PERFORMANCE EVALUATIION OF SALT HYDRATES FOR THERMOCHEMICAL ENERGY STORAGE SYSTEM

A PROJECT REPORT

Submitted by

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BONAFIDE CERTIFICATE

Certified that this project report**" Performance Evaluation of Salt Hydrates for Thermochemical energy storage system"** is a bonafide work of

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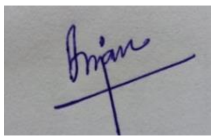
who carried out the project under my supervision, for the partial fulfilment of the requirements for the award of the degree of Bachelor of Engineering in Mechanical Engineering. Certified further that to the best of my knowledge and belief, the work reported herein does not form a part of any other project report or dissertation on the basis of which a degree or an award was conferred on an earlier occasion on these or any other candidates.



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ABSTRACT

Thermochemical materials are a promising solution for heat storage, providing the possibility for waste heat recovery. This project has an impact on design and development for thermochemical storage system as it influences how performance can be degraded or improved by careful selection of Thermochemical salt used.

A custom made reactor(prototype) is used for evaluating the performance of salt hydrates for Thermochemical energy storage system. The conditions for waste heat recovery are simulated by using heater for the charging cycle. Humidified air is used for discharging cycle. This project aims to determine the salt which would be ideal in terms of performance for low temperature storage application.

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 GENERAL

Energy is one of the major requirements for the human community worldwide. The demand for energy is growing steadily, and is likely to reach increasingly higher levels as populations and economies expand. During the last quarter-century, the world's energy demand increased by over half, and a similar increase is projected between now and the year 2030. A major part of the increased demand will occur in developing countries, where populations, economic activity and improvements in the quality of life are growing most rapidly. However, future growth builds from today's much larger base, meaning that tomorrow's energy requirements will be unprecedented in scale. This will pressure the global supply system and require increased emphasis on energy use efficiency in transportation, residential, commercial, and industrial sectors. The dual challenge is how to meet the world's growing energy needs, while also reducing the impact of energy use on the environment. Today's industrial developments are based upon abundant and reliable supplies of energy. Considering environmental protection, and also in the context of the great uncertainty over future energy supplies, attention is focused on the utilization of sustainable energy sources and energy conservation methodologies.

At present more than 80% of the world energy is provided by the combustion of fossil fuel, which includes coal, oil and natural gas. The energy requirements of the developed world are presently fulfilled by the stockpiling of fossil fuels by both suppliers and consumers of energy. These types of commodity stores are critically stocked, in order to meet sudden and seasonal variations in demands. However, shortages still occur and very often, even a small deviation from the normal use pattern can create rapid shortages of primary energy supply. Hence the industrial countries of the world become more conscious of their energy requirements. They have found it economically necessary to develop energy usage patterns that incorporate alternative sources of energy to reduce the dependence on primary fuels, and on other nations for energy producing fuels. On the other hand, industrial and commercial organizations have established energy management systems whose primary objectives are to reduce energy demands through the installation of energy conservation measures.

The energy demand pattern in the commercial, industrial and utility sectors varies on a daily, weekly and seasonal basis. Energy storage units can be used with energy management systems to reduce energy consumption in commercial and industrial establishments, by using the available waste heat or alternate energy sources. Thermal Energy Storage (TES) is one of the key technologies for energy conservation and has recently been developed to a point where it can have a significant impact on modern technologies. TES is the temporary storage of high or low temperature energy for later use, and it is the most appropriate method to reduce the mismatch between the energy supply at the source and its demand.

1.2 THE NECESSITY OF ENERGY STORAGE SYSTEMS

The major technical constraint that prevents the successful implementation and effective utilization of renewable energy sources, is its intermittent nature and time mismatched availability and demand. In order to reduce this mismatch, the system of such sources should be integrated with energy storage units. Renewable energy, particularly solar energy, is gaining more importance worldwide, for it is clean, non polluting, inexhaustible and cost free. Though there are many applications possible, an important factor is that solar energy is time dependant in nature. Hence, the commercial acceptance and the economics of solar thermal utilities or devices are tied to the design of an efficient thermal storage system, to meet the time-dependant supply and end use requirements.

There are many types of energy storage systems and they are broadly classified as below.

1. Mechanical Energy Storage
    - Hydro storage (pumped storage)
    - Compressed air storage
    - Flywheels
2. Chemical Energy Storage
    - Electrochemical batteries
    - Lead acid batteries
    - Lithium iron sulfide batteries
    - Sodium sulfur batteries
    - Organic molecular storage
    - Chemical heat pump storage
3. Biological Storage
4. Magnetic Storage
5. Thermal Energy Storage.

Among these storage methods, Thermal Energy Storage (TES) is one of the key technologies for energy conservation, and therefore, is of great practical importance. TES systems can contribute significantly to meet the society's needs for more efficient, environmentally benign energy use in building heating and cooling, aerospace, power, and utility applications. TES is perhaps as old as civilization itself. Since recorded time, people have harvested ice and stored it for later use. Large TES systems have been employed in recent years for numerous applications, ranging from solar hot water storage to building air conditioning systems. The TES technology has only recently been developed to a point where it can have a significant impact on modern technology.

Thermal Energy Storage systems have an enormous potential to increase the effectiveness of the energy conversion equipment use, and for facilitating large scale fuel substitutions in the world's economy. The use of the TES system has the following significant benefits:

- Reduced energy costs Reduced energy consumption
- Improved indoor air quality
- Increased flexibility of operation
- Reduced initial and maintenance costs
- Conservation of fossil fuels (by facilitating more efficient energy use and/ or fuel substitution).
- Reduced pollutant emissions (e.g. CO_2 and CFCs)

1.3 THERMAL ENERGY STORAGE METHODS

Thermal energy can be stored in the form of the sensible heat of a solid or liquid medium, the latent heat of a phase change substance or by a chemical reaction. Energy is supplied to a storage system for removal and use at a later time. The choice of the storage media depends on the amount of energy to be stored in unit volume or weight of the medium, and the temperature range at which it is required for a given application.

1.3.1 Sensible Heat Storage

In SHS systems, energy is stored by increasing the temperature of a storage medium, such as water, air, oil, rock beds, bricks and sand or soil. In the case of a liquid medium, water appears to be the most convenient, because it is inexpensive and has a high specific heat. However, the storage tank cost increases considerably for storing heat beyond 100°C. Organic oils, molten salts and liquid metals do not exhibit the same pressure problems but their use is limited because of their handling, containment, storage capacities and cost.

The difficulties and limitations relative to liquids can be avoided, by using solid materials for storing thermal energy as sensible heat. But larger amounts of solids are needed than while using water, due to the fact that solids, in general, exhibit a lower storing capacity than water. The cost of the storage media per unit energy stored is, however, still acceptable for rocks.

