Investigation of a Liquid Desiccant Enhanced Evaporative Cooling System for Building Application

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ABSTRACT

This research presents an investigation on a desiccant enhanced evaporative cooling system. In the last decade, increase in the occupant comfort demands leads to a rising requirement for air conditioning. On the other hand deteriorating global energy and environment crisis are starving for energy saving and environmental protection. The need to come up with the new energy saving as well as environmental friendly air conditioning systems has been more urgent than ever before. In hot and humid areas, the liquid desiccant air-conditioning systems based on evaporative cooling was proposed as a promising invention. In such cycles, the desiccant decreases the air humidity which is achieved by the moisture removal from the air. Later, reduction in the temperature is obtained by the following evaporative cooling unit.

Desiccant Enhanced Evaporative Cooling System is a promising technology which is different from the conventional ways of cooling systems such as vapor compression heat pumps. Air conditioning impacts our environment as well as it uses substantial amount of electrical energy. Desiccant based air conditioning is a sustainable, simple, practical method for cooling the buildings, Besides that, it is efficient and cost-effective since it can provide between 40 and 80% of energy savings in comparison with vapor compression air conditioning. When compared to direct evaporative coolers, desiccant assisted evaporative cooling provides higher cooling effectiveness for the same amount of water added to the air. For those reasons, recently, desiccant cooling systems for domestic and residential building applications have been a global trend to be used in order to reduce energy-operating consumptions as well as the costs.

This study illustrates a novel desiccant assisted evaporative cooling system and evaluates its performance. It deals with such a system and investigates vermiculite – calcium chloride as desiccant material in order to examine the performance of the system. According to the study results, temperature drop around 10 °C with an average cooling rate of 700 W and cooling COP in the range of 5- 6 was obtained. Economic analysis for the payback period showed that the return on investment is 3 years for only summer operation of the system. Accordingly it is found feasible to invest on such system in hot humid climate (such as North Cyprus) for building air conditioning.

Keywords: Air-Conditioning, Cooling, Desiccant, Evaporative, Humidity.

ÖZ

Bu çalışma kapsamında desikant hava kurutuculu evaporatif soğutma sistemi incelenmiştir. Son dönemde artan konfor talebi bina iklimlendirme ve soğutma sistemlerine olan ihtiyacı arttırmıştır. Diğer yandan, artan küresel enerji tüketimi ve çevresel sorunlar nedeniyle enerjiyi verimli kullanma ve çevrenin korunumu giderek önem kazanan alanlar olmuştur. Bu bağlamda, enerji verimli ve çevre dostu soğutma sistemlerinin geliştirilmesi gerekmektedir. Sıcak ve nemli bölgelerde, desikkant hava kurutuculu evaporatif soğutma sistemlerinin kullanımı yenilikçi ve verimli bir yöntem olarak öne çıkmaktadır. Bu soğutma sisteminde havanın ilk olarak desikant kurutucu yardımıyla nemlilik seviyesi azaltılmakta, ikinci aşamada ise hava evaporatif yöntemle soğutulmaktadır.

Desikant kurutuculu evaporatif soğutma sistemi birçok yönden buhar sıkıştırmalı soğutma çevriminden farklılık gösteren yenilikçi bir soğutma sistemidir. Konvansiyonel soğutma sistemi yüksek miktarda elektrik enerjisi tüketmekte ayrıca çevreyi negatif şekilde etkilemektedir. Desikant kurutuculu soğutma; sürdürülebilir, uygulaması kolay ve pratik bir soğutma yöntemi olmakla birlikte, buhar sıkıştırmalı soğutma sistemlerine göre 40-80% arasında enerji tasarrufu sağlamaktadır. Diğer yandan direkt evaporatif soğutucularla karşılaştırıldığında, desikant kurutuculu soğutma sistemleri, aynı soğutma kapasitesi için daha düşük miktarda su tüketmektedirler. Bu avantajlardan dolayı desikant kurutuculu soğutma sistemlerinin binalarda kullanımı son yıllarda önem kazanmış ve bu alandaki araştırmalar yoğunlaşmıştır.

Bu çalışma kapsamında desikant kurutuculu soğutma sistemi incelenmiştir. Çalışma kapsamında desikant malzemesi olarak vermikulit – kalsiyum klorid kompozit malzemesi kullanılmış, geliştirilen deney düzeneğinde desikantlı soğutma sistemi performansı test edilmiştir. Çalışma sonuçlarına göre sistemde ortalama 10 °C hava sıcaklık düşüşü, 700 W soğutma kapasitesi ve 5-6 aralığında soğutma performans katsayısı elde edilmiştir. Yapılan ekonomik analiz, geliştirilen sistemin sadece yaz dönemi kullanımı göz önüne alındığında 3 yıllık geri ödeme süresine sahip olduğunu göstermiştir. Çalışma sonuçları, desikant kurutuculu evaporatif soğutma sisteminin performans ve ekonomiklik açılarından sıcak ve nemli iklim koşullarında (örnek: Kuzey Kıbrıs) uygulanabilir bir teknoloji olduğunu ortaya koymuştur.

Anahtar kelimeler: Desikant kurutucu, Evaporatif, İklimlendirme, Nemlilik, Soğutma.

To My Family

My Dear Father

My Dear Mother

My Dear Brother

My Dear Sisters

Thanks for your words, love and supports along my journey

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AC	Air Conditioning
COP	Coefficient of performance
DC	Desiccant cooling
DEC	Desiccant evaporative cooling
DEVAP	Desiccant evaporative
EC	Evaporative cooling
EVAP	Evaporative
FEA	Finite elements analysis
HVAC	Heating, ventilation and air conditioning
PWF	Present worth factor
WBS	Work breakdown structure

LIST OF SYMBOLS

A	$[m^2]$	Area
C_p	[J/k]	Specific heat
h	[kJ/kg]	Enthalpy
$\dot{m}$	[kg/s]	Mass flow rate
$\dot{M}_{added}$	[kg/s]	Mass of water added
$\dot{M}_{removed}$	[kg/s]	Mass of water removed
m_a	[kg]	Mass of the dry air
m_v	[kg]	Mass of water vapor
P_a	[Pa]	Pressure of the dry air
P_a	[Pa]	Pressure of water vapor
OC	[$]	Operating cost
Qc	[w]	Cooling rate
RH	[%]	Relative humidity
T	[°C]	Temperature
t	[sec]	Time
T_{dp}	[°C]	Dew point temperature
w	[%]	Absolute humidity

Chapter 1

INTRODUCTION

1.1 Significance of the System

Statistics have proven that the potential of human being is much more efficient in a comfortable and conditioned environment if it is compared to its performance in unconditioned workplace, due to that, the demand for thermal comfort has become essential. Comfort conditions for human are accomplished as long as the temperature and humidity are maintained at specific ranges. According to ASHRAE standards, temperature as well as relative humidity suitable for the comfort of human being are between 20 to 26 °C and humidity range between 30 to 60 % [1]. As a result, the need for air conditioning increases dramatically, either for commercial or for residential applications. Conventional cooling system investigation needs to consume huge amount of power in order to achieve the conditions of thermal comfort. Therefore, this conventional technique cannot be considered as energy efficient for all climates conditions especially where the latent loads are the dominant feature. Even vapor compression systems are widely used, but they can never be environmental friendly applications due to the investigation of carbon dioxide or ammonia as the refrigerants which have hazardous impact to the environment, so the use of such units should be monitored in order to avoid any leakage for the refrigerant which could be harmful [2].

In order to face the obstacles and the increasing demands of traditional air conditioning systems for commercial and residential applications, new alternatives are required.

The demand of using HVAC applications is significantly growing in all regions. Due to this demand, the utilization of the conventional energy has increased as well. Desiccant cooling approach emerges as a promising alternative. Since it has high ability to both absorption and adsorption of the moisture. The desiccants can be regenerated if they being dried so that this cycle can be repeatable. Directly beyond the dehumidification stage, the processed air is driven to enter the evaporative cooling stage which aims to decrease the processed air temperature in order to meet the condition of human comfort. Desiccant cooling system is highly efficient and cost-efficient technique to achieve the comfort requirements either for the temperature or for the humidity of the environments what makes it preferable and more comfortable than the other air conditioning methods.

The desiccant enhanced evaporative cooling approach can be classified according to the type of the used desiccant material. Liquid and solid desiccant assisted cooling are two significant types of such a thermally driven approach. Solid desiccant based cooling technique is more reliable if it is compared with the liquid desiccant based cooling. However, liquid desiccant requires regeneration with lower temperatures around (60–85 °C) than it is in the case of solid desiccants, what makes the investigation of renewable energy resources such as biomass, solar, etc. has become more needed since it is feasible as well as an effective solution. Nevertheless, plenty of the researches conducted on liquid desiccant based dehumidifiers, the processed air flow were with direct contact liquid desiccant. However, dehumidifiers with direct contact faces the problem of carrying droplets of desiccant by the air stream which has negative effect for the system equipment especially the corrosion issues through the ducts carrying the stream which will directly affect the operational cost as well as the maintenance in addition to the real increase in the life cycle of the system setup [3].

1.2 Concept of the Study

Evaporative cooling system might be classified into two types; direct evaporative cooling (DEC) type as well as indirect evaporative cooling (IEC) type. However, the direct type mechanism by cooling the air passing with a direct connection with either liquid or wet solid surface. So, in a DEC, water is used as a refrigerant and it is vaporized in the airstreams and the heat and mass exchanged between air and water decrease the air-dry bulb temp with an increase in the air stream humidity, with no change in its enthalpy, the system effectiveness of an evaporative cooling system is evaluated according to the dry bulb temperature where it is the ratio of the real decrease to the max theoretical decrease that the dry bulb temperature can measure in case the cooler has 100% efficiency and the ambient airstream was saturated.

Desiccant cooling approaches are generally open cycle systems, investigating the water to be considered as a refrigerant with direct contact with the processed air. This thermally driven application of cooling is the combination of both evaporative coolers together with air dehumidifiers by the mean of using desiccant or a hygroscopic material, applied where latent loads are present and the purpose of desiccant is to absorb the moisture from air and to decrease relative humidity of air by 20 percentage.

For this purpose, liquid or solid materials can be employed. The term ‘open’ is often used to specify that the water will be discarded from the system after achieving the cooling need and then a new refrigerant is to be instead of it with an open-ended loop. Hence, only possible refrigerant to be used is water since it is in direct contact with the surrounding air. This system has a great potential to provide thermal comfort in places where air humidity is low, being, however, less efficient where air humidity is high.

1.3 Objectives of the Study

This system successfully overcome the issue, rising humidity with cooling in an evaporative cooler, which makes it unstable and invalid for blazing and muggy atmospheres, air first underneath it is evaporative cooled by dehumidifying. By cooling water circulation, the heating impact of dehumidification operation is repaid. Evaporative cooling turned out to be more vital by incorporation the dehumidification stage together with the cooling. The objectives of this study can be classified as following:

- Design and develop a desiccant enhanced evaporative cooler.
- Prepare desiccant material (vermiculite-calcium chloride) in order lower the relative humidity of air using desiccant solution which absorbs moisture from the humid ambient air.
- Perform experimental studies on the developed prototype in order decrease the temperature of air by 10 degrees and provide a relatively cold air for the surrounding as well as lowering the relative humidity of air using desiccant solution which absorbs moisture from the humid ambient air and analyzing the effect of mass flow rate of moisture with respect to time.
- Carry out economic feasibility analyses for the use of the system under specific climate conditions such as North Cyprus.

1.4 Novelty of the Study

Desiccant based evaporative Cooling System could be a revolutionary technology that is completely different from the standard ways of cooling systems. AC impacts the environment in addition to that it uses plenty of power. This specific AC approach will offer air that's way more comfy and healthier than the conventional air con. Moreover, it's incredibly efficient and cost-efficient since it saves around 40% and 80% of that energy that we tend to use in air conditioning. In hot and humid region as North Cyprus' weather, this technique can be a promising invention in order to provide cooling effect with healthier and environmental friendly approaches.

Moreover, no recent studied have been found in literature under North Cyprus climate conditions (hot – humid) on desiccant assisted evaporative cooling. This study aims comparing direct EVAP/DEVAP which is useful to investigate the performance improvement of EVAP through the use of desiccant materials. Besides that, several conventional desiccants such as zeolite and silica gel are widely researched for desiccant cooling. However, V-$CaCl_2$ has not been utilized in a desiccant cooling system previously.

1.5 Limitations of the Study

- This study will not cover a detailed numerical investigation of desiccant assisted cooling systems.
- Regeneration process in real life condition is not investigated for desiccant cooling performance.
- The study focuses on discharge outcome of the system.

1.6 Organization of the Thesis

- Chapter 1 is the introduction, state of the system, limitations, in addition to the thesis organization.
- Chapter 2 is the literature review of the thesis where few researches are presented with a previously published papers are illustrated in tabulated form.
- Chapter 3 is about designing and modeling of the system as well as the materials and relevant design parameters are mentioned.

- Chapter 4 is the experimental study and the obtained results are fully explained with some relevant graphs needed for the explanation and the comparing of the performed tests.
- Chapter 5 is for economic analysis.
- Chapter 6 is the conclusion of the research.

1.7 Work Breakdown Structure (WBS)

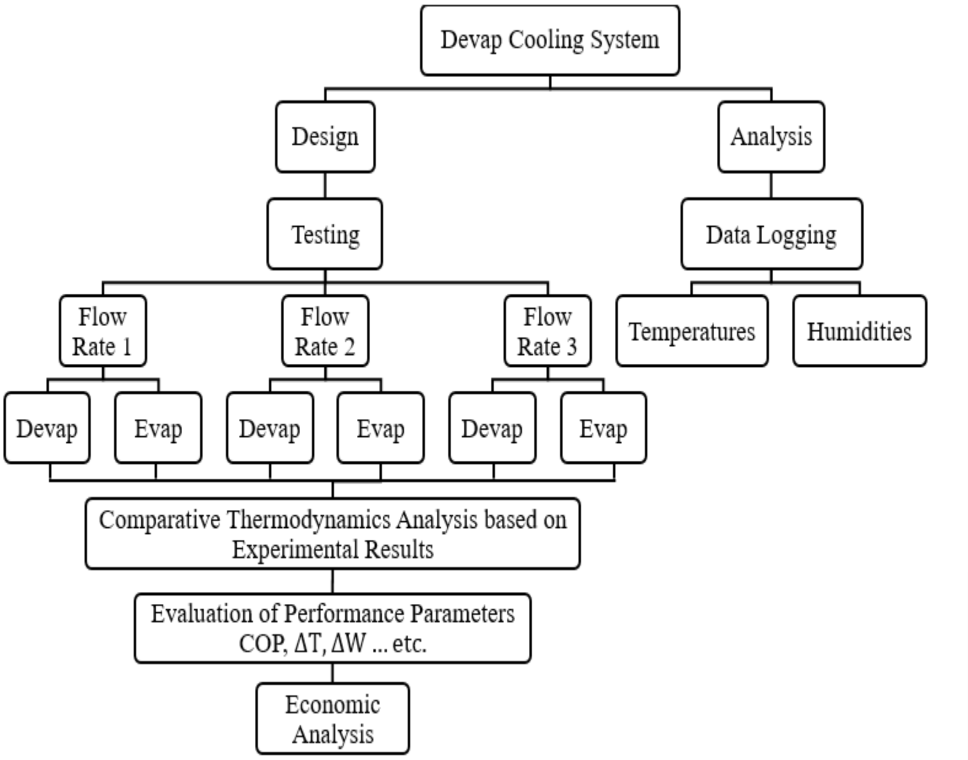

Figure 1: Working Plan.

