Experimental Investigations of Thermochemical Heat Storage System Using Hydrated Salt Based Composite Sorbents for Building Space Heating Applications

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ABSTRACT

Energy is one of leading problem all around the world. Increasing urbanization and industrialization, improving life conditions and standards and increasing world population have been creating a dramatic rise of energy demand. As a consequence of population growth, this resulted in high rate fossil fuel consumption. Besides, use of fossil fuels creating irrecoverable environmental damages such as global warming. Renewable energy and its storage systems are most promising solutions to overcome this problem. North Cyprus is an island good and suitable candidate for renewable energy utilization and its storage applications. Particularly, solar energy is abundant throughout year in North Cyprus and it represents a high potential to be used for building space heating. The main barrier is the imbalance between the heating demand and solar energy availability. Due to the cyclic nature of it, there is no solar radiation available at nighttime once the heat losses increasing. This condition indicates the need of utilizing thermal energy storage coupled with solar collector systems to store the solar energy once it is available to be used later when it is needed. Despite latent and sensible heat storage systems have been researched widely for this purpose, they have some major drawbacks such as low energy storage density and high heat losses limiting the storage potential and duration. A new thermal energy storage method; thermochemical heat storage, based on reversible sorption-desorption cycles is purposed in this study. Such thermal energy storage system could provide higher heat storage density and long-term heat storage potential making it attractive for solar thermal applications. From this point of view, aim of the presented study is; to develop a prototype thermochemical heat storage system and to test it under laboratory conditions. A novel composite sorption material; $CaCl_2$–Vermiculite was synthesized and used as the heat storage material. Three different cycles (discharging-charging) with the same flow rate were carried out. Throughout the testing, some optimal results were obtained. For charging temperature between 80-90 °C, discharging average temperature lift of air between 15-20 °C was obtained. Besides, cumulative energy output in the range of 1.6-1.8 kWh was attained, corresponding to an energy storage density between 200-230 kWh.

Observed results in this experimental study demonstrated that, for both long and short term heat storage, thermochemical process using V-$CaCl_2$ sorbent is satisfactorily promising and a good candidate to be utilized in solar thermal applications in buildings for sustainable space heating.

Keywords: Thermochemical Heat Storage, Vermiculite-$CaCl_2$, North Cyprus, Climate, Sorption, Chemical Reactions

ÖZ

Enerji dünyanın her yerinde önde gelen sorunlardan biridir. Artan kentleşme ve sanayileşme, yaşam koşullarının ve standartların iyileştirilmesi ve dünya nüfusunun artması, enerji talebinin çarpıcı bir şekilde artmasını sağlamıştır. Yüksek oranda fosil yakıt tüketiminin bir sonucu olarak, kaynaklar azalmaktadır. Ayrıca, küresel ısınma gibi geri dönüşü olmayan çevresel zararlar oluşturan fosil yakıtların kullanılması. Yenilenebilir enerji ve depolama sistemleri, bu sorunun üstesinden gelmek için en umut verici çözümlerdir. Kıbrıs Adası yenilenebilir enerji kullanımı ve depolama uygulamaları için iyi ve uygun bir adaydır. Özellikle, güneş enerjisi, yıl boyunca Kıbrıs'ta bol miktarda bulunur ve alan ısıtması için kullanılmak üzere yüksek bir potansiyeli temsil eder. Ana bariyer, ısıtma talebi ve güneş enerjisi kullanılabilirliği arasındaki dengesizliktir. Döngüsel yapısı nedeniyle, ısı kayıpları arttıkça geceleri güneş radyasyonu yoktur. Bu durum, gerektiğinde daha sonra kullanılabildiğinde güneş enerjisini depolamak için güneş enerjisi kollektör sistemleri ile birleştirilmiş termal enerji depolama ihtiyacını göstermektedir. Gizli ve duyarlı ısı depolama sistemlerinin bu amaçla yaygın olarak araştırılmasına rağmen, düşük enerji depolama yoğunluğu ve depolama potansiyelini ve süresini sınırlandıran yüksek ısı kayıpları gibi bazı önemli dezavantajları vardır. Yeni bir termal enerji depolama yöntemi; Bu çalışmada, geri dönüşümlü sorpsiyon-desorpsiyon çevrimlerine dayanan termokimyasal ısı depolama amaçlanmıştır. Bu tür bir termal enerji depolama sistemi, daha yüksek ısı depolama yoğunluğu ve uzun süreli ısı depolama potansiyeli sunarak, bunu güneş termal uygulamaları için çekici hale getirmektedir. Bu bakış açısıyla sunulan çalışmanın amacı; prototip termokimyasal ısı depolama sistemi geliştirmek ve laboratuvar koşulları altında test etmek. Yeni bir kompozit sorpsiyon malzemesi; $CaCl_2$-Vermikülit sentezlendi ve ısı depolama malzemesi olarak kullanıldı. Aynı akış hızına sahip üç farklı döngü (boşaltma-şarj) gerçekleştirilmiştir. Test boyunca, bazı optimal sonuçlar elde edildi. Sıcaklığın 80-90 ° C arasında tutulması için, 15-20 ° C arasındaki hava boşaltma ortalama sıcaklık artışı elde edildi. Ayrıca, 200-230 kWh arasında bir enerji depolama yoğunluğuna karşılık gelen, 1.6-1.8 kWh aralığında kümülatif enerji çıkışı elde edilmiştir. Bu deneysel çalışmada gözlemlenen sonuçlar, hem uzun hem kısa süreli ısı depolaması için V-$CaCl_2$ sorbenti kullanan termokimyasal işlemin, sürdürülebilir alan ısıtması için, binalarda güneş enerjisi uygulamalarında ümit vaat eden, iyi bir aday olduğunu göstermiştir.

Anahtar kelimeler: $CaCl_2$, Vermikülit, Açık Sorpsiyon Çevrimi, Kompozit Malzeme, Termokimyasal Isı Depolama, Kuzey Kıbrıs

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Δm	[kg]	Mass Differences
Δ_{mar}	[kg]	Charging Cycle Mass Loss
Δm_{ar}	[kg]	Discharging Cycle Mass Uptake
E_{co}	[kWh]	Cumulative Energy
Ed	[kWh/m^3]	Energy Density
E_{xec}	[kWh]	Charging Exergy
E_{xedra}	[kWh]	Discharging Exergy
E_{go}	[kW]	Instantaneous Exergy Gain
f_{or}	[g_{wv}/g_{abs}]	Charging Total Mass Uptake
f_{or}	[g_{wv}/g_{abs}]	Discharging Total Mass Uptake
h_i	[kJ/kg]	Inlet Enthalpy
h_{ow}	[kJ/kg]	Outlet Enthalpy
$\dot{m}_{cr}$	[m/s]	Charging Flow Rate
$\dot{m}_{dr}$	[m/s]	Discharging Flow Rate
$\dot{Q}_g$	[kW]	Instantaneous Heat Gain
s_i	[kJ/kg.K]	Inlet Entropy
s_o	[kJ/kg.K]	Outlet Entropy
T_o	[°C]	Outlet Temperature
T_a	[°C]	Ambient Temperature
T_i	[°C]	Inlet Temperature
t_c	[s]	Charging Time
t_d	[s]	Discharging Time
V_{ads}	[m^3]	Volume of adsorbent

Ø	[mm]	Diameter
ρ	[kg/m^3]	Density
Δ	-	Difference
η_I	-	1st Law Efficiency
η_{II}	-	2nd law Efficiency
A/C		Air Conditioning
C_{ap}		Specific Heat at Constant Pressure
CSPM		Composite Salt in Porous Matrix
COP		Coefficient of Performance
IWT		Insipient Wetness Technique
LHS		Latent Heat Storage
nZEB		Net Zero Energy Building
PW		Partial Pressure
RH		Relative Humidity
SCH		Solid Crystalline Hydrates
SHS		Sensible Heat Storage
SIM		Salt in Matrix
TES		Thermal Energy Storage
THS		Thermochemical Heat Storage
X		Reaction Advancement
V		Vermiculite
W		Absolute Humidity

Chapter 1

INTRODUCTION

1.1 Background

Due to the rapid industrialization, increase in the global population and increasing comfort demand, energy security is becoming vital for countries. Most developed counties are fighting to secure more energy resources, as in the current condition, both the industrial and economic development are directly related with the amount of fuel reserves. On the other hand, fossil fuel sourced energy consumption is a vast problem which is gaining unavoidable acceleration all over the world. This condition underlay that the energy problem is at a critical level and innovative solutions are required. However, dependency on fossil fuels is very high resulting in substantial amount of carbon emissions, depleting resources and high costs for energy production [1]. In this context, developed countries found solution with investing on renewable sources to meet their rapidly increasing energy demand. The origin of renewables states that these sources are recycling themselves without giving any harm to the environment. Utilizing renewable energy sources presents several promising aspects such as enhancement of environmental sustainability, reducing dependence on fossil fuels and reducing energy production costs. From this point of view, up to now, we have been experiencing many renewable energy applications in the areas such as electricity production, heating, cooling etc. The main renewable energy sources can be classified as solar, wind, geothermal, biomass and hydro [2].

One of the mostly invested renewable energy source across the world is solar energy. This is due to its abundancy, year round availablility and technological maturity to harvest that source. A common solar technology widely used is solar collectors to obtain hot water in buildings and in industrial applications. Besides, due to the technological simplicity, solar energy is also used for space heating with the use of solar air heaters. However the main barrier within the use of such solar heating units is the imbalance between solar availability and building heat demand. A common solution for that problem is to couple thermal energy storage units with solar heating units, to store solar energy when its available for later use. This is both enhancing the utility of solar energy while reducing the dependence on fossil fuels.

Mainly, three types of heat storage methods are available, as decribed below. Among these, sensible heat storage (SHS) and latent heat storage (LHS) are widely investigated. Thermochemical heat storage, which is proposed within this study is a relatively new method operating based on reversible sorption/desorption cycles.

SHS: It is a kind of heat storage that complies with temperature differences and usually applied for large plants (i.e aquifer). Most common materials; water, rock, soil and brick [3].

LHS: This type of heat storage comply with phase changes and chosen to be used low temperature heat sources. Most common materials; ice, paraffin and salts [3].

THS: It has higher density than other types of thermal energy storage and allows to store a high amount of energy with small volume requirement. Thermochemical storage system is especially important at long term storage processes. During THS process' heat loss is negligible which is a positive aspect for achieving high heat storage efficiency also storing heat over long periods (*i.e.* seasonal). Heat storage based on chemical reactions can be applied both small and large buildings for heating and cooling. Most common storage materials are zeolite, $CaCl_2$-H_2O, Silica gel. All these thermal storage materials energy storage densities (kWh/m^3) comparison shown and summarized in Fig.1 by Aydin at al. [4]. This figure presents that thermochemical materials have higher storage density comparing to other types. In other words, THS materials requires less volume to store same amount of energy when compared with SHS and LHS, which makes this storage method attractive.

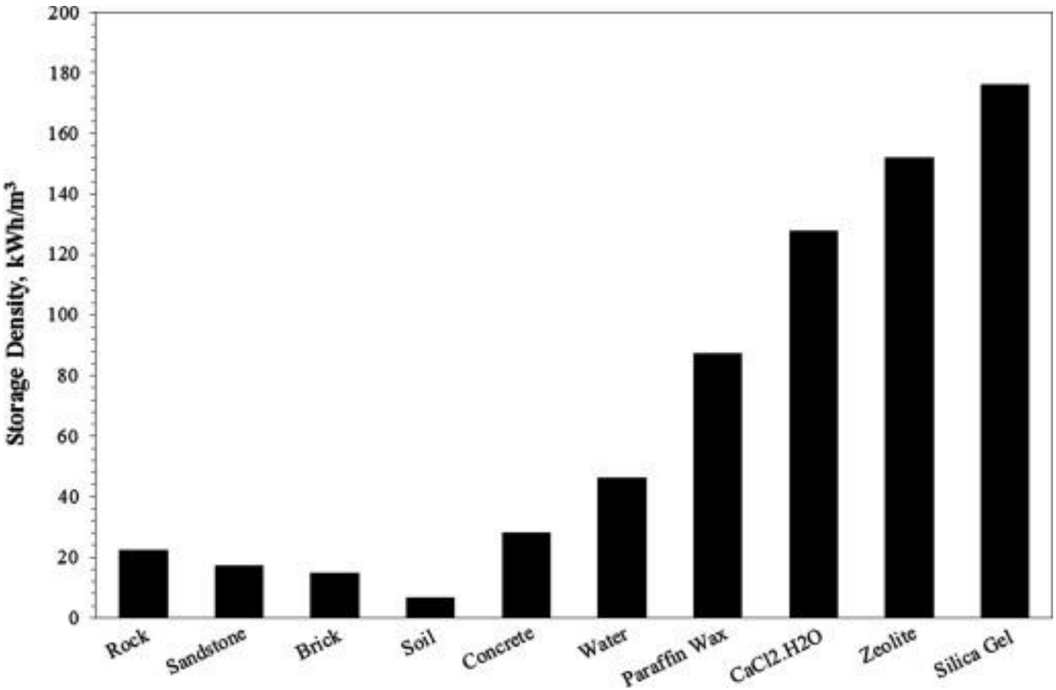

Figure 1: Material's Storage Densities (kWh/m^3) With Three Different Storage Methods [4].

