that the adsorber is cooled and heated with small driving temperatures and thereby decreases the entropy generation in the adsorber.

2.3 Cycles based on stratisorp concept

2.3.1 Adsorption half cycle

A particular adsorption half cycle that enables the recovery of a large fraction of heat is the ‘Stratisorp’ cycle. This cycle is based on the idea to store the heat recovered by an adsorber at various temperatures in a stratified thermal storage tank with the temperature controlled loading and unloading mechanism. This cycle concept was first published by F.P. Schmidt and was further developed by his research group.

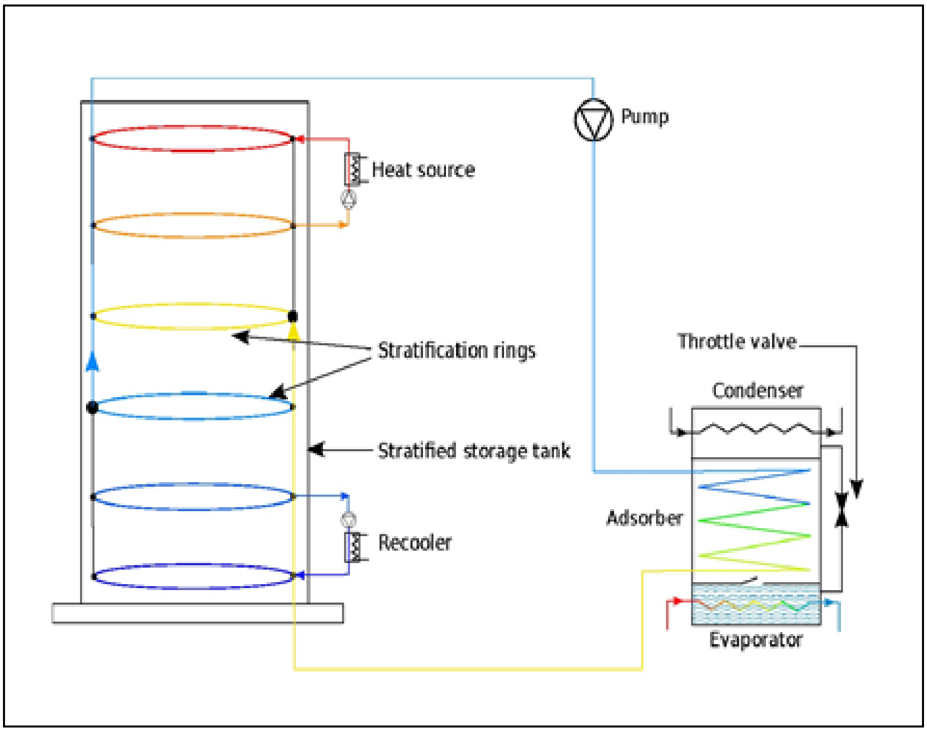

Figure 2.3: Adsorption half cycle [3]

The tank used in the set up consists of 6 rings each connected to 2 switching valves, so in total consisting of 12 switching valves mounted at specific height. These rings are the channels for supplying water to and from the storage tank. The fluid extraction is controlled by the external multi switch valve described above. A stratification pipe enables the water to enter in to the level at same temperature. These rings helps the whole process so that the water at a certain temperature does not get mixed up with other temperature level. This helps to prevent the mixing of water at different temperature level. The heater is used to heat the top portion of the storage tank and keep it at a set temperature. The cooler cools down the bottom portion of the tank at lower temperature. A heater and a cooler extracts water from a fixed height of the tank and reinsert the flow into the tank at the top and at the bottom of the tank respectively.

Adsorption Cycle: Suppose that the cycle begins at the adsorption. The refrigerant coming out of an emulator (cooling load unit) is at certain temperature level say in between 20 - 25 ºC. This refrigerant enters the chiller placed inside the vacuum chamber unit and releases heat of adsorption and return flow to the emulator unit is at 19 ºC, which is to be maintained constant. The extraction of the water at the second highest level in the tank is used to cool down the adsorber. The water heats up and returns back in to the tank at the highest level of the storage. During the adsorption half cycle, the adsorber is cooled by taking water from decreasing heights of the tank. The adsorber receives the water at medium temperature from the bottom of the tank towards the end of the adsorption half cycle.

The water returning to the tank is warm due to the heat of adsorption. The tank is loaded with this warm return flow by using a suitable stratification system.

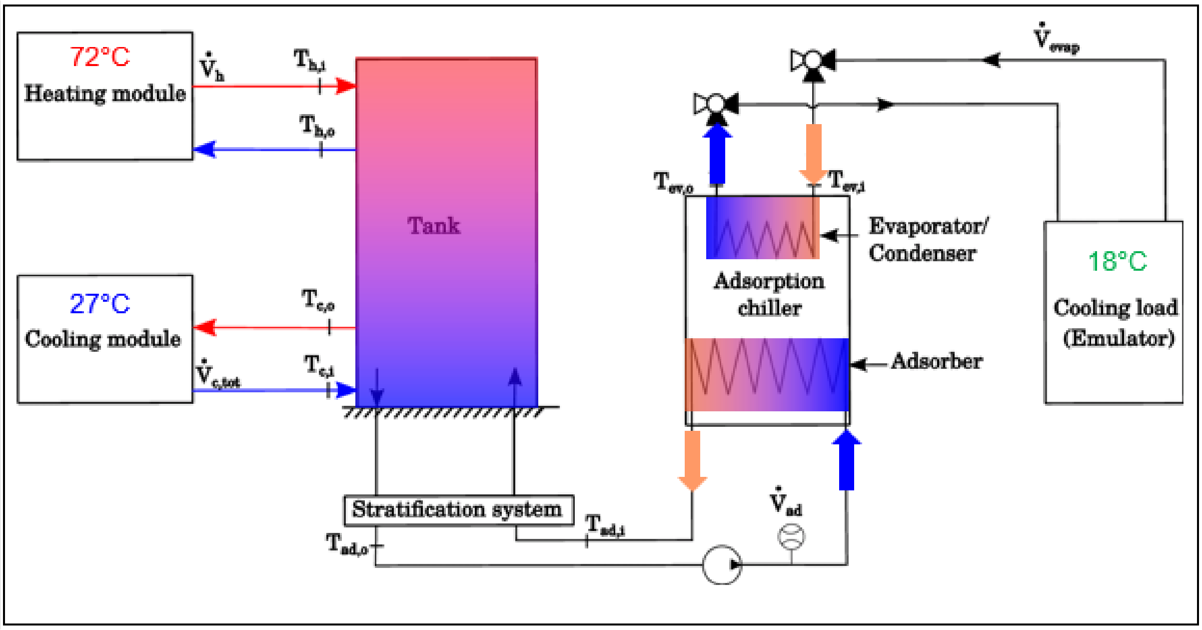

Figure: 2.4: Schematic Layout of adsorption half cycle

2.3.2 Desorption Half Cycle

Desorption Cycle: Conversely during desorption half cycle, the adsorber is heated up by extracting hot water initially from the lower part of the stratified tank and when the temperature difference between the supply and return water is less than a certain value, the supply water is extracted from the next higher level until it arrives at the top of the storage. The heat stored in the tank is utilised to heat the adsorber which can be used as waste heat for district heating. The adsorber is desorbed by extracting water at maximum desorption temperature at the end of desorption half cycle. Due to the use of stratified thermal storage for the sorption cycle, this cycle has been termed as ‘stratisorp’ cycle (stratified sorption). The heater and cooler circulate water with the tank at a low flow rate compared to the adsorber flow rate.

During one cycle, the heat generated in adsorption half cycle is recovered in the stratified storage. The part of that heat that is available at high enough temperature is used for desorption during the next half cycle.

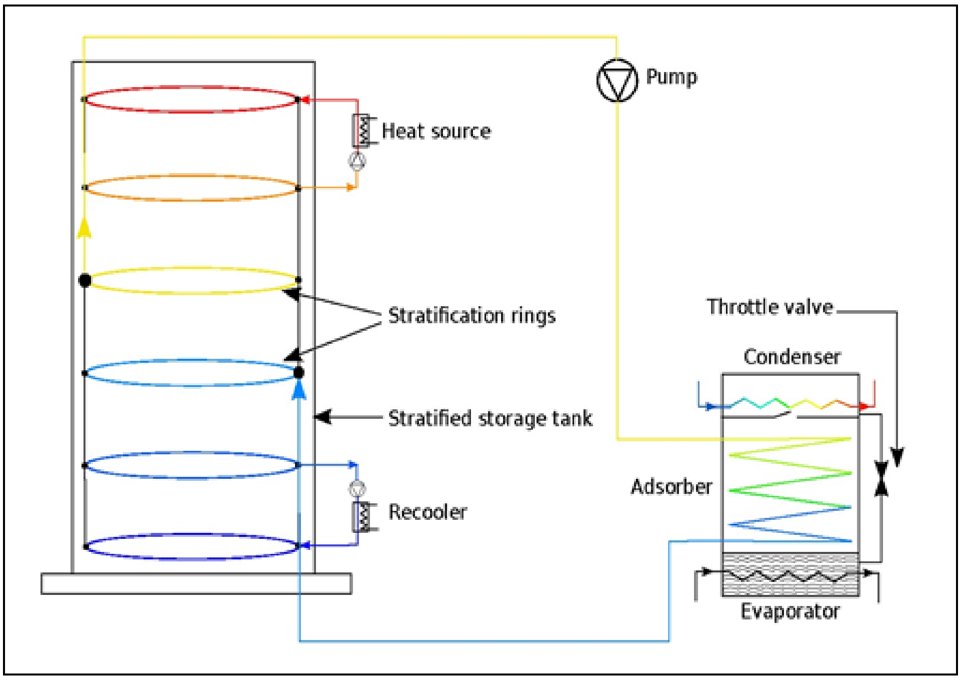

Figure 2.5: Desorption half cycle [3]

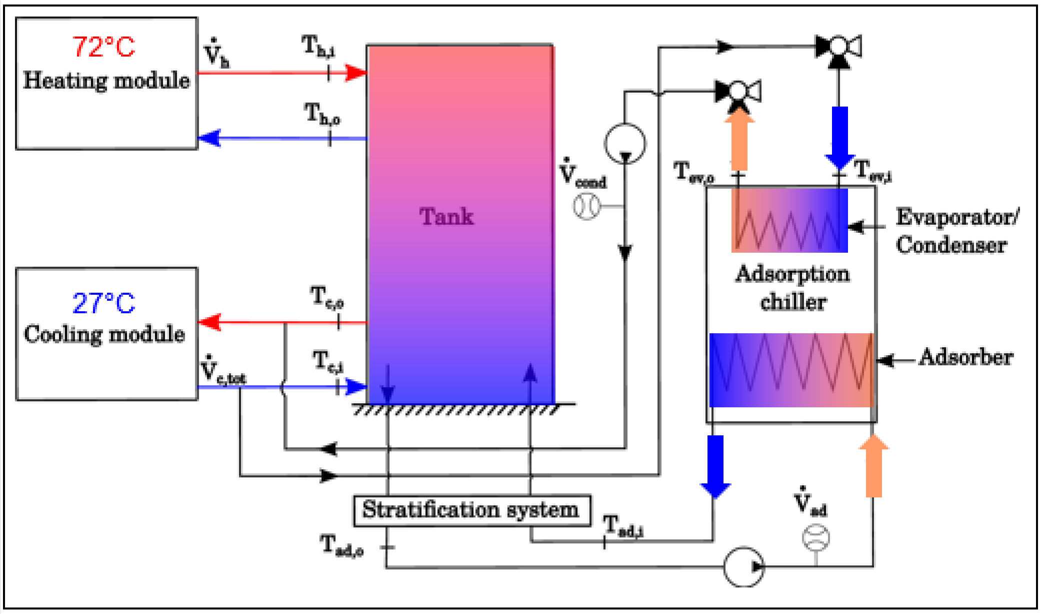

Figure: 2.6: Schematic Layout of desorption half cycle

2.4 Application of the proposed methodology

2.4.1 Cogeneration / combined heat & power (CHP)

Combined energy generation or use of power and heat or cold enables energy saving up to 60% compared to separated generation. In case of the separate electricity production, some energy is discarded as waste heat whereas cogeneration or combined heat & power refers to the use of heat engine or power station to generate the electricity and useful heat at the same time. CHP captures the heat released during the electricity generation to provide the heating effect which can be further utilized for district heating. It can also be termed as combined heat & power district heating [25].