1.3.2 Latent Heat Storage

Latent Heat Storage (LHS) is based on energy absorption or release, when a storage material undergoes a phase change process. The LHS unit is particularly attractive due to its high-energy storage density and its isothermal behavior during the energy storing and retrieval process (phase change process). A wide range of PCMs have been investigated, including salt hydrates, paraffin waxes and non-paraffin organic compounds, for heating and cooling applications. Any LHS system must possess at least the following three components. A heat storage substance (PCM) that undergoes a phase transition within the desired operating temperature range, wherein the bulk of the heat added is stored as latent heat Containment for the storage substance. A heat transfer fluid (HTF) for transferring heat from the heat source to the storage substance, and from the latter to the application.

1.3.3 Thermochemical Energy Storage

Thermochemical heat storage systems use thermo-reversible chemical reactions. The storage system is charged by an endothermic reaction, absorbing the resulting enthalpy. This is then discharged by an exothermic reaction. As the name implies it uses salt chemicals for thermal energy storage which usually has water molecules. This method involves two reactions, hydration reaction (charging process) and dehydration reaction (discharging process).

$$Salt.xH_2O \longleftrightarrow Salt+xH_2O + Heat$$

A thermochemical energy storage system can be categorized as either open or closed system. Closed sorption systems have been researched for many years for cooling system refrigeration, chillers, heat pump and energy storage system. In general, the term ‘closed’ is referring to the system which is isolated from the atmospheric environment. In open cycle systems, the sorbent is released to and absorbed from the ambient environment, which means that the system is ‘open’ or connected to the environment. Therefore, the only form of sorbent able to be used in this type of open system is water.

1.4 TYPES OF THERMOCHEMICAL STORAGE

Thermochemical Energy Storage (TCES systems can be further classified as reversible chemical reactions and sorption processes. In a sorption process, heat is stored by breaking the binding force between the sorbent and the sorbate in terms of chemical potential. For the sorption heat storage, the process will only happen when the stored charged (dried) materials are exposed to the working fluid or sorbent. Thus, in principle, as long as the materials are hermitically sealed, the storage is loss-free.

1.4.1 Solid Adsorption

In solid adsorption, the reactions are typically exothermic (release heat). The most common example of solid adsorption material is Silica gel/H2O of which, the range of its specific surface is typically from 750 to 850 (m^2/g) . Silica gel is also widely used due to its hydrophilic properties. However, the sorption materials are quite frail. Experiments have shown that when the materials were mixed with water as salts solutions, after several cycles the silica gel particles would turn into powders.

1.4.2 Liquid absorption

Liquid absorption is a chemical/physical phenomenon when liquid adsorbent penetrates into the surface layer of a sorbent, entering the structure of the sorbent and results in the change of its composition. For THS application, with liquid as the working pair, among the common TCMs are hygroscopic inorganic salts, such as LiCl , LiBr and $MgCl_2$, $MgSO_4$, $LiNO_3$, Na_2S, $SrBr_2$.

1.4.3 Composite Materials

Recent research in THS is innovating towards composite material which combines salts and matrix, or salt in matrix . Composite materials are formed by impregnating hygroscopic salt into the pores of porous desiccant host material. It has been identified to be capable of exhibiting excellent humidity adsorbing ability and attain deep dehumidification of moist air.

The most common method is impregnating matrix with an aqueous salt solution by following steps: (1) drying the matrix to removed absorbed water; (2) impregnate the grains with salt solution; (3) filtration and (4) drying the composite matrix to remove the adsorbed water

1.5 SALT HYDRATES

Salt hydrates for thermal energy storage have a minimum storage density of 1 GJ/m^3 (depending on operating conditions) and no loss of heat occurs during storage. Using salt hydrates, a storage volume of 4 – 8 m^3 would be sufficient for the storage of the energy needed for an average household for one year. The energy density of the TCM will determine the precise volume of the storage system, the cost and the storage capacity.

REACTIONS	M (kg/mol)	ρ (kg/m3)	Δ*hr* (kJ/mol hyd. salt)	Δ*h*m (kJ/kg hyd. salt)	Δ*h*v (GJ/m3 hyd. salt)	Price (€/1000 kg)	Price (€/GJ)
$CaCl_2 \cdot 6H_2O \leftrightarrow CaCl_2 \cdot 2 H_2O + 4 H_2O$	**0.2190**	**1710**	**361.2**	**1649**	**2.82**	**2.82**	**70**
$MgCl_2 \cdot 6H_2O \leftrightarrow MgCl_2 + 6 H_2O$	**0.2033**	**1569**	**406.7**	**2001**	**3.14**	**154**	**77**
$MgCl_2 \cdot 6H_2O \leftrightarrow MgCl_2 \cdot 1H_2O + 5 H_2O$	**0.2033**	**1569**	**360.9**	**1775**	**2.79**	**154**	**87**
$MgCl_2 \cdot 6H_2O \leftrightarrow MgCl_2 \cdot 2H_2O + 4 H_2O$	**0.2033**	**1569**	**252.0**	**1239**	**1.94**	**154**	**125**
$Na_2S \cdot 5H_2O \leftrightarrow Na_2S + 5 H_2O$	**0.1681**	**1580**	**312.2**	**1857**	**2.93**	**348**	**220**
$Na_2S \cdot 5H_2O \leftrightarrow Na_2S \cdot 0.5H_2O + 4.5H_2O$	**0.1681**	**1580**	**283.3**	**1685**	**2.66**	**348**	**242**
$Na_2S \cdot 9H_2O \leftrightarrow Na_2S + 9 H_2O$	**0.2402**	**1430**	**532.7**	**2218**	**3.17**	**348**	**203**
$MgSO_4 \cdot 7H_2O \leftrightarrow MgSO_4 + 7H_2O$	**0.2465**	**1680**	**411.8**	**1671**	**2.81**	**77**	**73**
$Na_2SO_4 \cdot 10H_2O \leftrightarrow Na_2SO_4 + 10 H_2O$	**0.3222**	**1464**	**536.4**	**1749**	**2.56**	**54**	**56**

Table 1.1 The energy densities and prices of selected salt hydrates for the mentioned reactions

1.6 APPLICATIONS OF THERMAL ENERGY STORAGE SYSTEMS

The use of Thermal Energy Storage (TES) systems for thermal applications, such as heating and cooling, has recently received much attention. In various energy sectors, the potential benefits of TES for heating and cooling applications have been fully realized. Although these systems provide energy at a higher cost than fossil fuels, the major advantages are their limited impact on the environment and sustainability of the energy source. The various applications of TES systems are described in the following subsections

1.6.1 Solar Water and Air Heating

Solar energy is an important alternative energy source that is likely to be utilized more in the future. It is already mentioned, that the main factor, which limits the application of solar energy, is that it is a cyclic time dependent energy resource. Therefore, solar systems require energy storage to provide energy during the night and overcast periods. The TES systems are incorporated in solar air heating systems that are used for space heating, crop drying, poultry egg incubation etc.