1.2 Problem Statement

Investments in renewable energy and its applications has been a challenging problem in developing countires like North Cyprus. This condition ends up with high dependency on fossil fuels and urgent solutions are required. Therefore, this case strongly insisting on to shift renewable energy zone for coming near future necessities. Otherwise, in the North Cyprus there will be a serious energy shortage in the coming future. Thus, economic and enviromental conditions are also big concern.

Particulary some peak times of the island which is mostly in summer production rate remains insufficient due to the wide usage of vapour compression A/Cs in domestic buildings and residential offices. In winter period, mainly direct electric heaters or heat pumps are widely used which are also increasing the demand of electricity thereby creating shortage at some periods. The emission from the stack of power plants is another main concern

Considering the year round abundant solar energy in North Cyprus also the simplicity and low cost of solar thermal systems, solar space heating should be widely applied in buildings to provide sustainability and to reduce the load of fossil fuel driven power plants. The key point to enable solar heating in buildings is the storage of THS. Redundant thermal energy generated during the day time and can be stored for either short or seasonal terms [5,6]. With the currently used sensible storage techniques, heat storage duration is short, heat losses are high and storage density is low. Thus,the required heat storage volume. In this context, presented study demonstrates a novel and efficent solar thermal energy storage concept, that could overcome the mentioned drawbacks with the use of environmentally friendly sorption materials.

1.3 Aim and Objectives

The aim of this study is to design, develop and demonstrate a prototype THS system, that uses composite Vermiculite-$CaCl_2$ sorbent for solar space heating applications in buildings.

Technical research objectives of the study;

- To synthesize an effective salt based (V-$CaCl_2$) composite sorbent as an alternative to conventional sorbents such as zeolite and silica gel
- To design and develop a laboratory scale prototype thermochmical heat storage unit
- To investigate the cyclic performance of V-$CaCl_2$ for thermal energy storage through experimental investigations in the developed prototype
- To evaluate the thermal performance of the developed THS process through thermodynamic analysis

General research objectives of the study;

- Storing the solar energy using innovative THS method for residental and commercial building applications.
- Reducing peak demand and providing energy-supply demand balance
- Reducing energy costs and fossil fuel usage

In general, North Cyprus climate conditions mostly sunny, especially in summer. However there is no suitable energy storage methods applied currently to manage excess energy to last during the peak times and to provide a long term seasonal storage. This study aims to demonstrate a process that could store considerable amount of energy during the peak times (charging) and use it at required (discharging) with the help of sorption materials. Based on past reviews, because of good thermal conductivity, non-poisonous feature, low cost, high storage density and low charging temperature[7]. $CaCl_2$ is selected as inorganic salt and due to the low cost and high water absorption capacity vermiculite is used as host matrix in the developed composite sorbent.

1.4 Research Gap

Thermochemical energy storage has been gaining significant improvements especially these days. To manage the energy production and consumption in regards to supply and demand, energy storage systems are innovative solution for the usage of renewable energy sources optimally for heating, cooling and air conditioning purposes. Furthermore, it is thought that, instead of establishing new power plants, it is better to work on energy storage systems. From this sight of view thermochemicals while having high energy density with small volume requirement they are also economic and environmentally friendly materials for thermal energy storage. In this study, open system THS is examined to find out operational efficiency and selected material performance. This study basicly aims to sort out using solar energy optimally for energy storing process. Despite several researches performed on heat storage systems for buildings, experimental investigation of open THS systems is limited and constitutes a gap in the literature. Performed study aims to fullfil this gap and contribute to the development of THS technology through the demonstration of V-$CaCl_2$ composite sorbent performance in a lab scale experimental unit.

1.5 Novelty of the Study

Thermal energy storage systems are widely searched in the literature. Water as a SHS material is commonly used as storage medium. Besides several other storage materials were investigated in the past. Proposed open THS method in this study is relatively new and very few studies performed in that field. Adjacent to the reactor design and prepared composite sorption material V-$CaCl_2$ with the use of low cost calcium chloride monohydrate are novel aspects of the study. Further to this cyclic performance, investigation of V-$CaCl_2$ is missing in the literature. In addition, THS performance has not been previously investigated for North Cyprus climate conditions. Therefore, presented study outcomes could serve as basis for future THS research and give new insights to the researchers working in that field.

1.6 Thesis Structure

The presented study consists of six chapters and the outline is summarized below:

Chapter 1 Introduction: General energy trends, use of thermal energy storage systems, gap in the literature also the aims and objectives are discussed.

Chapter 2 Literature Review: Fundamentals on THS theory and its operating principles were presented. Apart from operating principle and THS theory, completed studies in the literature and recent studies are summarized.

Chapter 3: Design and Thermal Analysis of THS System: Experimental design of the system explained. Thermal analysis methods applied in the study were described.

Chapter 4: Experimental study: Experimental THS unit and functions of the system components were explained. System operating conditions and experimental methodology were presented.

Chapter 5: Results and Discussion: Experimental results were shared. Experimental results were compared and discussed. Main obstacles faced throughout the study, also the limitations and systematic errors were mentioned.

Chapter 6: Conclusions and Future Work: Main outcomes of the study were summarized. Future work and implications of the study explained.

Chapter 2

LITERATURE REVIEW

2.1 Background and State of the Art Review on THS Systems

Renewable energies commonly identified by means of instability and discontinuousness with weather conditions, geographical location, time and seasons of the year. For the aim of generating successive high-efficiency utilization of renewable energy, advanced thermal energy storage system is crucial technology [8]. Solar and wind are the most popular renewables which have been investigated and utilized almost everywhere specifically in the developing countries. In this study, presents the current studies on THS and thermochemical composite materials for building applications. To conduct a favorable supply and demand for sustainability of buildings, THS systems are the most convenient way to improve the efficiency of the system [7]. In North Cyprus, in order to get benefit from sun, storage methods should be used effectively for short term and long term storage as well. Besides short-term solar energy storage, long-term seasonal solar energy storage has been also paid much attention in recent years in order to achieve energy saving in buildings by storing solar heat in summer for building heating in winter [9]. Thermal energy storage systems can be classified in three categories namely SHS, LHS and THS. SHS is a storage system that can be done via temperature differences in the storage medium. In the LHS, the process is completed via phase change process at a constant temperature. The THS is conducted with sorption process and chemical reactions.

Table 1 represents the characteristics of SHS, LHS and THS and comparisons between these storage methods.

Table 1: Characteristics and Comparison of the Thermal Energy Storage Systems [10]

	Sensible heat storage system	**Latent heat storage system**	**Thermochemical storage system**
Volumetric density	Small ~50 kWh m^{-3} of material	Medium ~100 kWh m^{-3} of material	High~500 kWh m^{-3} of reactant
Gravimetric density	Small~0.02–0.03 kWh kg^{-1} of material	Medium ~0.05–0.1 kWh kg^{-1} of material	High ~0.5–1 kWh kg^{-1} of reactant
Storage temperature	Charging step temperature	Charging step temperature	Ambient temperature
Storage period	Limited (thermal losses)	Limited (thermal losses)	Theoretically unlimited
Maturity	Industrial scale	Pilot scale	Laboratory scale
Technology	Simple	Medium	Complex

Based on the promising features of THS presented in Table 1, it can be said that the sorption technology is an innovative method for energy storage process. In this method, desired materials could be brought together as a compound in order to increase the reaction speed and capacity also to increase the energy storage density and to enhance hygroscopic properties. Gordeerva and Aristov states that, in order to find most suitable adsorbent for any particular application, it is important to use matching method by showing which application is suitable for kind of demand according to properties of adsorbents [11]. Up to now, several sorbent composites were developed where small percentage of them responded satisfactory. Gordeeva emphasis that, enhancing the heat and mass transfer in thermochemical processes strongly depends on the type of composite material, design of reactor and the host matrix [12]. In thermochemical process, reactions are completed as reversible cycles. Conceptually, during sorption/desorption cycles, as the heat is stored at ambient temperature level, heat losses are minimal, approaching to zero in most cases. The volume of storage material determines the storage capacity in this storage method. The higher the heat storage density, the lower the storage volume required for the same storage capacity. Thereby developing high density sorbent is crucial, which is proposed within the study.

Sorption process is classified as absorption and adsorption. If the sorption is happening up to the internal part of the sorbent, it is named absorption. On the other hand, if sorption is happening on the surface of the material it is called adsorption. In open cycle systems, the sorbent is in direct contact with ambient environment and the process occurs at ambient temperature and pressure conditions [13]. In open sorption cycles, water is generally used as sorbate and solid desiccants such as zeolite, silica gel and activated carbon are used as sorbent. The use of hygroscopic salts and their composites are recently started to be investigated as alternative sorbents. The advantages of using salts, in comparison with solid desiccants is their relatively low charging temperature requirement and high storage density. However, their main disadvantage is the liquefaction problem due to the dissolution inside the absorbed water [14]. In North Cyprus, there are a few obstacles about applying renewable energy and a promising solution for these obstacles is to impregnate salts inside a porous host matrix. In the experienced work vermiculite is proposed as host matrix, which is organic, low cost, highly porous and has high water holding capacity [15]. The operating principle of salt/water sorption process is illustrated in Figure 2. As seen, salts impregnated inside a host matrix, absorb water vapor and as a result release heat. As the water vapor is absorbed, salts initially turn to solid crystalline and later to salt hydrates. Meanwhile, external heat should be supplied (*i.e.* solar energy) to desorb the water vapor, which is called charging cycle [15].

N’Tsoukpoe et al. have concluded that, as heat and entropy released to the environment during only water sorption process, long term THS application is a promising option to store excess solar energy in summer to be used in winter [16]. In open THS process, the first stage starts with charging where the materials are dissociated with the external heat supply. Storage process occurs when the sorbent/sorbate couple are kept separately that period. Then, once there is a heat demand, sorption process is driven by contacting the sorbate and sorbent.

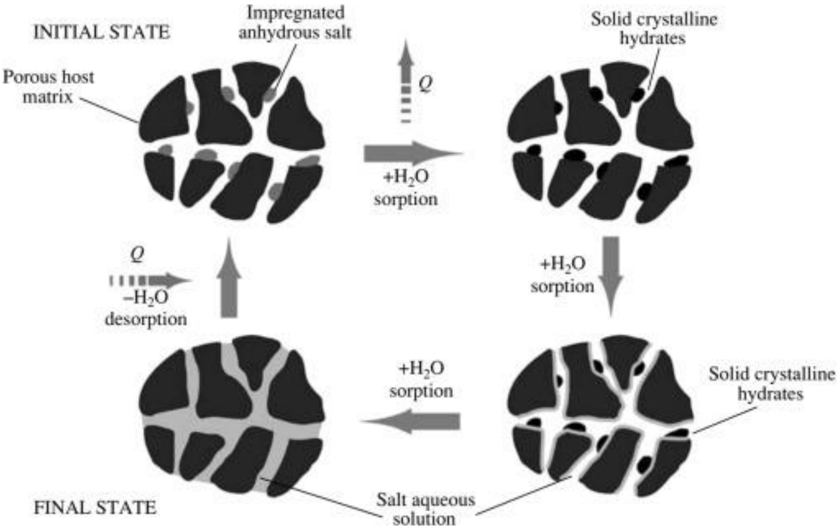

Figure 2: Solid-gas thermochemical sorption process [4]

The main feature of THS is that charging could be performed in summer by using the abundant solar energy and discharging in winter once the heating demand is high. Between these periods, sorbent/sorbate couple could be stored separately without any heat loss. The charging (endothermic), storage and discharging (exothermic) processes during THS process is illustrated in Figure 3.