The CHP unit can be coupled with the thermally driven heat pump which runs as an adsorption chiller, where the heat extracted from the CHP unit as the waste heat can be recovered in the chiller by the adsorption cooling process to heat the incoming water flow and store the heated fluid for the further district heating. Thus the CHP unit acts as an air conditioner where the incoming flow is also low temperature to provide the cooling effect. Thus the cooling is achieved by passing of waste heat to an adsorption chiller. Absorption chillers can help to increase the performance of the cogeneration plants. The modifications adapted on the test setup could be coupled with an emulated CHP unit [27].

2.4.2 Trigeneration / combined cooling, heat & power (CCHP)

Combined cooling, heat and power or trigeneration involves heat engine or a power station which simultaneously generates both electricity and useful heat. The heat produced is further used to drive the chillers to provide the cooling. CCHP helps to reduce the gas emissions, since the waste heat instead of releasing to the environment is recovered. Also the transmission and distribution losses are minimised. Trigeneration or combined cooling heat and power (CCHP) systems are based upon CHP systems coupled to absorption chillers fired with heat produced in cogeneration [25]. The application of the test setup can also be coupled with the CCHP unit using the stratisorp concept to increase its effectiveness.

2.5 Design aspects of the stratified thermal storage tank

The figure 2.7 shows the 3D CAD model developed for the modified test setup. The stratified thermal storage tank is modelled with 6 stratification rings inside the tank. The temperature sensors are installed vertically throughout the tank to measure the temperature of the fluid at the insertion and extraction in to the tank. Based on the monitoring of the physical parameters relative to the tank the result data is interpreted.

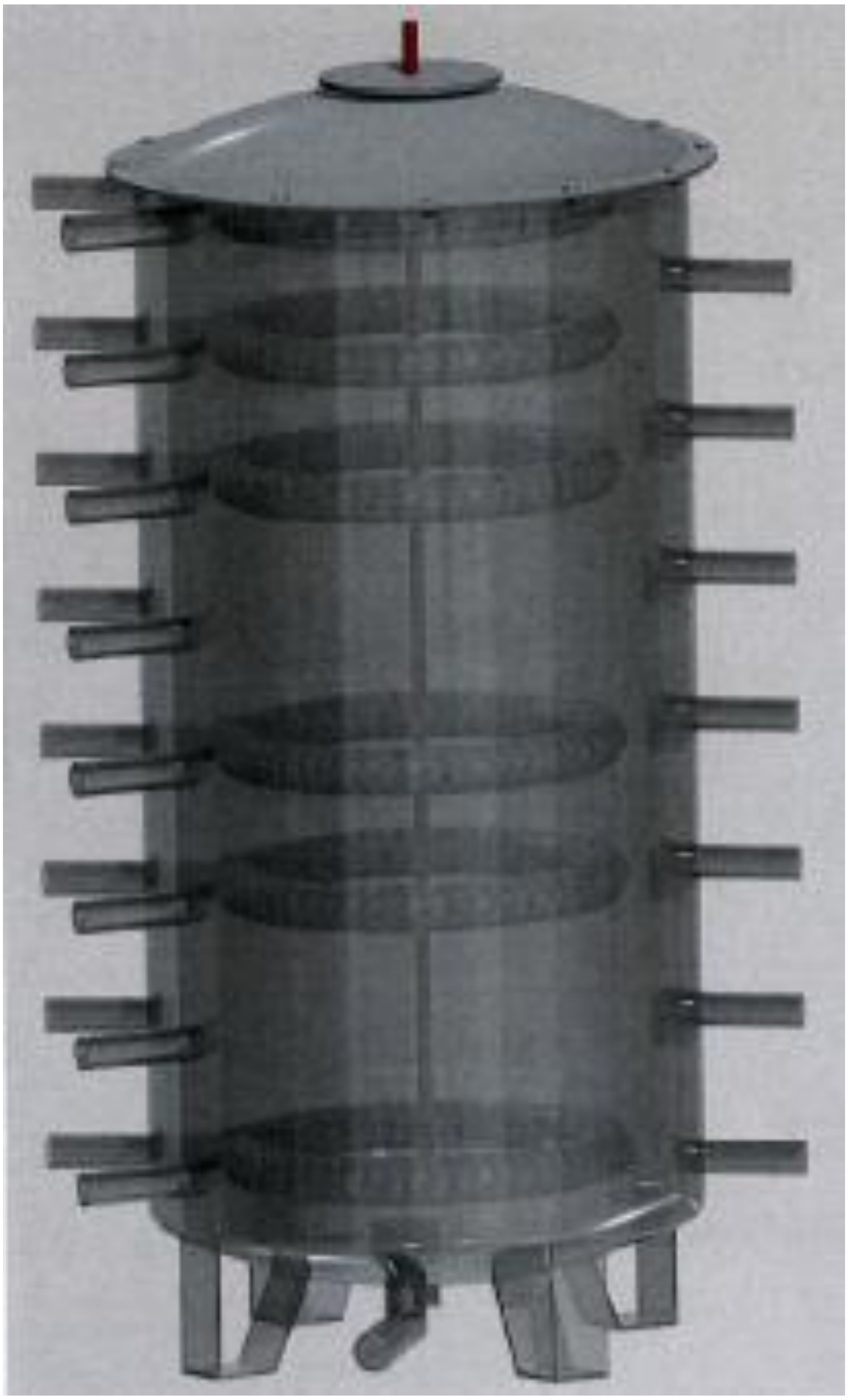

Figure 2.7: 3D Model of the Stratified Thermal Storage Tank with Stratification Rings

The stratified thermal storage tank is very important component of the experimental set-up for the internal heat recovery of the adsorption chiller's cycle. The design aspects of the stratification systems consisting of rings is discussed further in this chapter. The tank is made up of steel with anti-corrosion coating from the inside. Glass wool laminated with aluminium foil is in use to insulate the tank. One ring is placed just below the free water surface while another ring placed at the bottom of the tank. The remaining four rings are placed equidistantly along the height of the tank. The tank consists of 15 temperature sensors from T_1 to T_{15}. These temperature sensors records the temperature in to the tank at different heights. Each ring is associated with two switching valves 'SW', which are simultaneously used for in flow and outflow of the water in to the rings during adsorption and desorption cycles. These rings incorporated number of holes drilled on the inside of the inner perimeter of the rings.

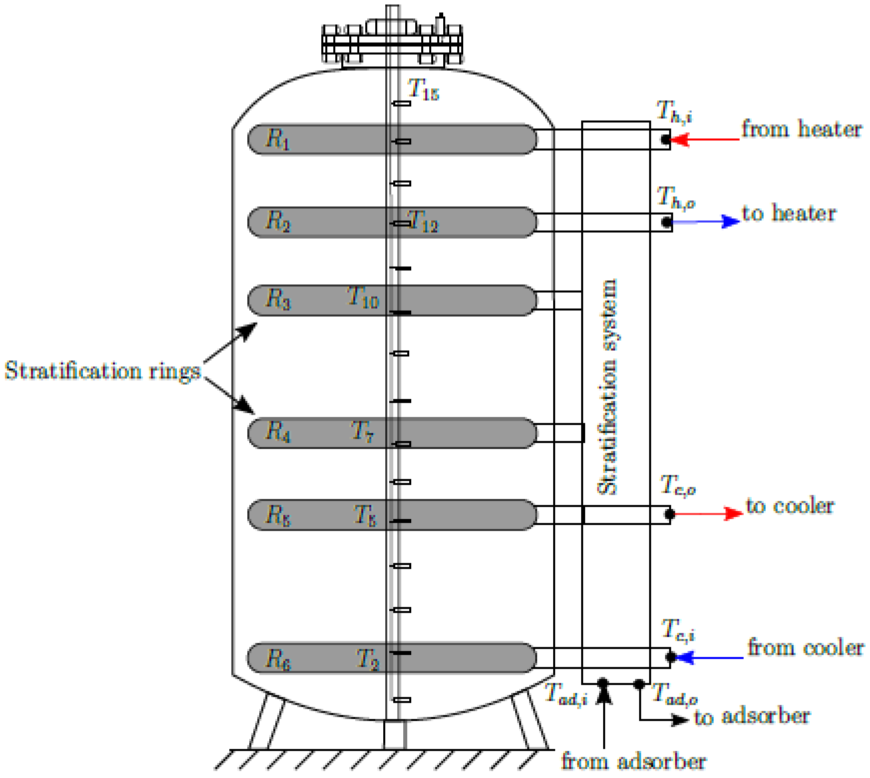

Figure 2.8: Tank profile with rings and temperature sensors [11]

Figure 2.8 shows the situation at the start of the adsorption and desorption half cycles respectively. During the start of an adsorption half cycle, the emulator discharges cooler water from the tank using the lowered position rings (here from R_2 and SW) and inserts warm water returning back to the tank (here in R_1 and SW). At the end of the cycle the outflow is from Ring 6 and SW while the inflow in to the tank is in Ring 5 and SW.

On the contrary, during desorption half cycle, the warm water is discharged from the tank using the higher positioned rings (here from R_5 and SW) and inserts the cool water returning back to the tank (here in R_6 and SW). At the end of the cycle the outflow is from the R_1 and SW and the inflow in to the tank is in the R_2 and SW. As the name suggests, this system makes use of the stratification rings for charging and discharging the tank.

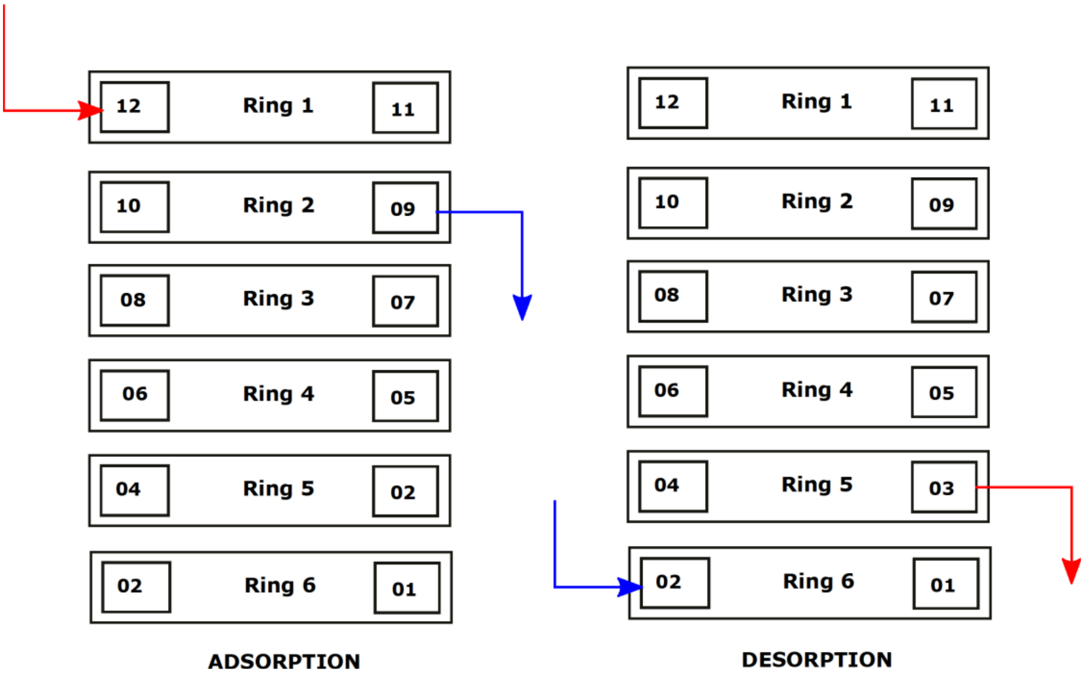

Figure 2.9: Schematic view of the hydraulic connections

3. EXPERIMENTS ON ADSORPTION CHILLER PERFORMANCE

3.1 Experimental Layout

At the initial stage some preliminary experiments were carried out to present setup to feed the true and false value for the component set up. These values corresponding to the voltages were used to monitor the flow rate and physical measurements of the components to be later used for the modified test set up.

3.1.1 Single Adsorption Chiller

This experimental setup consisted of heating module, cooling module, storage tank, cooling load unit and adsorption chiller. As a trial one experiment was carried on this set up. The temperature set point of the heating module was 85 ºC, and of cooling module was 27 ºC and of emulator was 19 ºC.

The results obtained were as follow (average of last 5 cycles):

$$COP_{cool} = 0.38$$

$$COP_{heat} = 1.28$$

The detail study of the experimental plots associated with storage tank, reflects some drawbacks on the thermal parameters. The mixing of the water at different temperatures occurs in the storage near the rings of the thermal storage tank. The mixing taking place in the tank during extraction and insertion of fluid significantly hampers the performance of the cycle. The temperature spread at the set flow rate across the adsorber does not match to the temperature spread across the adjacent rings. It further leads to mixing in the tank and the heat of adsorption is not efficiently stored. One of the measure to minimize the mixing is use of double adsorption chillers connected in series. However, using two or three adsorption chillers connected in series, a wider temperature spread across the first and last chiller can be achieved. Such temperature spread would then suit to the temperature spread across the adjacent rings and cause less mixing than thee single adsorption chiller.