Chapter 2

LITERATURE REVIEW

2.1 Overview

The demand on air conditioning is increasing dramatically across the world, with this increase, real actions has to be taken in order to compensate this demand. Therefore, the need for new environmental friendly air conditioning technologies has become urgent. Specifically in hot and humid regions, the liquid desiccant air-cooling systems based evaporative cooling systems have proposed. Desiccant cooling systems are generally considered as open-cycle systems, investigate the water as refrigerant which is directly in contact with air. The system can be defined as a thermally driven cooling cycle and in more details it is a combination of two units; the evaporative cooling unit which comes after with air dehumidification by a desiccant or hygroscopic materials as the first unit. Solid as well as liquid desiccant can be utilized. It is called open because the refrigerant is discharged out of the system after being cooled and to provide the cooling effect, new refrigerant will be supplied continuously in an open-ended loop. So only possible refrigerant to be used is water, directly contacted with the surrounding air.

2.2 Conventional Evaporative Cooling Systems

2.2.1 Indirect evaporative cooling system

This classification utilizes the outside air in order to cool an interior environment, preventing outer and inner airstreams to be mixed. Outer cool air will be drawn by a heat recovery stage till it is directly exhausted, on the other hand, the inside air will be drawn from the room and force to pass along the heat recovery section before it introduced again to the room. The external air's cool thermal energy is consequently given to the internal air by the heat recovery stage and without directly mixing the two streams. By humidifying the external air before it enters the heat recovery stage, its temperature is economically reduced as well as low cost cooling is obtained. Because of that the capacity of the system will be enhanced and making it more effective even when the external temperature is higher than the desired room temperature [4]. The concept of indirect evaporative cooling system is shown in Figure 2 below.

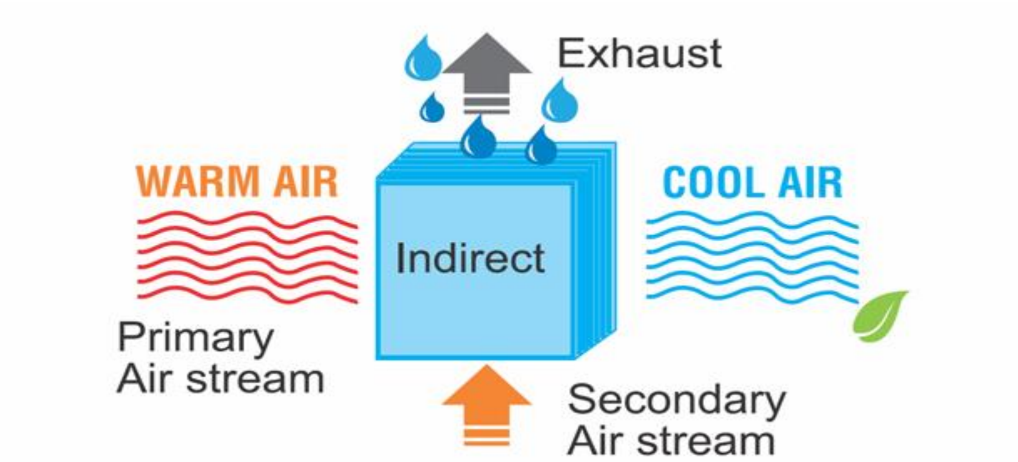

Figure 2: Indirect Evaporative Cooling Concept [5].

There will be less probability of inner atmosphere continually traded off by outer pollutants so this might be a prefect plan for critical environment or incredulous situations, if the inner air never mixes with the outer air. It also leys the speed of the ambient out air stream through the heat regeneration section to be much higher than the internally circulating air, Therefore "scavenging" even magnificent levels of cooling from the system [6].

2.2.2 Direct evaporative cooling system

Such kind will be efficient for buildings and the applications where there is no central air conditioning system. Direct air evaporative cooling is considered as a very economical and creative technique in order to decrease the temperature. Spray humidifiers convey moisture to an atmosphere processing either compressed or high pressure air to guarantee evaporation. Basically located throughout the space, spray nozzles gives cooling with lower cost than conventional air conditioning. The amount of cooling obtained depends on the levels of humidity of the region, as a high humidity will not allow further moisture to be absorbed and its effect on cooling as it is show in Figure 3 [4].

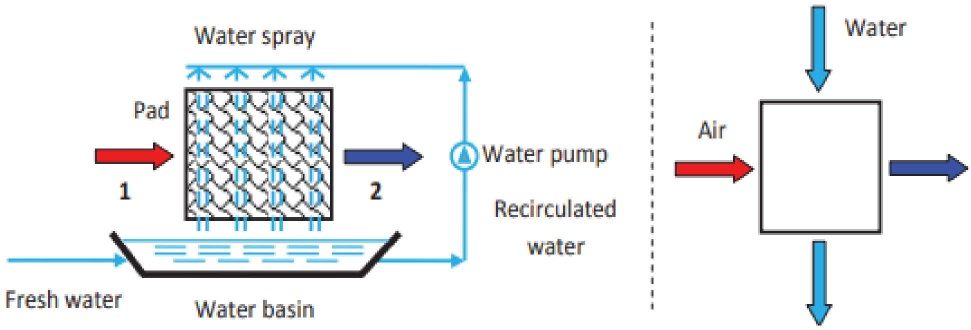

Figure 3: Direct Evaporative Cooling Concept [4].

This approach is best investigated a region with an active ventilation and a relatively high level of air exchange to maintain the atmosphere humidity sufficiently low to constantly absorb moisture. Direct evaporative cooling is technique utilized to simply remove heat by evaporating water within an airstream. Same procedure as our bodies do when we sweat. Direct evaporative cooling systems can be differed from conventional or mechanical cooling systems by the need of electricity operating, the first does not need to consume electricity for cooling the air.

2.3 Desiccant Evaporative Cooling

2.3.1 The concept of desiccant cooling

Desiccant cooling can be simply summarized by the mean of dehumidification of the flowing air stream which is achieved by leading the stream to pass through desiccant material followed by drying the air in order to reach at the desired temperature. To increase the system efficiency, water vapor has to be regenerated or in other words to be driven out of the desiccant material so that it can lose more moisture and be more ready to adsorb water vapor in the following cycle. Flow chart in Figure 4 shows the consequence of the system.

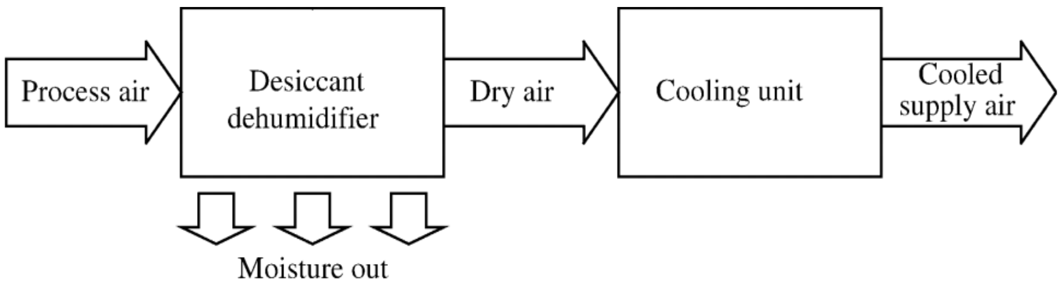

Figure 4: Principles of Desiccant Cooling.

With the help of a desiccant dehumidifier, the moisture will be removed out from the air and the required temperature can be obtained with the help of using evaporative cooler. For continuous operation of the cooling system, by utilizing a heat energy, the desiccant materials is regenerated, this heat can be obtained from a solar collector or any other resource of energy. In such a system the latent and sensible loads are removed by the usage of desiccant dehumidification system along with the cooling unit. The objective of the cooling unit is to handle the both factors of the load. The cooling depends on the humidity and temperature of the air [7].

2.3.2 Solid desiccant cooling

In this system, hot and humid air is forced to flow through the rotating desiccant wheel to be dehumidified by the mean of water adsorption process. Although the air temperate is rise up by the heat adsorption, a heat recovery wheel is passed, which is considered as the pre-cooling stage of the air stream. Moreover, the air enters humidifier and gets cooled by a controlled humidification process based on the set-values of air stream supplied temperature as well as the humidity. Then, the exhaust air stream is humidified to the saturation point or close to it in order to investigate the full cooling potential [8].

2.3.3 Liquid desiccant cooling

This type of desiccant cooling systems use a desiccant material in a liquid phase and the most commonly used desiccant is the solution of water-lithium chloride playing the role of sorption agent. One of the good aspects of such a system is; it results higher air dehumidification rate when it is performed with similar driving temperature gradient of solid desiccant cooling In addition this method provides a possibility of high energy storage which can be obtained when the concentrated solution is being stored. This technique is a promising choice for more increase in investigation as well as the exploitation of solar assisted air conditioning. . Recently, a few similar systems have started to be utilized in Germany in several applications, driven either by solar thermal heat or by any other heat sources [9].

2.4 Desiccant Materials

A desiccant is a kind of hygroscopic substance that is being investigated for drying purposes. Desiccants are utilized for moisture absorption and humidity removal from the air resulting in dry and moisture free environment as well as eliminating the moisture damages. The absorption characteristics of desiccants can be classified under two main categories; physical or chemical approach. In physical absorption, moisture is physically absorbed by desiccants by trapping the moisture in our on the surface of the desiccant materials grains, without any changes in the chemical properties of the water molecules, due to that, this concept is reversible [10].

For this specific type of absorption, silica gel and molecular gel desiccants are mostly being used. Where the chemical absorption process aims to change the state or the composition of the absorbed mixture into new one by changing its chemical properties, due to that, this mechanism is irreversible and for such usage; calcium chloride as well as magnesium sulfate are typically used. Table below demonstrates the widely used desiccants and their characteristics [11].

Table 1: Specifications of four common desiccant materials [11].

Desiccant	**Remark**	**Details**	**Rate of Absorption**	**Application Temperature**
Silica Gel	Main component SiO_2, solid transparent spheres	Physical absorption, high mechanical strength, can be reused even after oven drying	10% - 27%	Less than 35˚C
Calcium Chloride	The main absorption agent is $CaCl_2$	Chemical and High ability for absorption	To 700%	-5˚C - 90˚C
Clay	Powder or spherical forms	Environmental friendly, nontoxic	15% - 23%	Less than 50˚C
Molecular Sleve	Large surfaces for moisture absorptions	Can be recycle, has corrosion resistance, stable chemically	10% - 25%	Relatively high temperatures

2.5 Literature Survey

Ronghui Qi et al. [12] examined the energy consumption of desiccant enhanced evaporative cooling system. They investigated the air-conditioning load profile for typical building applications in Honk Kong. From the simulation results they concluded that the cooling load led to at least 98% of the annual load. While M. M. S. Dezfouli et al. [13] performed simulation for solar-driven desiccant cooling in Malaysia and they proved that, the isothermal dehumidification COP of the ventilation stages is higher than the recirculation stages. Hence, the desiccant cooling system in humid and hot regions will lead to higher efficiencies than other cooling techniques. In another study Dong La et al. [14] have theoretically studied the analysis of a solar hybrid desiccant air conditioning system, combining the approaches of desiccant cooling together with vapor compression AC. The results showed that such a combination is effective to be used in extreme humid regions and they achieved 87% thermal COP with 27.7% solar fraction.

J. L. Niu et al. [15] proposed a heating, ventilation, and air conditioning (HVAC) system assisted with chilled ceiling associated with desiccant cooling for humid climates and they discussed the energy saving potential where the results indicated that such a system would save up to 44% of the energy demands comparing with the conventional AC systems. Furthermore, Y. J. Dai et al. [16] used a hybrid AC system containing desiccant dehumidification and evaporative cooling along with vapor compression air conditioning. The experimental results illustrated that the COP of this hybrid system had significant increase by 20-30% as well as the ECOP increased dramatically. A study has been conducted by A. E. Kabeel et al. [17] investigating the regenerator of the liquid desiccant apparatus using solar panels. Studies resulted in improved growth of forced flow due to improved mass exchange coefficients. In another study M. Goldsworthy et al. [18] optimized a desiccant enhanced indirect evaporative cooling system and the results indicated that such an optimization can improve the cooling performance and energy savings. Another experiment has been carried out by T. S. Ge et al. [19] who has done a comparison between the potential of solar driven desiccant and the conventional vapor compression under two different climate conditions, Berlin and Shanghai, and they concluded that the regeneration temperature required in Berlin is 55˚C where it was around 85˚C in Shanghai. Their economic feasibility analysis showed that the periods of the dynamic investment paybacks for Berlin and Shanghai are 4.7 years and 7.2 years respectively. Due to the corrosive nature of the liquid desiccant solutions, the majority of researches have been conducted on its use in the solar cooling applications.

Enteria, N. et al [20] who studied the use of solar dependent liquid desiccant solutions in air conditioning units. The study revealed an important result that the efficiency of both regenerator and solar collector increased with an increase in the mass flow rate of the desiccant solution. Several factors such as the inlet air temperature, inlet desiccant temperature, the solar radiation and the climate had an influence on the operation of the analyzed system. However, Li Yutong et al. [21] focused their study on finding the optimal arrangement for an open cycle liquid desiccant AC network. The study consisted of using counter flow in the moisture removal unit and the use of solar heater to evaporate the extra moisture absorbed by the liquid desiccant while it is in contact with the processed air. Their system proved out to be a better choice than vapor compression systems in the sense that it saved 25-50 % more energy than its counterparts. However, Peng, D. et al. [22] carried out performance and numerical study on the energy and mass transfers in solar assisted liquid desiccant dehumidification system. Their results show that the final concentration of desiccant solution rose to 70%, the efficiency of regenerator increased to 45.7 % and the water absorption capacity of the desiccant materials increased to 44 %. In addition to that, N. Audah et al. [23] developed a solar driven liquid desiccant dehumidification apparatus and researched about its sustainability which involves the use of Calcium chloride as the liquid desiccant and parabolic solar collectors as a source of liquid regeneration. The study revealed that a small 25 change from 50.5 °C to 52 °C was noticed in the optimum regeneration temperature together with a small reduction in sink temperature from 19 °C to 16 °C. Moreover, the research also approximated the amount of water that could be absorbed by the liquid desiccant solution. Besides that, Aly, A. A. et al. [24] carried out a research with lithium chloride and calcium chloride as the liquid desiccant solutions in his apparatus. The FEA technique was used to obtain the combined mass and heat transfer methods.. By using this method several influencing parameters such as the length of the regenerator, mass flow rate and concentration of the desiccant solution and air mass flow were studied. According to the study results higher values of vapor pressure were found for calcium chloride compared to lithium chloride and with the FEA technique the system's performance was optimized under several weather seasons. In another research performed by She, X. et al. [25] developed a liquid desiccant moisture removing and regeneration apparatus and compared its performance with conventional vapor compression refrigeration unit. The results obtained from his study showed that the COP for this system with warm incoming air which was 18.8% greater than that obtained results for vapor compression and Carnot cycle under the same operating conditions. In a similar research carried out by A. Khalid et al. [26] simulation and experiment on a solar assisted hybrid desiccant cooling were performed in Pakistan. The simulation results using TRNSYS showed that the desiccant cooling can lead to a significant energy saving more than the reheat vapor air conditioning system.