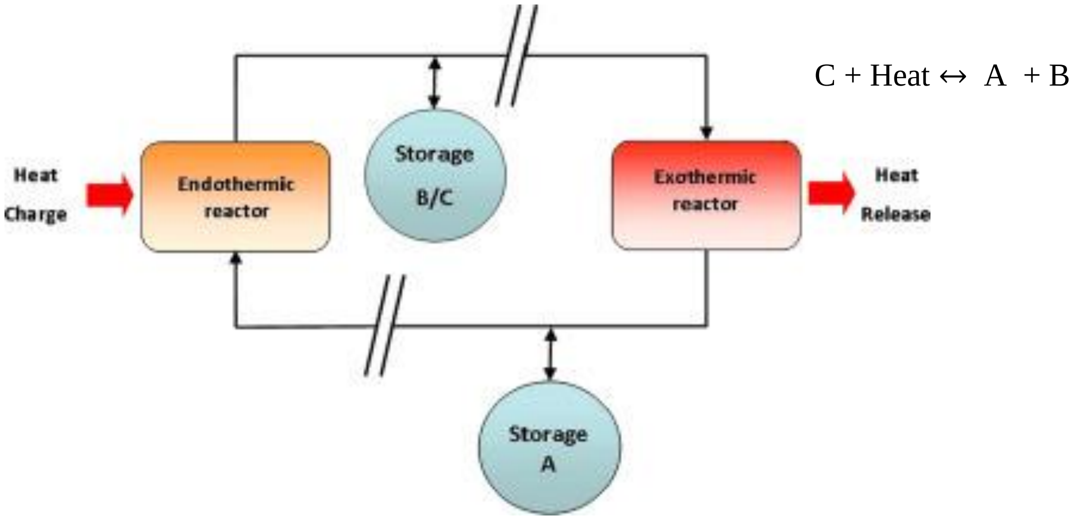

Figure 3: Illustration of THS Chemical Reaction Procedure [17]

In THS process, the material that is used to store heat is strongly affects the performance and cost of the storage system [3]. The technique used to synthesize the material was pioneered Yuri Aristov [18]. The method called “The Insipient Wetness Technique (IWT)” uses the desiccant matrix materials’ natural wetting or liquid absorption capacity to fill the pore structure with a selected salt solution [18]. Therefore, the scope of this reasearch is built on investigating a a novel composite (V-$CaCl_2$) performance in the developed open prototype reactor.

In the literature, several researches performed on open THS process and material development. A large-scale open adsorption thermal storage system employing zeolite 13X/H_2O, was installed in Munich by ZAE Bayern (Center for Applied Energy Research) to heat a school building in winter and to cool a jazz club in summer [19,20]. The school (with a heating load of 130 kW) and the club (with a cooling load of 50 kW) are connected to the local district heating system of Munich (See: Figures 4a and

4b). Temperatures of system components during charging and discharging modes are illustrated in Figure 4.

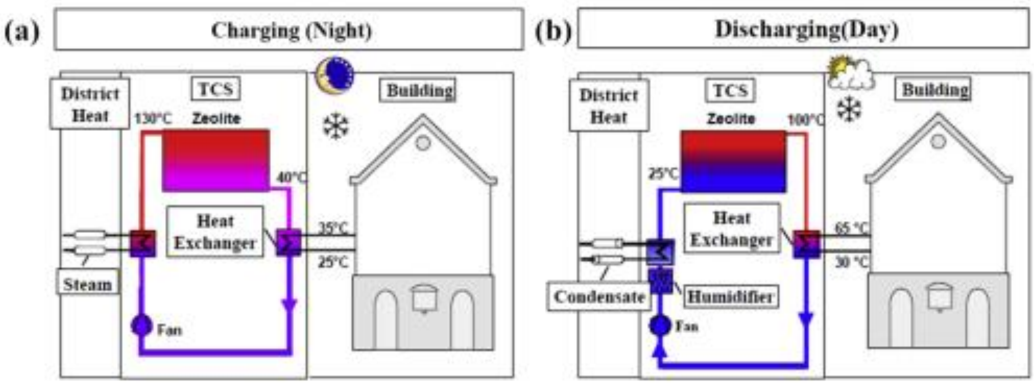

Figure 4: Illustration of (a) Charging and (b) Discharging Cycles of An Open THS Using Zeolite [19,20]

Henninger et al. checked out latest improvements on materials varying from zeolites across aluminophosphates (AlPO4) and silicoaluminophosphates (SAPO-34) to the novel class of metal organic framework materials for the use in adsorption processes for heat storage and transformation [21]. The similar study conducted by the same authors investigated the water adsorption characteristics and performance of selected materials, for the use in thermally driven adsorptive heat pumping and cooling applications with water as refrigerant [22]. Many studies carried out especially on the basis of host matrix Zeolite due to its high water sorption capacity. For instance, Hongois et al. synthesized a novel magnesium sulphateMgSO$_4$–Zeolite composite material and investigated it for long term seasonal solar energy storage [23]. Obtained results were promising as only with 10 mg samples, although material is not fully dehydrated; researchers achieved 80% heat storage efficiency at 150 °C charging temperature. In another similar study, Janchen et al. analyzed the water adsorption characteristics of Zeolites and altered mesoporous materials for seasonal solar thermal energy storage [24]. Janchen et al. characterize the sorption properties of water in potential THS materials such as low silica X zeolites, microporous AlPO4, SAPO-34 and calcium chloride ($CaCl_2$) located in the pores of attapulgite [25]. Gordeeva and Aristov worked on novel two component composites ‘salt in porous matrix’ (CSPMs) and figured out the latest advancements on the development of efficient CSPMs for different adsorption heat transformation cycles [26]. Aristov looked over the new family of CSPMs for adsorptive cooling and examined the water sorption/desorption mechanism and characteristics of these materials [27]. In another research, N'Tsoukpoe et al investigated the portential of $CaCl_2$ to be used in thermal applications. Due to its hygroscopic and deliquescent behavior calcium chloride can easily adsorb moisture from the ambient at various rates depending on the salt concentration, relative humidity and water vapor pressure of the surrounding air. Therefore, calcium chloride is widely used in dehumidification processes and desiccant cooling applications. [28]. Considering the promising properties of $CaCl_2$ in addition to its low cost, this material was found suitable to be employed in the proposed study.

Chapter 3

DESIGN AND THERMAL ANALYSIS OF THS SYSTEM

3.1 System Design and Operation

Nowadays, solar thermal energy storage technologies need to be developed urgently for near future in order to meet the increasing demand for sustainable energy. The available storage technologies like SHS and LHS suffers from drawbacks of low energy density, short storage duration, temperature changes and drops, losses and limited storage duration. Therefore a new method, THS is proposed in this study that uses the reversible sorption and desorption processes for heat storage as illustrated in Figure 5.

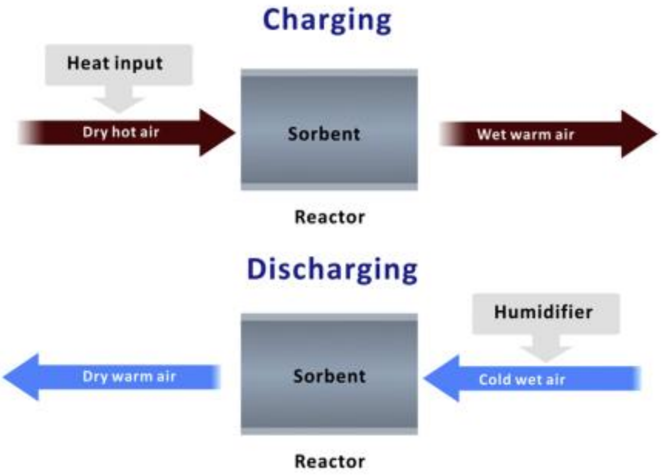

Figure 5: Operation of Open Sorption Reactor System [28]

THS design is cruical for obtaining high heat storage efficiency, where insufficient heat-mass transfer and non-uniform air flow could result in a drastic drop in system performance. In this context, the design of the system appealing as one of the extremely vital requirements for the working conditions of reactor. An optimal THS design should provide a steady discharge temperature output, uniform moisture sorption rate and effective heat transfer and minimal heat losses.

3.1.1 Design of THS Prototype

Developed THS prototype consists of two main parts namely an air conditioning unit and a THS reactor. Air conditioning unit controls the mission of providing air flow with a fan and heating the air with the electric heating coils (only in charging process). Reactor is a rectangular shaped box with an internally placed tray holding the composite material perpendicular to the air flow. Design of prototype concerns several parameters. These parameters are heat and mass transfer of material and reactor, insulation, working and ambient conditions of the prototype, accessibility of the material and practicality of system operation. From this sight of view; for charging process, prepared wet composite material dried (charged/desorption) in the reactor with the help of electric heater and fan. In order to get higher efficiency of the system hot and dry air for the material to be charged at better conditions and for discharging, dried material well moisturized with an external ultrasonic humidifier. In this manner, developed prototype was tested under laboratory-controlled conditions in both charging and discharging modes. The schematic view of the realized system is presented in Fig.6. In the figure, system components also the sensor locations for measuring ambient, inlet and outlet temperature and humilities in charging / discharging cycles were illustrated.

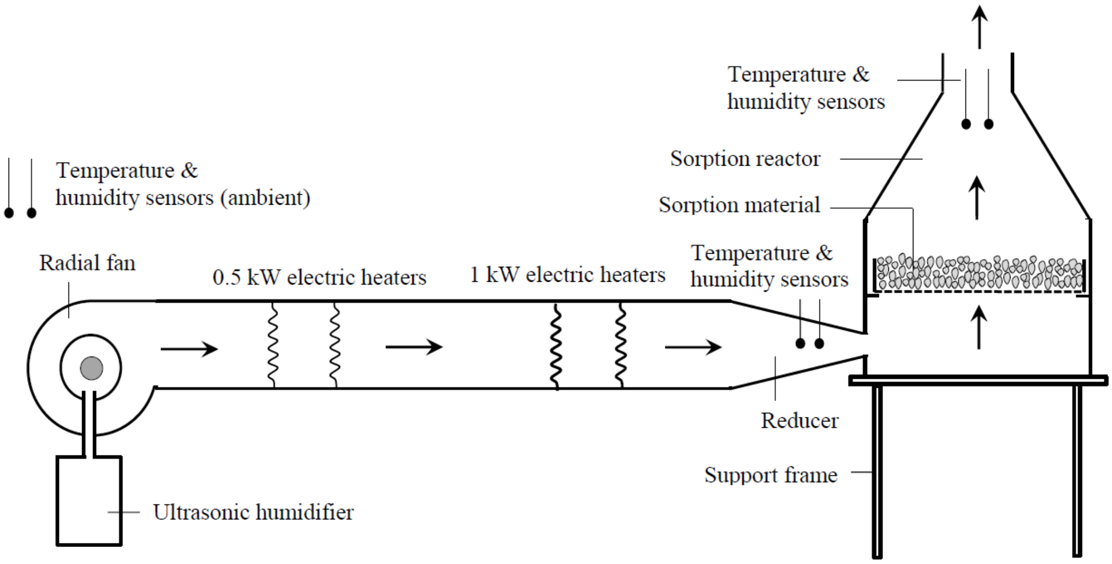

Figure 6: Schematic Illustration of the Designed Experimental THS Prototype

3.1.2 System Operation Description

THS system operation can be explained in cyclic order. In the developed system, during discharge process, ambient air blown through the channel (see: Figure 6) to the sorption reactor. Prior to entering the channel, air is humidifed up to ~80-90% relative humidity by using an ultrasonic humidifier. The temperature of the air at the reactor inlet was 19-20 °C. The humid air than passes accross the sorption bed, where moisture is absorbed and heat is generated. Finally hot air with low moisture content leaves the system. In charging mode, air is heated up to 80-90 °C and hot dry air passes accross the sorption bed. As a result, moisture inside the sorbent is removed and wet moist air is exhausted.

During the experiments, following the discharging and charging processes, weight of the material was measured in order to determine the amont of moisture absorbed. The obtained results were used to identify the amount of energy relased per unit of moisture sorption and also to find out the energy density and regeneration potential of the material at 80-90 °C temperature level.

Table 2: Description of Charging and Discharging Processes

Charging

1. The air is heated (up to 80-100 ℃) with an electric coil prior to entering the reactor.
2. Hot dry air flows into reactor and passes across the material. As a result, moisture inside the sorbent is desorbed and transferred to the air.
3. Warm moist exhaust air is released to the environment

Discharging

1. Ambient air blown to the reactor with a fan.
2. Air is humidified to a relative humidity level of 80-90% prior to entering the reactor.
3. Humid air enters reactor and passes across the sorbent.
4. Sorbent adsorbs the vapor and as a result sorption heat is generated. Produced heat is transferred to the air and hot air leaving the system is used for space heating

3.2 Thermodynamic Analysis of the System

At present THS systems have been gaining inevitable improvements. For having high energy density with small volume opportunity but also they are economical and environmentally friendly. In this study, open THS is examined according to the First and Second Laws of Thermodynamics. The First and Second Law of Thermodynamics explained by means of energy and exergy respectively. Exergy is known as the amount of useful work or in a way ability that system has to do work [28]. Thus, approximately every system needs exergy analysis to define its ability to do useful work. Energy has definition which is transformation of forms of potential energy, kinetic energy and enthalpy which is pressure related energy internal energy. In this analysis potential energy and kinetic energy changes were neglected and only enthalpy changes were considered for system analysis.

3.2.1 Exergy and Energy Analysis of The Open Thermochemical TES

In order to analyse the performance of the developed THS, mass, energy and exergy equalities based on First and Second Law of Thermodynamics have been used. Formulations used in the analyses are presented below.

In THS process, in discharging cycle, enthalpy differences of inlet and outlet values define instantaneous heat gain ($\dot{Q}_g$)

$$\dot{Q}_g = \dot{H}_o - \dot{H}_i \tag{1a}$$

where $\dot{H}_o$ is outlet enthalpy and $\dot{H}_i$ is inlet enthalpy.

