B. TECH. PROJECT REPORT

On

Development of Highly Wetted Polypropylene Plate for Liquid Desiccant Application

BY

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DISCIPLINE OF MECHANICAL ENGINEERING

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Development of Highly Wetted Polypropylene Plate for Liquid Desiccant Application

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

Of

BACHELOR OF TECHNOLOGY
In
MECHANICAL ENGINEERING

Submitted by:
Akhilesh Kumar Meena
Guided by:
Dr. Ritunesh Kumar

INDIAN INSTITUTE OF TECHNOLOGY INDORE
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CANDIDATE’S DECLARATION

I hereby declare that the project entitled **“Development of Highly Wetted Polypropylene Plate for Liquid Desiccant Application”** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in ‘Mechanical Engineering’ completed under the supervision of **Dr. Ritunesh Kumar (Associate Professor),** IIT Indore is an authentic work.

Further, I declare that I have not submitted this work for the award of any other degree elsewhere.

Akhilesh Kumar Meena

DATE:

CERTIFICATE by BTP Guide

It is certified that the above statement made by the students is correct to the best of my knowledge.

Dr. Ritunesh Kumar

Associate Professor

Mechanical Engineering

Preface

This report on “Development of Highly Wetted Polypropylene Plate for Liquid Desiccant Application" is prepared under the guidance of Dr. Ritunesh Kumar.

This report is about Development of Highly Wetted Polypropylene Plate for Liquid Desiccant Application.

I have tried to the best of our abilities and knowledge to explain the contact in a lucid manner. I have added figures and experimental results to make it more illustrative.

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It is his help and support, due to which I was able to complete the design and technical report.

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Abstract

Use of metallic air-liquid desiccant contacting surface is common in falling film system due to high wettability. Metallic surface in general suffers from corrosion problem .Corrosion prone metallic surfaces need expensive anticorrosive coating or require frequent replacement. Plastic plates can be used as an alternative to metallic surface, provided wetting characteristics of plastics surface can be elevated up to metallic surface .Plastic surface have excellent corrosion resistance property, low cost and light weight. In this project, wetting factor of modified polypropylene plates have been experimentally measured for liquid desiccant system. Surface modification technique have been used for improving the wetting characteristics of polypropylene plates. Vertical grooves have been fabricated on four different polypropylene plates by CNC milling machine. Width of vertical grooves for four different plates have been kept 2mm,3mm,4mm,5.5mm respectively. Consistent wetting performance is obtained for surface having 3mm grooves width. The developed surface having 3mm grooves width has been used further to carry out absorption liquid desiccant study at low flow rate conditions. Falling film tower have been fabricated for liquid desiccant application.

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Chapter 1 Introduction

1.1 Background

Electricity is used for many building operations including residential and commercial; the two largest uses of electricity from the building sector are lighting and air conditioning. Air conditioning affects not only personal comfort, but also economics. The state of comfort improves the productivity of human being. Air-conditioning plays an important role in our day to day life considering the fact that most of us pass around 70-90% of our life in built environment [1]. The situation is execrated by the global warming as well as increasing levels of air pollution. Air-conditioning systems are no more with old luxury tag; in fact they have become necessity of human life. HVAC industry is today aiming for off-loading electricity consumption and greenhouse gas emissions. It is only possible through the use of renewable energy or low grade waste heat for air-conditioning with the help of environment benign refrigerant.

Vapour compression air conditioning system (VCR) is widely used to meet the comfort necessities of conditioned space since the inception of its concept around a century ago. This system handles sensible and latent load simultaneously. However, sensible and latent loads both are handled through cooling effect. Cooling is produced through the repetitive compression and expansion of refrigerant in the compressor and expansion devices. Figure 1.2 shows a schematic representation of vapour compression cycle. Heat is absorbed from the process air inside the evaporator and ejected back to the surrounding through the condenser of the unit. If evaporator coil surface temperature is lower than the dew point temperature then air gets cooled and dehumidify. This low temperature and humidity air is sent back to the air conditioned space to balance heat and humidity loads of conditioned space. To achieve the low evaporative coil surface temperature (for condensation purpose of the air) compressor consumes lot of energy. Vapour compression system primarily needs energy in form of electricity. Performance of vapour compression system is very poor against of the latent load and it deteriorates at very fast rates in case latent load demands increases especially during the monsoon season or in tropical climates. Hence there is a need of alternative process/system to meet latent load. Desiccant systems are emerging out as a sustainable option of conventional vapour compression systems, they can work using any low grade waste heat or renewable energy.