G. Lychnos et al. [27] modeled an experiment in order to verify the effect of using solar-powered liquid desiccant for food production in regions which have hot climate. They concluded that the desiccant cooling help to lower the average daily temperature in hot seasons by 5.5-7.5˚C compared to the conventional evaporative cooling, making the condition much more suitable for greenhouse food production. J. R. Camargo et al. [28] have discussed an evaporative cooling enhanced by desiccant and they found that any increase in the reactivation temperature is directly related to another increase in the air steam leaving the dehumidification unit as well as a decrease in the absolute humidity. And the gradient in temperature is higher than the humidity gradient.

2.5.1 Research gap

Desiccant cooling technique is considered a concurrent approach in order to provide cooling effect with healthier as well as environmental friendly ways. It has been noticed from the literature that no recent researches have been investigated desiccant assisted evaporative cooling under North Cyprus climate conditions (hot – humid). This study focuses on the performance comparison of direct evaporative cooling and desiccants enhanced evaporative cooling system in order to evaluate the improvement of evaporative cooling system potential by the mean of using desiccant materials. In addition to that, plenty of researches have been investigated conventional desiccants such as zeolite and silica gel for desiccant cooling. However, V-$CaCl_2$ has not been previously researched in a desiccant cooling system. Due to that, a gap of research in such a system with this specific material under North Cyprus climate is found.

2.5.2 Summary of the researches

Table 2: Summary of an already published researches.

S/N	Researchers	Year	Type	Location	Remark
1	Y. J. Dai et al.	2000	Exp.	China	Vapor compression AC associated with LDCS.
2	J. L. Niu et al.	2001	Exp.	China	Chilled ceiling combined with DC for energy saving performance.
3	A. E. Kabeel et al.	2005	Exp.	Egypt	Evaluation the performance of LDCS driven by solar regeneration.
4	Donggrn Peng et al.	2008	Sim.	China	Simulation of the potential of solar collector using LD.
5	L. Yotong et al.	2008	Sim.	China	Numerical Simulation of LD dehumidifier with solar regeneration.
6	A. Khalid et al.	2009	Sim. Exp.	Pakistan	Experimental investigation of solar powered DC with TRNSYS Simulation.
7	T. S. Ge et al.	2010	Exp.	Germany China	Comparison of the potential of solar assisted desiccant along with vapor compression unit.
8	Dong La et al.	2011	Sim.	China	TRNSYS simulation of solar assisted DC associated with vapor compression AC.
9	N. Enteria et al.	2011	X	X	Reviewing the effect of DC techniques on the energy consumptions.
10	M. Goldworthy et al.	2011	Sim.	Australia	Optimization of indirect EVCS Combined with DEVAP.
11	Ayaman, A. A. et al.	2011	Sim.	KSA	Liquid DEVAP cooler analyses.
12	M. Audah et al.	2011	Sim.	Lebanon	Optimization of Solar driven DEVAP cooling.
13	Ronghui Qi et al.	2012	Exp.	China	Investigation of the latent load of AC using LDCS.
14	G. Lechnos et al.	2012	Exp.	UK	Experimental validation of solar assisted DC needed for food production.
15	M. S. Dezfouli et al.	2014	Sim.	Malaysia	TRNSYS simulation of solar assisted DEVAP cooling.
16	Xiaohui She et al.	2014	Exp.	China	Liquid DEVAP cooling analyses.

Chapter 3

DESIGN AND METHODOLOGY

3.1 Proposed Design Configuration

The selected design is a combination of two major units which are the desiccant dehumidification unit and evaporative cooling unit. A centrifugal fan is used in conjunction with an air heater to supply warm air in order to achieve the required ambient conditions at the inlet of the dehumidification unit (1) where the desiccant material V-$CaCl_2$ is placed perpendicular to the air flow, forcing the incoming air to pass through it, in order to absorb the moisture from the air and lower its humidity at the exit of the desiccant dehumidifier. This warm but dry air then continues its travel through the ducts (2) to flow into the evaporative cooling unit. The processed air is then cooled down by spraying water over it due to the evaporation process which requires energy that is taken at a greater extent from the hot and dry air and partly from the water. As moisture is added into the air stream, the air gets cooler and a fan can be utilized to deliver this air into the space (3). After continuously absorbing moisture from the air, the desiccant will get diluted with water after some time and loses its absorbing potential. In order to prevent that, regeneration stage should be incorporated with the system in order to dry the desiccants and preserve their moisture absorption capacity which can be achieved by solar regeneration stage. Solar collector may be attached and it can generate the heat required for the regeneration purposes.

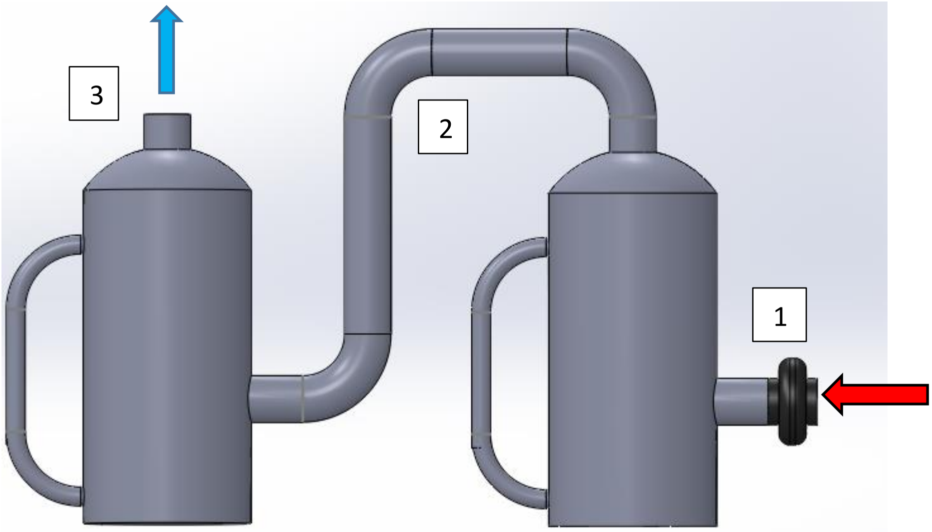

Figure 5: CAD Model of the Proposed Design.

Figure 5 above demonstrates the 3D Model of the system designed by SolidWorks software. The arrows refer to the processed air flow direction. (1) The desiccant dehumidification unit inlet – ambient conditions -. (2) The desiccant dehumidification unit outlet and the evaporative cooling inlet - warm, less humid air-. (3) The system outlet – cooled air -. The cross section of the system is illustrated in Figure 6 below.

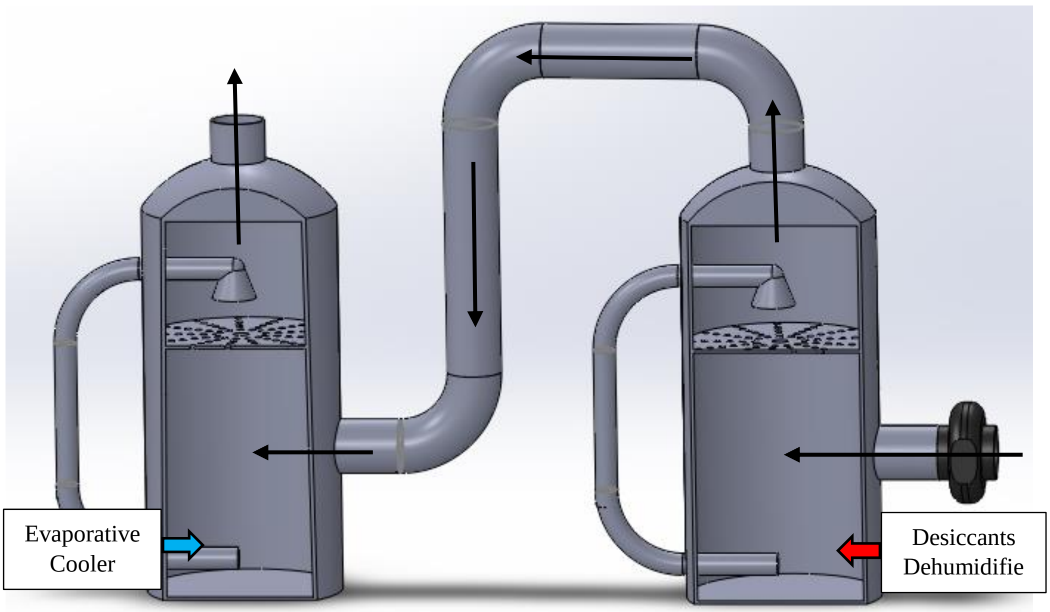

Figure 6: Cross-Section of the CAD Model.

3.2 Design Components

3.2.1 Data logger

It is a specific data logger for both humidity as well as temperature measurements. It has capability to check and record around 21000 readings within time interval can be adjusted by the user from 1 sec and it can reach 24 hours, and then the recorded data can be easily transferred to the PC in order to be analyzed directly through simple software. It can display the recorded data in excel format so it is easy to be translated into the relevant graphs or charts for making the comparison and the required analyses. It needs 3.6V lithium battery. It is illustrated in Figure 7 below.

Figure 7: Temperatures & Humidity Sensor.

3.2.2 Centrifugal fan

15 cm diameter inline centrifugal exhaust fan shown in Figure 8 is commonly used for ventilation purposes. Its power can be controlled through an electrical actuator in order to set the system to the desired air flow rate. Max power is 120 watt.

Figure 8: Ventilation Duct Fan.

3.2.3 Flexible ducts

It is a metallic inflammable flexible duct. It is widely utilized in heating, ventilation and air conditioning applications. As seen in Figure 9 and due its flexibility the variety of the sizes that may fit all demands. It has been used in the experiment as a processed air flow channel.

Figure 9: Flexible Metal Pipe.

3.2.4 Process chambers

A galvanized steel with 500 mm diameters, 1500 mm height and 1 mm thickness have been formed in order to fabricate both the dehumidifier and the evaporative cooler. They both have similar dimensions with a net looks like a tray near the top of each cylinder, this tray where the materials will be placed later. They have inlet and outlet for the air flow as demonstrated in Figure 10.

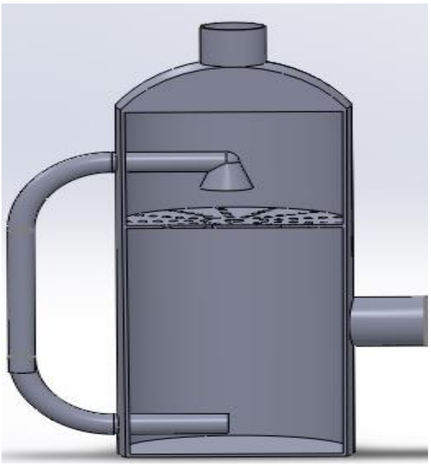

Figure 10: EVAP/DEVAP Chambers.

3.2.5 Water pumps

Submersible water pump with 25W power shown in Figure 11, used for the water circulation inside the evaporative cooler, it circulate the water from the bottom of the cooler and spray them with the help of water sprinkler valve over the wood chips inside the evaporative cooling unit.

Figure 11: Submersible Water Pump.

3.3 Experimental Setup

3.3.1 Preparation of the desiccants (Vermiculite – Calcium Chloride)

The preparation of the solid desiccant material is done through the utilization of:

1. Calcium chloride salt solution.
2. Solid vermiculite materials.
3. Furnace.

Figure 12: V-Ca Cl_2 Desiccant.

And the preparation procedure passed through several stages as following:

1. Preparing saturated $CaCl_2$ salt solution.
2. Drying the vermiculite materials in the furnace at 100 C° in order to be fully dried and remove any residual moisture that may affect the performance of the system.
3. Impregnating $CaCl_2$ salt solution to the pores of vermiculites.
4. Drying the final state of the materials (Vermiculite – Calcium Chloride) in the furnace in order to remove the water as shown in Figure 12.
5. Anhydrous salts remains inside the vermiculite porous.

3.3.2 Data logger settings

Three data loggers were adjusted to record both the relative humidity and the temperatures in every single minute. The sensor positions are illustrated in Figure 13.

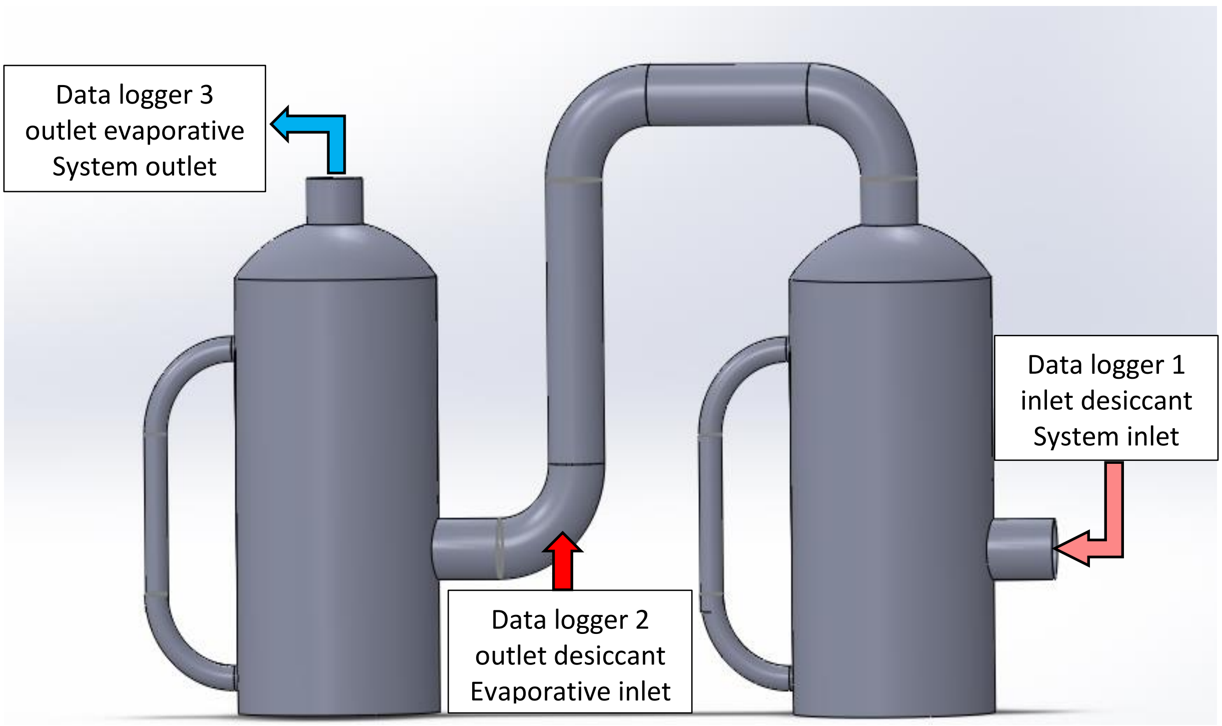

Figure 13: Data Logger's Positions.