Instantaneous heat gain can also be calculated by this formula;

$$\dot{Q}_g = m_{dr}.c_p.(T_o - T_i) \tag{1b}$$

Where m_{dr} is discharging mass, c_p is specific heat, T_o is outlet temperature, T_i is inlet temperature

Cumulative energy is calculated as summation of energies over the process duration. Cumulative energy output for t_d (discharging) and energy input over t_c (charging) period is obtained with the Eq. (2) and Eq. (3) below;

$$E_{cum} = \dot{m}_{dr}.c_p.\int_0^{t_d}(T_o - T_i)dt \tag{2}$$

$$E_{i,cr} = \dot{m}_{cr}.c_p.\int_0^{t_c}(T_i - T_o)dt \tag{3}$$

where m_{cr} is charging mass, $c_p$is specific heat, T_o is outlet temperature , T_i is inlet temperature.

Instantaneous exergy gains in discharging process is gained with the subtraction of exergy potential of inlet form outlet;

$$\dot{E}x_g = (\dot{E}x_o - \dot{E}x_i) \tag{4a}$$

Exergy gain is demonstrated via differences of air enthalpy and entropy inlet and outlet as below;

$$\dot{Ex}_g = \dot{m}_{dr}.\left[(h_o - h_i) - T_a.(s_o - s_i)\right] \tag{4b}$$

Exergy gain obtained is the function of enthalpy and entropy terms as expressed with the Eq. (4c);

$$\dot{Ex}_g = \dot{m}_{dr}.c_p.\left[(T_o - T_i) - T_a.ln\left(\frac{T_o}{T_i}\right)\right]dt \tag{4c}$$

Instantaneous exergy input is for charging cycle derived as below,

$$\dot{Ex}_{i,cr} = \dot{m}_c.c_p.\left[(T_i - T_o) - T_a.ln\left(\frac{T_i}{T_o}\right)\right]dt \tag{5}$$

Deriving the integral of Ex_g (See: Eq. (4c)) and $Ex_{i,c}$ (See: Eq. (5)) over with constraints of t_d and t_c process durations, cumulative exergy gains (discharging cycle) and cumulative exergy input (charging cycle) is found like below;

$$\dot{Ex}_{cum} = \dot{m}_{dr}.c_p.\int_0^{t_d}\left[(T_o - T_i) - T_a.ln\left(\frac{T_o}{T_i}\right)\right]dt \tag{6}$$

$$\dot{Ex}_{i,cum} = \dot{m}_{cr}.c_p.\int_0^{t_c}\left[(T_i - T_o) - T_a.ln\left(\frac{T_i}{T_o}\right)\right]dt \tag{7}$$

The ratio of the energy/exergy gain in discharging cycle to the energy/exergy input to the sorbent in charging cycle, defines the heat storage energetic (I. Law) and exergetic (II. Law) efficiencies;

$$\eta_I = \frac{E_{cum}}{E_{i,cr}} \tag{8}$$

$$\eta_{II} = \frac{Ex_{cum}}{Ex_{i,cr}} \tag{9}$$

Absolute humidity, as a function of temperature and relative humidity, could be obtained with the Eq. (10);

$$w = 216.7.\left[\frac{\frac{RH}{100\%}.6.112.exp\left(\frac{17.62.T}{243.12+T}\right)}{273.15+T}\right] \tag{10}$$

Partial pressure of air existing in vapor is;

$$p_w = \frac{RH.p_{w,s}}{100\%} \tag{11}$$

Sorption and desorption rates at any moment of $t_{x,d}$ and $t_{x,c}$ minutes of discharging and charging processes were determined via Eqs.(12) and (13) respectively,

$$z_{ads} = \int_{t_{x,dr}}^{t_{x+1,dr}} \dot{m}_{dr}.c_p.(w_i - w_o)dt \tag{12}$$

$$z_{des} = \int_{t_{x,cr}}^{t_{x+1,cr}} \dot{m}_{cr}.c_p.(w_o - w_i)dt \tag{13}$$

For calculation of mass change of the sorbent, Δm is used expression, which is defined as the mass difference between dry and wet composite material;

$$\Delta m = m_{wv} = m_{ads,w} - m_{ads,d} \tag{14}$$

For discharging cycle mass uptake of the sorbent could be expressed like;

$$\Delta m_{dr} = \int_0^{t_d} \dot{m}_{dr}.c_p.(w_i - w_o)dt \tag{15}$$

For charging cycle mass loss, which is denoted like Δm_{cr}, is calculated as the derivation of the integral given in Eq. 16;

$$\Delta m_{cr} = \int_0^{t_c} \dot{m}_{cr}.c_p.(w_o - w_i)dt \tag{16}$$

For discharging cycle total mass uptake ratio and mass loss ratio were calculated with the Eqs. given below;

$$f_{dr} = \left\{\int_0^{t_d} \dot{m}_{dr}.c_p.(w_i - w_o)dt\right\}/m_{ads,d} \tag{17}$$

$$f_{cr} = \left\{\int_0^{t_c} \dot{m}_{cr}.c_p.(w_o - w_i)dt\right\}/m_{ads,w} \tag{18}$$

Based on the obtained E_{cum} (See: Eq. (2)) there are two methods to demonstrate the E_d of the sorption material. The first demonstration is the E_{cum} of the sorbent per gr of adsorbed water vapor (See: Eq. (19)). Other than this volumetric energy density of the material could be expressed as the ratio of E_{cum} to V_{ads} (See: Eq. (20));

$$E_d = \frac{E_{cum}}{\Delta m} \tag{19}$$

$$E_d = \frac{E_{cum}}{V_{ads}} \tag{20}$$

Chapter 4

EXPERIMENTAL STUDY

4.1 Selection and Synthesize of Sorption Material

THS systems are recently investigated for short term and seasonal heat storage on the domestic and commercial basis. Material selection is vital in such applications. Materials with high porosity property, heat and mass transfer and faster adsorption capacity which increase efficiency of the reactor. Faster heat and mass transfer rates are possible with liquid absorption. Materials recently investigated include aqueous solutions of Calcium Chloride ($CaCl_2$), Lithium Chloride ($LiCl_2$), Lithium Bromide (Libra), Sodium Hydroxide (Nao), Potassium Hydroxide (KOH) and Ammonia [18, 23].

In this study $CaCl_2$ is selected as sorption and vermiculite as host matrix due to their promising properties as discussed in Chapter 2. In composite material preparation process, initially saturated $CaCl_2$ solutions were prepared. Following this, vermiculite was dried in the oven to ensure that all existing moisture is removed. Then, saturated solution was impregnated inside the dry vermiculite pores. Impregnation continued until some solution was leaked out of the material as a confirmation that the vermiculite is saturated. Following this material was dried in the oven at 120 °C to remove the water and leave the dry salt crystals inside the pores of vermiculite. Finally, dry composite material was stored in a sealed container to prevent ingress of moisture until the experiments performed. The material synthesize procedure is illustrated in Fig.7.

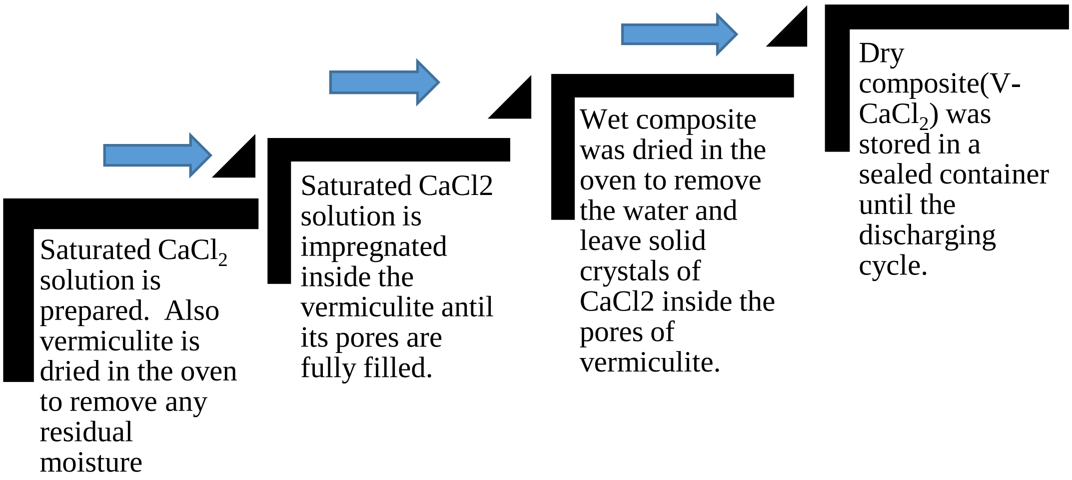

Figure 7: Flowchart Illustrating Material Synthesis Procedure

Figure 8 shows the views of $CaCl_2$ and vermiculite at different stages of preparation. In Figure 8a and 8b unhydrous $CaCl_2$ granules and raw vermiculite before salt impregnation are seen. In Figure 8c and 8d salt impregnated vermiculite at partially and fully dried levels are presented. Scanning Electron Microscopy images of vermiclite and $CaCl_2$ impregnated vermiculite were also presented in Fıgures 9a and 9b. $CaCl_2$ crystals inside the lamellar pores of vermiculite is clearly seen in Figure 9b.

Figure 8: (a) Anhydrous $CaCl_2$, (b) Vermiculite, (c) V-$CaCl_2$After Charging (not well dried), (d) V-$CaCl_2$ After Charging (well dried)

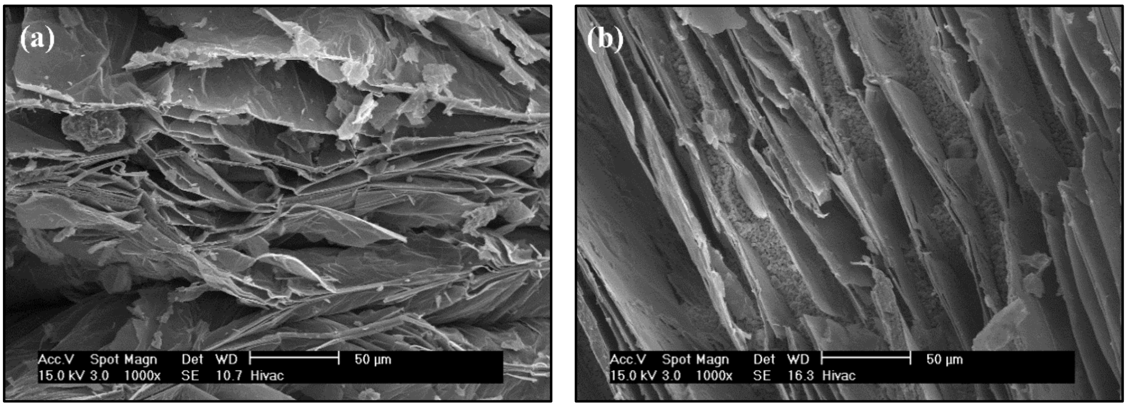

Figure 9: SEM Images of (a) Dry Vermiculite, (b) V-$CaCl_2$ [10]

4.2 Apparatus Used for Data Collection

Experimental data collection completed with PCE temperature data logger (See: Figure 10a), USB type humidity sensor (See: Figure 10b) and Explorer GLX weather anemometer (See: Figure 10c). During the experiment, three different temperatures and relative humidity’s at the inlet and outlet of the reactor also for the ambient conditions were recorded. In the experiment PCE T-390 was used to record the temperatures. It has 4 channels connected to K type thermocouples with a sensitivity of ±1 °C. The USB type humidity sensors used in the experiments are also have sensitivity of % ±3.