1.6.2 Building Applications

The atmosphere in a room is found comfortable if its temperature varies little during the course of a day. For this reason, homes with very thick walls are found especially comfortable, cool in summer and warm in winter. An important disadvantage of lightweight buildings is their low thermal mass. They tend to have high temperature fluctuations, which result in a high heating and cooling demand. The PCM based storage system incorporated in the buildings decreases the frequency of the internal air temperature swings, and maintains the temperature closer to the desired value for a longer period of time (by absorbing heat at the peaks, e.g. during sunshine, and delayed release in the night; in most cases, one can even do without air conditioning).

1.6.3 Waste Heat Recovery

Waste heat recovery systems are of prime importance for the efficient use of energy in industrial processes. These include, reduction in the primary energy demand by recycling rejected waste heat using recuperative or regenerative heat exchangers. Although most waste heat recovery systems have been of the non-storage type, future trends may well see a significant increase in the use of the TES. This will be necessary, in order to expand the rational use of large waste heat sources, to match temporally the cyclic variation of hitherto independent thermal processes, and to permit the possibility of energy cascading and storage to overcome imbalances in plant energy systems.

1.6.4 Automobiles

Many difficulties that are experienced in automobiles, such as starting the engines at low temperature, inefficient combustion during warmup, high exhaust emissions and fuel consumption, etc., can be overcome by preheating the engine before starting it. Conventional preheating devices are expensive and require a source. Energy saving and performance improvement are possible, if the engine waste heat can be stored and utilized effectively. Therefore, several companies have investigated and developed an LHS for automobile vehicles. In this application, the heat store is heated up by the cooling fluid while the engine is running, and the stored heat can be used to preheat the engine on a new start, and also provide comfort to the driver cabinet during winter. The PCM is used in the tail pipe of the vehicles to absorb the exhaust heat. This will maintain the catalytic converter at its design temperature, reducing excessive hydrocarbon emissions during vehicle start-up.

CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

Literature papers were reviewed and the works done by other researchers related to advancement and development attained in the thermochemical energy storage has been used as a reference sources, support and background for this project. Many papers have been reviewed and papers with most significant contribution to the field are discussed with respect to the design of the reactor, humidification and dehumidification unit which will helpful in executing the project.

2.2 REVIEW OF LITERATURE

- **A review on the properties of salt hydrates for thermochemical storage, published on 2014**

  Fanny Trauselet al., Based on this the volumetric energy densities $MgCl_2$, Na_2S, $CaCl_2$ and $MgSO_4$ are the most promising candidates for thermochemical storage. More inquiries have to be made to gain information about other properties of the salt hydrates in order to make a solid choice for the material to use in thermochemical storage, depending on the operating conditions and other requirement.

- **An innovative composite sorbent for thermo-chemical energy storage applications for solar buildings, published on 2018**

  Vincenza Brancatoet al., The paper deals with innovative composite sorbents for sorption storage applications, realised by embedding $MgSO_4{\cdot}7H_20$ inside a polymeric matrix. The polymeric material, a polymeric foam that represents the hosting matrix for the salt hydrate, $MgSO_4{\cdot}7H_2O$, which was chosen for its excellent sorption capacity. The polymers were selected for their high permeability to water vapour in order not to affect the water vapour diffusion during real operating conditions.

- **A review of salt hydrates for seasonal heat storage in domestic applications, published on 2017**

  P.A.J. Donkerset al., An extensive review of 563 hydrate reactions is performed resulting in a database, wherein the thermodynamic data of these reactions are summarized. With help of the current database it is possible to select an appropriate hydrate reaction for any application.

- **Review on the recent progress of thermochemical materials and processes for solar thermal energy storage and industrial waste heat recovery, published on 2018**

  Hasila Jarimiet al., This paper presents a comprehensive overview on the recent advancements on THS systems. Development of THS could be classified in three main directions namely; sorption materials, sorption reactor design and sorption process design. In the last decade, several advancements have been achieved in these fields.

  However, further research is needed for advancing THS technology to commercial level. $CaCl_2$, LiCl, $MgCl_2$, SrBr, $LiNO_3$ and their mixtures are most promising and proven sorption materials in terms of high sorption enthalpy, relatively lower costs, good cyclic ability and adequate charging temperatures.

- **State of art on gas-solid thermochemical energy storage system and reactors for building applications, published on 2015.**

  Aran Soléet al., TGA-DSC coupled reactor techniques are employed to characterize the TCM. This way could be useful for first material selection for screening. However, to properly characterize TCM and for further reactor design TCM should be characterized in lab sized instruments. From the literature review first prototype for building heating applications were focussed with composites like zeolite and silica gel.

- **Application of $MgCl_2 \cdot 6H_2O$ for thermochemical seasonal solar heat storage, published on 2010.**

  H.A. Zondaget al., The dehydration of $MgCl_2.6H_2O$ and subsequent hydration at 12mbar vapour pressure gives a good temperature rise of 20°C. This is a promising result for the future use of this material for seasonal domestic heat storage for space heating and tap water heating. It was found that upscaling of the reactor was possible and a reasonable performance was obtained even with a low cost simple reactor design. Furthermore, on hydration of 3.5 kg of the magnesium chloride composite, it was found that after delivering a heated airflow for 24 hours the bed still was not fully hydrated, indicating the large storage capacity of the material.

- **High Temperature Thermochemical Energy Storage Using Packed Beds, published on 2016.**

  Qasim Ranjhaet al., A three dimensional circular bed filled with $CaO/Ca(OH)_2$powder is modelled as thermochemical energy storage for high temperature applications. Previously, circular reactor beds with indirect heat transfer were considered with either central pipe or coil type heat exchangers for heating and cooling of the bed. This study considers an outer annular shell for the flow of HTF to study the heat transfer within the bed.

- **A study of novel high performance and energy dense zeolite composite materials for domestic inter-seasonal thermochemical energy storage, publishedon 2018.**

  Daniel Mahonet al., This research has shown a composite material consisting of zeolite+$MgSO_4$ and a binder had good characteristics (i.e. power output and energy density) for use as an inter-seasonal domestic thermochemical heat storage material. Composite materials made from zeolite and $MgSO_4$ were shown to have increasing dehydration enthalpy with increasing weight percentage of $MgSO_4$. The 35wt% composite material had a dehydration enthalpy of 708 J/g.