At initial phase implementation of a 4 way valve is done in the experimental setup. Using this valve more than 50% volume of the tank will be heated to the given set point by extracting the water from different heights of the tank by the heating module.

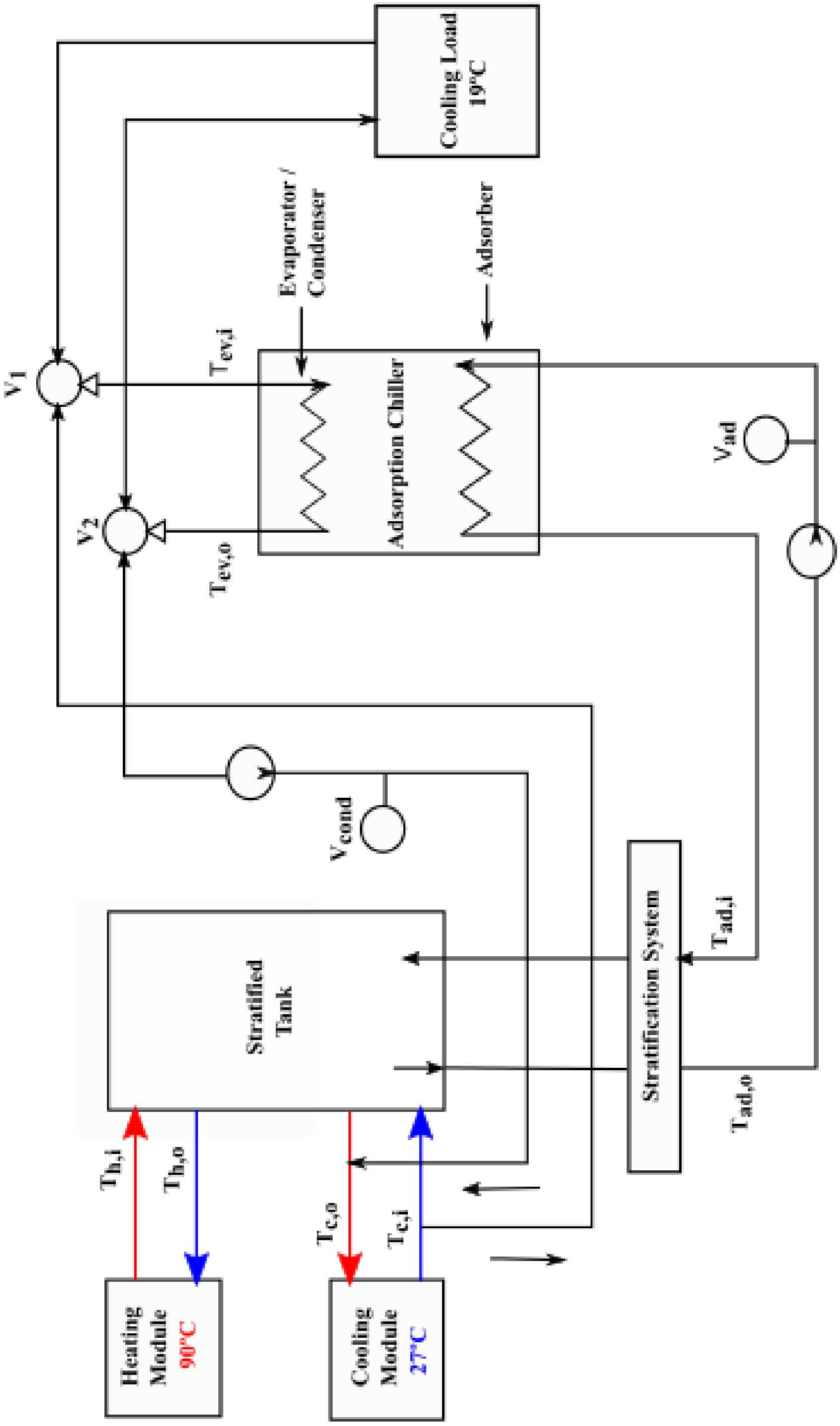

Figure 3.1: Experimental setup of single adsorption chiller used for the stratisorp cycle

3.1.2 Double Adsorption Chiller

In the newly developed set up one more adsorption chiller is connected in series. Initially experiments were carried out at preliminary stage to study the test setup and the performance obtained by varying different experimental parameters.

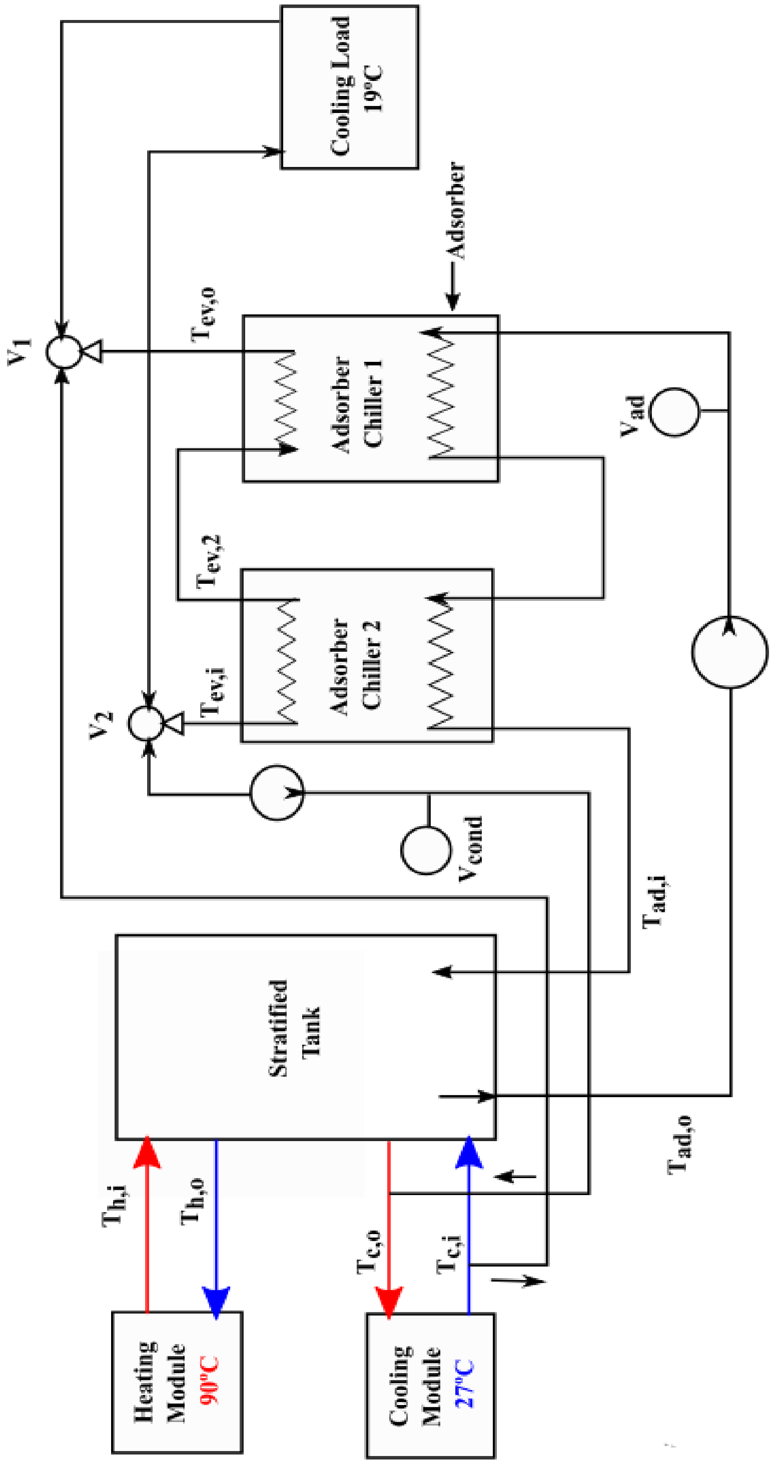

Figure 3.2: Experimental setup used for investigation of the stratisorp cycle

The experimental procedure and results for the experiment with based on the stratisorp concept cycle condition 90/27/19 ºC using the ring stratification system are analysed and the series of different experiments demonstrating different possibilities are discussed in this chapter. Throughout the experimental work, the heater module was maintained at 90 ºC, the emulator temperature was maintained at 19 ºC and the re-cooler (cooling module) at 27 ºC. The heating and cooling modules are operated at 720 lph, much lower flow rate than the adsorber flow rate 1200 lph.

3.2 Analysis of the Experiments

The temperature based criteria was chosen say (e.g. 4 K) for switching the valves between the adsorption and desorption half cycles. When the temperature difference between the extracted water from the tank and the water inserted in to the tank is less than the set point value 4 K, it means the adsorption is nearly complete at this temperature region and the water is extracted from the next lower ring and continuously cools down the adsorber. The process continues and finally in the last step of the adsorption half cycle, the water is extracted from the R_6 at the bottom part of the tank. When the temperature difference between the water extracted from the R_6 and inserted back in to the R_5 is ≤ 4 K, adsorption half cycle is finished and thus the system switches to desorption. Opposite to adsorption, desorption half cycle first uses the water from the R_6 to heat up the adsorber. When the temperature difference between the water extracted from R_5 and inserted back in R_5 water is ≤ 4 K, the water is extracted from the next higher R_4 until it is extracted from the top of the storage. During one cycle, the heat generated in adsorption half cycle is recovered partly and stored in the stratified storage tank. There is heat lost to the surroundings, heat lost due to the mixing in to the tank. The part of that heat that is available at high enough temperature is used for desorption during the next half cycle.

The experiments were carried out with varying switching criteria carried out as the temperature based switching criteria for 2 K, 4 K, 6 K, and 8 K respectively. Table 3.1 shows the volume flow rate of each component for the entire experimental setup.

Component	Symbol	Flow Rete (lph)
Heater	V_h	720
Cooler	V_c	720
Adsorber	V_{ad}	1200