They are placed in specific places in order to give the required readings necessary for applying the thermodynamics analysis and evaluating the performance parameters. Data loggers' positions are clearly shown in the figure above.

- *Data logger 1*: at the inlet of the system just after the fan.
- *Data logger 2*: at the outlet of dehumidifier / inlet of the evaporative cooler.
- *Data logger 3*: at the outlet of the system.

3.4 Thermodynamics Analysis

The system can be broken down into three main states:

- *State 1*: inlet of the desiccants dehumidifier / inlet of the system.
- *State 2*: outlet of the desiccants dehumidifier / inlet of the evaporative cooler.
- *State 3*: outlet of the evaporative cooler / outlet of the system

In each state both temperatures and relative humidity were continuously recorded in order to calculate the performance evaluation required parameters.

Tests have been conducted on two categories:

1. ***Mode 1*:**

   Evaporative cooling after desiccants dehumidification unit.

2. ***Mode 2*:**

   Evaporative cooling.

System again is divided into three main stages as it is presented above. In each step, several thermodynamics parameters were calculated.

The following equations shows the applied equations for finding the required parameters.

- ***Rate of cooling***

Aims to find the max heating rate which is obtained by the system taking into consideration the inlet temperature as well as the outlet temperatures with the flow rate of the processed air stream [29].

$$Q_{cooling} = \dot{m}C_p\, \Delta T = \dot{m}\, C_p\, (T_3 - T_1) \quad (1)$$

- ***Humidity***

Humidity is typically the expression that measures the amount of water vapor in the air. It can be classified into two classifications [30].

1. <u>Relative humidity</u>: used as percentage and it is the fraction of the water partial pressure in the atmosphere compared to the maximum amount of vapor that may the air has at its present temperature. This term is widely used for humidity explanation.

$$Rh\,(\%) = \frac{Vapor\ Pressure_{dp}}{Vapor\ Pressure_{db}} * 100 = \frac{Partial\ Presure}{Vapor\ Presuure} * 100 \quad (2)$$

When,

$P_{H_20} < P_{vapor}$ $(Evaporation)$

$P_{H_20} = P_{vapor}$ $(Saturation)$

$P_{H_20} > P_{vapor}$ $(Condensation)$

2. <u>Absolute humidity</u>: it measures the water vapor or the real amount of moisture in the atmosphere, with no cares about the air temperature. It is expressed as mass of water vapor per the unit mass of the dry air.

$$\omega = \frac{m_v}{m_a} = \frac{P_v\, v/R_v\, T}{P_a\, v/R_a\, T} \quad (3)$$

$$\omega = \frac{P_v\,/R_v}{P_a\,/R_a} = 0.622\, \frac{P_v}{P_a} \quad (4)$$

- ***Mass of water***

The mass of water can be determined in two cases, the amount of water removed out from the air through the desiccants dehumidification unit as well as the amount of water added to the processed air through evaporative cooling unit. The mass of water removed through the desiccant dehumidifier is directly related to the absolute humidity of both the desiccant dehumidification unit and its outlet as well as the flow rate of the processed air [31].

$$\dot{M}_{Removed} = \dot{m}\ \ \Delta w_{1,2} \tag{5}$$

$$\dot{M}_{Removed} = \dot{m}\ \ (w_1 - \ w_2) \tag{6}$$

While the mass of water added through the evaporative cooler is directly related to the absolute humidity of both the desiccant outlet and the evaporative cooling inlet with regard to the air stream flow rate.

$$\dot{M}_{\ Added} = \dot{m}\ \ \Delta w_{3,2} \tag{7}$$

$$\dot{M}_{\ Added} = \dot{m}\ \ (w_3 - \ w_2) \tag{8}$$

- ***Dew point temperature***

The dew-point temperature is that temperature at which the air cannot be able to hold all the vapors involved in it. So that, some of this vapor should be condensed into liquid state of water. Dew-point temperature value is lower than or maybe equal to the temperature of the air. The following equation expresses how the dew-point temperature can be obtained [32].

$$T_{DP} = (^{RH}/_{100})^{1/8}\ (112 + 0.9\ T) = 0.1\ T - 112 \tag{9}$$

- ***Effectiveness***

Since the system is experimentally has been tested, so its performance should be evaluated in order the check where the system is efficient or not. One of the best indicators for the performance evaluation is the effectiveness of the system which is calculated as following [33];

$$\varepsilon = \frac{T_1 - T_3}{T_1 - T_{DP}} \qquad (10)$$

Where all parameters are measured by the data loggers except the dew point temperature which can be calculated by equation (10).

- ***Coefficient of performance***

Coefficient of performance (COP) is the defined as the ratio of the useful work output to the input energy. It basically illustrates the efficiency of the energy the HVAC different applications. Its calculation should involve the energy consumption of all power consumed through the system. COP is never an independent parameters, several factors may highly affect the COP of the system [29].

$$COP_{cooling} = \frac{T_{cold}}{T_{hot} - T_{cold}} \qquad \text{(Ideal COP)} \qquad (11)$$

In general,

$$COP_{cooling} = \frac{Q_L}{W_{in}} \qquad (12)$$

$$W_{in} = W_{pump} + W_{fan} \qquad (13)$$

$$COP_{cooling} = \frac{Q_{cooling}}{W_{pump} + W_{fan}} \qquad (14)$$

3.5 Uncertainty Analysis

Uncertainty analysis is necessary to prove the accuracy of the experimental results. The result W_R is calculated as a function of the independent variables x_1, x_2, x_3, …, x_n and w_1, w_2, w_3, …, w_n represents the uncertainties in the independent variables.

In the developed experimental rig 3 sensor locations were used for determining the T_1, T_2, T_3, RH_1, RH_2 and RH_3 of the ambient, outlet of desiccant and outlet of the evaporative cooler. Then, uncertainty W_R is expressed as [34]:

$$W_R = \left[\left(\frac{\partial R}{\partial x_1} w_1\right)^2 + \left(\frac{\partial R}{\partial x_2} w_2\right)^2 + \left(\frac{\partial R}{\partial x_3} w_3\right)^2 + \cdots + \left(\frac{\partial R}{\partial x_4} w_4\right)^2\right]^{1/2} \tag{15}$$

Experiments were conducted by using following instruments: Thermocouples with the maximum deviation of ±0.4°C for temperature and ±3% for relative humidity.

It is obtained from the equation (10), the effectiveness (ε) is the function of T, RH and measured during the testing, each subject to uncertainty:

$$\varepsilon = f(T_1, T_2, T_3, RH_1, RH_2, RH_3) \tag{16}$$

Total uncertainty for overall system efficiency can be expressed as;

$$W_R = \left[\left(\frac{\partial \eta}{\partial T_1} w_{T_1}\right)^2 + \left(\frac{\partial \eta}{\partial T_2} w_{T_2}\right)^2 + \left(\frac{\partial \eta}{\partial T_3} w_{T_3}\right)^2 + \left(\frac{\partial \eta}{\partial RH_1} w_{RH_1}\right)^2 + \left(\frac{\partial \eta}{\partial RH_2} w_{RH_2}\right)^2 + \left(\frac{\partial \eta}{\partial RH_3} w_{RH_3}\right)^2\right]^{1/2} \tag{17}$$

Total uncertainty rate affecting the efficiency of the drying chamber was computed by using Equations 15 – 17. The estimation implies that total uncertainty in calculation of the (ε) is found to be 3.84%.

3.6 Psychometric Process

The below chart explains the working mechanism of desiccant enhanced evaporative cooling process.

1. Desiccant dehumidification unit inlet (humid, hot air).
2. Desiccant dehumidification unit outlet (less humid, hotter air).
3. Evaporative cooling unit outlet (less humid than inlet of system, and cool air).

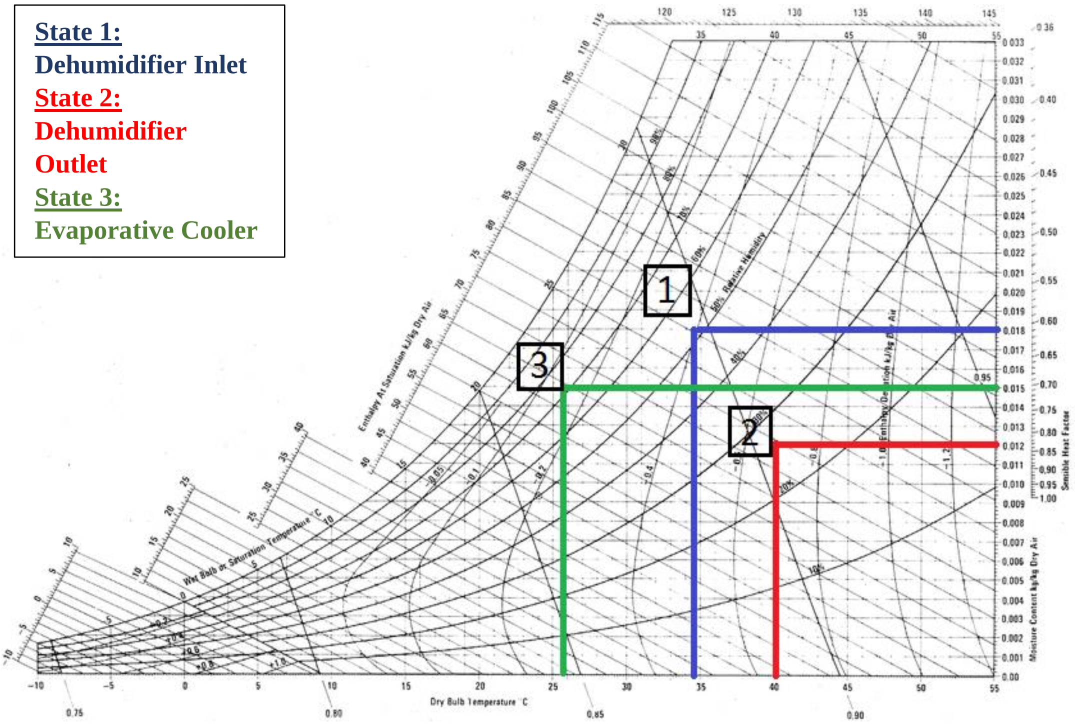

Figure 14: Psychometric Process of Desiccant Dehumidification [35].

Chapter 4

RESULTS AND DISCUSSION

4.1 Experimental Procedure

4.1.1 Main procedure

Experiments were conducted according to the processed air stream flow rate variations. Six experiments were performed. They have been tested as pair of experiments for the proposed flow rate, one experiment for the system where the desiccant dehumidification process is involved, and one without the dehumidification unit for evaporative cooling. The setup of the experiment is illustrated in Figure 15.

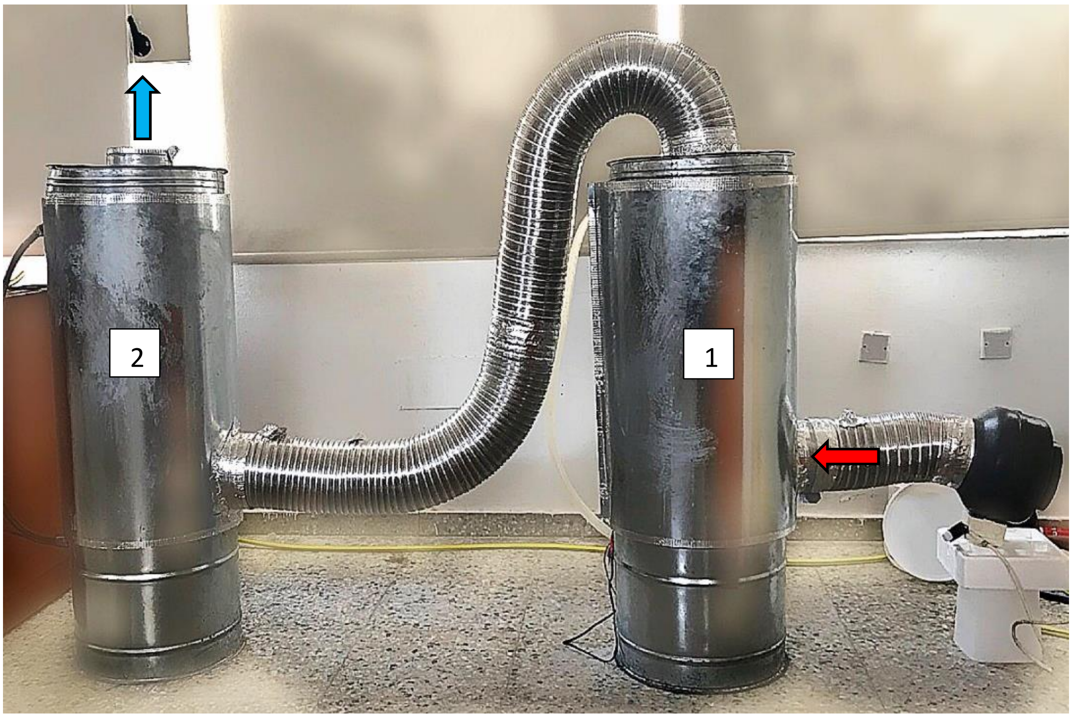

Figure 15: Setup of the System.

4.1.2 Desiccant regeneration

Air is pumped by the centrifugal fan with the required flow rate. And then it is forced to bass through the mixture of vermiculite- calcium chloride desiccant material inside (1) which plays the role of the desiccant dehumidification stage. Then the processed air is being guided to flow through the shown flexible ducts to the next chamber (2) which plays the role of the evaporative cooling stage. The process continues till the desiccant materials get diluted with water absorbed from the air stream and then the material will start to lose its sorption capability and has to be regenerated by drying it through an external heat source. And this is the limitation of our system. Since no regeneration stage is installed, desiccant material were dried by a laboratory furnace till it retain dry and get its ability to absorb the moisture again. Figure 16 below shows the setup used for desiccant material drying (regenerating) process. Where the material is being kept inside the furnace for around 3 hours at 180 °C.

(a). Furnace (b). Moist desiccant

Figure 16: Alternative Desiccant Regeneration Solution.

4.2 Results Analysis

Tests have been conducted for two cycles, desiccant based cooling as well as evaporative cooling system. The testes are evaluated under three different air stream flow rate; 0.07, 0.06, and 0.05 kg/s. the initial conditions were approximately same for the inlet temperatures, which was around 35 ˚C and relative humidity was ranging between 45 to 55% at the system inlet.

Based on that the following parameters were evaluated:

1. Temperatures.
2. Relative humidity.
3. Water removal vs addition.
4. Rate of cooling.
5. Cooling effectiveness and COP of the system.