- **Thermochemical process for seasonal storage of solar energy: Characterization and modelling of a high density reactive bed, published on 2012.**

  Benoit Michelet al., This work aims at estimating in order to later optimize the performances of a seasonal thermochemical storage process, based on solid/gas reaction in a fixed bed configuration. First, it focuses on the characterizations of mass transfer within the reactive salt bed, and on the different implementation parameters that could enhance the performances (energy density, specific power). Secondly, a simulation tool has been developed to represent the reaction in the reactive salt bed, and to estimate the thermal power.

- **Hydration and dehydration of salt hydrates and hydroxides for thermal energy storage - kinetics and energy release, published on 2012.**

  Holger Urs Rammelberget al., The dehydration onset temperature and the temperature with the maximum heating rate depend of the heating rate. The heating rate seems to have some influence on the decomposition for magnesium chloride, although it has to be proven by structural characterization of the intermediate states. In comparison with literature temperature our dehydration temperatures are most lowly caused in our lower heating rate. The heat storage at lower temperature is essential for $MgCl_2 \cdot 6 H_2O$ to avoid irreversible decomposition. The peak power of the hydration of $MgCl_2 \cdot 6H_2O$ strongly depends on the water vapour pressure.

- **Inorganic salt hydrate for thermal energy storage, published on 2017**
  Xuenong Gaoet al., The available information of salt hydrate has been concluded on the basic of thermal and physical classification, properties, problems, possible solutions and applications in this paper. It is generally agreed that salt hydrates have significant merits among TCM materials for heat storage. In spite of some disadvantages may limit their application in certain aspects, corresponding solutions are developed continuously.

- **Thermochemical energy storage technologies for building applications: a state-of-the-art review, published on 2011.**
  Yate Ding et al., A review on the state of the art of thermochemical storage technologies has been carried out. Consequently, thermochemical energy storage has provided with some advantages over TES, which can be summarized as higher energy density compared with physical change, long-term storage as reactants with small thermal loss, easily transmitted to generate heat at another location, wide temperature range and characteristics.

- **Research progress of solar thermochemical energy storage, published on 2013.**
  Juan Wuet al., This paper summarizes the chemical heat storage density is significantly higher than the sensible and latent heat storage, while the heat loss during storage can be ignored. TCS systems are not yet commercial, and many problems exist in the practical applications such as a complicated storage system for specific chemical reactions, relatively large investment and low efficiency, limited experience for long-term operation, and poor reversibility and thermal conductivity.

2.3 INFERENCE FROM LITERATURE REVIEW

From the review of literature works stated above, the following inferences were drawn.

- The salt undergoes subsequent hydration and dehydration which results in reduced number of working cycles.
- The mixture of different salts may result in decrease in dehydration temperature, hence the method can be very much useful for domestic applications where the temperature of source of heat is very low.
- The cascading of different salts arranged in decreasing order of their dehydration temperature results in higher efficiency of the system.

CHAPTER 3

EXPERIMENTAL SETUP

3.1 STORAGE SYSTEM REQUIREMENTS

For optimum working of the salt hydrates it requires suitable storage system. As there are lot of reactors available from literature review the most suitable reactor design were done. And also during dehumidification process (charging process) the heating of storage material were done using external heat source usually electric heater for research purpose. The heat transfer fluid such as ditherm were used for transferring heat from heater to secondary heat transfer fluid (air). The air must be above dehydration temperature for reaction to start and it must be of minimum relative humidity so that it can carry as much as moisture content. This process normally taken place for about 8 hours continuously. As the dehydration process completes now the wet air with relative humidity of above 90% were sent to the storing medium. For which it requires humidification unit (spray unit) was designed for the required capacity.

The air flow rate must be controlled according to requirement of the application such as room heating, drying, desalination etc. All the above units must be well insulated for avoiding heat loss. And few other equipment like temperature controller, temperature sensors, humidity sensors, air flow rate measuring device were selected accordingly. The storing capacity of salt hydrates depends on air flow rate, reactor design, temperature and humidity which must be accounted properly. The connections between the units were done using PVC pipes and insulated properly.

3.2 GEOMETRIC DIMENSIONS

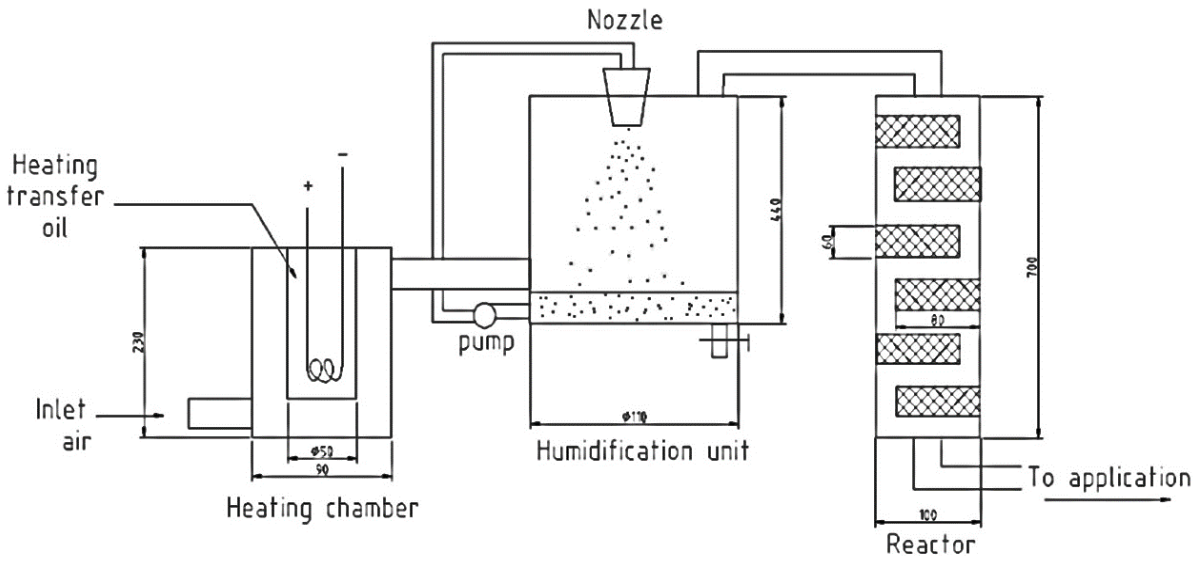

Figure 4.1: Two dimensional representation of experimental setup

Reactor		Humidification unit		Dehumidification unit	
Length	**700mm**	Diameter	**110mm**	Diameter	**90mm**
Breadth	**100mm**	Height	**440mm**	Height	**230mm**
Width	**100mm**				