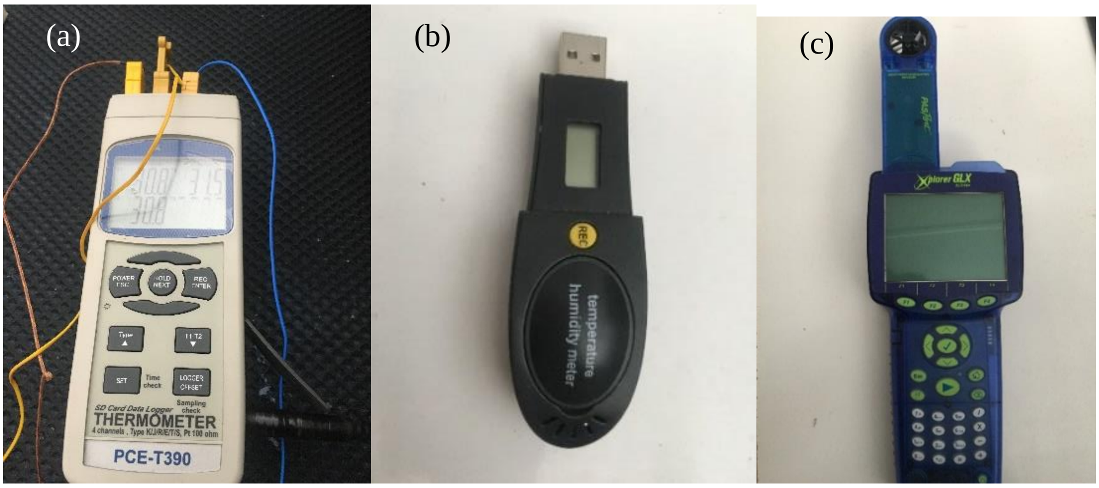

Figure 10: (a) PCE Temperature Data logger, (b) USB type Humidity Sensor, (c) Xplorer GLX Weather Anemometer

4.3 Experimental Setup

The view of the developed experimental THS prototype is illustrated in Figure 11. The internal view of the reactor , the tray used in the experiments and the electric furnace are presented in Figures 12a, 12b and 13 respectively. Experimental set up comprised of a rectangular shaped reactor with conical diffusers at the inlet and outlet, air conditioning unit with electric heating coils, fan, two ultrasonic humidifiers, computer and dataloggers The functions of the components of the system are explained in briefly in the following section;

- The Reactor is used for charging and discharging purposes in order to place the tray and composite material inside it.
- Computer and sensors used for collecting data ,monitoring and analyzing it.
- Air conditioning unit employed to provide desired inlet air conditions for charging and discharging.
- Fan is providing air to the system.
- Humidifiers, humidify the inlet air during the discharging cycle

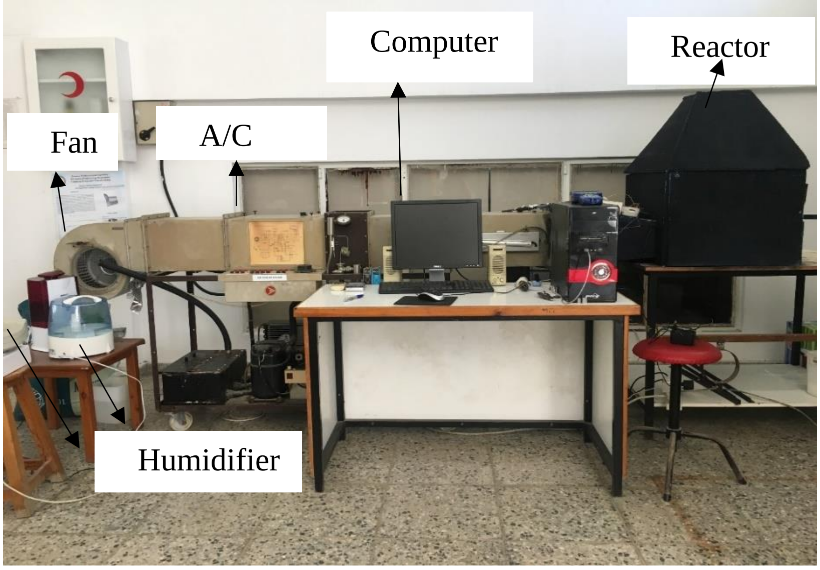

Figure 11: View of the Experimental THS System

Figure 12: (a) Internal View of Sorption Reactor, (b) Perforated Tray

Figure 13: Electric Furnace

4.4 Experimental Methodology

The basic illustration of the sorption / desorption cycles proposed in this experimental study is presented in Figure 14. Throughout the experiments, three repeating cycles (charging and discharging) were completed. Important concept of this research is to highlight the performance of the material in repeating cycles thereby to determine its cyclic stability. The discharging cycles were performed for 360 minutes and the charging cycles were performed for 180 minutes. During both in discharging and charging cycles, temperatures and air humidities were measured. By using the data recorded in dicharging cycles, key performance parameters such as average temperature lift, sorption rate, heat and cumulative energy and exergy outputs, also the enegy storage density of the material were determined. For charging cycle, desorption rate, rate of heat supply, cumulative energy and exergy inputs were investigated. Then, based on the results obtained for discharging and charging cycles, energetic and exergetic heat storage efficiencies also the hygro-cyclic efficiency of the system were calculated.

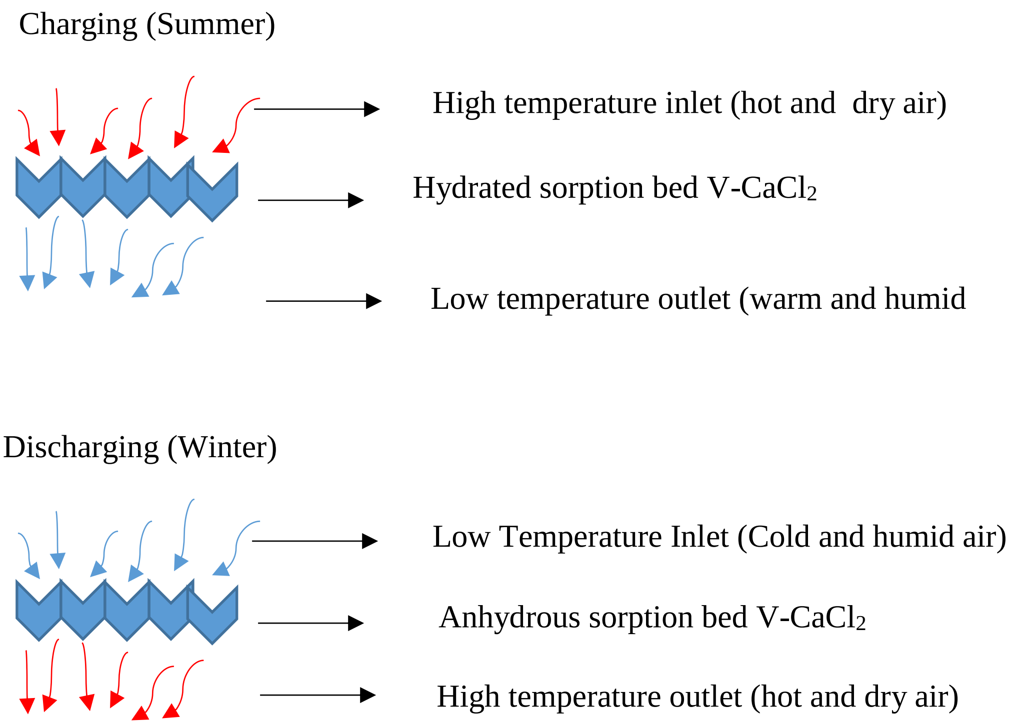

Figure 14: Illustration of Sorption and Desorption Cycles of Proposed THS System

Chapter 5

RESULTS and DISCUSSION

5.1 Experimental Results

Case study completed under laboratory conditions in North Cyprus. The experiment was carried out for three repeating cycles. There are a number of parameters influencing the performance of the THS system. Investigated parameters throughout the study were charging and discharging temperatures, mass uptake and loss, heat output in discharging, heat input in charging also the energy density were calculated. Furthermore, overall performance evaluation of the system has performed.

5.1.1 Discharging Analysis

Outlet and inlet temperatures for three discharging cycles of V-$CaCl_2$, with respect to time are presented in Figure 15. During the experimental testing, inlet temperature varied between 19-21 °C depending on the surrounding environment conditions. As illustrated in the figure there are no considerable fluctuations in three different cycles indicating that the V-$CaCl_2$ performance is steady. The peak outlet temperatures were in the range of 48-50 °C, where the peak temperature lifts were between 28-30 °C. Over three hours testing period, average temperature lift was 16-18 °C, demonstrating that the developed system is capable of generating sufficient amount of heat to create a considerable temperature lift of air in discharging process.

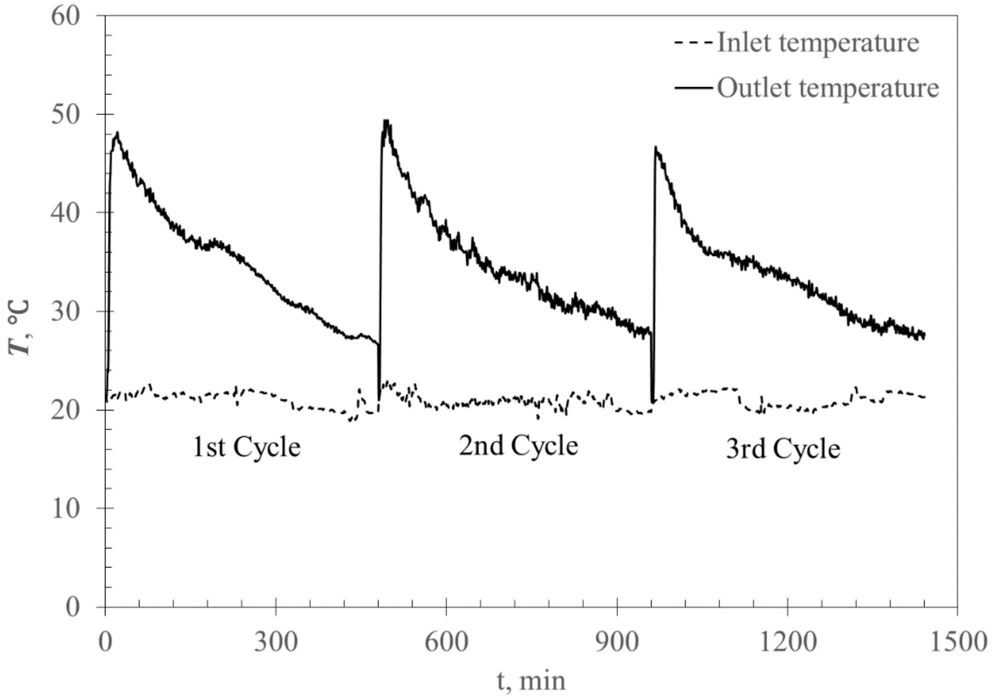

Figure 15: Variation of Inlet and Outlet Air Temperatures Over Three Discharging Cycles of V-$CaCl_2$

Another important parameter throughout the discharging analysis was the change of the heat content of air. Thermodynamically; as generated sorption heat increases, heat input and output difference increases. In three cycles similar trend observed. Minor flactuations in the performance of the system occured due to the slighltу varying ambient air conditions during the experiments. In all cycles, the heat content of air was approximately 350 W and the heat content of outlet air was nearly 800W.

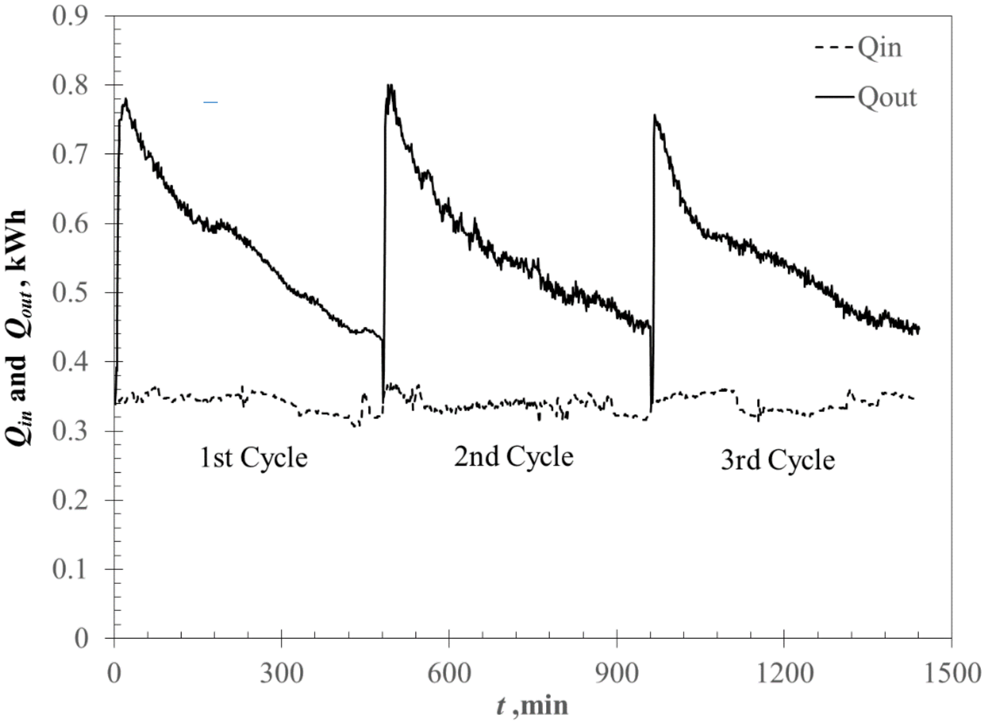

Figure 16: Variation of Q_{in} and Q_{out} Over Three Discharging Cycles of V-$CaCl_2$

The difference in heat content between the inlet and outlet gives the net sorption heat gained by the air as illustrated in Figure 17. Similarly, exergy difference of air across the sorption bed gives the net exergy gain. The net heat gain is the function of the inlet-outlet temperatures, mass flow rate and specific heat of the air. On the other hand, in net exergy gain calculation, entropies of inlet and outlet air were also considered. Exergy is defined as the potential to do useful work; therefore, exergy gain was found lower than the heat gains as expected. Determining exergy gain is important in heat storage systems as it gives an insight on the quality of the energy produced. During the performed experiments peak heat gain was found between 0.45-0.40 kW whilst peak exergy gains were in the range of 0.002-0.015 kW. Averagely ~0.21 kW and 0.003 kW heat and exergy gain were obtained in three consequent discharging cycles.