4.2.1 Temperatures

Temperature variation of the air for desiccant assisted evaporative cooling and evaporative cooling tests were presented in Figures 17-18-19 respectively. As it is seen in Figures 17a-18a-19a due to the sorption process in desiccant chamber temperature of the air rose to 40- 42 °C initially and showed a gradual drop over 2 hours testing period. Later, air enters the evaporative cooler where a temperature drop in the range of 18-10 °C was achieved. As a results system outlet temperature remained almost constant and changed between 25-27 °C. On the other hand for evaporative cooling test a temperature drop in the range of 10-12 °C as it can be seen in Figures 17b-18b-19b.

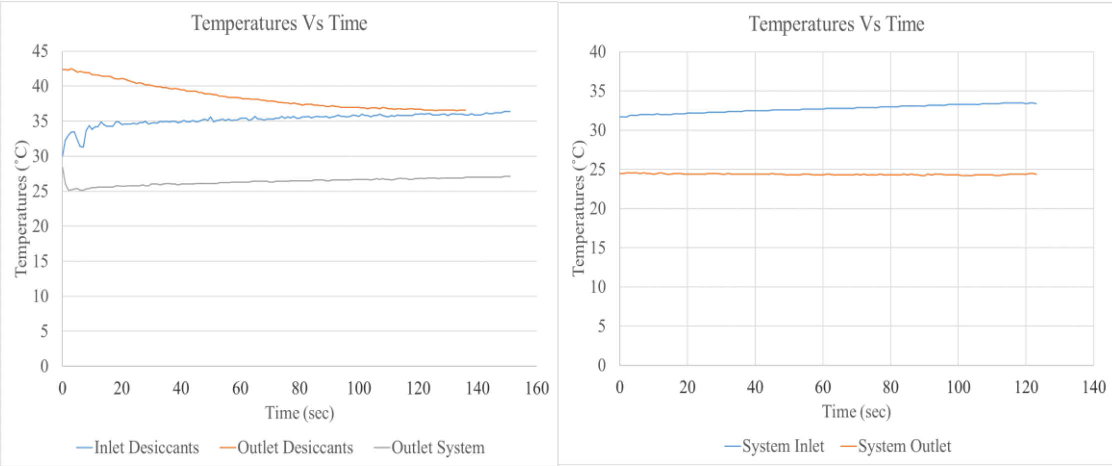

Figure 17: Temperature Variation (a) DEVAP 04.07 Test, (b) EVAP 03.07 Test.

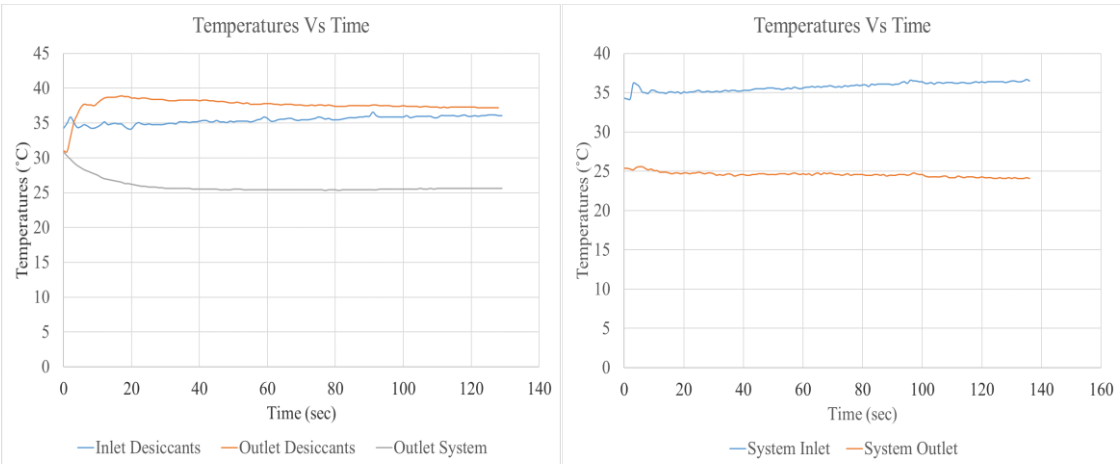

Figure 18: Temperature Variation (a) DEVAP 06.07 Test, (b) EVAP 06.07 Test.

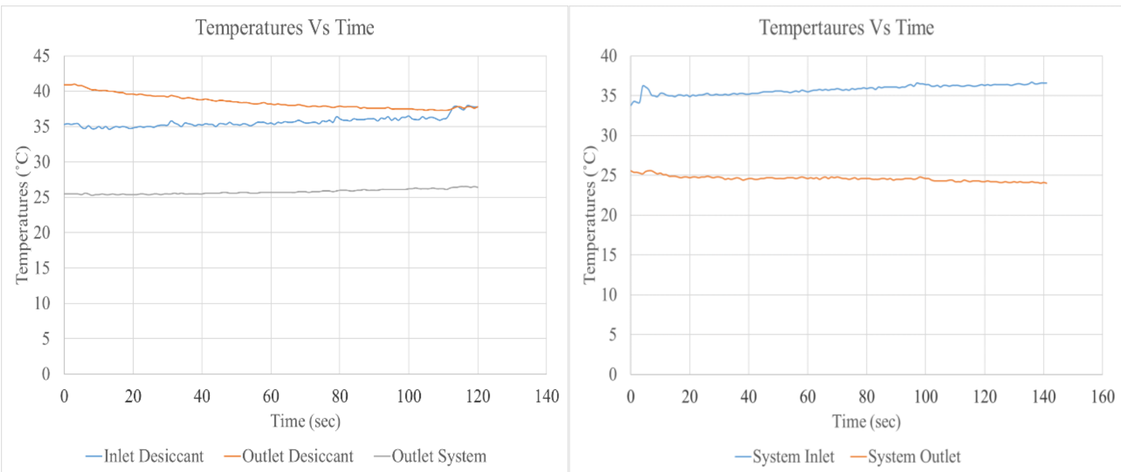

Figure 19: Temperature Variation (a) DEVAP 10.07 Test, (b) EVAP 09.07 Test.

4.2.2 Relative humidity

Relative humidity variation of the air for desiccant based evaporative cooling and evaporative cooling tests were shown in Figures 20 -21-22 respectively. As it is clearly seen in Figures 20a-21a-22a and due to the sorption process in desiccant dehumidification chamber the relative humidity of the air dropped to the range of 30-45 % as it was in the range of 50-55% initially at the system inlet. Generally, it decreased dramatically over two hours testing period. Then, dehumidified air flows through the evaporative cooler where the air leaves it with relative humidity in the range of 75 -95 % was observed.

On the other hand for evaporative cooling test shows a relative humidity ranges of 40-60% and 70-95 % at the system inlet and outlet respectively and that can be seen in Figures 20b-21b-22b below.

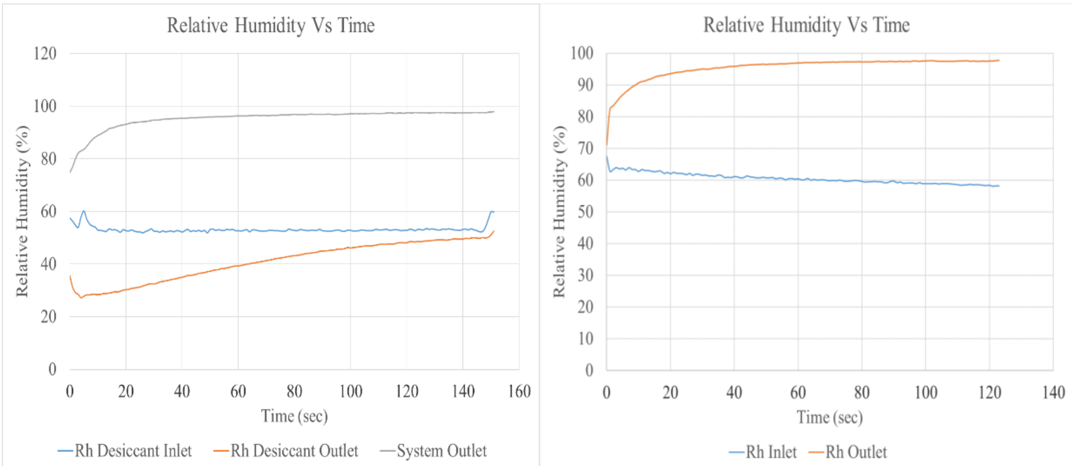

Figure 20: Rh Variation (a) DEVAP 04.07.2018 Test, (b) EVAP 03.07.2018 Test.

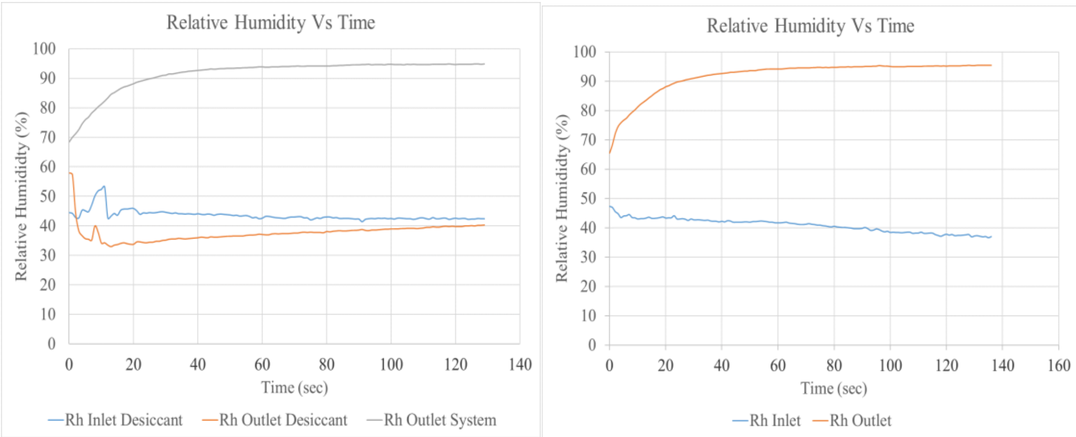

Figure 21: Rh Variation (a) DEVAP 06.07.2018 Test, (b) EVAP 06.07.2018 Test.

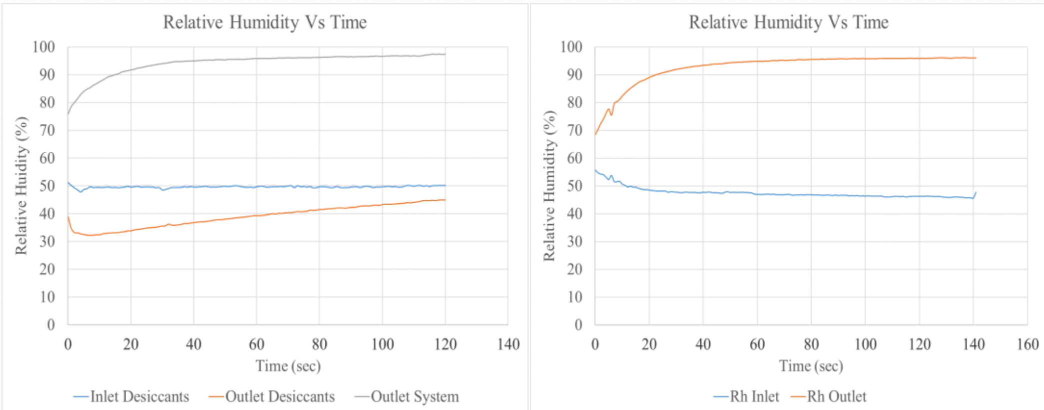

Figure 22: Rh Variation (a) DEVAP 10.07.2018 Test, (b) EVAP 09.07.2018 Test.

4.2.3 Water content

An indicator for evaluating the performance of such a system, is the water content of the air. Figures 23-24-25 presents the amount of water removed due to the desiccant sorption function inside the dehumidification to the amount of water added through the evaporative cooler. Results in Figures 23a-24a-25a for desiccant assisted cooling ranges between (0.47-03), (0.25-0.2), (0.4-0.3) and (0.35-0.05), (0.05-0), (0.2-0.07) kg per cubic meter as water addition and water removal rate respectively. Where the water addition behavior for evaporative cooler were in the range of (0.2-0.25) as shown in 23b-24b-25b.

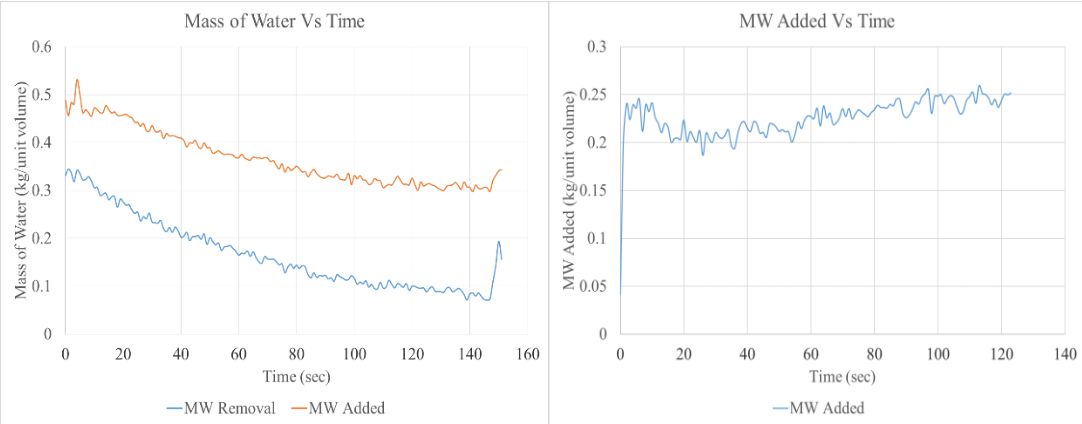

Figure 23: Mw Variation (a) DEVAP 04.07.2018 Test, (b) EVAP 03.07.2018 Test.

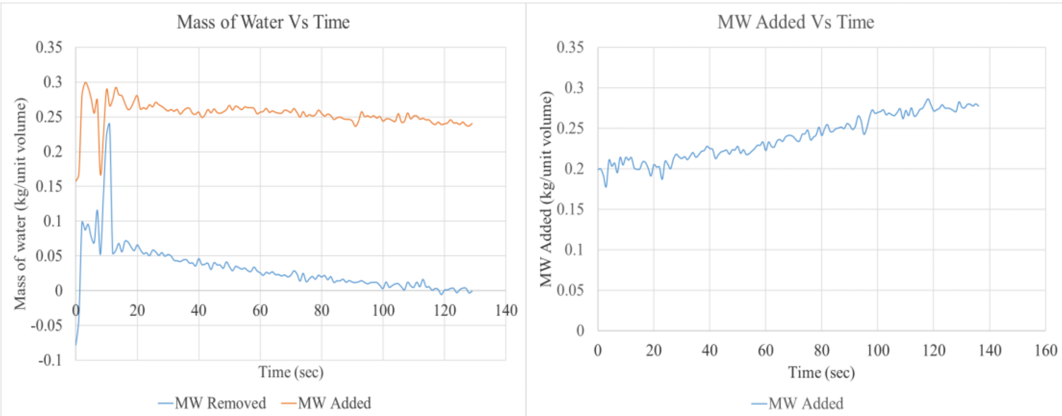

Figure 24. Mw Variation (a) DEVAP 06.07.2018 Test, (b) EVAP 06.07.2018 Test.