Table 3.1: Flow rates used in different hydraulic circuits

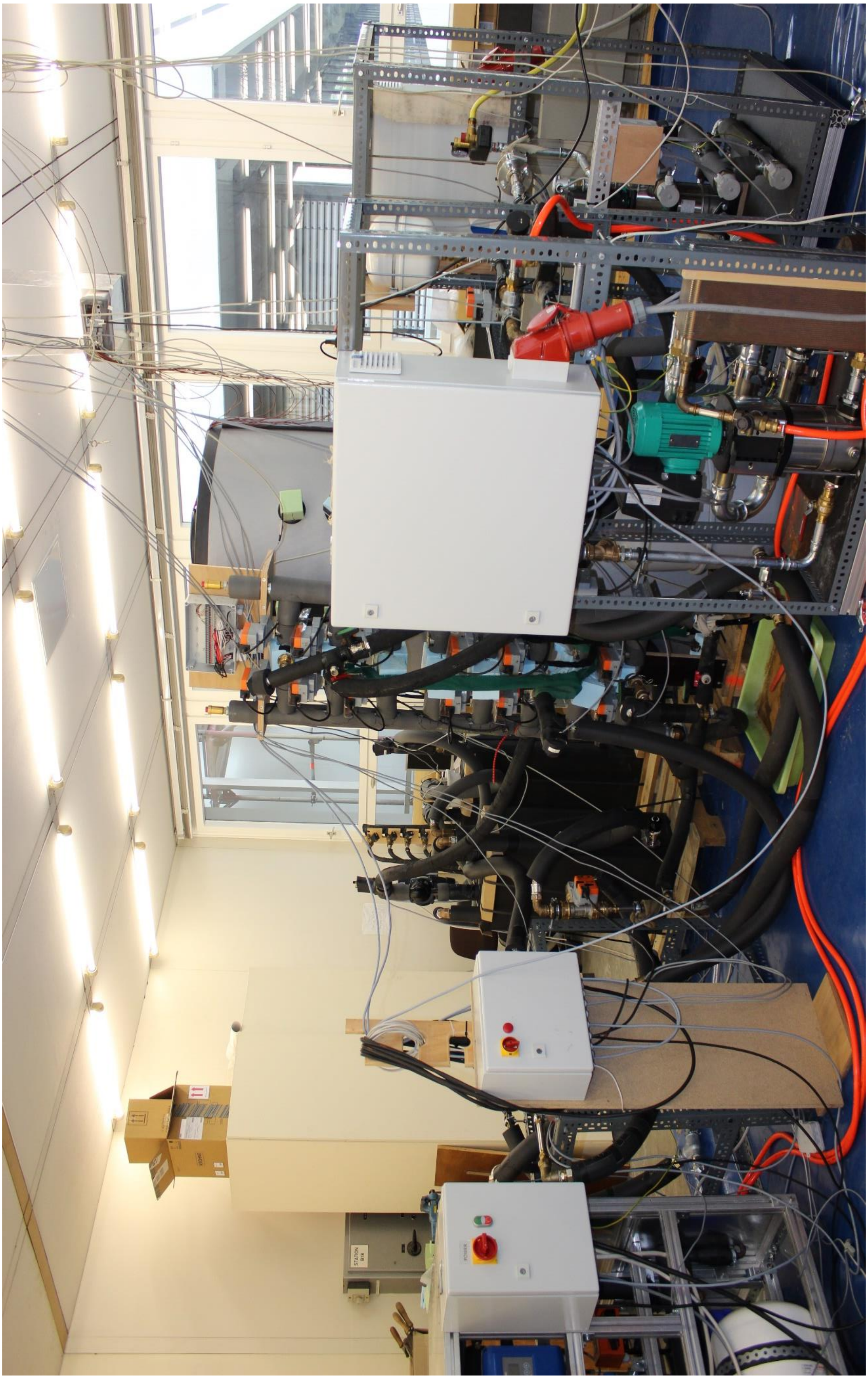

Figure 3.3: Experimental test setup in the laboratory

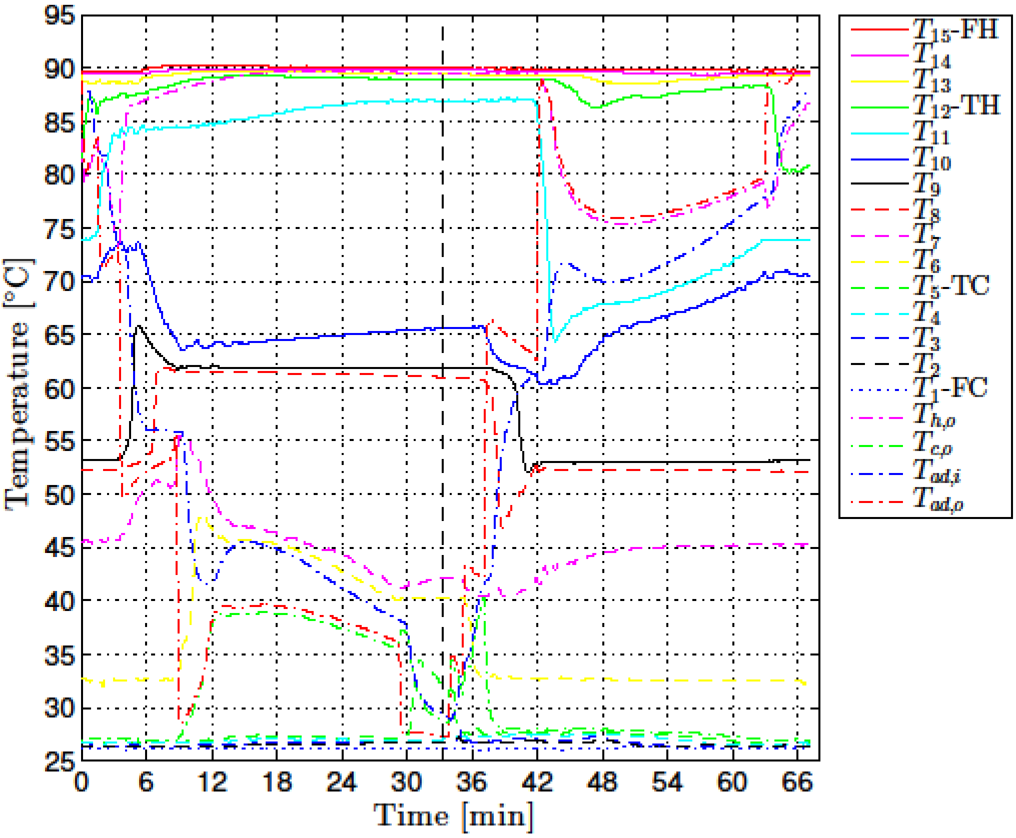

Figure 3.4: Temperature profile along the tank height with cycle switch 2 K

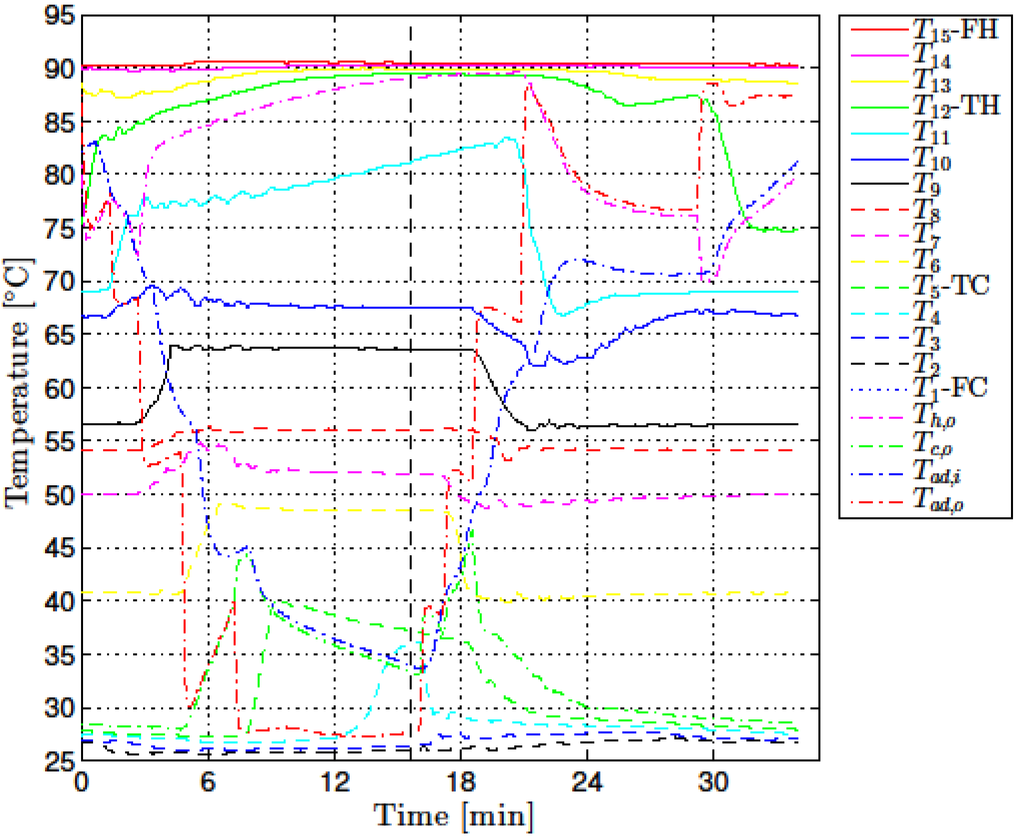

Figure 3.5: Temperature profile along the tank height with cycle switch 6 K

The COP_{cool} and COP_{heat} for the experiments are noted in the Table 3.2

Temperature Variation (dT)	COP_{cool}	COP_{heat}
2 K	0.439	1.326
4 K	0.457	1.374
6 K	0.445	1.379
8 K	0.331	1.257

Table 3.2: *COP* variation witch temperature variations

Adsorption half cycle, $\Delta T_{ad} = (T_{ad,i} - T_{ad,o}) \leq 4$ K

Desorption half cycle, $\Delta T_{ad} = (T_{ad,o} - T_{ad,i}) \leq 4$ K

where, ΔT_{ad} = Temperature spread across the adsorption chiller

During the adsorption half cycle, hot water is stored in the storage tank insertion from the adsorber. During desorption half cycle the hot water stored in to the tank is utilised for the heating purpose. During the half cycles, as seen in the figure distinct jumps in are observed in the supply temperature to the adsorber and occurs when the temperature based switching criteria is reached and the extraction takes place from the next selected ring. The overall time required for the completion of the two half cycles goes on decreasing with increase in the switching temperature limits.

For the switching temperature criteria, 4 K, COP_{cool} as well as COP_{heat} are observed to be maximum. For the 6 K criteria COP_{cool} is almost the same but the cooling power achieved for the cycle is high and hence this criteria is selected for the further study. It can also be noted that the second last stage in the adsorption half cycle is shortened, and the adsorber does not get completely dried up which reduces the efficiency of desorption half cycle. For criteria 2 K, from the plot it is observed that due to small temperature difference severe mixing takes place in the 4th step of the adsorption and desorption half cycles, which can be seen from the profiles of T_7 and T_{10}. This ultimately hampers the COP_{cool} of the stratisorp cycle. The mixing in the tank is primarily caused by momentum of flow entering the tank. The mixing taking place in the tank during the extraction and insertion of the fluid thus affects the performance of the adsorption chiller cycle.

Atleast 10 consecutive cycles were measured in the experiment and the COP_{cool} and COP_{heat} over the last 5 cycles were calculated by making the average and the last cycles were plotted. The total duration of approximately 10 hours were required per experiment. By studying the results obtained from the above experiments at preliminary stage, it can be concluded that the performance of the half cycle can be further improved by implementing the control strategies for the stratisorp cycle. The control strategy used in this concept is the variation in the switching criteria.

4. RESULTS & DISCUSSIONS

4.1 Variation in switching criteria

Variation in the switching criteria is considered to be one of the measure, which will have potential to increase the COP_{cool} and thus the cooling power of the original stratisorp cycle and hence is further discussed in the following section.

Step	Half Cycle	Extraction	Insertion	ΔT_{ad}
0	Adsorption	R2	R1	>6K
1	Adsorption	R3	R2	>6K
2	Adsorption	R4	R3	>6K
3	Adsorption	R5	R4	>6K
4	Adsorption	R6	R5	>2K
5	Desorption	R5	R6	>6K
6	Desorption	R4	R5	>6K
7	Desorption	R3	R4	>6K
8	Desorption	R2	R3	>6K
9	Desorption	R1	R2	>2K

Table 4.1: Variation in switching criteria

The two half cycles are divided in to the following steps: adsorption half cycle from step 0 to 4 and desorption half cycle followed by step 5 to 9 respectively. The idea in this experiment is to run the first 4 steps of each half cycle with ΔT_{ad} = 6 K and change the temperature based switching criteria to 2 K, for the last step in each half cycle These two steps (step 4 and step 9) are prolonged because of shortened ΔT_{ad} = 2 K and will consume more time in the experiment as compared to other steps.

The main task in this experiment is to increase the performance of the cycle which leads to increase in the COP_{cool} as well as the cooling power by implementation of the variation in the switching criteria in the same experiment. This will provide the combined effect of the variation criteria of 6 K, for the first 4 steps (step 0 to 3) and of 2 K, for the last step (5th step) of each half cycle. This measure also reduces the mixing of the fluid that takes place in to the storage the tank. . Also by making the last step long in each half cycle by reducing ΔT_{ad} to 2 K assures that the last step of the adsorption and desorption half cycle is completed and the adsorber gets completely dried up and the efficiency of the cycle increases along with the increase in COP_{cool}.