Table 3.1: The geometric details of storage system

3.3 PROJECT SETUP

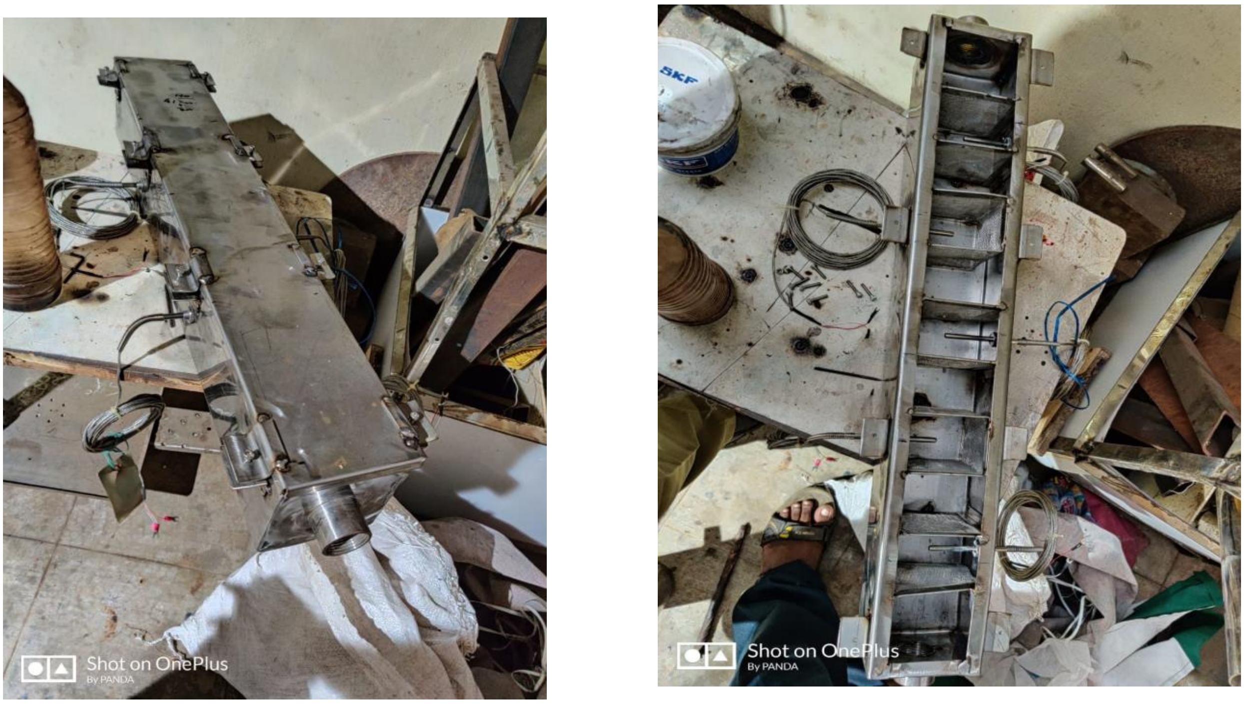

FIGURE 3.2 : Reactor used in the Project

FIGURE 3.3 : Heating Unit

FIGURE 3.4 : Humidification Chamber

3.4 DESIGN OF REACTOR

1. The reactor is to be designed for a total of 1250g of material divided across 5 racks at 250g per rack
2. There are to a total of 5 compartments each of these are to be separated from each other by 60 mm to allow for diffusion. Total length of rector therefore is 660 mm allowing for clearance attach the connecting pipes it is 700 mm.

3.5 DESIGN OF HUMIDIFICATION CHAMBER

- Calculation of cross section of spray chamber:

$$\text{Area} = \frac{\text{volume flow rate of air}}{\text{velocity of air inside chamber}}$$

Fixing flow velocity as 0.5m/s,

Area = 0.00471/0.5 = 9.42×10^{-3} m^2

Diameter = 0.109m

- Calculation of length and volume of spray chamber:

Sensible heat loss by air = h × volume × (LMTD)

LMTD = $(T_{hi}-T_{co})$ or $(T_{ho}-T_{ci})$

LMTD = 5^0C

Assuming h for air = 150 W/m^2k

- Sensible heat loss:

$$\text{Mass flow rate of air} = \frac{\text{volume flow rate of air}}{\text{specific humid volume of air (Vh)}}$$

$$V_h = \frac{1}{28.97}+\frac{W1}{18.02}\times 22.4\times\frac{(40+273.15)}{273.15}$$

W_1=humidity at the inlet= 0.0357 kg/m^3 (40^oC and 70 % RH)

V_h = 0.9373 m^3/kg

Mass flow rate = 0.00471/0.9373 =**0.00502 kg/s**

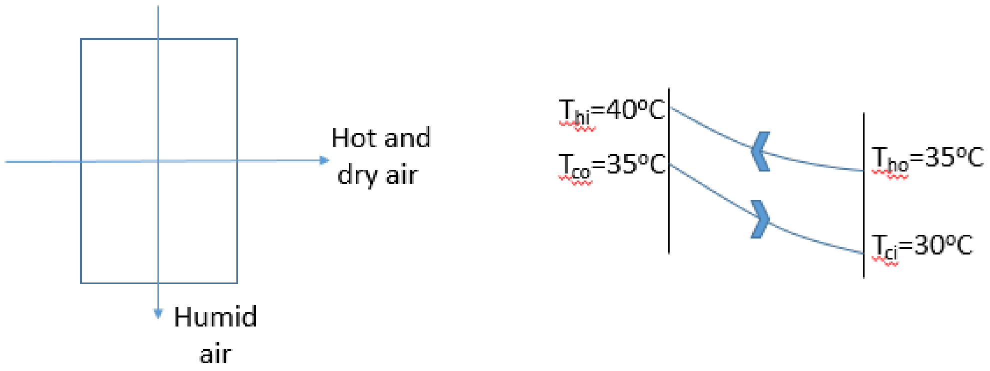

Figure 3.5 : Temperature variation of hot and cold fluid

- Enthalpy of entering air,

  $$\mathbf{h_1 = 1.005\, t_{db} + w_1(2500 + 1.88\, t_{db})\ kJ/kg}$$

  w_1 - specific humidity of entering air(kg of moisture per kg of dry air)

  t_{db} - dry bulb temperature in K

  $$= 1.005 \times 303 + 0.0357(2500+1.88 \times 303)$$

  $$= \mathbf{303.18\ kJ/kg}$$

- Enthalpy of exit air,

  $$\mathbf{h_2 = 1.005\, t_{db} + w_2(2500 + 1.88\, t_{db})\ kJ/kg}$$

  w_2 =specific humidity of exit air(kg of moisture per kg of dry air)

  $$= 1.005 \times 308 + 0.0377(2500+1.88 \times 308)$$

  $$= \mathbf{297.80\ kJ/kg}$$

  Therefore, sensible heat loss = 1.522-1.495 = 0.28 kJ/s

  $$0.28 \times 1000 = 150 \times A \times (273+5)$$

  $$A = 6.71 \times 10^{-3}\ m^2$$

  When, **Area = $\mathbf{0.0093\ m^2}$,**

  D = 11cm, L = 72 cm

- **Moisture carried out by air:**

  At 40°C, 70% RH, w = 0.0357 kg/m^3

100% RH, w = 0.0510 kg/m^3

Capacity = 0.0510-0.0357

= 0.0153 kg/m^3

We know Q = 10cfm

= 0.0056 m^3/s carries**8.568 × 10kg/s**

For 1 hour it carries **308 g** of water.