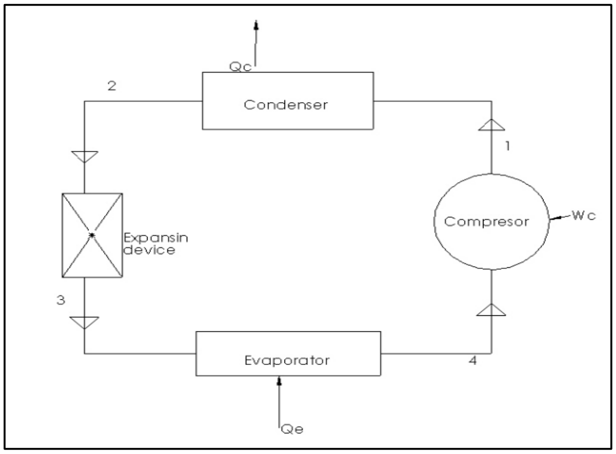


Fig. 1.1 Simple vapour compression cycle [2]

1.2 Desiccant System

A desiccant is a hygroscopic material which has strong affinity toward water vapour. In desiccant based air-conditioning systems, the latent load is handled by the direct dehumidification of air through desiccant solution. Desiccant systems are categorized based on the state of desiccant material as follow:

1.2.1 Solid Desiccant System

This system uses a solid desiccants mainly silica gel, activated alumina and activated carbon. Solid desiccant are used in variety of industries such as pharmaceutical industries, wood seasoning processes etc. Figure 1.2 shows the working principle of the solid desiccant system [3]. This system consists of rotating desiccant wheel divided in two parts: adsorption section and regeneration section. In order to dehumidify air, wet and humid air is passed through adsorption section, thus moisture level of air decreases. The moisture absorbing capability of solid desiccant wheel is reinstated by passing hot air on regeneration section.

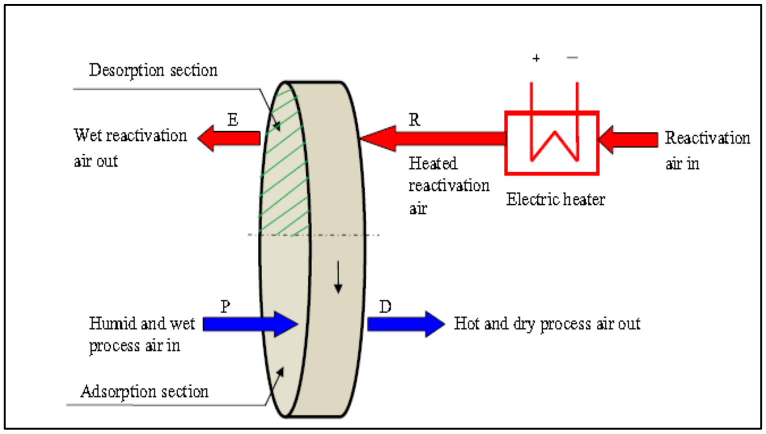


Fig. 1.2 Solid desiccant wheel [3]

The desiccant used for this system is in granular form coated over solid wheel. These systems are widely used due to its compact size, ability to dehumidify air at very low moisture content and low degradation rate of desiccant.