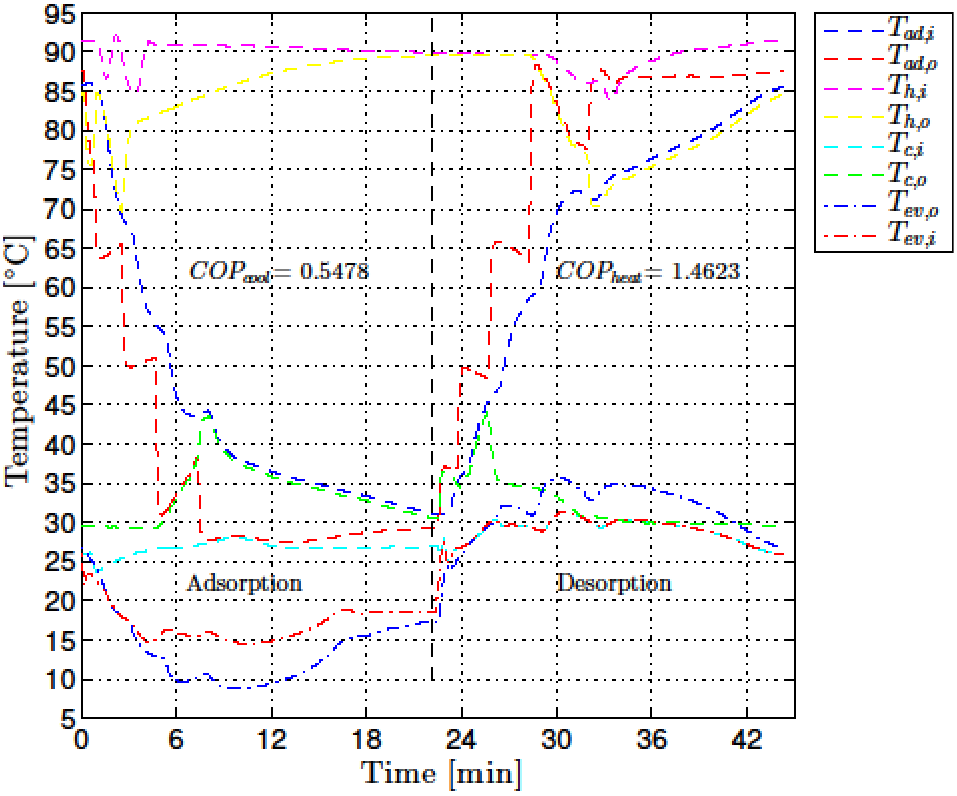

Figure 4.1: Thermal cycle plot for temperature variation 6 K and cycle switch 2 K

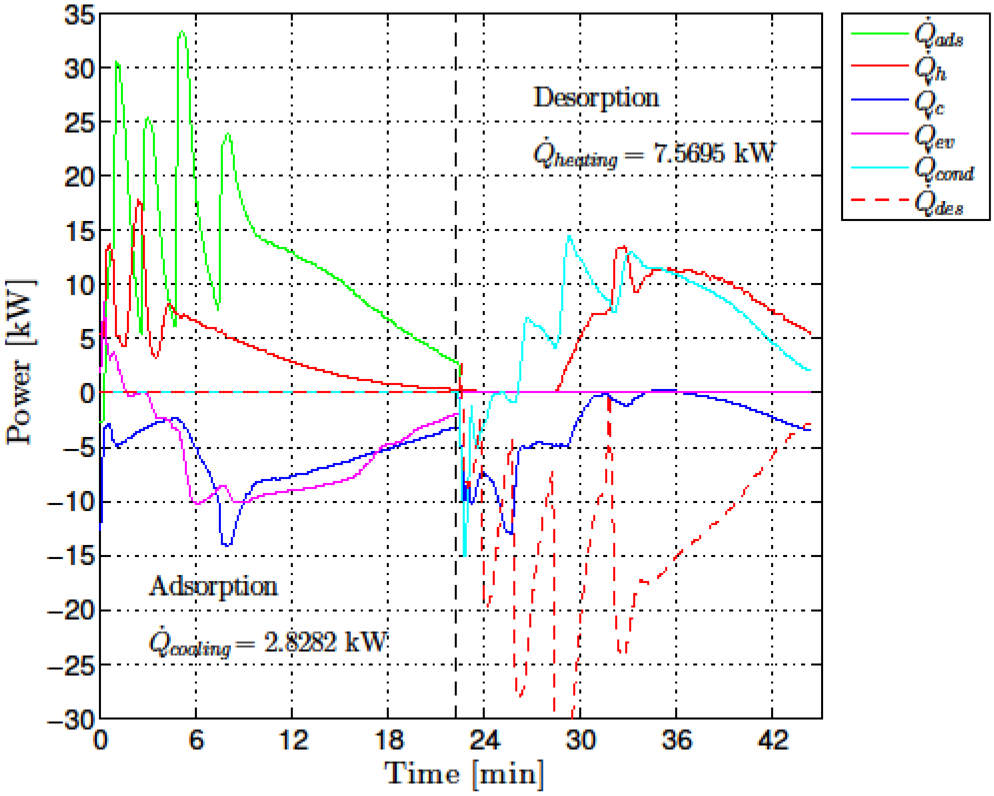

Figure 4.2: Power cycle plot for temperature variation 6 K and cycle switch 2 K

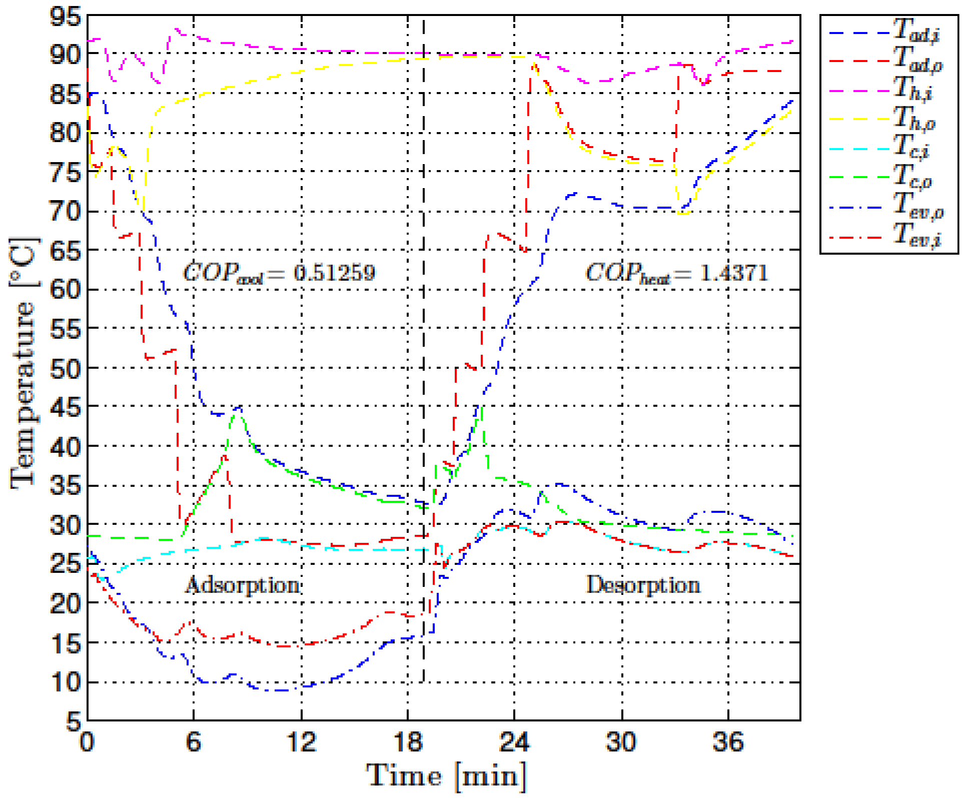

Figure 4.3: Thermal cycle plot for temperature variation 6 K and cycle switch 4 K

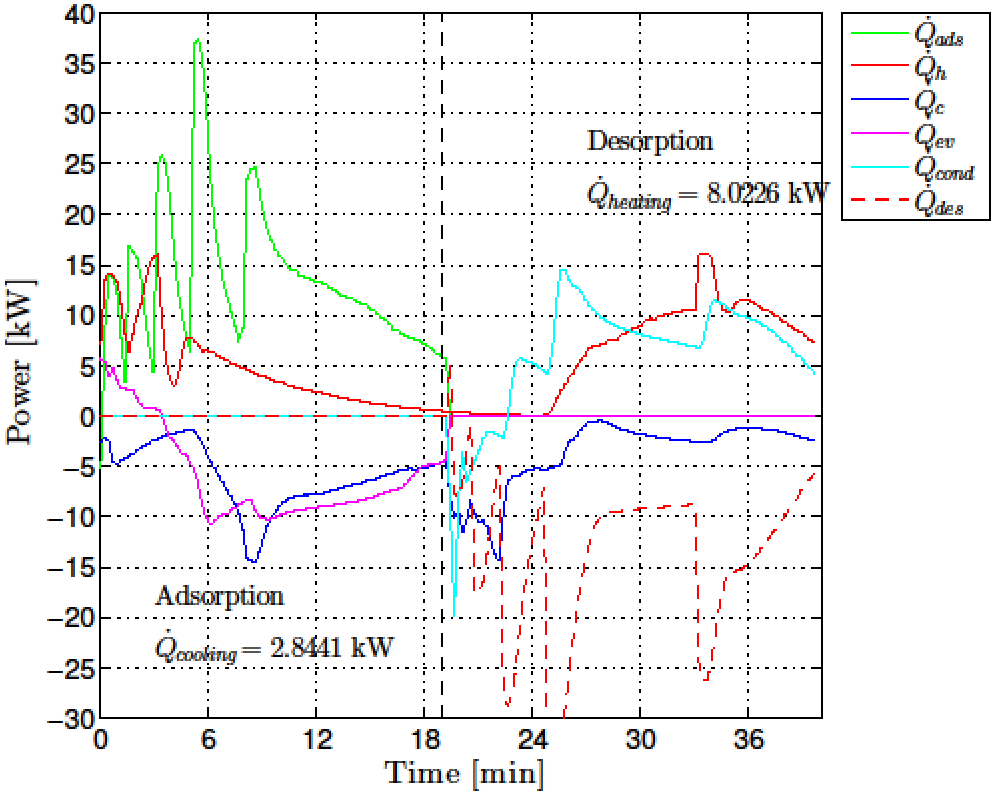

Figure 4.4: Power cycle plot for temperature variation 6 K and cycle switch 4 K

Similarly, another readings from the experiment, were measured with the modification in the variation of switching criteria to 4 K in the last step of the two half cycles that is the 4th and the 9th step, keeping the first 4 steps of the two half cycles unchanged, that is $\Delta T_{ad} = 6$ K. Analysis of this experiment the COP_{cool} of the cycle was observed to be on the lower side while it was noted that the cooling power was increased maximizing the cooling effect. Moreover 4th step means actually less mixing in the last step. However this effect is over compensated by selecting lower switching criteria of 2 K. By using this criteria the adsorber would be in a drier state. This helps in increasing the loading stage of the adsorber which means more heat of adsorption is released and stored in the lower section of the tank.

During the adsorption half cycle, the heat exchanger acts as an evaporator and the flow rate of an evaporator, $V_{ev,cond}$ is nearly about 1400 lph, while during desorption half cycle, the heat exchanger acts as a condenser and the flow rate of a condenser is about 2200 lph. Hence from the power curve plotted above it is observed that Q_{cond} and Q_{ev} are zero during the adsorption and desorption half cycle respectively. The peaks in the graphs of Q_{ads} and Q_{des} in the power curve indicates the maximum power in each step of the two half cycles.

Table 4.2 shows the COP_{cool} with variations in switching criteria:

Variation in SW	COP_{cool}	COP_{heat}	$Q_{cooling}$	$Q_{heating}$
dT_6K_CycleSW_2K	0.548	1.462	2.82 KW	7.57 KW
dT_6K_CycleSW_4K	0.513	1.437	2.84 KW	8.02 KW

Table 4.2: COP_{cool} with variations in the switching criteria

From analysis of the above preliminary experiments, it can be concluded that the potential for the heat recovery is significantly higher for the cycle switch with 2K at the end of each half cycle and the remaining steps of each half cycle having higher switching criteria of 6K. This cycle condition were chosen for further investigation to improve the performance of the stratisorp cycle with different control strategy.

4.2 Advanced control strategies with the stratisorp cycle

1. Temperature variation of 6 K with cycle switch 2 K and 4th step short in each half cycle:

As discussed above, the improved efficiency of an experiment can be achieved with the temperature variation 6K and cycle switching criteria of 2K. The performance of the cycle was tested by implementing efficient control strategies which would minimize the mixing of the water in to the tank. One of the strategy, to achieve the goal was implemented in the 4th step of the adsorption and desorption half cycle respectively. The 4th step of each half cycle was made short with minimum switch time of 30 seconds and temperature difference criteria of 20K.