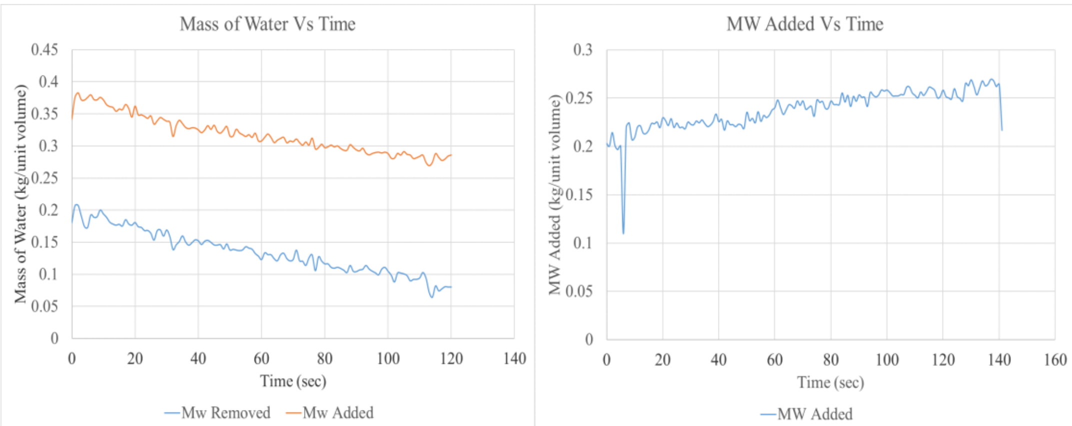

Figure 25: Mw Variation (a) DEVAP 09.07.2018 Test, (b) EVAP 10.07.2018 Test.

4.2.4 Cooling rate

The cooling capacity of the system is an effective parameter has to be considered during the evaluation of any heating, ventilation and air conditioning applications. Figures 26a-27a-28a and 26b-27b-28b show the variation of the rate of cooling for desiccant based evaporative cooling and only evaporative cooling respectively, over the two hours of testing period for the three tests conducted with three different air stream flow rates. For desiccant cooling the results shows a stable trend with a slight increase between (600-700W) where it shows a slight drop in the values for the second test as it ranges between (500-600W). However, it steadily increased in the case of evaporative cooling system and take the values between (500 -800W) over the three tests.

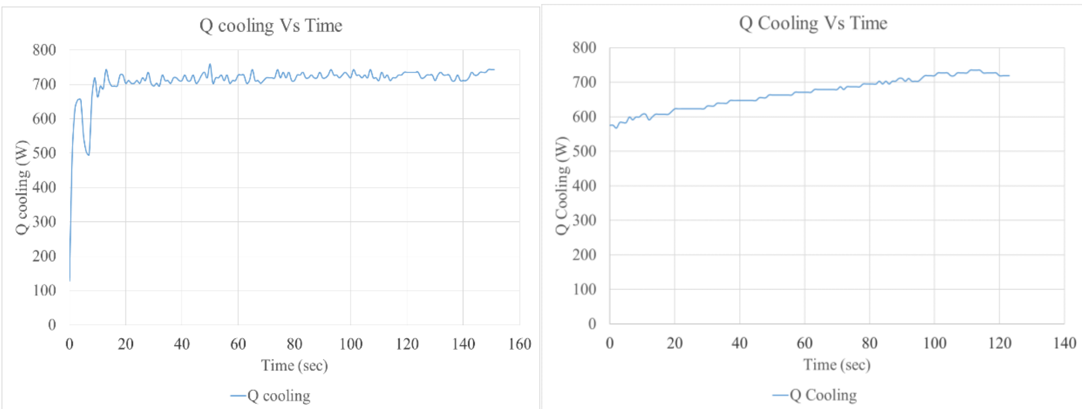

Figure 26: Cooling Rate Variation (a) DEVAP 04.07 Test, (b) EVAP 03.07 Test.

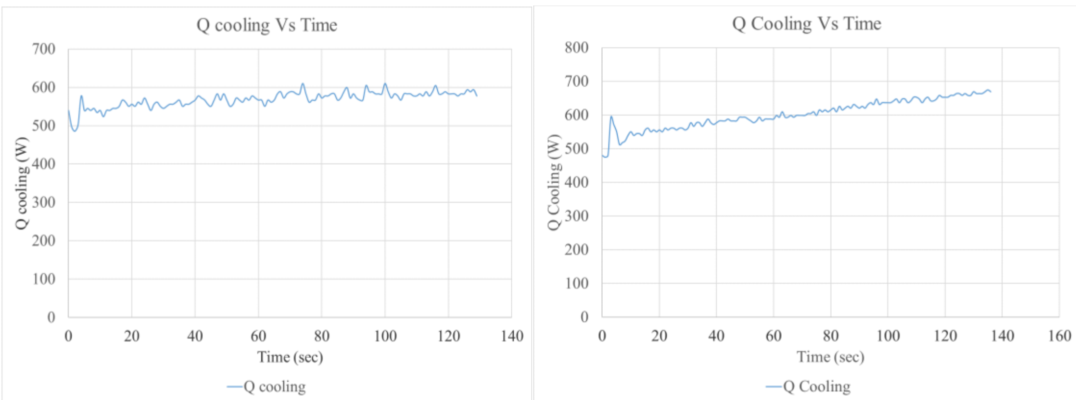

Figure 27: Cooling Rate Variation (a) DEVAP 06.07 Test, (b) EVAP 06.07 Test.

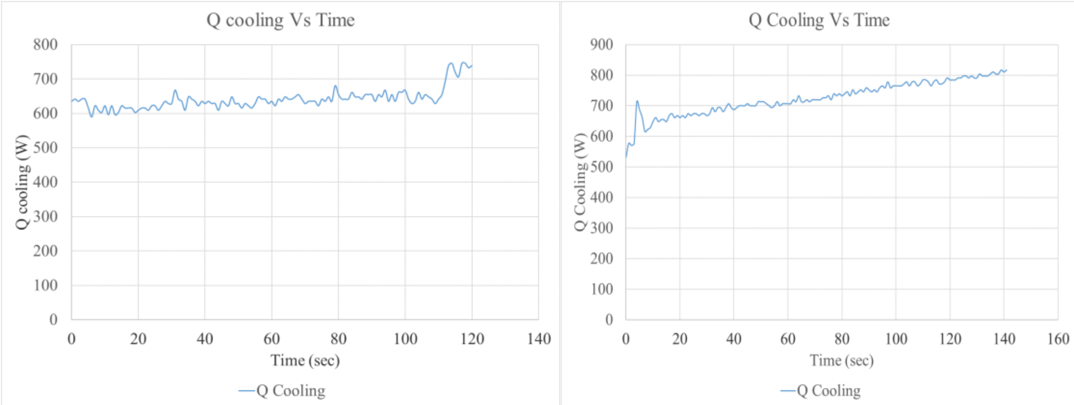

Figure 28: Cooling Rate Variation (a) DEVAP 10.07 Test, (b) EVAP 09.07 Test.

4.2.5 Cooling effectiveness and coefficient of performance

Cooling effectiveness and coefficient of performance are two important factors that are usually evaluated in order to check the performance of air conditioning systems. As this research is an experimental study, the system potential has to be investigated in order to interpret the system efficiency. The cooling effectiveness parameter is calculated and the results have been shown in Figures 29-30-31 below. It represents the variation of the cooling effectiveness of both systems over the two hours of testing period. It has an increasing trend at the beginning till it enters a stage of stabilization around 90 % for desiccant as well as evaporative cooling system.

The following graphs depicted in Figures 32-33-34, the COP of the system which generally involves the energy consumption of all power consumed through the system in the calculation. Its values were in the range of 5 to 6 for the desiccant assisted cooling and 5.5 to 6.5 for evaporative cooling system.

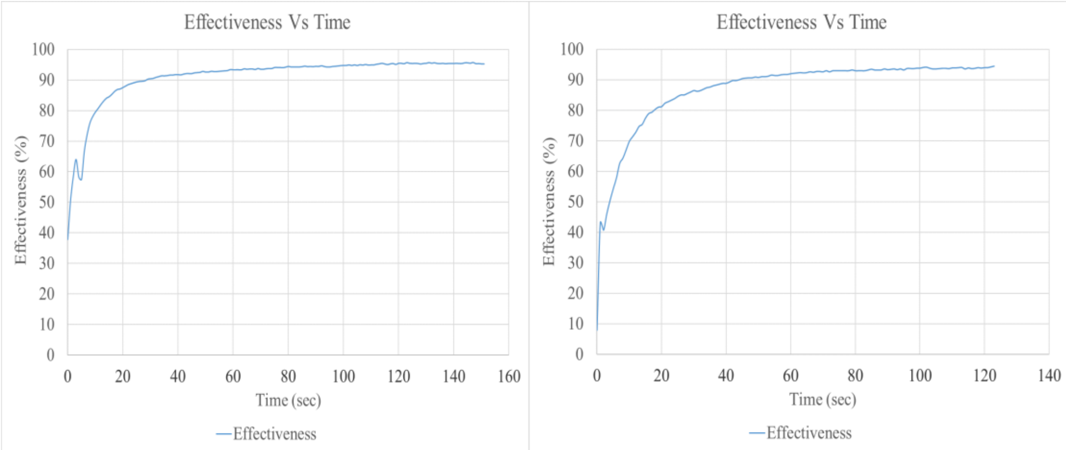

Figure 29: Effectiveness Variation (a) DEVAP 04.07 Test, (b) EVAP 03.07 Test.

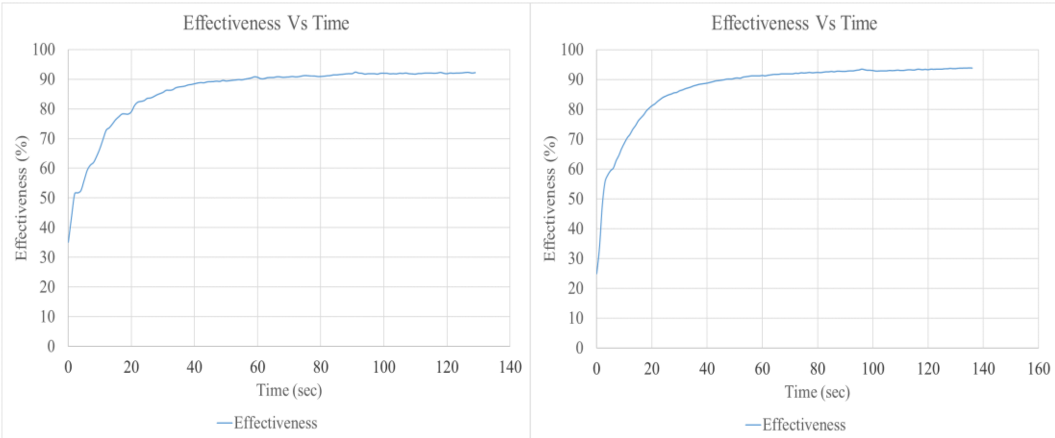

Figure 30: Effectiveness Variation (a) DEVAP 06.07 Test, (b) EVAP 06.07 Test.

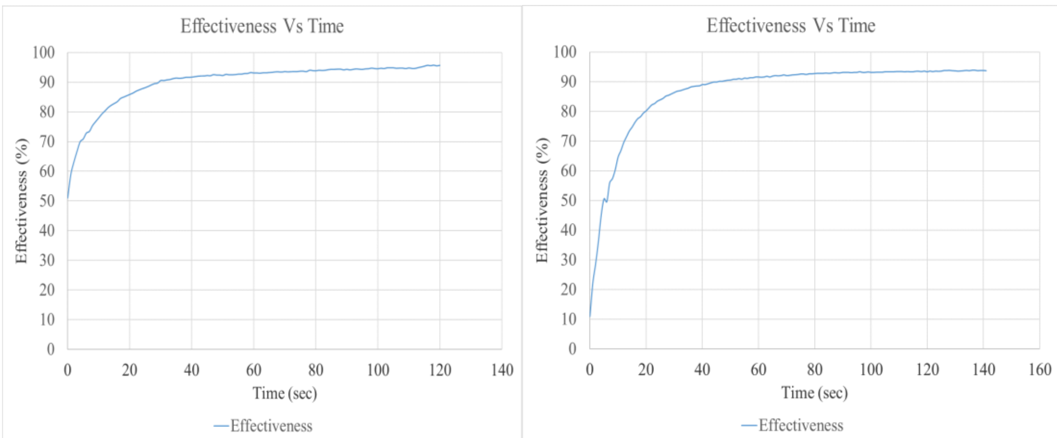

Figure 31: Effectiveness Variation (a) DEVAP 10.07 Test, (b) EVAP 09.07 Test.

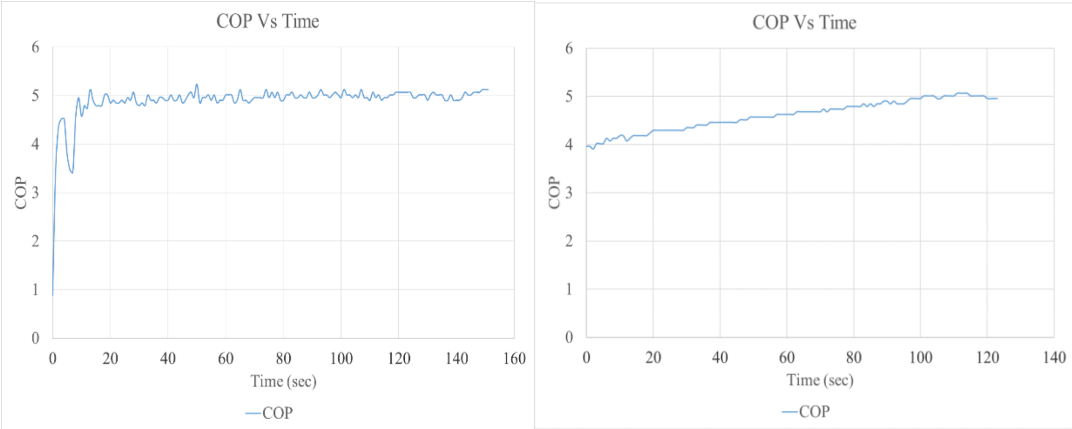

Figure 32: COP Variation (a) DEVAP 04.07.2018 Test, (b) EVAP 03.07.2018 Test.