1.2.2 Liquid Desiccant System

Liquid desiccants are aqueous salt solutions or organic solvents. Inorganic liquid desiccants are aqueous mixtures of calcium chloride, lithium chloride, lithium bromide and binary mixture of these salts. Organic desiccant solutions are mainly glycols like monoethylene glycol, diethylene glycol, triethylene glycol (TEG), and propylene glycol. The typical liquid desiccant system is shown in Fig. 1.3. In the absorber; the process air comes in direct contact of counter flowing cold and concentrated liquid desiccant solution and gets dehumidified. The desiccant solution needs to be cooled before entering the absorber. The cooled liquid desiccant has lower vapour pressure than the process air thus moisture transfers from the process air to liquid desiccant. Vapour pressure difference between solution and process air acts as the driving force for the mass transfer. After absorption of moisture from air, solution gets diluted and loses its capacity to dehumidify air. Liquid desiccant solution affinity to dehumidify air is restored back inside the regenerator unit. For the regeneration of diluted liquid desiccant, it is first heated up (prior to regenerator/inside the regenerator) then it is bring in contact of outside atmospheric air. Heating of diluted solution raises the vapour pressure of the desiccant solution and thus mass transfer direction is reversed (from liquid desiccant to air). At outlet of regenerator hot and concentrated desiccant solution is obtained.

Solution to solution heat exchanger is added between absorber outlet and regenerator outlet for internal heat recovery purpose. So that the cooling load of solution cooler (absorber side) and heating load of solution heater (regenerator side) can be minimized. This cycle is very energy efficient as only low grade heat energy is required for regeneration of solution [4].

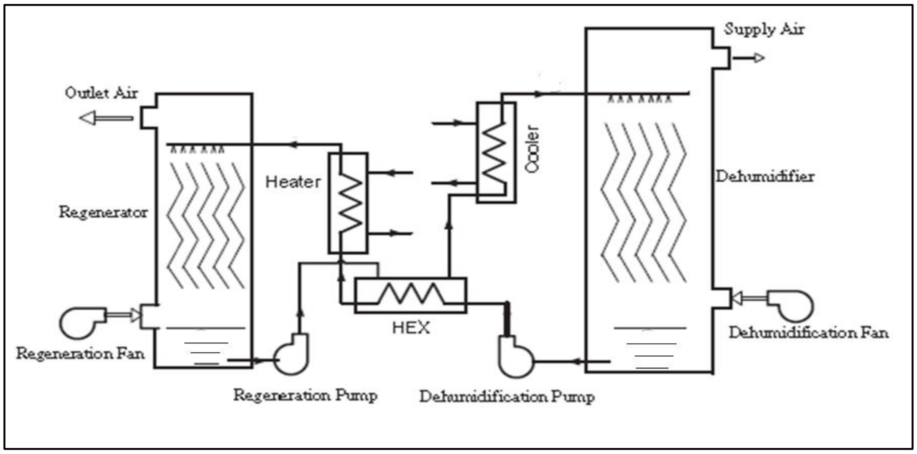


Fig. 1.3 Working of liquid desiccant system [4]

Liquid desiccant systems have several advantages over solid desiccant systems:

1. Feasibility of simultaneous cooling during dehumidification.
2. Flexibility in the orientation and coupling of the absorption and the regeneration processes provide several technical advantages. Several small absorbers can be coupled with one central regeneration unit through separate liquid lines. The restriction of continuous supply of energy for air-conditioning can be relaxed since regeneration of the liquid desiccant solution can be carried out when energy is available, [or day time in solar operated systems] and the solution stored for use during "load" conditions.
3. Require lower regeneration temperature, enable internal heat recovery between the absorption and regeneration processes, and require lower power for air blowers.

Absorber and regenerator are the heart of this system. Important constraints for an efficient design of this equipment are as follows:

1. Enabling very good contact between the liquid desiccant and the air.
2. Ability to handle high air flow rate.

3. Ability to operate at low desiccant flow rates without affecting the overall dehumidification of air.

4. Low air side pressure drop.

5. No carryover of the liquid desiccant. Carryover of the liquid desiccant not only causes the loss of costly liquid desiccant solution but also creates serious health hazards [5].

Conventionally three types of designs are used as the absorber and the regenerator: packed bed, spray tower and falling film towers. Their details and merits/demerits are given in following section.