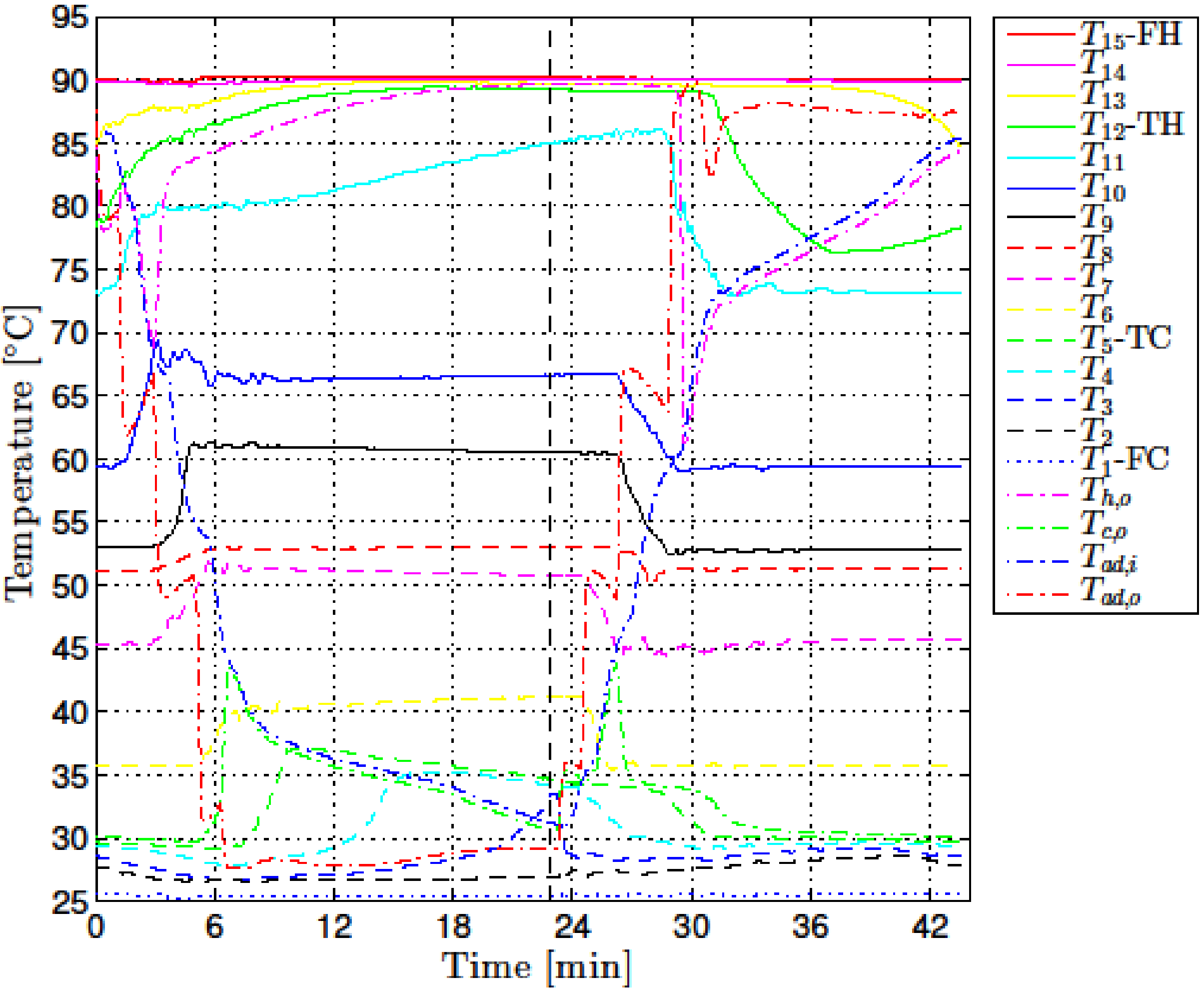

Figure 4.5: Storage tank profile temperature with 4th step short

It can be observed from the above plot that 4th step is shortened that reduces the time period of the insertion and extraction of water from the tank and ultimately less to less mixing in the central portion of the tank and increase in the cycle performance can be demonstrated. However an increase in the COP_{cool} of the cycle is to very less extent, but there is significant increase in the cooling power as compared to the cycle, with the variations in switching criteria. The upper most tank profile is comparatively warm, where large amount of the heat is stored in the tank. Also it can be seen that there is a significant drop in the return flow of heater temperature, $T_{h,o}$ in the 4th step of desorption half cycle.

2. Temperature variation of 6 K with cycle switch 2 K, cycle delay and 4th step short:

The other strategy in addition to the 4th step short of the two half cycles, implemented in the experiment was termed as cycle delay. The purpose of the cycle delay of 20seconds was to reduce the mixing in to the tank during the insertion and extraction of the fluid while valve switching. Here in this experiment during the adsorption half cycle, the extraction of the fluid is taken at certain level (ring 3) and the insertion is done at the level above the next higher level (ring 1) by delay of 20 seconds. Similarly during desorption half cycle the extraction of fluid is at ring 5 and the insertion is at the ring 2, below the lower ring with 20 seconds delay.

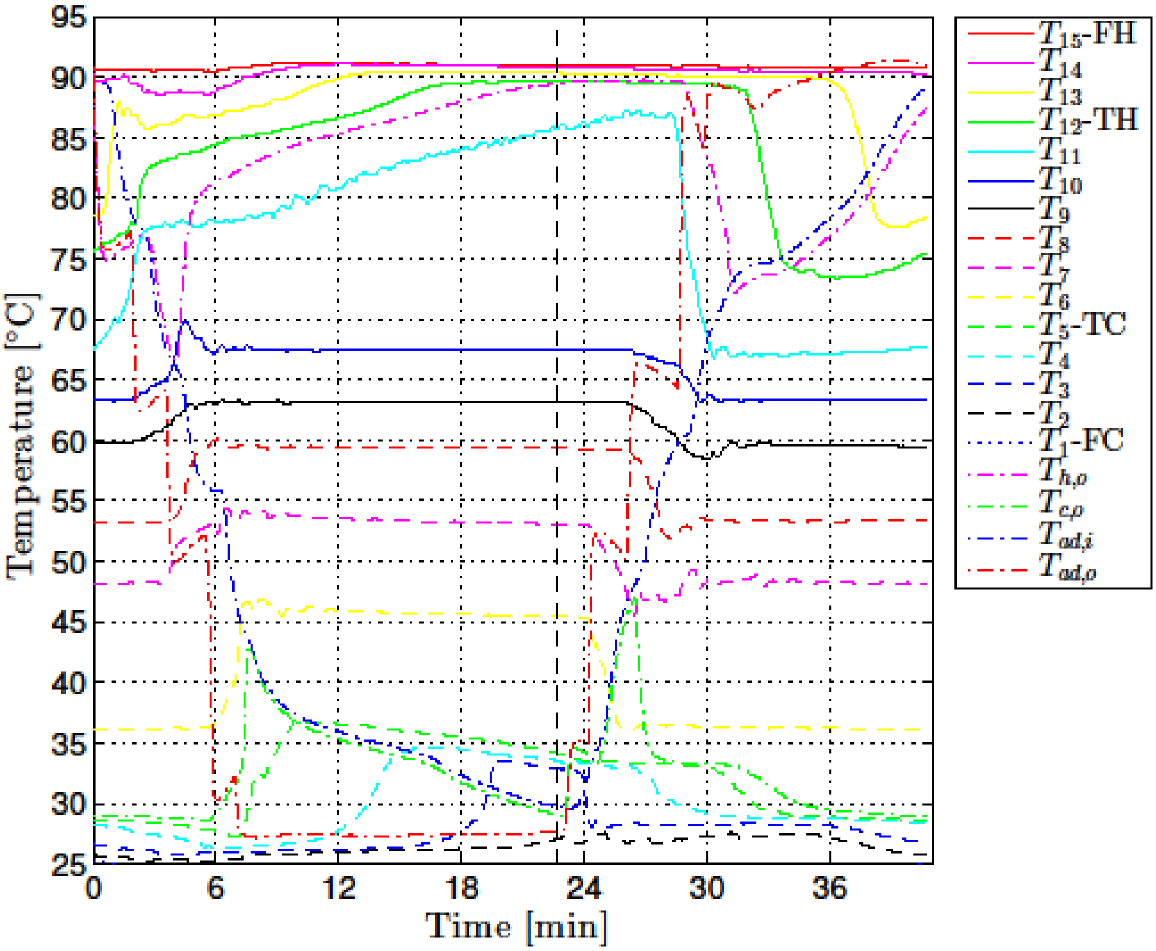

Figure 4.6: Storage tank profile temperature with cycle delay and 4th step short

Due to the cycle delay, the mixing of fluid at different temperature levels in the rings is minimised, which increases the cooling power. Finally the higher COP_{cool} is achieved which leads to increase the efficiency of the cycle.

4.3 Intermittent Heating and cooling

The heating and the cooling module causes significant mixing in the respective tank zones due to its continuous operation throughout the cycle. The purpose of this experiment is to investigate the performance of the cycle when these modules are decoupled from the stratified thermal storage tank. The modified stratisorp cycle with intermittent heat supply and heat rejection is analysed in this experiment where the driving heat is only intermittently available as in case of CHP unit.

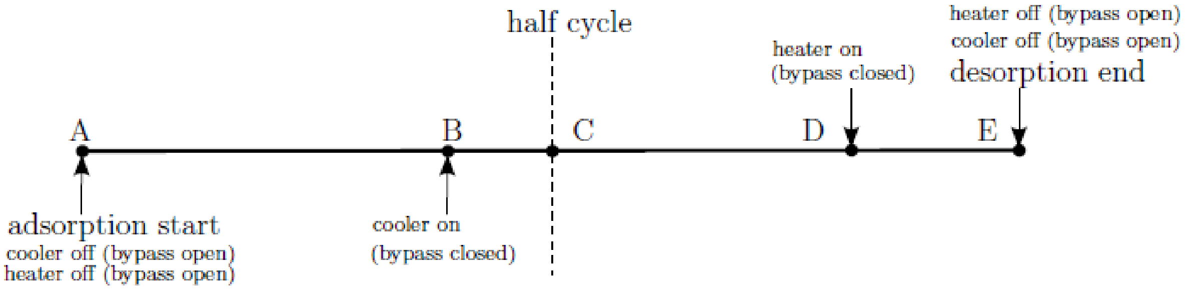

Figure 4.7: Sequence of operation of heater and cooler in the modified stratisorp cycle

At the end of desorption half cycle, the temperature of the water which is being extracted from the storage tank becomes too low for continuing desorption cycle and hence the temperature of the water being extracted needs to be raised up to certain temperature for smooth functioning of the cycle. At this stage the heater is activated. Similarly during the adsorption half cycle the cool water is extracted from the tank and as the cycle approaches towards the end, the water in the lower section of the tank available is not enough cool for continuing the adsorption cycle. At this stage the cooler is switched on. The cooler needs to in operation mode during the complete desorption cycle as well in order to reject of condensation. It can be noticed that the heater and cooler are thus intermittently active only at the end of each half cycle. Point B is the last step in adsorption half cycle, where the cooling module supplies the cool water at V_c, directly to the adsorber and receives the warm water coming from the adsorber at next upper level. Similarly at the last step of desorption half cycle the noted at Point D, the hot water is directly supplied from the heating module at V_h, to the desorber and receives the cool water coming from the desorber at next lower level in the cycle. Table 4.3 demonstrates the follow up process of an entire cycle in this experiment.

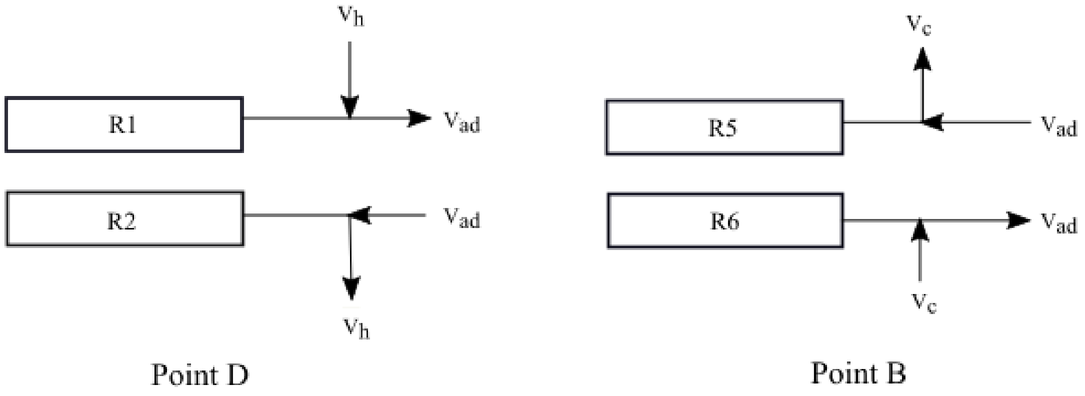

Figure 4.8: Flow scenario in the stratified rings

Step	Half Cycle	Extraction	Insertion	ΔT_{ad}	Cooler	Heater
0	Adsorption	R2	R1	>6K	OFF	OFF
1	Adsorption	R3	R2	>6K	OFF	OFF
2	Adsorption	R4	R3	>6K	OFF	OFF
3	Adsorption	R5	R4	>6K	OFF	OFF
4	Adsorption	R6	R5	>4K	OFF	OFF
5	Adsorption	R5	R6	>2K	ON	OFF
6	Desorption	R5	R6	>6K	ON	OFF
7	Desorption	R4	R5	>6K	ON	OFF
8	Desorption	R3	R4	>6K	ON	OFF
9	Desorption	R2	R3	>6K	ON	OFF
10	Desorption	R1	R2	>4K	ON	OFF
11	Desorption	R1	R2	>2K	ON	ON