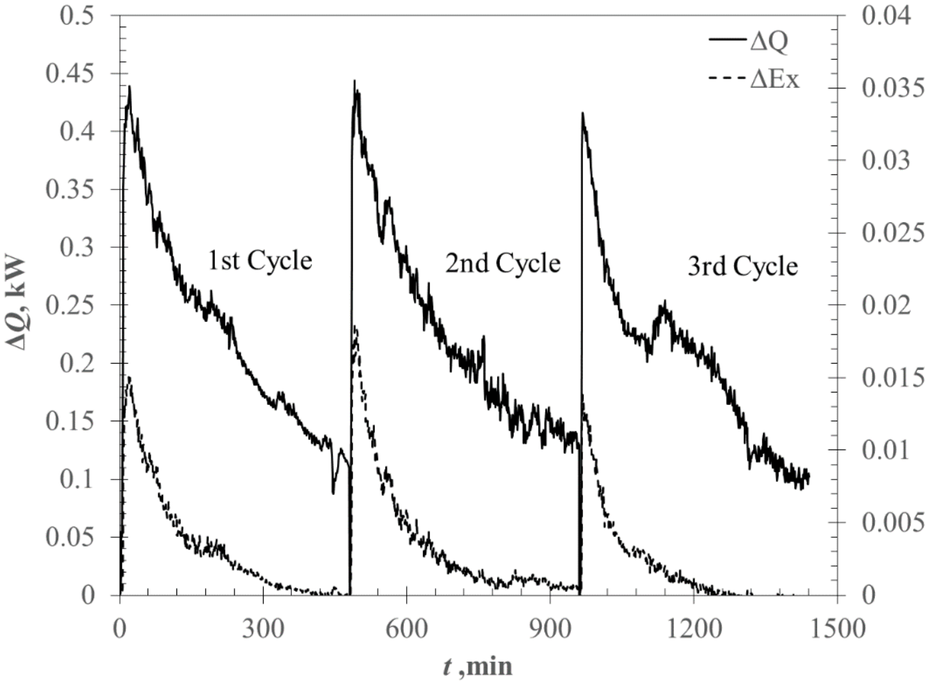

Figure 17: Variation of Heat and Exergy Input-Output Over Three Discharging Cycles of V-$CaCl_2$

Cumulative energy and cumulative exergy defines overall summation of available energies and exergies in the cycles. The cumulative energy and exergies are obtained by integrating the rate of heat and exergy gains over the discharging durations. As seen from Figure 18, highest cumulative energy and exergy values were obtained in the second cycle where they reached to 1.8 kWh and 0.028 kWh respectively. In contrast the lowest cumulative energy and exergy values observed in the third cycle with the values of 1.6 kWh and 0.016 kWh respectively. Such a fluctuation might have occurred due to any residual moisture inside material or due to the minor differences of inlet air conditions in different cycles. Figure 15 confirms this, as it can be seen that the inlet temperature in cycle three is slightly lower than the inlet temperature in cycle two. This resulted in lower temperature lift in that cycle, demonstrating that inlet air parameters have an impact on system performance and should be optimized in real life applications.

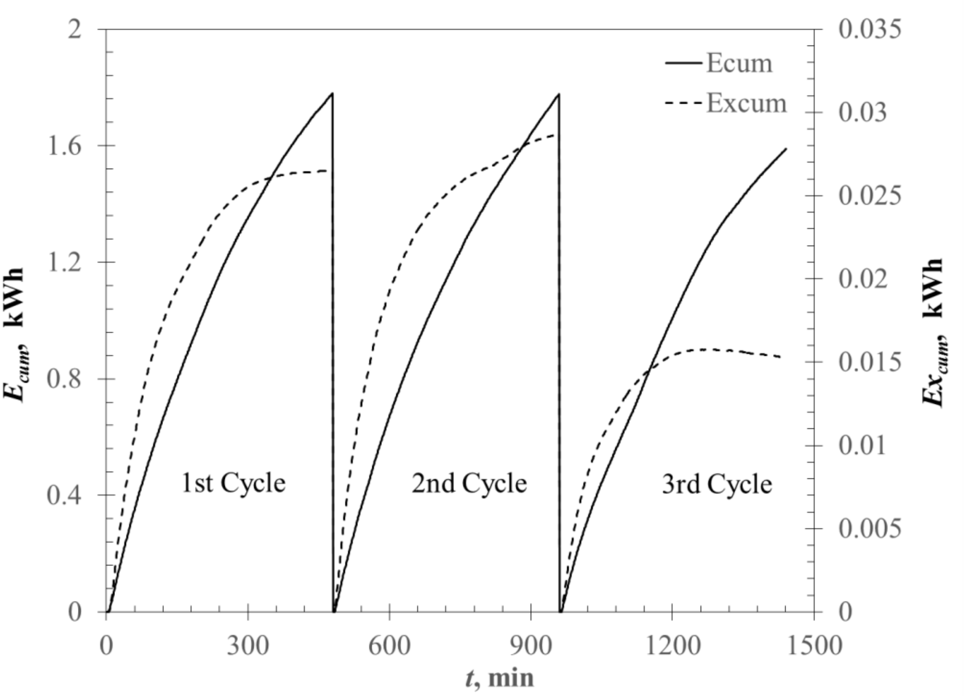

Figure 18: Variation of Cumulative Energy and Exergy Over Three Discharging Cycles of V-$CaCl_2$

An important parameter to define system performance in heating and cooling systems is coefficient of performance (COP). Despite, efficiency is most important performance indicator in heat storage applications, COP is also used to demonstrate the discharging effectivity. Discharging COP in heat storage systems is defined as the ratio of the net useful heat output to the net electric work input to the system. In the developed system electric consuming components in discharging cycle were the fan and ultrasonic humidifiers. In THS discharging process, despite the electric consumption rate is steady, heat output shows a decreasing trend due to the reduced sorption rate as the material approaches to the saturation point. Therefore, COP also decreases with time as shown in Figure 19. In all cycles, COPs reached to 10-11 range at the beginning, where they dropped to nearly two at the end. Average COP values were found nearly 6, which is promising, in terms of high heat generation rate per unit of electricity consumed.

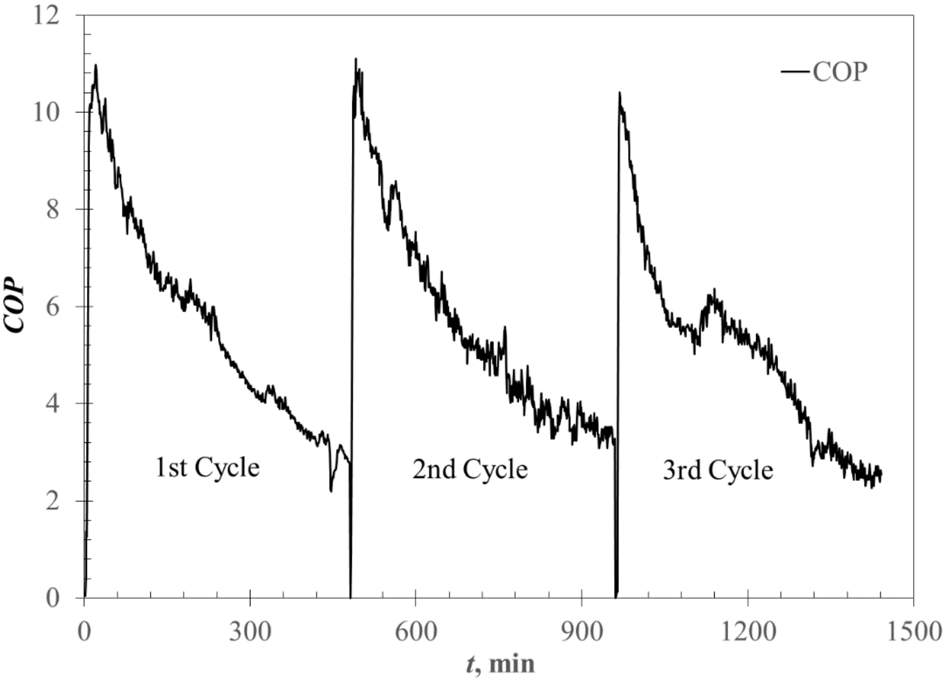

Figure 19: Variation of COP With Time

Besides the energy related parameters, it is important to analyze the sorption kinetics in THS discharging cycles. As the heat generated is the function of the rate of moisture sorption, the relation between these two should be defined for better understanding of system operation. The relative humidity of inlet and outlet air during the cycles were given in Figure 20. Inlet RH varied in the range of 80-90%, where outlet RHs were dropped below 20% and rose steadily due to the reduced sorption rate by the time. While RH might give some general indication of the humidity levels of air, it does not clearly demonstrate the real moisture contents of air in order to determine the variations in sorption rate. For that reason, absolute humilities should be calculated via Eq. 10. Later by multiplying the mass flow rate with the absolute humidity of air, total moisture content of it could be calculated.

Absolute humidity, is moisture content per unit kilogram of dry air. As sorbent is fully dried at the beginning of the process, sorption rate is quite fast. During that period, majority of the moisture inside the air is absorbed by the sorbent. This is due to the highly hygroscopic nature of $CaCl_2$ salt and it is high affinity to water vapor when it is anhydrous. Sorption rate was the highest in the second cycle, where absolute humidity differences across the sorbent reached to a maximum of 10 gr/kg. On the other hand, in first and third cycles. Highest Δw values were measured as 7.6 gr/kg and 8.4 gr/kg respectively. Over 360 minutes testing period Thus average values of absolute humidity difference of air values are 5.4 gr/kg , 7.4 gr/kg and 6.9 gr/kg respectively

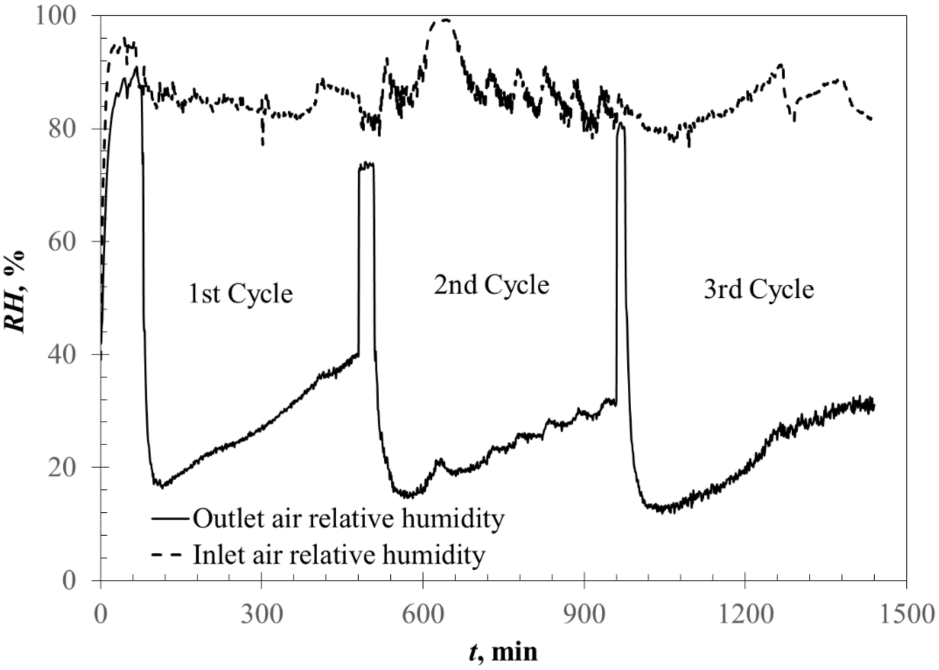

Figure 20: Variation of Inlet and Outlet Relative Humidity Over Three Discharging Cycles of V-$CaCl_2$

By integrating the sorption rate over the discharging duration, mass increase of the sorbent, which is also referred as “mass uptake” is determined. The results of mass uptake in three discharging cycles are presented in Figure 21. As seen, mass uptake reached to 1600 gr in the second cycle, which is followed, by third and first cycles with the values of 1400 gr and 1100 gr respectively. Accordingly, reaction advancement (X), which is the ratio of mass uptake to initial dry mass of the sorbent has also determined. In second cycle, X was again the highest at 0.9 and first cycle was the lowest at around 0.75.