1.3 Absorber/ Regenerator Tower

Overall system performance is dependent on the design of tower selected for the absorption and the regeneration processes. Different flow configurations have been used, like parallel flow, counter flow or cross flow. However, due to its high effectiveness, the counter flow configuration is generally preferred.

1.3.1 Packed Bed Tower

The packed beds are well known for their compactness, high efficiency, and the large heat and mass transfer area. Tower consists of random packing or structure packing spherical or special designed shape and size to provide high void fraction. Basically packed towers are operated in a counter flow configuration, with the solution distributed from the top and air entering from the bottom of the tower as shown in Fig. 1.4.

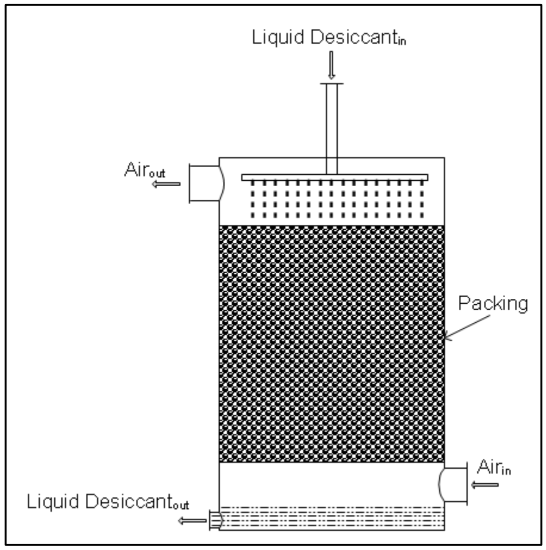


Fig. 1.4 Packed bed tower [5]

Random packing provides good contact between air and liquid but they have to operate at higher L/G ratio and pressure drop is also higher for them including the mass transfer. Overall, packed bed design is very efficient from the mass transfer prospects but they consume lot of energy for liquid desiccant circulation and needs high capacity air blower for circulating air.

1.3.2 Spray Tower

In spray tower, large surface area for heat and mass transfer is obtained by breaking the liquid into small droplets with the help of nozzles in a hollow chamber as shown in Fig. 1.5. Spray tower has very simple design and very low air side pressure drop. But, they require high pumping power for breaking liquid in to fine droplets. Carryover of solution is another major limitation that not only causes monetary losses but also suffocates human in case permitted and is also responsible for poor performance of the system in case not remedied.

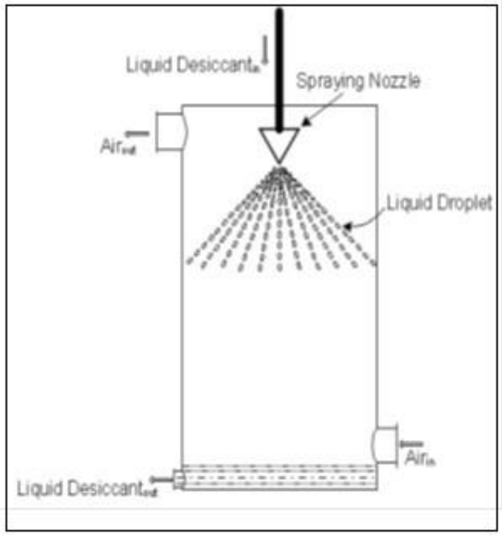


Fig. 1.5 Spray tower [5]

1.3.3 Falling Film Tower

In falling film tower liquid desiccant flows down along the solid surface under the influence of gravity. Tower consists of tubes or plates as surfaces, as shown in Figure 1.6. It is used in many industrial applications like distillation columns, vertical condensers, film evaporators, absorption towers, falling film coolers and nuclear reactor cores, etc. These kinds of towers are preferred due to good performance, effective working even at low L/G ratio and possibility of removal/addition of heat generated/consumed during absorption/regeneration process. Falling film towers are generally used due to their high energy and mass transfer rates at low liquid flow rates [6]. They are drawing attention as they have moderate air side pressure drop and less pumping power required for liquid distribution. Corrosion of solid surfaces and maldistribution of the liquid among solid surfaces are the main limitations of the falling film tower [7]. Anticorrosive coatings such as of nickel or molybdenum may help but they are very costly.