Table 4.3: Intermittent heating and cooling experimental process

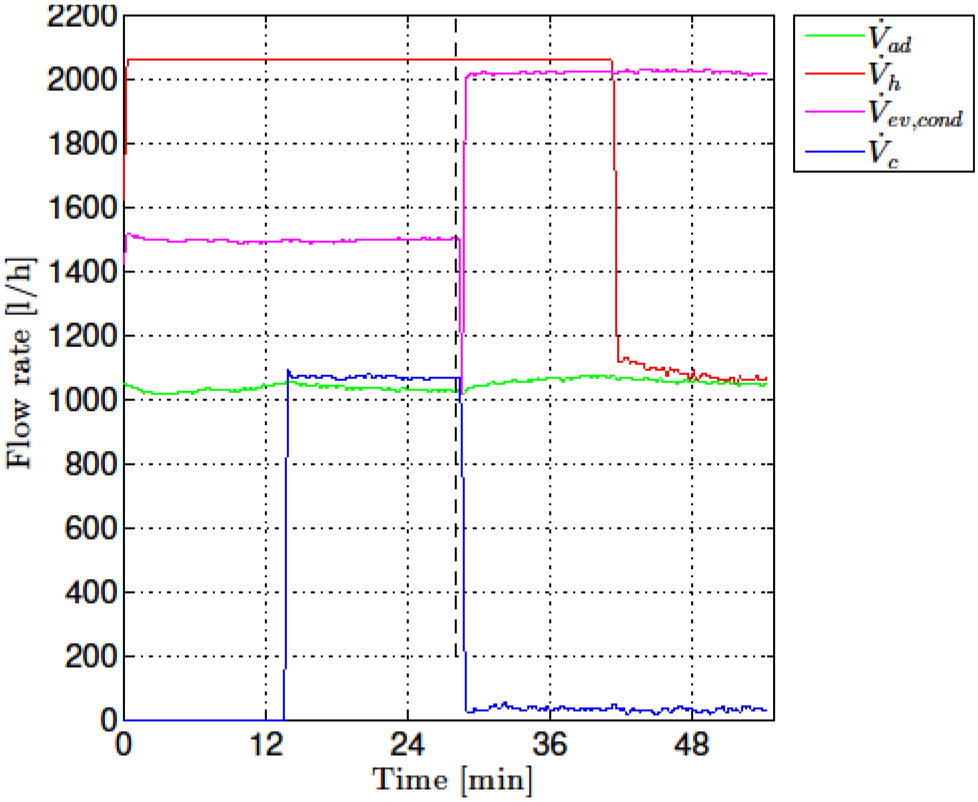

Figure 4.9: Flow rate of intermittent heating and cooling

The above plot represents the flow rate of the heater, re-cooler, adsorber and heat exchanger which acts as an evaporator during the adsorption half cycle and as condenser during desorption half cycle. In this type of cycle operation the stratified tank is used to store the sorption heat released during the adsorption phase and utilise the same for desorption phase. The tank is decoupled form the heating and cooling modules. In the experiment, flow rate of the heating module, cooling module and the adsorption chillers are kept equal.

From the previous investigation of the experiments, as per the analysis made it was concluded that the ideal results were obtained for the flow rate of 1200 lph which justifies the smooth functioning of the performance of the cycle. But, in this case at 1200 lph, flow rate of the heating module was dropping continuously which would significantly affect the performance of the experiment in later stage. Due to its limitation, the COP_{cool} and thus the cooling power available would drop down to very small extent.

Hence, the flow rate of each module were chosen by adjusting the true and false value of the voltages of the respective module pump and was set to be at 1000 lph.

$$V_h = V_c = V_{ad} = 1000 \text{ lph}$$

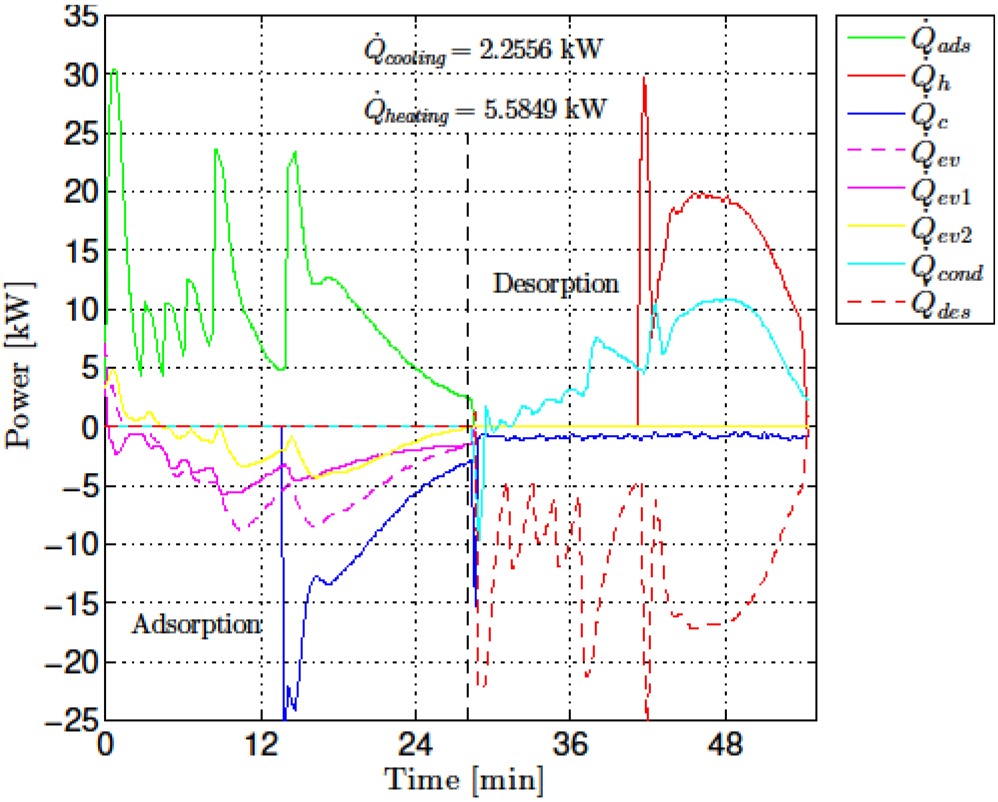

Figure 4.10: Power cycle plot of intermittent heating and cooling

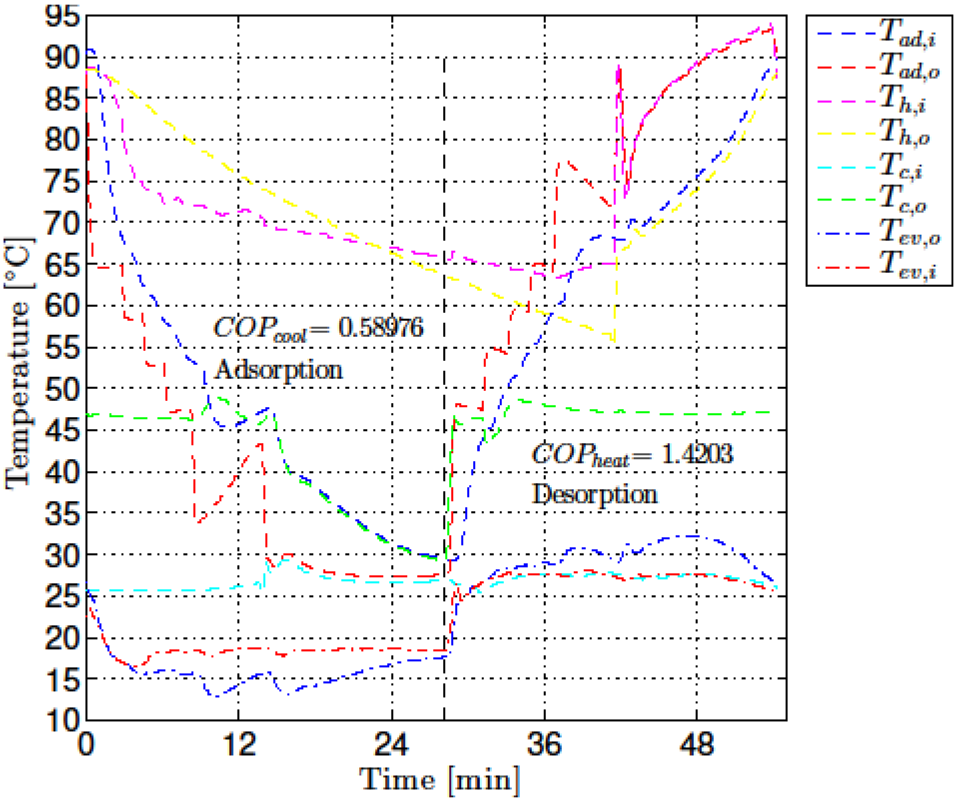

Figure 4.11: Thermal cycle plot of intermittent heating and cooling

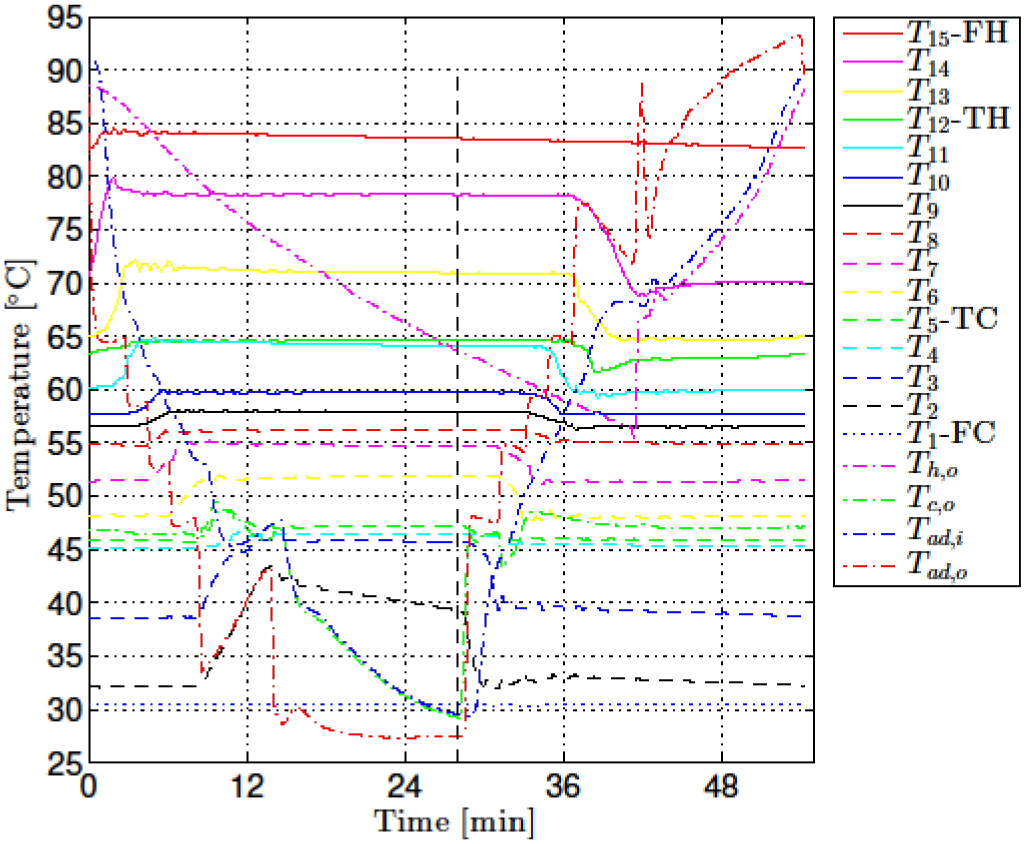

Figure 4.12: Storage tank profile temperature with intermittent heating and cooling

The heater flow rate is off during the adsorption half cycle and for the first 5 steps of desorption half cycle and hence we can observe from the above plot that the return temperature to the heater, $T_{h,o}$ is dropping continuously throughout the cycle and for the last step of the desorption half cycle the role of the heater is active and there is rise in the return temperature. Since the tank is decoupled in this experiment the temperature of supply and return flow from adsorption chiller, $T_{ad,i}$ and $T_{ad,o}$ are at elevated level as compared to the temperature measured by the sensor T_{15} in the upper most profile of the tank when the heater is active, which ensures that the insertion and extraction of water takes place completely from the heating module. Similarly, the temperatures measured by sensors, $T_{ad,i}$ and $T_{ad,o}$ falls below T_2 in the bottom part of the tank when the cooler is active at last step of the adsorption half cycle, which means that the insertion and extraction of the water takes place completely from the cooling module. Also the temperature measured by the sensor $T_{c,o}$ drops down immediately at the last step of adsorption which is supplied to the chiller and the return flow to the cooler module is the warm water. Due to decoupling of the tank from the heater and cooler the mixing of the water in the tank is reduced, which in turn increases the *COP* and performance of the cycle.