Hence for every one hour the humidification tank must be filled with 308grams of feed water.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 EXPERIMENTAL DATA

The experiment was conducted for dehydration of Magnesium chloride and Magnesium Sulphate salts and readings were noted for every 2 minutes. From the readings, the moisture content removed will be calculated so as to decide the preferable salt for the low temperature heat storage application.

1. $MgCl_2.6H_2O$

T_{in} (^{0} C)	RH in	T_{out} (^{0} C)	RH out	T_{bed} (^{0} C)	Time (min)	Outlet moisture	Inlet moisture	Net moisture	cumulative value
60.6	16.3	32.4	65	36	2	0.023009	0.020502	0.000251	0.000251
60.8	16.3	32.8	63.9	37	4	0.023234	0.020628	0.000261	0.000511
63.1	14.5	33.4	62.1	37	6	0.023094	0.020754	0.000234	0.000745
65.9	12.8	34	60.3	38	8	0.023289	0.020861	0.000243	0.000988
66.4	12.5	34.7	57.8	38	10	0.023284	0.020815	0.000247	0.001235
66.3	12.5	35.2	56.6	39	12	0.023175	0.020973	0.00022	0.001455
64.5	13.4	35.5	55.5	40	14	0.022817	0.020919	0.00019	0.001645
62.7	14.5	35.8	54.5	41	16	0.022655	0.020896	0.000176	0.001821
60.6	15.9	35.9	54.1	42	18	0.022444	0.02086	0.000158	0.001979
61.3	15.5	36	53.9	42	20	0.022636	0.020902	0.000173	0.002153
64.6	13.1	36	53	43	22	0.022412	0.020553	0.000186	0.002339
65.1	12.8	36.5	52	43	24	0.022425	0.020744	0.000168	0.002507
64.6	13.1	36.7	51.6	44	26	0.022412	0.020818	0.000159	0.002666
63.3	13.7	36.9	51.1	44	28	0.02203	0.02085	0.000118	0.002784
62.1	14.6	36.9	50.9	45	30	0.022162	0.020769	0.000139	0.002923
60.4	15.7	36.9	51	45	32	0.021947	0.020809	0.000114	0.003037
60.2	15.9	36.9	51	45	34	0.022011	0.020809	0.00012	0.003157
64.5	13.1	36.9	50.8	46	36	0.022306	0.020728	0.000158	0.003315
65.6	12.4	37.1	50.3	46	38	0.022244	0.020756	0.000149	0.003464
65.3	12.5	37.3	49.7	46	40	0.022107	0.020741	0.000137	0.003601
64.4	13.1	37.4	49.5	46	42	0.0222	0.020774	0.000143	0.003743
63.5	13.5	37.3	49.7	47	44	0.021917	0.020741	0.000118	0.003861
61.7	14.8	37	50.6	47	46	0.022036	0.020763	0.000127	0.003988
60	16.1	36.5	52.5	47	48	0.022072	0.020943	0.000113	0.004101
64.7	13.1	36	53.4	47	50	0.022519	0.020708	0.000181	0.004282

65.4	12.6	35.7	54.3	48	52	0.02239	0.020701	0.000169	0.004451
64.2	13	35.2	54.2	48	54	0.021822	0.020083	0.000174	0.004625
63.4	13.7	35.8	54	48	56	0.022136	0.020704	0.000143	0.004768
61.9	14.5	36	53.2	48	58	0.021799	0.02063	0.000117	0.004885
60.5	15.5	36.2	52.6	48	60	0.021773	0.02063	0.000114	0.004999
61.5	14.8	36	52.4	48	62	0.021824	0.02032	0.00015	0.00515
63.7	13.5	36.2	52.8	48	64	0.022128	0.020708	0.000142	0.005292
63.8	13.5	36	53.4	48	66	0.022233	0.020708	0.000153	0.005444
61.9	14.6	35.8	53.6	48	68	0.021949	0.020551	0.00014	0.005584
61.9	14.5	37.5	53.9	48	70	0.021799	0.022748	-0.0009	0.005489
63.3	13.7	35.6	54.3	48	72	0.02203	0.020584	0.000145	0.005634
66.4	12	35.6	54.3	48	74	0.022353	0.020584	0.000177	0.005811
66.6	11.8	35.6	54.5	49	76	0.022188	0.02066	0.000153	0.005963
66	12.2	35.6	54.3	49	78	0.022302	0.020584	0.000172	0.006135
69.3	10.6	35.5	54.5	49	80	0.022602	0.020543	0.000206	0.006341
69.3	10.6	35.6	54.5	49	82	0.022602	0.02066	0.000194	0.006535
68.1	11.1	35.7	54.9	49	84	0.022387	0.02093	0.000146	0.006681
66.8	11	35.7	54.2	49	86	0.020879	0.020663	0.00002	0.006703
64.5	12.9	35.7	53.9	49	88	0.021966	0.020549	0.000142	0.006844
61.9	14.5	35.5	54.4	49	90	0.021799	0.020505	0.000129	0.006974
59.6	16.1	35.3	54.7	49	92	0.021644	0.020385	0.000126	0.0071
64.9	12.6	35.2	55.1	49	94	0.021866	0.020417	0.000145	0.007245
66.9	11.6	35.2	55.2	49	96	0.022121	0.020454	0.000167	0.007411
66.4	11.8	35.1	55.3	49	98	0.02198	0.020375	0.000161	0.007572
								0.003448	0.01102
64	13.1	35	56	50	138	0.021781	0.020515	0.000127	0.011147

TABLE 4.1 : Tabulation of Experimental readings for Dehydration of $MgCl_2.6H_2O$