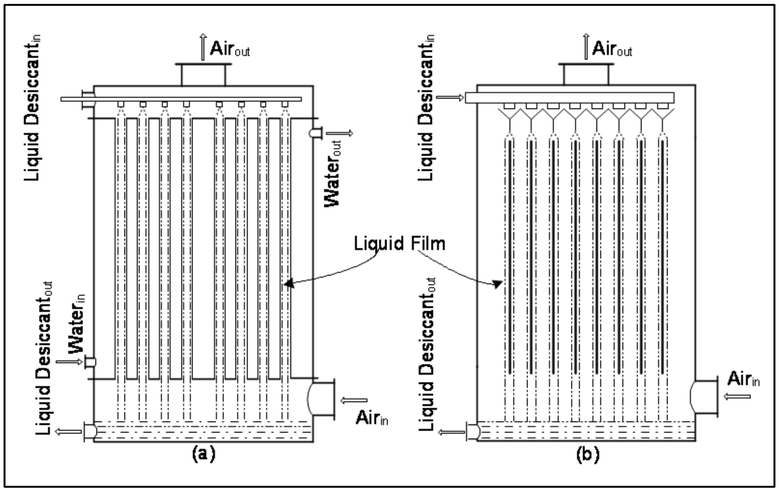


Fig. 1.6 Falling film tower (a) tube (b) plate [5]

1.4 Outline of Thesis

The major objective of the present work is to explore the possibility of using polypropylene as a material in plate falling film tower for liquid desiccant application such that problem of corrosion of surfaces can be sorted out and system longevity increases. The whole report is divided into five chapters. **Chapter 1** introduces the topic in topic. Works carried out by the previous researchers related with desiccant cooling systems are summarized in **chapter 2**. The chapter ends with the summary and scope of current work. **Chapter 3** gives details of the in-house developed experimental test facility and methodology of experimentation. Results & discussion are described in **chapter 4**. The conclusions derived from the work carried out absorber mode are summarized in **chapter 5**.

Chapter 2 Literature Review

Liquid desiccant cooling system is the most prophetical alternative of conventional vapour compression system. The liquid desiccant system mainly consists of the dehumidifier, regenerator and combination of direct and indirect evaporative coolers. The performance of the system mainly depends on the efficient designs of the dehumidifier and the regenerator units. Conventionally, three types of designs packed bed tower, spray tower and falling film tower are used as the absorber and the regenerator. The summary of the literature reviewed during this work are presented in following section.

2.1 Literature on Packed Bed Tower

The packed towers have attracted the attention of many researcher due high its high effectiveness and compactness. Intimate contact between liquid desiccant and air, and the large surface area per unit volume are the main reasons responsible for the above. The main limitations of this type of design are very high air side pressure drop and large air side pressure drop. Although, modern packings (structured) reduces the problem of air side pressure drop up to large extent but still their pressure drop is even higher than falling film and packed bed towers. One another limitation reported by previous researchers is the requirement of even distribution of liquid across the whole area of the packing. Thus, emphasis on efficient liquid distribution is must**.**

2.1.1 Experimental and Theoretical Study on Packed Bed Tower

Esam [8] carried regeneration study using structured packed tower and TEG as liquid desiccant. They reported the effects of various operative parameters (effects of air and liquid flow rates, air humidity, desiccant temperature and desiccant concentration) on humidity effectiveness and evaporation rate of the regenerator. They also claimed that structured packing should not be operated at L/G ratio higher than 1 – 1.6.

Yin et al. [9] carried out experimental studies on liquid flow distribution of large scale packed bed column. The liquid flow distribution was studied for various bed height (varying from 0.9 to 3 m) and liquid flow rate 2.66 to 6.66 kg/s-m^2 and gas flow rate up to 3 kg/s-m^2. They found that liquid flow distribution was strongly influenced by packed bed height, gas flow rate and liquid viscosity, slightly influenced by liquid flow rate.