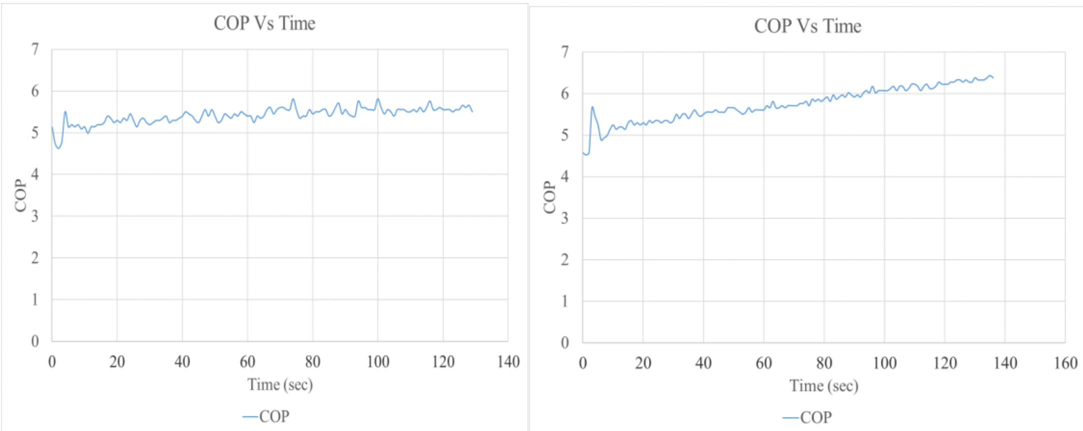

Figure 33: COP Variation (a) DEVAP 06.07.2018 Test, (b) EVAP 06.07.2018 Test.

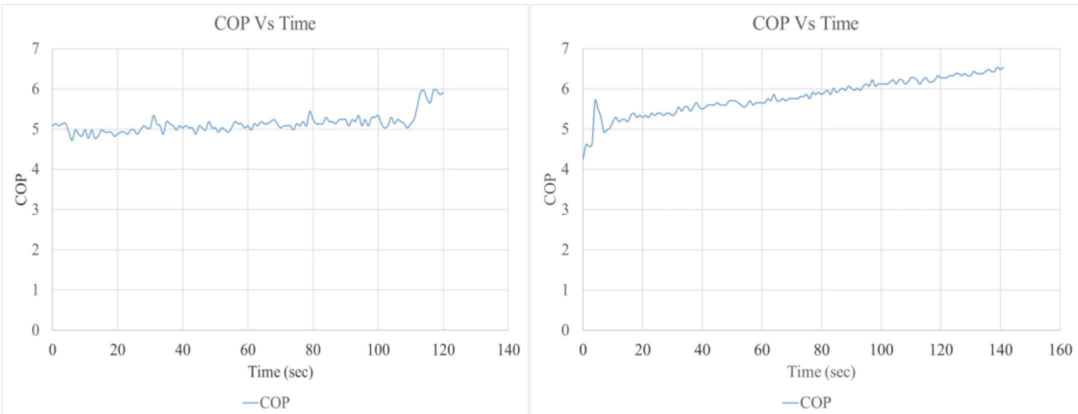

Figure 34: COP Variation (a) DEVAP 10.07.2018 Test, (b) EVAP 09.07.2018 Test.

4.2.6 Cycles comparisons

In order to analyze the performance of DEVAP and EVAP systems, the net water content added to the air is compared. For the desiccant cycle the net water is obtained by subtracting the water added by the evaporative cooling unit from the water removed by the desiccant dehumidification unit. The following graphs show the net water comparison following by cooling rate to net water content ratio. The result were promising and as expected. Where in the first and third test, results were very close as it is illustrated in Figure 35, Figure 36, Figure 38, and Figure 39. Results in those two tests were somehow steady with a slight increase over the test period. water content in evaporative cooling was higher than its values in the case of desiccant cooling and this is the main function that successfully achieved by investigating desiccant in such systems. Desiccant aims to dehumidify the air and dry it in order to achieve the human comfort conditions. Net water content were in the range of 0.2 to 0.25 and 0.15 to 0.15 kilogram per cubic meter as well as Q/Netwater ratio in the ranges 2.5 to 3 and 3 to 4 for evaporative cooling and desiccant cooling respectively. Figure 37 and 40 represent the results of the second test, results are fluctuating and they are close and that was due to the test ambient conditions at the outlet of the system. It has been noticed that whenever the humidity level is already low, desiccators are not as efficient as it would be when the humidity level is high. Desiccant has a critical limit to afford the sorption potential. If the levels of humidity is relatively high, desiccants will have the flexibility to decrease the humidity till its critical capacity, after the desiccant reaches its critical limit, it starts to lose its sorption ability and it will not afford to absorb much moisture and as a result, a noticeable drop in the system performance will be clear, as it is seen in Figure 37 and 40 where the inlet humidity range was relatively low around 40^{th} % and due to what the results were close to each other in both cycles. A potential improvement that could be applied to the system is to use a heat exchanger to cool down the air down to ambient temperature after the desiccant dehumidification process. This could enhance the cooling potential of the system as well as would allow to achieve lower temperatures at the system outlet.

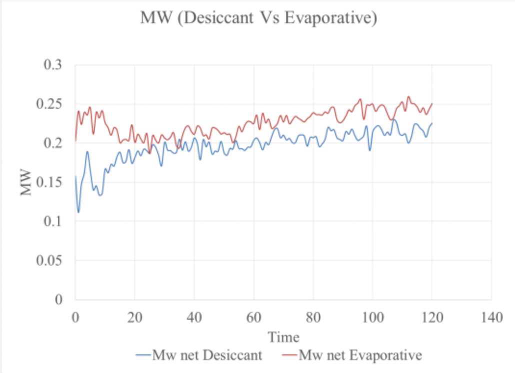

Figure 35: Net Water Content Comparison, 0.07 kg/s Flow Rate.

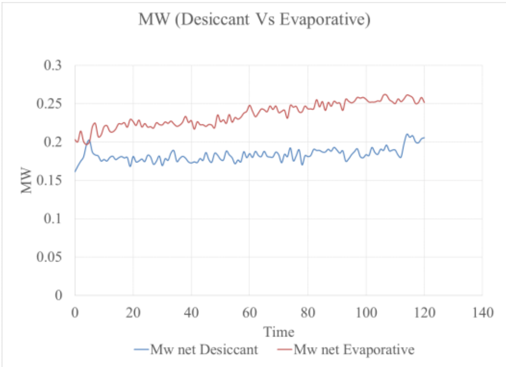

Figure 36: Net Water Content Comparison, 0.06 kg/s Flow Rate.

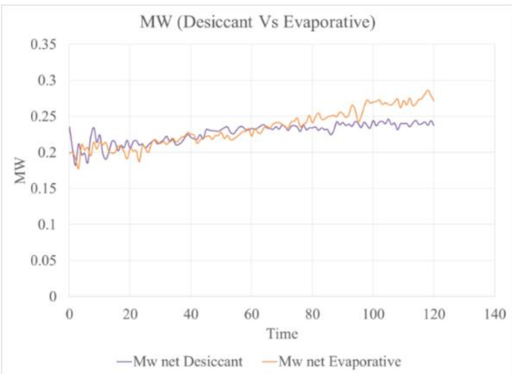

Figure 37: Net Water Content Comparison, 0.05 kg/s Flow Rate.

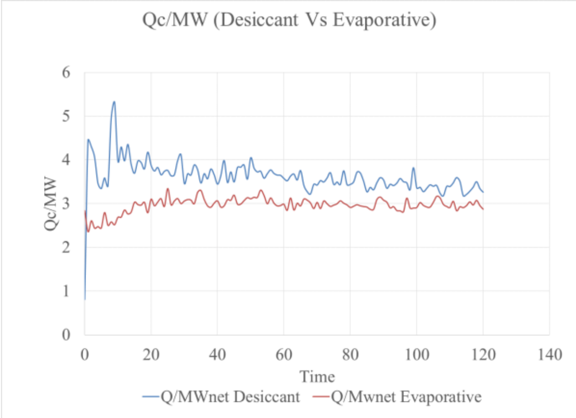

Figure 38: Cooling Rate to Net Water Content Ratio, 0.07 kg/s Flow Rate.

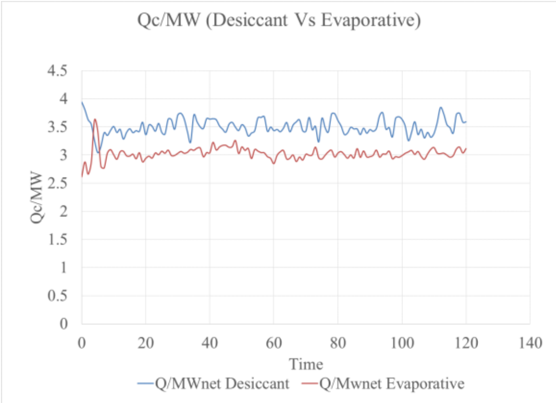

Figure 39: Cooling Rate to Net Water Content Ratio, 0.06 kg/s Flow Rate.

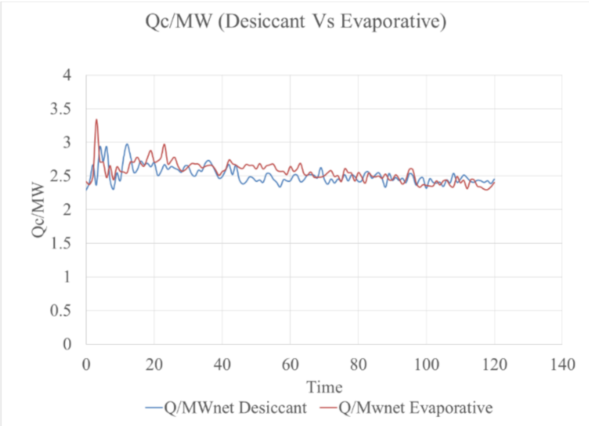

Figure 40: Cooling Rate to Net Water Content Ratio, 0.05 kg/s Flow Rate.

Chapter 5

ECONOMIC ANALYSIS

5.1 General Overview

At the beginning of the design of a building, the most important task that the HVAC engineer has on his responsibility is to involve a proper HVAC system for the given application.

The proposed system has to:

1. Achieve the thermal comfort to this building residents all the time.
2. Meet all specific requirements of the building.
3. Try to minimize the total cost; investment, operation and maintenance…etc.
4. Optimizing the use of energy.
5. Energy impact on the environment.

In order to achieve that, engineers have to estimate the profile of energy needed to air condition the air of the given building according to some factors related to the building structure as well as considering the weather conditions. The measures of the design performance is not only about its thermal effectiveness, it should be related to some economic aspects which nowadays has become the most important factors. Several methods have been proposed for economic analysis such as payback period calculation. In the following, payback period analysis is presented for investigating desiccant based evaporative cooling based on the obtained results [36].

5.2 Case Study

In the study, an investment of 300$ on a desiccant assisted evaporative cooling system which has a capacity of 1.5 kW (based on the developed experimental prototype) and which operates 10 hours daily was considered. COP of the system is assumed 5.5 as obtained in experimental studies and electric unit price was obtained as 0.12$/kWh form Electric Authority's (KIBTEK) of North Cyprus website [37]. By the following calculation, the payback period of such a system taking into consideration of the monthly saving when it is replaced with the conventional vapor compression system is analyzed.

- ***Given Parameters***

Table 3: Given parameters.

Capacity (kW)	Operating Time (h/day)	Unit Price ($/kWh)	Capital Cost ($)	COP
Desiccant Cooling				
1.5	10	0.12	300	5.5
Vapor Compression Cooling				
1.5	10	0.12	300	2.5

- ***Assumptions***

Table 4: Assumed parameters.

Discount Rate (g)	Inflation Rate (i)	Monthly Maintenance Cost
12%	15%	1% of capital cost

Interest rate can be obtained from the following equation

$$r = \frac{i+g}{1-g} \tag{18}$$

$$r = \frac{0.15 + 0.12}{1 - 0.12} = 0.3$$

- ***Monthly Operating Cost***

1. Desiccant Cooling

$$OC = \frac{Q_c}{COP} * Operating\ Time * Unit\ Price * Month\ Conversion \quad (19)$$

$$OC_D = \frac{1.5}{5.5}\ kW * 10\ \frac{h}{day} * 0.12\ \frac{\$}{kwh} * 30\ \frac{day}{month} = 9.82\ \$/month$$

2. Vapor Compression Cooling

$$OC_V = \frac{1.5}{2.5}\ kW * 10\ \frac{h}{day} * 0.12\ \frac{\$}{kwh} * 30\ \frac{day}{month} = 21.6\ \$/month$$

These two values indicates the cost of operation for the both systems. Which is obvious that it is for vapor compression is twice more than what it is in desiccant cooling.

- ***Monthly Income***

By considering similar unit price the monthly income from investigating both system are same and it is as follow:

$$income = capacity * Operating\ time * Unit\ cost * Month\ Conversion \quad (20)$$

$$income = 1.5\ kW * 10\ \frac{h}{day} * 0.12\ \frac{\$}{kwh} * 30\ \frac{day}{month} = 54\ \$/month$$

- ***Monthly Savings***

1. Desiccant Cooling

$$S_D = Monthy\ Income - Monthly\ Operating\ Cost \quad (21)$$

$$S_D = 54 - 9.82 = 44.2\ \$/month$$

2. Vapor Compression Cooling

$$S_V = 54 - 21.6 = 11.78\ \$/month$$

These two values indicates the monthly savings for the both systems. Which is obvious that it is for vapor compression is much less than what it is in desiccant cooling. Based on the obtained values of savings for both systems the monthly saving is calculated.

$$Net\ Saving = \ Desiccant\ Cooling\ Saving - \ Vapor\ Compression\ Savings \quad (21)$$

$$Net\ Saving = 44.2 - 11.78 = 11.78\ \$/month$$

- ***Payback Period***

The *Payback Period* is generally an approach used for the determination of the time required for the inventor in order to recover the initial capital cost for the investment. In economic aspects, it is the time required for an investment in order to breakeven which is the point at which benefits will be equal to the cost.

For this calculation present worth factors which related to the time value of money has to be calculated for each time unit (daily, weekly, monthly, quarterly, yearly…etc.). In this case we are considering time unit as months.

$$PWF = \frac{1}{(1+r)^n} \quad (22)$$

Where;

r; is the rate of interest.

n; is the number of years.

The following table shows the detailed analysis of payback period calculation. The table above shows the typical payback period analysis, where it involves all required calculations for the cost either capital, maintenance, as well as the operating cost with taking into consideration the comparison of the operating cost between the conventional cooling system and this studied system. And it is found, the investment will be returned before the eighth month. But by considering that the system will operate only for three months a year, during summer period. So that, the real payback period will be around three years.