2. $MgSO_4.7H_2O$

RH in	T_{in} (°C)	RH out	T_{out} (°C)	T_{bed} (^{0} C)	Time (min)	Inlet moisture	Outlet moisture	Net moisture	Cumulative moisture
30.2	53.9	30.2	57.8	32	2	0.0305673	0.03715828	-0.00066	-0.0006
30.3	51.5	32.8	46.4	33	4	0.0271329	0.02250248	0.000463	-0.0001
30.4	51.5	33.1	45.8	33	6	0.0272225	0.02199529	0.000523	0.00039
30.4	51.5	33.3	44.9	33	8	0.0272225	0.02108947	0.000613	0.001
30.4	51.7	33.4	44.8	33	10	0.0275037	0.02103975	0.000646	0.00165
30.4	52.1	33.4	45.4	34	12	0.0280737	0.02172614	0.000635	0.00228
30.3	52.5	33	45.9	34	14	0.0285599	0.02204593	0.000651	0.00293
30.2	52.8	33	46.1	35	16	0.028905	0.02228177	0.000662	0.00359
30.1	52.8	32.9	46	35	18	0.0288093	0.02209641	0.000671	0.00427
30	53	33.4	51.3	35	20	0.0290078	0.02960273	-0.0005	0.00421
29.9	53.6	29.8	53.4	36	22	0.0298068	0.02940686	4.00E-05	0.00425
29.7	54.1	35.5	42.7	36	24	0.0303672	0.01996678	0.00104	0.00529
29.7	54.1	36.1	40.8	37	26	0.0303672	0.01830171	0.001207	0.00649
29.6	54.3	36.3	40	37	28	0.0305726	0.01760922	0.001296	0.00779
29.5	54.9	36.2	39.9	38	30	0.0314057	0.0174639	0.001394	0.00918
29.5	55.3	35.9	40.7	38	32	0.0320438	0.0181005	0.001394	0.01058
29.5	55.4	35.5	41.5	38	34	0.0322052	0.0187021	0.00135	0.01193
29.5	55.5	35.4	41.7	39	36	0.0323672	0.01885456	0.001351	0.01328
29.5	56	35.3	42.2	39	38	0.0331881	0.01932146	0.001387	0.01467
29.5	56.2	35.4	42.1	40	40	0.0335216	0.01927086	0.001425	0.01609
29.4	56.4	35.3	42.4	40	42	0.0337432	0.01953305	0.001421	0.01751
29.4	56.8	34.8	43.3	41	44	0.0344226	0.02022026	0.00142	0.01893
29.4	56.9	34.5	44	41	46	0.0345943	0.02081813	0.001378	0.02031
29.4	57.5	34.2	45	41	48	0.0356405	0.02177577	0.001386	0.0217
29.3	58.1	34.1	46.7	42	50	0.0365895	0.02376943	0.001282	0.02298
29.3	58.4	35	47	42	52	0.0371351	0.0247872	0.001235	0.02421
29.2	58.8	36.2	43.6	42	54	0.0377445	0.02137765	0.001637	0.02585
29.2	59	37	41.5	42	56	0.0381173	0.01949233	0.001863	0.02771
29.2	58.8	37.3	40.4	42	58	0.0377445	0.01849822	0.001925	0.02964
29.2	58.7	37.2	40.2	42	60	0.0375593	0.01824624	0.001931	0.03157
29.2	57.8	36.9	39.9	43	62	0.0359279	0.0178016	0.001813	0.03338
29.2	57.3	37	39.4	43	64	0.0350487	0.01736231	0.001769	0.03515
29.3	57.1	36.7	39.6	43	66	0.0348212	0.01741354	0.001741	0.03689
29.2	56.8	36.6	40.3	44	68	0.0341885	0.01805126	0.001614	0.0385
29.2	56	36	40.5	44	70	0.0328506	0.01795217	0.00149	0.03999
29.3	54.1	35.7	39.5	44	72	0.0299582	0.01684544	0.001311	0.04131
29.2	54.3	35.3	40.2	44	74	0.0301595	0.01731431	0.001285	0.04259
29.2	54.5	35	41.1	44	76	0.0304657	0.01803886	0.001243	0.04383

29.2	54.2	34.7	41.4	44	78	0.0300074	0.01818082	0.001183	0.04501
29.2	53.2	34.4	41.5	44	80	0.0285232	0.01812259	0.00104	0.04606
29.2	53.9	34.2	42.6	44	82	0.0295552	0.01913136	0.001042	0.0471
29.2	54	35	43.2	44	84	0.0297052	0.02022668	0.000948	0.04805
29.1	53.6	36.2	40.3	44	86	0.0290093	0.01785398	0.001116	0.04916
29.2	54	37	38.3	44	88	0.0297052	0.01633097	0.001337	0.0505
29.2	54.8	37.5	37.5	44	90	0.0309301	0.01582637	0.00151	0.05201
29.2	54.7	37.5	37.1	44	92	0.0307746	0.01547438	0.00153	0.05354
29.2	55	37.3	37.6	44	94	0.0312432	0.01583058	0.001541	0.05508
29.3	54.9	37.3	37.7	44	96	0.0311927	0.01591964	0.001527	0.05661
29.3	55.1	37	38.1	44	98	0.0315083	0.0161494	0.001536	0.05814
29.3	55.5	36.6	38.8	44	100	0.0321478	0.01661129	0.001554	0.0597
29.4	54.3	37.8	38.3	44	102	0.030366	0.01668408	0.001368	0.06106
29.4	54.4	39.8	35.2	44	104	0.0305198	0.01474761	0.001577	0.06264
29.4	54.3	40.2	34.1	45	106	0.030366	0.01398744	0.001638	0.06428
29.4	53.4	40.1	34	45	108	0.0290121	0.01387275	0.001514	0.06579
29.4	53.4	41.2	33.6	45	110	0.0290121	0.01392911	0.001508	0.0673
29.5	54.3	42.7	33.6	45	112	0.0304693	0.01443624	0.001603	0.06891
29.5	54.4	43.7	31	46	114	0.0306236	0.01270336	0.001792	0.0707
29.5	54.2	44	29.4	46	116	0.0303157	0.01164038	0.001868	0.07257
29.5	54	44.3	29.4	46	118	0.0300104	0.01171974	0.001829	0.07439
29.5	53.7	44.8	31.6	46	120	0.0295576	0.01348809	0.001607	0.076
29.6	52.7	46.4	28.1	47	122	0.0281865	0.01136219	0.001682	0.07768
29.6	52.3	47.7	24.8	48	124	0.0276163	0.00957039	0.001805	0.07949
29.7	51.5	46.9	24.6	48	126	0.0265956	0.00929561	0.00173	0.08122
29.7	50.5	46.3	24.4	48	128	0.0252588	0.00906511	0.001619	0.08284
29.7	49.4	46.4	25.6	49	130	0.0238569	0.00977423	0.001408	0.08425
29.7	49.3	48	23.9	49	132	0.0237329	0.00911421	0.001462	0.08571
29.7	49.5	48.2	22.9	49	134	0.0239814	0.0086052	0.001538	0.08725
29.7	49.2	49.2	21.9	50	136	0.0236095	0.00825531	0.001535	0.08878
29.7	48.5	49	21.5	50	138	0.0227613	0.00801928	0.001474	0.09025