Fumo et al. [10] studied the performance of packed bed dehumidifier and regenerator using lithium chloride (LiCl) as a desiccant in counter-flow arrangement. They studied the impact of design variables such as air inlet temperature, desiccant concentration, air and desiccant flow rate and inlet desiccant temperature on the water condensation rate and evaporation rate. They concluded desiccant temperature, desiccant concentration and air flow rates as the dominant parameters influencing the performance of the regenerator and the absorber.

In adiabatic regenerator exchange of heat and mass transfer occurs only between the air and desiccant, so it is possible that the moisture transfer rate reduces quickly because of decrease in desiccant temperature at the bottom of regenerator. Yin et al. [11] carried out experimental comparison of the performance of a adiabatic and internally heated regeneration process using regeneration rate and regeneration thermal efficiency as a performance index. They found that for a low flow rate of liquid solution internally heated regenerator can offer equivalent regeneration efficiency and regeneration rate, thus carryover of liquid droplet can be avoided.

Moon et al. [12] studied the performance of cross flow structured packed (packing density $608m^2/m^3$) liquid desiccant dehumidifier using Calcium chloride as liquid desiccant. They evaluated the performance of dehumidifier using dehumidifier effectiveness and moisture removal rate as performance index and developed new empirical correlation for predicting the effectiveness of cross flow packed dehumidifier. They also reported that desiccant flow rate has a predominant effect on the dehumidification effectiveness at low solution to air mass flux ratio.

Yin et al. [13] studied the effect of heating source temperature, air temperature, solution temperature, and solution concentration on rate of dehumidification and regeneration of packed bed tower. They reported average mass transfer coefficient to be $4g/m^2s$ for the regeneration process with varying concentration at 20% and 28%. The mass transfer coefficient is more for 20% concentration of lithium chloride desiccant solution also find out the correlation for mass transfer coefficient for regenerator and absorber.

Wang et al [14] evaluated the performance of structured packed bed dehumidifier (packing density 650m^2/m^3). They studied the impact of design variables such as air inlet temperature, desiccant concentration, air and desiccant flow rate and inlet desiccant temperature on the water condensation rate and evaporation rate. They concluded desiccant temperature, desiccant concentration and air flow rates as the dominant parameters influencing the performance of the regenerator and the absorber.

Gommed & Grossman [15, 16] studied the performance of a solar based open absorption liquid desiccant system using packed bed towers and lithium chloride as desiccant and did a simulation of the open absorption system has been conducted using the measured values, to determine the effect of operating parameters on performance.

2.2 Literature on Spray Tower

In spray type arrangement, heat and mass transfer between liquid desiccant and air takes places at the outer periphery of small liquid droplets. These small liquid droplets are formed by breaking the liquid with help of especially designed spray nozzles. Although spray towers are well known for their simplicity, low pressure drop on airside and low cost, but the system performance is not as good as falling film or packed towers due to very limited contact time between liquid desiccant and air (small droplets have very high speed). Carryover of liquid and large liquid side pressure drops are other prominent drawbacks of these systems.

2.2.1 Experimental and Theoretical Study on Spray Tower

Kumar [17] developed a spray tower for almost zero carryover of liquid desiccant; three different types of wire mesh packings were used to enhance the performance of the conventional design by spreading the liquid and slowing down the fast speeding fine liquid droplets. He compared results with conventional spray tower and reported improvement of 30% as compared to conventional design. Mass flow rate of air and desiccant, air and solution temperature, inlet specific humidity and concentration of solution had been identified as the major influencing parameters.