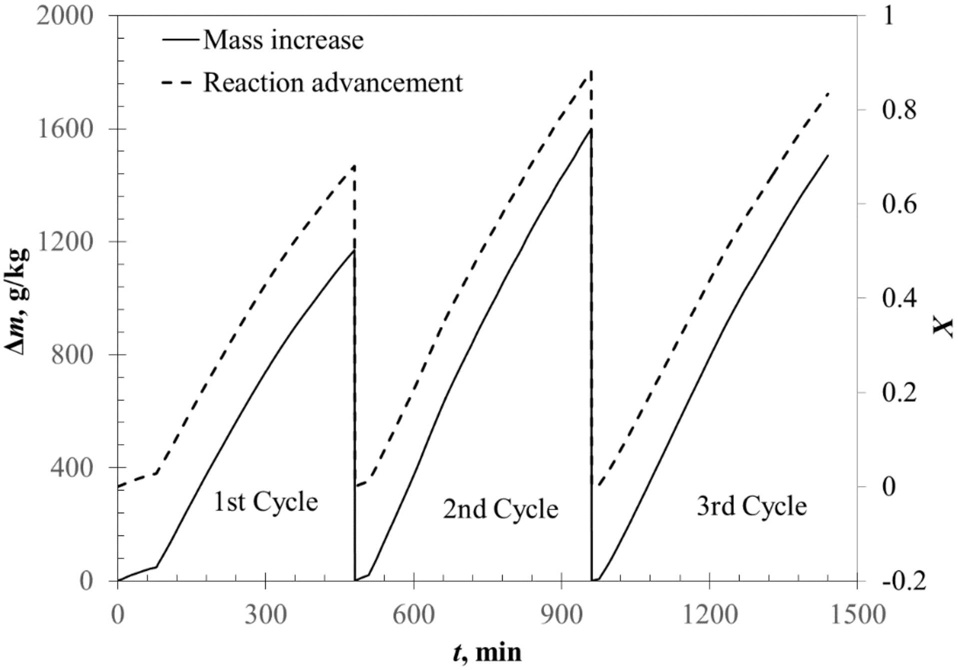

Figure 21: Variation of Mass of the Sorbent and Reaction Advancement Over Three Discharging Cycles of V-$CaCl_2$

5.1.2 Charging Analysis

Analysis of desorption processes is performed in order to determine the inlet and outlet air properties thereby to identify the energy and exergy transferred to the sorbent. Besides, rate of mass removal at the applied desorption temperature was investigated for three consequent cycles.

Figure 22 shows the inlet and outlet temperature versus time for three different cycles. As seen in the Figure, inlet air temperatures fluctuated between 85-95 °C, where outlet air temperatures dropped to near 30 °C initially and showed a gradual increase with the time. The reason of the sharp drop of outlet air at the beginning is the high amount of energy consumption for water desorption. Later on, with the reduced moisture content of the sorbent, energy spent for desorption gets lower, resulting with an increase in the temperature. At the end of the cycles, outlet temperature is in close approximation with the inlet air temperature. This condition demonstrates that there is no more moisture removal, therefore the charging process ended.

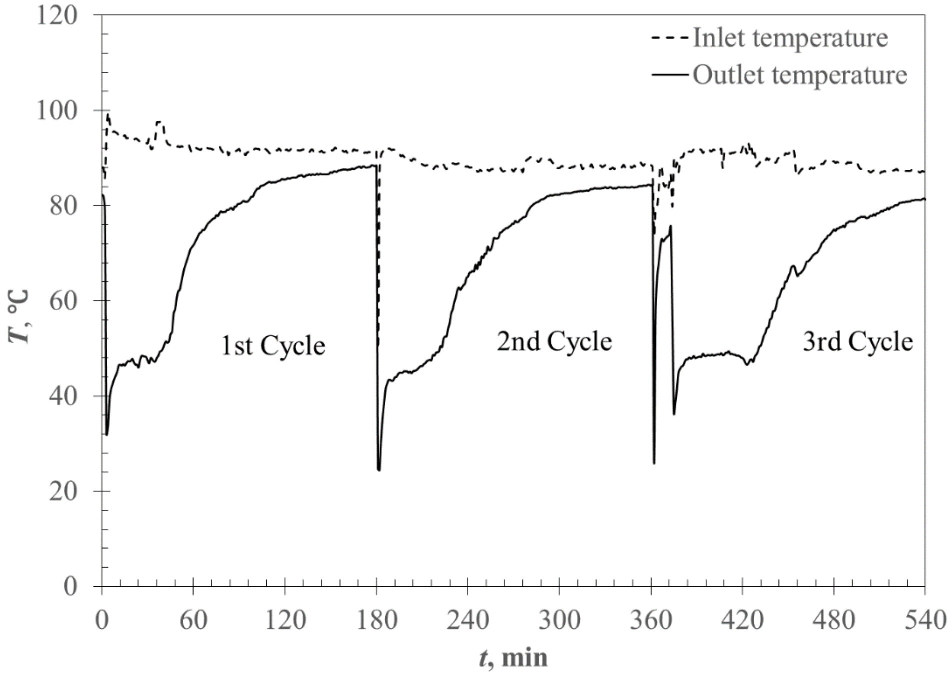

Figure 22: Variation of Inlet and Outlet Temperature Over Three Charging Cycles of V-$CaCl_2$

Based on the air temperature variations of air, the heat contents at the reactor inlet and outlet were determined as represented in Figure 23. In all charging cycles, rate of heat supply was approximately 3.5 kW. Heat content of outlet air was initially between 1-1.5 kW. In first two cycles, heat content of outlet air gradually rose and reached to nearly 3.5 kW, however in the last charging cycle heat content remained at 3 kW, indicating that there is still some moisture inside the sorbent. This has possibly occurred due to some excessive moisture supply to the sorbent in the third discharging cycle.

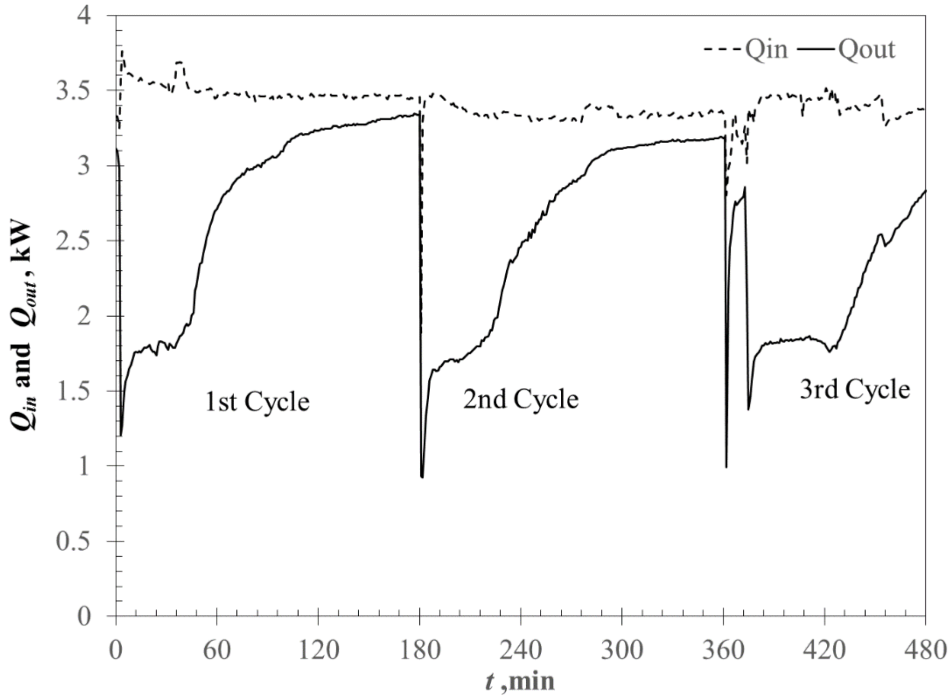

Figure 23: Variation of Heat input and Output Over Three Charging Cycles of V-$CaCl_2$

Figure 24 represents the net heat and exergy transfer to the sorbent during the charging cycles. Highest rate of heat transfer occurred in the first cycle at nearly 2.5 kW. In the consequent cycles, heat transfer reached to a peak of 2.4 kW and 2.1 kW respectively. In first two cycles rate of heat transfer was almost zero at the end of 180 min, whilst in the third cycle it was still 0.6 kW due to the possible reasons explained above.

The net exergy transfer values can also be seen from the Figure 24. As seen, the peak exergy transfer was 0.3 kW, 0.26 kW and 0.22 kW in first, second and third cycles respectively. During the charging period, exergy transfer dropped gradually due to the reduced temperature difference between inlet-outlet air and 0.03 kW in first two cycles and 0.09 kW in the last cycle. Compared to the discharging cycle, exergy transfer is much higher in charging cycle. This is due to the high operating temperatures in charging cycles. During discharging, system operates between 20-50 °C range, whilst in charging the air temperatures vary between 90-30 °C. According to the Second Law of Thermodynamics, high temperature and high temperature differences result in high exergy and high exergy transfer, this indicates the high quality energy requirement in charging cycle. This should be considered as a negative aspect of THS, and materials with lower charging temperatures needs to be sought for future development of THS systems.

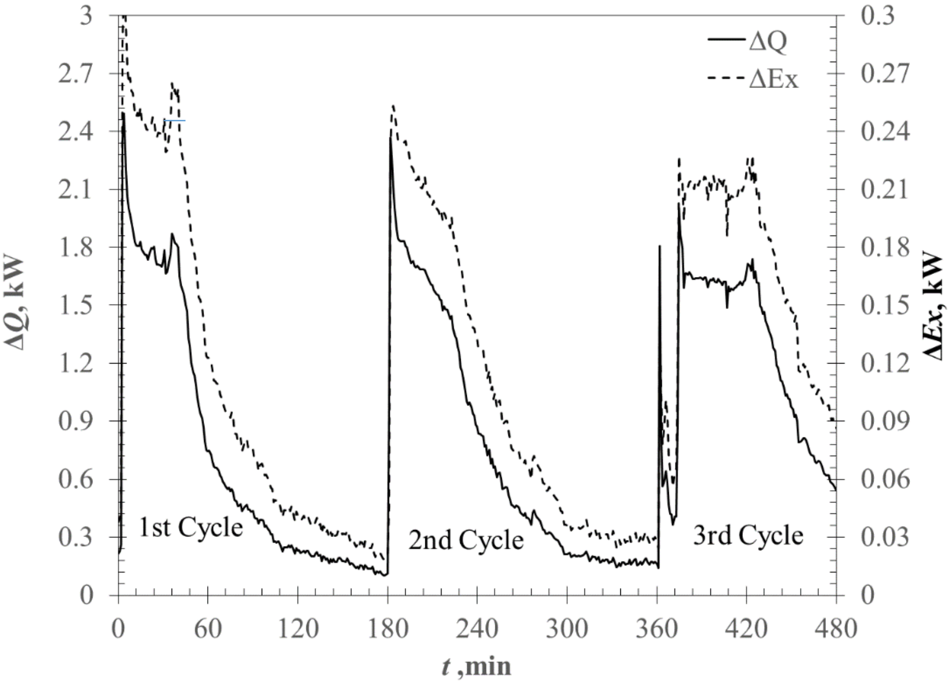

Figure 24: Variation of Heat and Exergy Input-Output Over Three Charging Cycles of V-$CaCl_2$

Figure 24 examines the cumulative energy and exergy versus time. As seen, there is a direct linear relationship between cumulative energy and exergy. Despite third cycle has the lowest heat and exergy transfer rates, cumulatively highest amount of energy and exergy spent in that cycle. While in first two cycles, total energy and exergy transfer were 2.2 kWh and 0.32 kWh, in the last cycle, these values reached to 2.8 kWh and 0.38 kWh respectively.

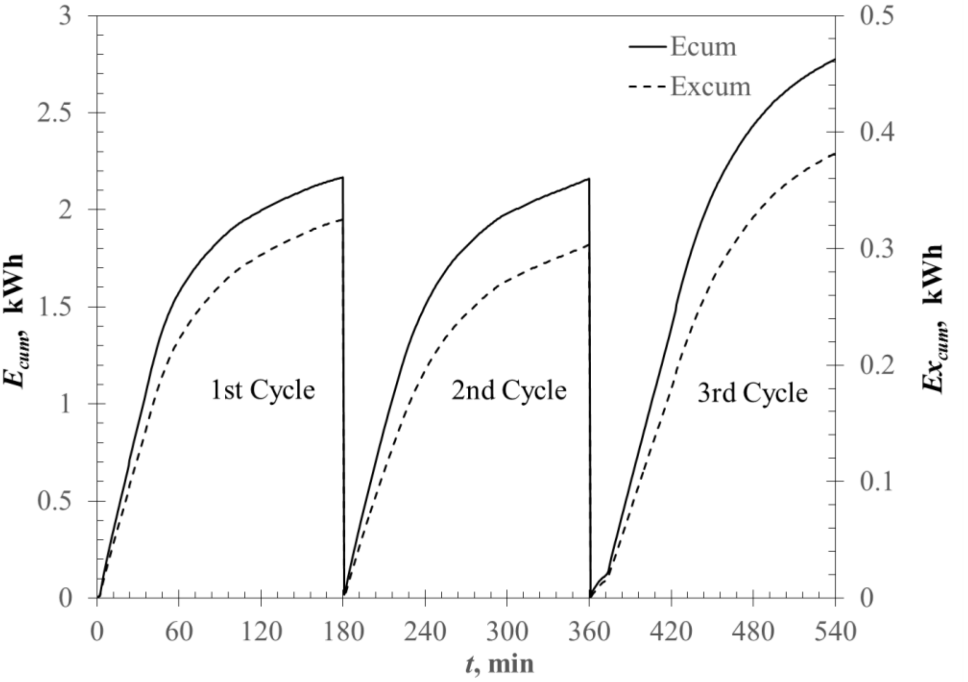

Figure 25: Variation of Cumulative Energy and Exergy Over Three Charging Cycles of V-$CaCl_2$

Besides the energetic analysis, desorption kinetics were also investigated for desorption process. The relative humidity variation of air across the reactor is presented in Figure 26. The inlet humidity at the inlet was nearly zero, indicating that the dry air is entering the reactor. The outlet air relative humidity's were above 40% initially, due to the high rate of moisture removal from the sorbent. By the time, outlet relative humidity gradually dropped down to zero.