The intermittent operation of the heater and the cooler module is easily identified in the power plot curve. The stratisorp cycle with intermittent heating and cooling thus offers a significant increase in the COP_{cool} as compared to the standard stratisorp cycle, which is with continuous operation of heating and cooling.

$$COP_{cool} = 0.59$$

There are also further possibilities of improving the performance of the cycle by implementing efficient control strategies which would ultimately lead to an increase in the COP_{cool} of cycle. This can be achieved by the combination of several approaches (variable switching criteria with intermittent heating and cooling, cycle delay by some seconds, reduction in the adsorber flow rate during the valve switching interval in order to reduce the mixing in the tank and by making the second last step short in the half cycle).

CONCLUSION

The practical investigations of the Stratisorp concept for the stratified thermal storage tank with two adsorber chillers connected in series was presented in this thesis work. The set up facilitated the operation of a zeolite water adsorption chiller based on the stratisorp concept. The potential of improvement in the coefficient of performance for the cooling applications was demonstrated in the course of this thesis work. The detail study of the mechanical equipment and its experimental set up is presented in this work.

At the initial stage, a 4 way valve was implemented in the existing set up and using this valve more than 50% volume of the tank was heated up to the given set point by extracting the water from different heights of the tank by the heating module. Mixing in the storage tank hampers the performance of the cycle to large extent. A novel stratification system consisting of stratification rings placed at different heights facilitated the insertion and extraction of fluid from the tank, which caused minimal mixing in the fluid stored in to the tank.

In the modified experimental set up, two adsorption chillers were connected in series. It facilitated the temperature spread across the adsorption chillers close enough to the temperature spread across the adjacent rings, which finally leads to an increase in the COP_{cool} of the cycle. At preliminary stage experiments with two adsorption chillers were performed, with the temperature based criteria. The further improvement of the results in the experiments were made by implementing the control strategies for the stratisorp cycle. The strategy in this work was variation in switching criteria. For temperature variation with 6 K and cycle switch with 2 K there was significant increase in the efficiency of the cycle and the further investigations were carried out with this criteria set up in the program. The combination of several approach like cycle delay by 60 seconds, variation in the adsorber flow rate, last step short for both the half cycles were implemented in the experiments for the analysis of the experimental results. Conclusion was that the COP_{cool} remains almost the same.

At later stage, experiment with intermittent heating and cooling strategy was carried out and the stratisorp cycle offered a significant increase in the COP_{cool} of the cycle which lead to an increase in the cycle efficiency as compared to the standard cycle.

$COP_{cool} = 0.38$ ….. [For standard cycle with single chiller]

$COP_{cool} = 0.59$ …… [Double adsorption chiller with control strategy]

Using two adsorber chillers in series causes very less mixing in the central section of the tank as compared to that of single adsorption chiller. The performance of the cycle can be further improved with advanced control strategies to maximise the potential of CCHP application.

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APPENDIX

A. Measurement Results of the tank temperature profile

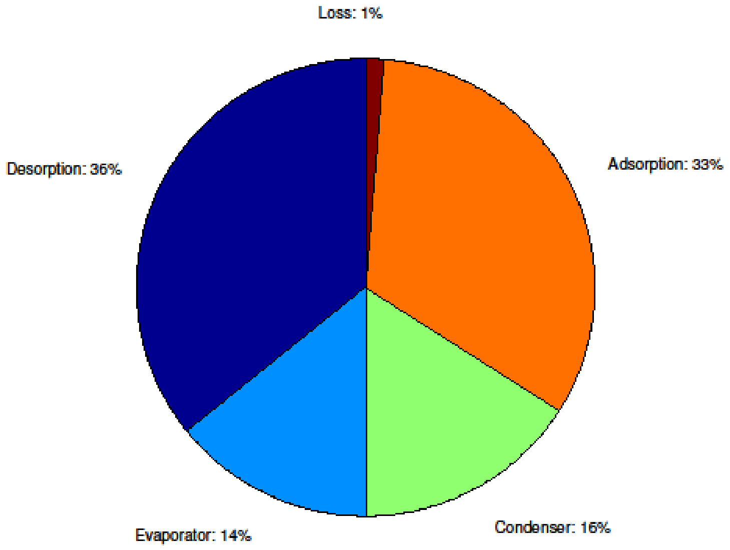

Figure A.1: Energy balance Module of the last cycle

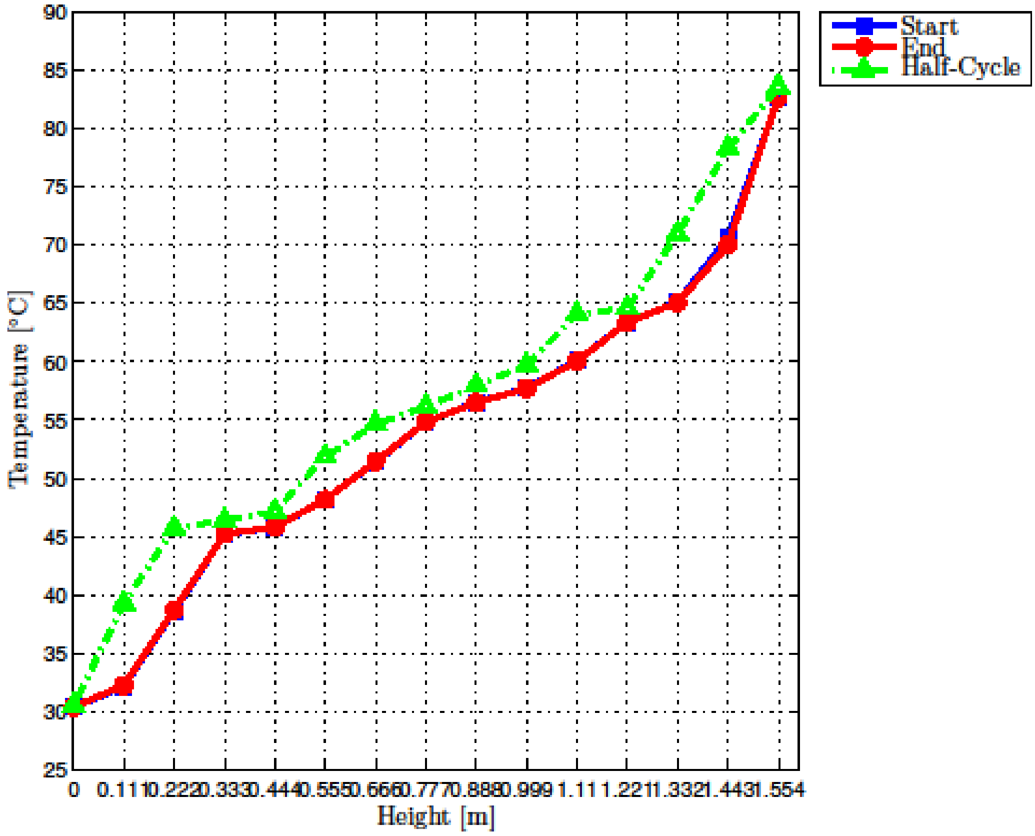

Figure A.2: Tank temperature profile for intermittent heating and cooling

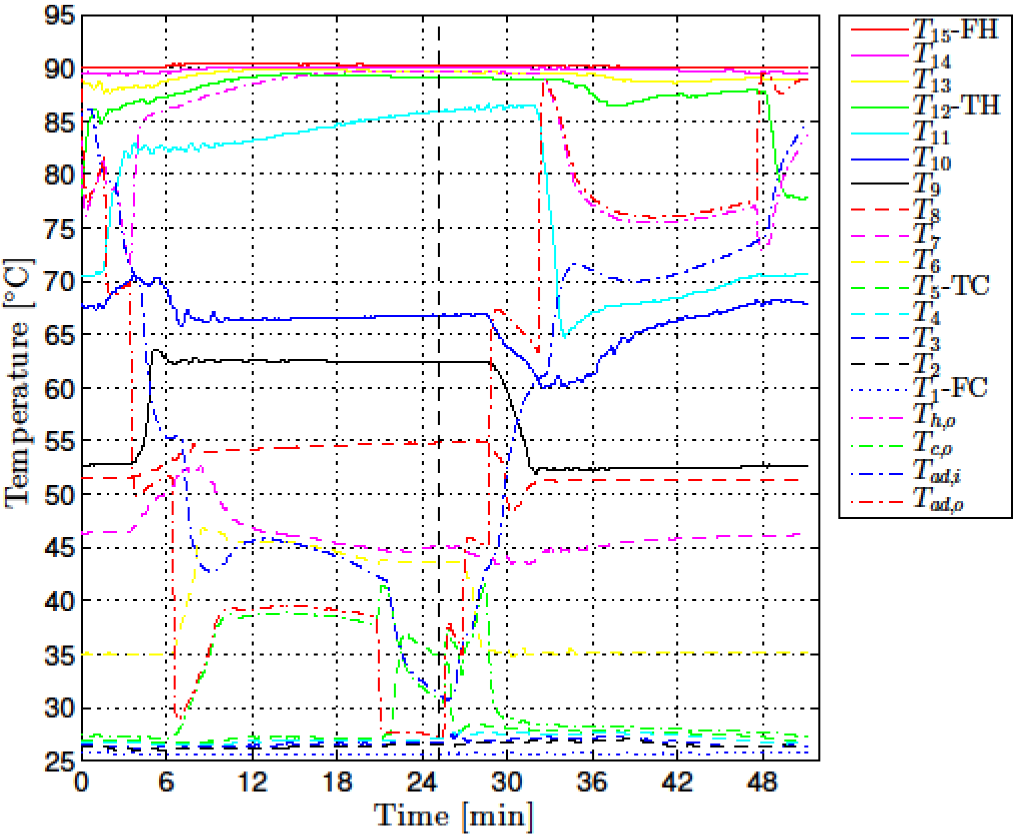

Figure A.3: Temperature profile along the tank height with cycle switch 4 K

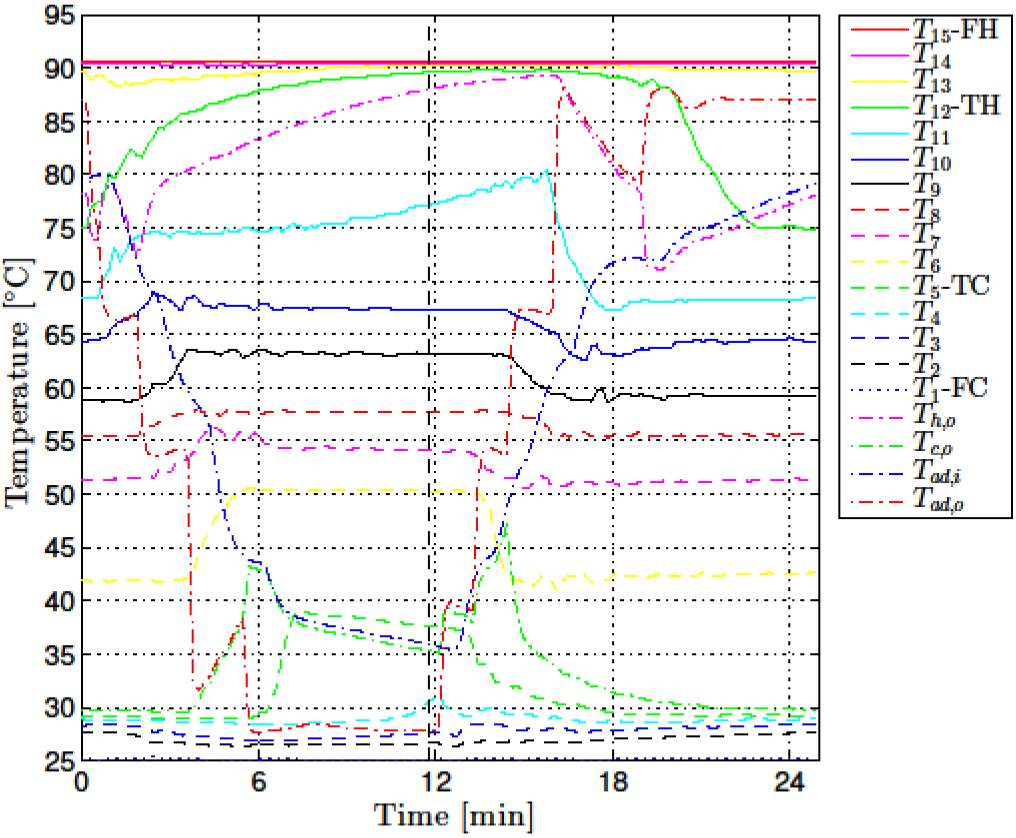

Figure A.4: Temperature profile along the tank height with cycle switch 8 K

B. Directories

B.1 List of Tables

B.2 List of Figures