TABLE 4.2: Tabulation of Experimental readings for dehydration of $MgSO_4.7H_2O$

4.2 COMPARISON OF SALT HYDRATES

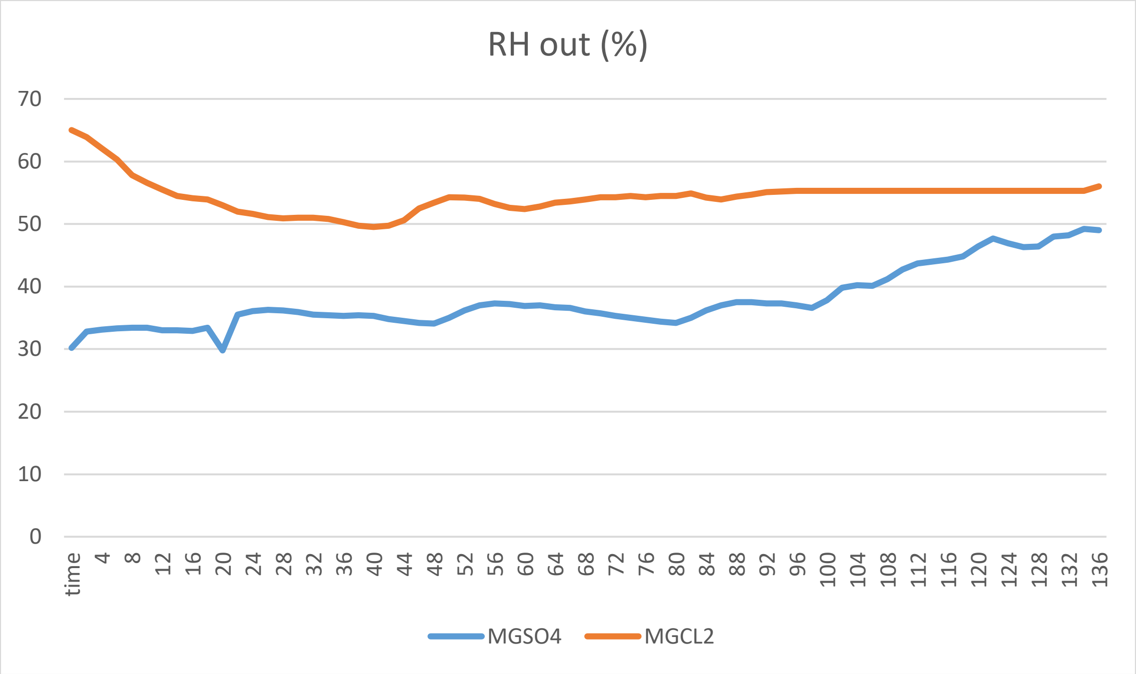

FIGURE 4.1 : Comparison of RH of the salts at outlet

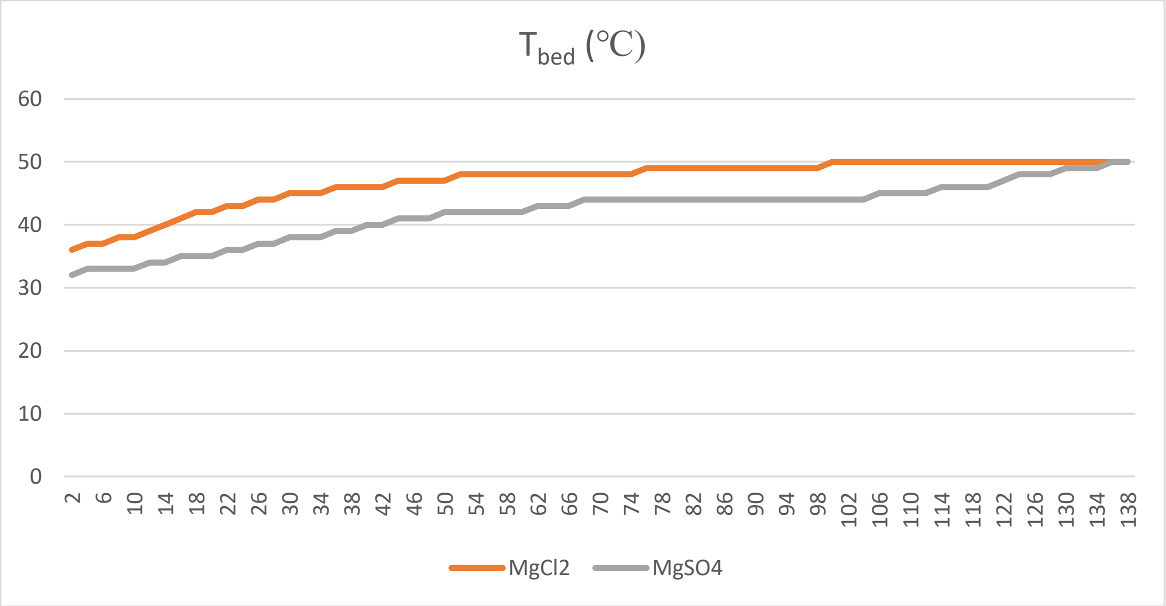

FIGURE 4.2 : Comparison of Bed Temperatures of the salts.

4.3 CALCULATION

1. **$MgCl_2.6H_2O$**

   -320 grams taken for testing

   $MgCl_2$=92 Kg/Kmol

   $6H_2O$=108 Kg/Kmol

   Mass fraction of H_2O=0.54

   Therefore for **320** grams amount of water present is **172.8** grams

   Out of which **111.3** grams moisture were removed (as seen from the experimental result)

   Percentage of water unremoved

   $= \frac{(172.8-111.3)}{172.8} * 100$

   =**35.59%**

2. **$MgSO_4.7H_2O$**

   -320 grams taken for testing

   $MgSO_4$=120 Kg/Kmol

   $7H_2O$=126 Kg/Kmol

   Mass fraction of H_2O=0.51

   Therefore for **320** grams amount of water present is **163.2** grams

   Out of which **90.2** grams moisture were removed (as seen from the experimental result)

   Percentage of water unremoved

   $= \frac{(163.2-90.2)}{163.2} * 100$

   =**44.73%**

4.4 INFERENCE

From the calculations and comparison, it is clear that the dehydration of $MgCl_2.6H_2O$ is more effective than that of $MgSO_4.7H_2O$. Hence, for the lower temperature heat storage applications Magnesium Chloride Hexahydrate ($MgCl_2.6H_2O$) is preferable.

CHAPTER 5

CONCLUSION

5.1 SCOPE FOR FUTURE WORK

This study focussed entirely on the fabrication of the reactor with testing of different Salt Hydrates. Due to the prevailing COVID 19 situation we were unable to perform the discharging cycle i.e; the hydration of the salts. The current reactor design also means considerable amount of losses occur in the form of heat loss through the side walls. All of these avenues are for the future growth and improvement.

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