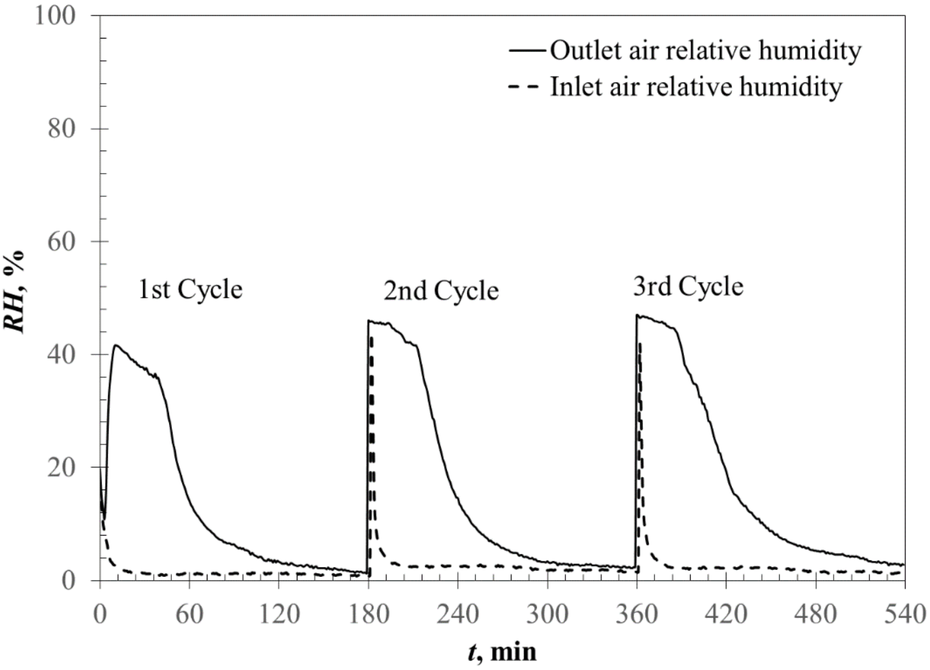

Figure 26: Variation of Inlet and Outlet Air Relative Humidity Over Three Charging Cycles of V-$CaCl_2$

By using the relative humidity and temperature variation, absolute humidity changes of air were also calculated (See: Figure 27). In all cycles absolute humidity change of air across the reactor exceed 20 g/kg, illustrating that the desorption process is very efficient. At the end of 180 min, differences were less than 3 gr/kg which was expected.

Based on the absolute humidity changes and air mass flow rate, total mass change of the sorbent has also analyzed for the charging processes (See: Figure 28). Highest cumulative moisture desorption was achieved in the first cycle in which ~1000 gr moisture was removed. This cycle was followed by the third cycle with ~900 g and second cycle was the lowest with 800 g moisture removal. Finally, reaction advancements for charging cycles were calculated as given in Figure 28. For charging process reaction advancement is defined as the ratio of total moisture removed to the initial wet mass of the sorbent. Accordingly, reaction advancements were 0.28, 0.26 and 0.23 for the order of first, third and second cycles.

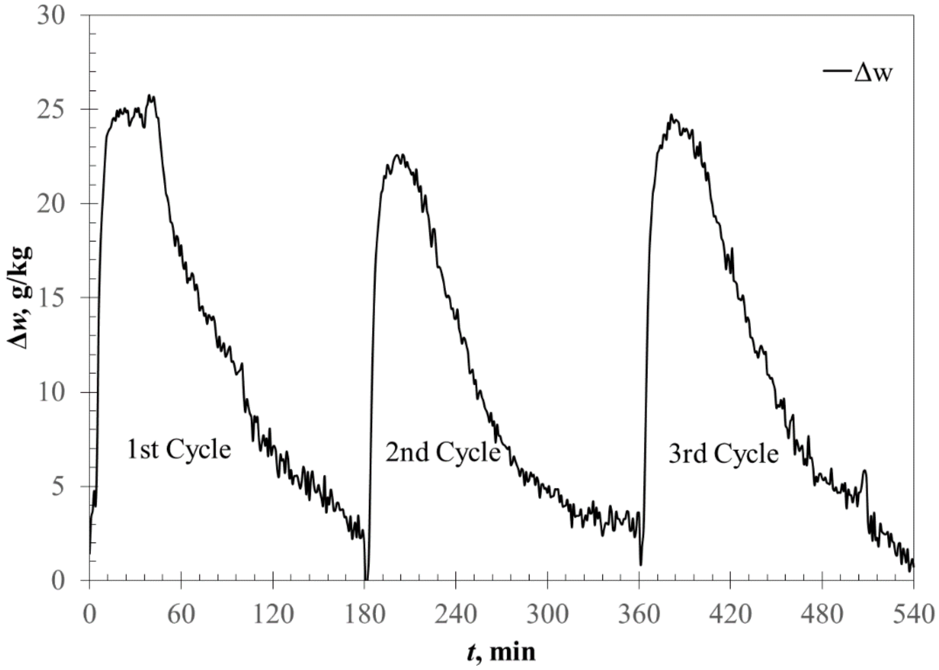

Figure 27: Variation of Absolute Humidity Over Three Charging Cycles of V-$CaCl_2$

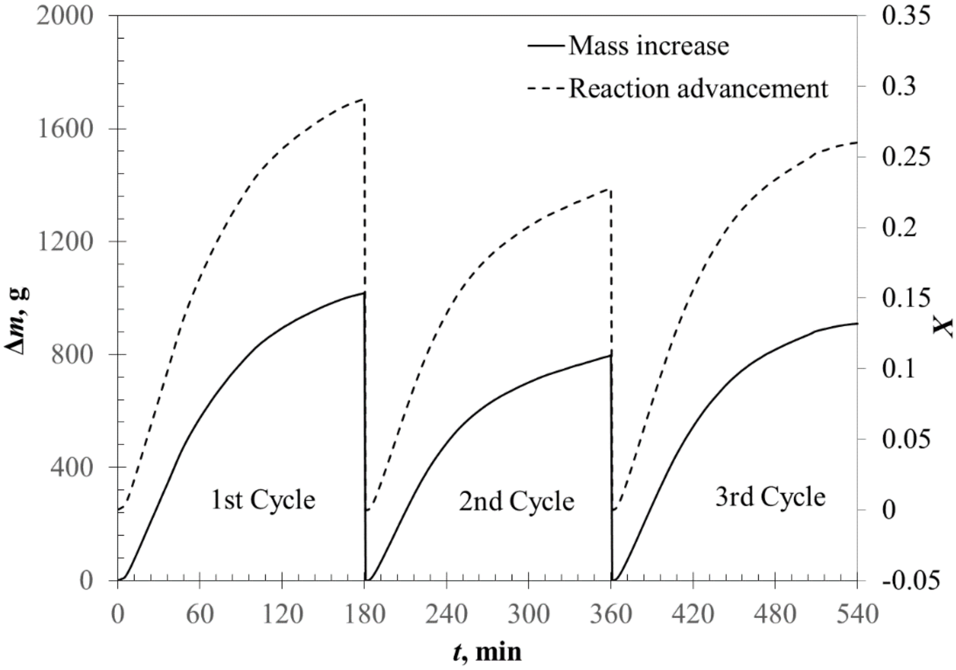

Figure 28: Variation of Mass and Reaction advancement of Sorbent Over Three Charging Cycles of V-$CaCl_2$

5.1.3 Overall Performance Analysis

For three cycles testing, obtained average performance parameters for discharging and charging cycles were presented in Tables 3 and 4 respectively. As seen average temperature lifting in three repeating discharging cycles were nearly 12-13 °C during 360 mins. testing duration. Accordingly, Q_{out} and COP discharging varied in the range of 0.19-0.22 kW and 5.5-5 respectively. Based on the obtained results, V-$CaCl_2$ performance was found stable over three repeating discharging cycles. For charging cycles, average heat transferred to the sorbent was calculated in the range of 0.72-0.92 kW. Average temperature drop was also found between 19-24 °C in charging cycles.

In Table 5, overall performance parameters were presented. Based on the obtained results in discharging and charging cycles, first and second law efficiencies of the THS were found between 0.82-0.57 and 0.08-0.04 respectively. Also, energy densities (E_d) was in the range of 200-250 kWh/m^3, which is higher than the conventionally used sensible (water, soil) and latent (paraffin) heat storage materials.

Table 3: Summary of the performance parameters in three discharging cycles

Cycle No	m_a	$T_{i\ ave}$	$T_{o\ ave}$	ΔT_{ave}	ΔRH_{ave}	$w_{i\ ave}$	$w_{o\ ave}$	Δ_{wave}	Q_{ave}	Ex_{ave}	E_{cum}	Ex_{cum}	COP	m_{ads}
Cycle 1	0.015	21.03	34.74	13.71	49.16	16.74	11.34	5.4	0.222	0.0033	1.78	0.026	5.55	1170
Cycle 2	0.015	20.80	34.54	13.73	60.71	18.19	10.79	7.4	0.224	0.0036	1.77	0.028	5.56	1599
Cycle 3	0.015	21.06	33.31	12.25	59.72	16.23	9.26	6.96	0.198	0.0019	1.59	0.015	4.96	1504

Table 4: Summary of the performance parameters in three charging cycles

Cycle No	m_a	$T_{i\ ave}$	$T_{o\ ave}$	ΔT_{ave}	ΔRH_{ave}	$w_{i\ ave}$	$w_{o\ ave}$	Δw_{ave}	Q_{ave}	Ex_{ave}	E_{cum}	Ex_{cum}	m_{ads}
Cycle1	0.035	92.31	73.31	19.00	12.16	4.61	17.10	12.49	0.72	0.11	2.17	0.325	1017.00
Cycle 2	0.035	88.44	69.25	19.19	12.39	6.49	16.31	9.82	0.73	0.10	2.16	0.303	796.00
Cycle 3	0.035	88.78	64.39	24.39	14.73	4.88	16.07	11.19	0.92	0.13	2.78	0.383	909.00

Table 5: Summary of the overall cyclic performance of V-$CaCl_2$ in three cycle testing

Cycle No	V_{ads}	η_I	η_{II}	η_{hyg}	E_d
Cycle 1	0.0075	0.82	0.08	0.87	237.33
Cycle 2	0.0075	0.82	0.09	0.50	236.00
Cycle 3	0.0075	0.57	0.04	0.60	212.00

Chapter 6

CONCLUSION AND FUTURE WORK

6.1 Conclusion

With the technological advancements, several systems were developed for utilizing renewable energies in different areas. For achieving sustainability in near future implementation of such technologies in buildings has a vital importance. In this context, for on-site heat generation in buildings systems on the solar energy conversion is crucial. Despite solar heat production technologies widely researched, the obstacle is the storage problem. Whilst hot water tanks used widely, they have some major drawbacks such has limited storage capacity and high heat losses. In order to fulfil this gap, an open THS system using V-$CaCl_2$ is experimentally investigated in this study. Three full cycles (discharging/charging) were comprehensively analyzed throughout the study. Thermodynamic analyses based on the First and Second Law were performed to analyze several operational parameters including energy, exergy and mass transfer rates.

According to the study results, it has found that V-$CaCl_2$ composite could provide a temperature lift up to 30 °C and could provide a heat storage density nearly in the range of 200-250 kWh depending on the operational conditions. Results also showed that this material could be regenerated effectively at 90 °C, which is favorable when compared to other conventional solid desiccants.

The developed unit could be applied in buildings both for short and long term heat storage. Use of such system in buildings could provide considerable reduce in energy consumption and costs. Particularly in North Cyprus, in recent years, a sharp rise in electric unit price was observed. Besides, electric shortage seems highly possible in near future due to the dramatically increasing energy demand. In this context, reducing the energy consumption in buildings could be a step-forward for sustainability and economic improvement of the Island. Presented THS method is hoped to be primitive for the kick-start on building energy renovation in North Cyprus.

6.2 Future Work

According to the study results, potential improvements on the developed open THS system and suggestions for future development of this technology are listed below;

- Waste heat recovery could be applied in charging process to utilize the energy in exhaust air. This could improve the overall efficiency of the heat storage process.
- THS process optimization could be carried out by using a computer simulation software to enhance the system performance and determine optimal operational conditions.
- Open THS System could be integrated to solar air collectors and in observe its stability over long term period in real life conditions.
- To develop new composites could be developed that has low charging temperature (50-60 °C)

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