Table 5: Payback period calculation.

n	PWF	Capital Cost	Cum C Cost	M Cost	Cum M&O	Profit	Cum Profit	Cumulative Total Cost
0	1	300	300	0	0	0	0	300
0.08	0.97	0	300	0.24	0.24	43.26	43.26	300.24
0.17	0.95	0	300	0.51	0.75	42.25	85.51	300.75
0.25	0.93	0	300	0.75	1.5	41.37	126.89	301.5
0.33	0.91	0	300	0.99	2.49	40.51	167.41	302.49
0.42	0.89	0	300	1.26	3.75	39.57	206.98	303.75
0.5	0.87	0	300	1.5	5.25	38.75	245.73	305.25
0.58	0.85	0	300	1.74	6.99	37.94	283.68	306.99
0.67	0.83	0	300	2.01	9	37.05	320.73	309
0.75	0.82	0	300	2.25	11.25	36.28	357.029	311.25
0.83	0.8043	0	300	2.49	13.74	35.53	392.5659	313.74

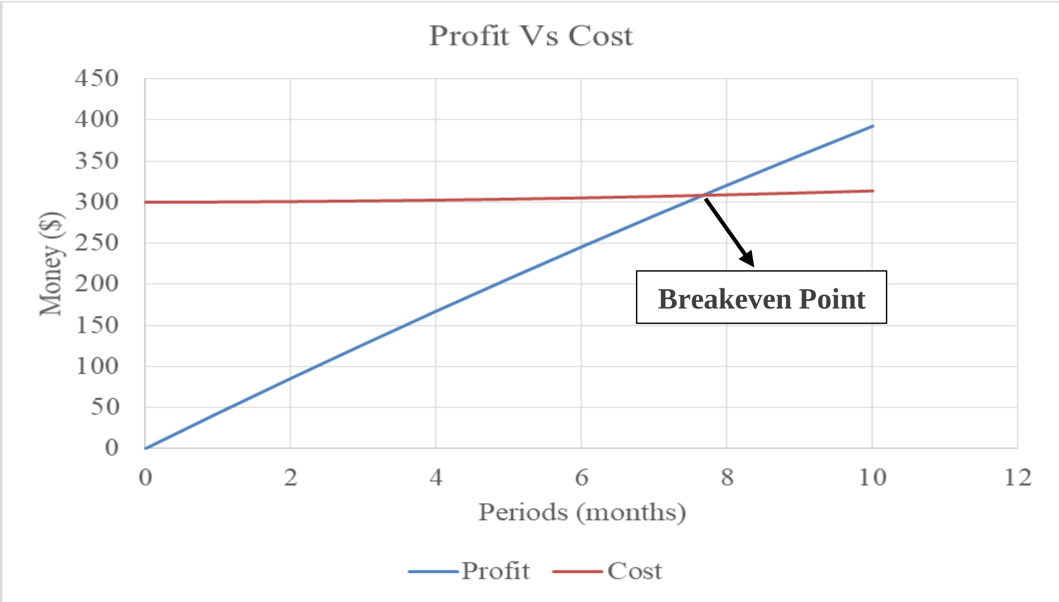

Figure 41: Breakeven Point Analysis.

Chapter 6

CONCLUSION

Desiccant based evaporative Cooling System is a promising technology that is completely different from the vapor compression based cooling systems. Since no recent researches have been studied such a system under North Cyprus climate conditions (hot – humid), it is compared with direct evaporative cooling system.

In both DEVAP and EVAP experiments, rate of cooling was around 700 W, COP was in the range of 5 to 6. And air temperature drop was approximately 11 °C. The main parameters which were distinguishing the performance of two systems were (i) the net water added to the air ($M_{w,net}$) and (ii) cooling capacity per kg water added to the air ($Q_c/M_{w,net}$). Based on the experimental analysis $M_{w,net}$ was found lower and $Q_c/M_{w,net}$ was higher in DEVAP when compared to EVAP process which are both advantageous aspects for evaporative cooling applications.

According to the study results, desiccant assisted evaporative cooling was found more efficient in terms of providing higher cooling capacity per unit kg of water added to air. This is an important feature as such condition could enable using evaporative cooling method in humid climates, such as in North Cyprus, more effectively.

Besides the process design, desiccant material performance is important in DEVAP systems. Several conventional desiccants such as zeolite and silica gel are widely studied in desiccant cooling. However there is no research in the literature using V-

$CaCl_2$ in desiccant cooling systems. Performed studies showed that V-$CaCl_2$ is efficient in terms of fast response and long term moisture removal from the air at a high rate, which could be easily clarified from the obtained results. In addition, due to the low cost, highly hygroscopic and environmentally friendly nature, V-$CaCl_2$ composite could be a promising candidate as a desiccant to be used in future desiccant assisted evaporative cooling systems.

One of the important factors, in feasibility evaluation of HVAC applications is the cost effectiveness. The economic analysis performed within the study showed that payback period for the replacement of DEVAP system with vapor compression unit is between the 7th and 8th month of continuously operating, but by considering the operation of such a system is only during the summer period which is about four months so that the payback period will be 2-3 years. In other words, use of DEVAP system start to provide energy and cost savings in the third year of operation when compared with the use of vapor compression A/C for space cooling purposes.

It can be concluded from the study results that; for high humidity conditions, desiccant cycles make a difference, when the humidity level is low there is not much difference of cooling performance and temperature drop compared to normal evaporative coolers, and this is the reason that makes this investigation a promising approach that has to be more utilized in hot and humid climate region such as in North Cyprus.

6.1 Future Work

The main features that could be added to the system in order to obtain better results, sustainability as well as better performance potential are:

1. The dehumidification process, associated with an increase of the processed air temperatures when it leaves the dehumidification unit. By using a heat exchanger after desiccator to cool down the outlet air from the desiccant chamber before it enters the evaporative cooler could lead to significantly better performance.
2. A solar air collector could be integrated to the system in order to regenerate the desiccant once it gets diluted with water start to lose its dehumidification capability. Besides PV panels could be used to drive the fan and pumps. This will minimize the energy usage and operating costs of the system.

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APPENDIX

Appendix A: Air Blower Selection Guide

How to Select a Fan or Blower

To select a fan, the required data includes the flow rate (CFM), static pressure (SP), and air/gas density.

Flow Rate (CFM)

SCFM stands for Standard Cubic Feet per Minute. It is the CFM at standard density, defined as .075 lb/cubic foot.

ACFM stands for Actual Cubic Feet per Minute. It is the CFM at an identified density other than .075 lb/ft^3. It is also the required mass flow rate divided by the density of the gas being handled. Since fans and blowers handle the same volume of air regardless of density, the ACFM value (and corresponding density) is the preferred value to use when selecting a fan or blower. Note that ACFM and SCFM are not interchangeable except at .075 lb/ft^3density.

Airflow is rated in cubic feet per minute (CFM) or the metric equivalent, cubic meters per hour (M^3/Hr).

1 CFM = 1.6990 x M^3/Hr.

If you will be conveying material, make sure you have enough CFM for the duct, pipe or hose size so the material will maintain the required velocity to carry it completely through the system and not settle in the duct, pipe or hose. See Engineering Data catalog for material conveying velocities.

Static Pressure (SP)

Static Pressure is the resistance to airflow (friction) caused by the air moving through a pipe, duct, hose, filter, hood slots, air control dampers or louvers. Static Pressure is rated in inches water gauge (inWG) or the metric equivalent, millimeters water gauge (mmWG). 1 inWG = 25.4 x mmWG.

Standard air has a density of .075 lb/ft^3 and is based on a temperature of 70°F and 29.92" Hg barometric pressure (sea level). Fan performance tables are based on using standard air. Corrections for density changes resulting from temperature and/or barometric pressure variations, such as higher altitudes, must be made to the static pressure before selecting a fan or blower based on standard performance data. The metric equivalent is in kilograms per cubic meter (kg/m^3). lb/ft^3 = 16.018 x kg/m^3.

The temperature of the air going through the fan or blower will affect the density and performance of the fan or blower. Temperature should be shown in degrees Fahrenheit (°F). The metric equivalent is degrees Centigrade (°C).

°F = 1.8 x °C + 32

If the air temperature will vary, what are the minimum and maximum temperatures?

The altitude the fan or blower will be operating at will also affect the density and performance of the fan or blower. The altitude should be given in feet above sea level. The metric equivalent is meters (m). 1 ft = .30480 x m

Air Temperature Altitude Correction

TEMPERATURE & ALTITUDE CONVERSION FACTORS

Air Temp.	Altitude In Feet Above Sea Level																				
Deg. F.	0	500	1000	1500	2000	2500	3000	3500	4000	4500	5000	5500	6000	6500	7000	7500	8000	8500	9000	10000	11000	12000
-50°	.77	.79	.80	.81	.83	.85	.86	.88	.89	.91	.92	.94	.96	.98	1.00	1.02	1.04	1.06	1.08	1.12	1.16	1.21
-25°	.82	.84	.85	.87	.89	.91	.92	.94	.95	.97	.98	1.01	1.03	1.05	1.07	1.09	1.11	1.13	1.15	1.20	1.24	1.29
0°	.87	.89	.91	.92	.94	.96	.98	.99	1.01	1.03	1.05	1.06	1.09	1.10	1.13	1.15	1.17	1.19	1.22	1.26	1.31	1.37
40°	.94	.96	.98	1.00	1.02	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.19	1.21	1.23	1.26	1.28	1.30	1.32	1.36	1.41	1.47
70°	1.00	1.02	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.18	1.20	1.22	1.25	1.27	1.30	1.32	1.35	1.37	1.40	1.45	1.51	1.57
80°	1.02	1.04	1.06	1.08	1.10	1.12	1.14	1.16	1.19	1.21	1.23	1.26	1.28	1.30	1.33	1.36	1.38	1.41	1.43	1.48	1.56	1.61
100°	1.06	1.08	1.10	1.12	1.14	1.16	1.19	1.21	1.23	1.25	1.28	1.30	1.33	1.35	1.38	1.41	1.43	1.46	1.48	1.54	1.60	1.66
120°	1.09	1.12	1.14	1.16	1.18	1.20	1.23	1.25	1.28	1.30	1.32	1.35	1.38	1.40	1.43	1.46	1.48	1.51	1.53	1.58	1.66	1.72
140°	1.13	1.15	1.18	1.20	1.22	1.25	1.27	1.29	1.32	1.34	1.37	1.40	1.42	1.45	1.48	1.51	1.54	1.57	1.58	1.65	1.72	1.78
160°	1.17	1.19	1.22	1.24	1.26	1.29	1.31	1.34	1.36	1.39	1.42	1.44	1.47	1.50	1.53	1.56	1.59	1.62	1.64	1.70	1.78	1.84
180°	1.21	1.23	1.26	1.28	1.30	1.33	1.36	1.38	1.41	1.43	1.46	1.49	1.52	1.55	1.58	1.61	1.64	1.67	1.70	1.75	1.84	1.90
200°	1.25	1.27	1.29	1.32	1.34	1.37	1.40	1.42	1.45	1.48	1.51	1.54	1.57	1.60	1.63	1.66	1.69	1.72	1.75	1.81	1.89	1.96
250°	1.34	1.36	1.39	1.42	1.45	1.47	1.50	1.53	1.56	1.59	1.62	1.65	1.68	1.71	1.74	1.78	1.82	1.85	1.88	1.94	2.02	2.10
300°	1.43	1.46	1.49	1.52	1.55	1.58	1.61	1.64	1.67	1.70	1.74	1.77	1.80	1.84	1.87	1.91	1.94	1.98	2.00	2.08	2.16	2.25
350°	1.53	1.56	1.59	1.62	1.65	1.68	1.72	1.75	1.78	1.81	1.85	1.88	1.92	1.96	2.00	2.04	2.07	2.11	2.14	2.22	2.31	2.40
400°	1.62	1.65	1.69	1.72	1.75	1.79	1.82	1.85	1.89	1.93	1.96	2.00	2.04	2.08	2.12	2.16	2.20	2.25	2.27	2.35	2.47	2.55
450°	1.72	1.75	1.79	1.82	1.86	1.89	1.93	1.96	2.00	2.04	2.08	2.12	2.16	2.20	2.24	2.29	2.33	2.38	2.41	2.50	2.61	2.70
500°	1.81	1.85	1.88	1.92	1.96	1.99	2.03	2.07	2.11	2.15	2.19	2.23	2.28	2.32	2.36	2.41	2.46	2.51	2.54	2.62	2.75	2.85
550°	1.91	1.94	1.98	2.02	2.06	2.10	2.14	2.18	2.22	2.26	2.30	2.35	2.40	2.44	2.49	2.54	2.58	2.63	2.68	2.77	2.90	3.00
600°	2.00	2.04	2.08	2.12	2.16	2.20	2.24	2.29	2.33	2.38	2.42	2.47	2.50	2.56	2.61	2.66	2.71	2.77	2.80	2.90	3.04	3.14
650°	2.10	2.14	2.18	2.22	2.26	2.31	2.35	2.40	2.44	2.49	2.54	2.58	2.63	2.68	2.74	2.79	2.84	2.90	2.94	3.04	3.19	3.30
700°	2.19	2.23	2.27	2.32	2.36	2.41	2.46	2.50	2.55	2.60	2.65	2.70	2.75	2.80	2.86	2.91	2.97	3.03	3.06	3.18	3.33	3.44
750°	2.28	2.33	2.37	2.42	2.47	2.51	2.56	2.61	2.66	2.71	2.76	2.81	2.87	2.92	2.98	3.04	3.10	3.16	3.19	3.31	3.47	3.59
800°	2.38	2.43	2.48	2.53	2.57	2.62	2.67	2.72	2.76	2.81	2.86	2.92	2.98	3.04	3.10	3.16	3.22	3.28	3.33	3.45	3.60	3.74

Chart found on Page 5 of Instructions for How to Properly Select a Fan or Blower

STATIC PRESSURE CORRECTIONS FOR SUCTION PRESSURE

Based on standard air at 70° F, 29.92" Hg Barometric Pressure, .075 lbs. Per cubic feet density.

Suction Pressure in Inches W.G.	Corrected Static Pressure	Suction Pressure in Inches W.G.	Corrected Static Pressure	Suction Pressure in Inches W.G.	Corrected Static Pressure	Suction Pressure in Inches W.G.	Corrected Static Pressure
16	16.6	33	35.9	50	57.0	67	79.7
17	17.7	34	37.1	51	57.9	68	82.3
18	18.8	35	38.5	52	60.0	69	83.5
19	20.1	36	39.5	53	61.2	70	84.7
20	21.1	37	40.8	54	62.3	71	85.9
21	22.2	38	41.9	55	63.5	72	87.1
22	23.3	39	43.0	56	64.6	73	88.3
23	24.3	40	44.4	57	65.8	74	91.0
24	25.5	41	45.9	58	68.0	75	92.3
25	26.8	42	46.8	59	69.1	76	93.5
26	27.8	43	48.1	60	70.3	77	94.7
27	28.9	44	49.3	61	71.5	78	95.9
28	30.1	45	50.3	62	72.7	79	98.8
29	31.6	46	51.9	63	75.0	80	100.0
30	32.4	47	53.4	64	76.2	81	101.2
31	33.7	48	54.4	65	77.4	82	102.6
32	34.7	49	55.7	66	78.5	83	104.3

Chart found on Page 4 of Instructions for How to Properly Select a Fan or Blower

Centrifugal fans or blowers use one of seven types of wheels that are enclosed in a scroll shaped housing. The air enters the fan wheel through the housing inlet, turns 90 degrees and is accelerated radially and exits the fan housing. Centrifugal fans are typically used for lower flows and higher pressures.

[*]Adapted from: The OEM & Industrial Fan Specialists: Cincinnati Fan.