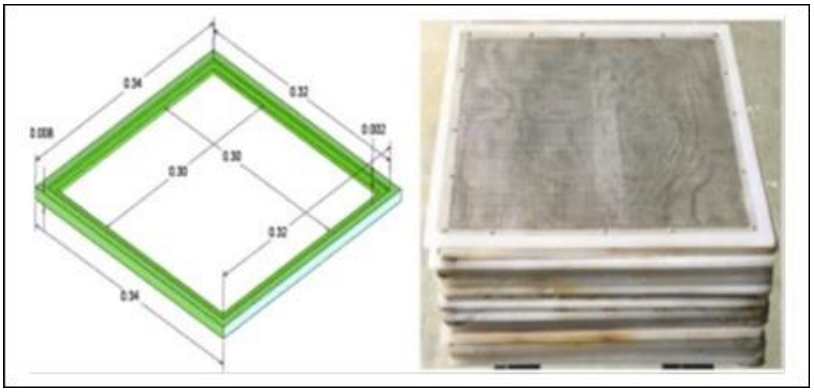


Fig. 2.1 Wire mesh packing [17]

Yin et al. [18] studied internally cooled/heated dehumidifier/regenerator using lithium chloride as desiccant. They evaluated the effect of inlet parameters variation on moisture removal rate and also compared the internally cooled/heated dehumidifier/regenerator with adiabatic dehumidifier/regenerator. They reported that internally cooled/heated dehumidifier/regenerator gives better performance at low value of operating variables.

2.3 Falling Film Tower

The falling film tower finds extensive application in various fields where simultaneous heat and mass transfer phenomenon are required. In the falling film towers liquid falls under the influence of gravity along the surfaces placed in towers thus less pumping power is required. Limited wetness of the solid surfaces and inefficient distribution of liquid are the main limitations of these kinds of towers. The performance of falling film tower can be enhancing by the addition of surfactants, modification of surface for good surface wetting, and by ensuring uniform wetting of individual solid surfaces

2.3.1 Experimental and Theoretical Study on Falling Film Tower

Kang et al. [19] studied the effect of surfactant addition on fluid flow and heat transfer on a stainless steel plate in falling liquid film. They found that addition of surfactant significantly increases the wetted area due to decrease in surface contact angle. The concentration of surfactant in their study was varies up to 1000 ppm. They observed that at 500 ppm film thickness decrease gradually. The result showed that enhancement in heat transfer from heated plate to falling film take place due to addition of surfactant.

Jain et al. [20] experimentally studied the falling film tubular absorber and falling film plate regenerator. The results were compared with the predictions from theoretical model and they introduced the wetting factor terms to account for limited wetting of solid surfaces. They found the value of wetting factor for regenerator (F_w=0.6, F_h=1) and dehumidifier (F_w=0.3, F_h=0.7), where F_w is wetting factor for mass transfer and F_h is wetting factor for heat transfer.

S. Bouzenada [21] experimentally studied the performance of low flow falling film absorber using chloride as liquid desiccant. They achieved the moisture removal rate up to 3.5g/s at average value of dehumidifier effectiveness up to 55%.

Qi et al. [22] did investigation on wetted area and film thickness, wetting of the solid surface enhance the heat and mass transfer performance. To keep plate resurface hot they circulate the hot water so that the surface tension of the desiccant is lower and hence enhancement in wetting of the surface accrues. They studied the effect of surface temperature on performance of system found that wetted area can be significantly increased by controlling the plate surface temperature especially at low flow rates.

Kessling et al. [23] used lithium chloride as liquid desiccant with plate & tube type falling film absorber. Cooling water was circulated through the tubes to remove the heat generated during the absorption process. They also explored the feasibility of storing the energy in the form of concentrated liquid desiccant solution. The effect of the ratio of the mass flow rate of air to the mass flow rate of liquid desiccant was analyzed on the performance in terms of m_{cond} and storage capacity. Unlike others works they used very high solution to air mass flow rate ratio in the range of 50-100.

Rahamah et al. [24] present the mathematical model for parallel flow falling film and validated it with available literature. They also studied the effect of variation of inlet parameters on the performance of dehumidification process using calcium chloride as desiccant. They concluded following important points regarding the performance of dehumidification process from their study.

1. Low air flow rates produce better dehumidification and cooling processes.
2. Increasing the channel height leads to better cooling and dehumidification processes for the outlet air; however, the rate is decreased.
3. The dehumidification process can be enhanced by decreasing the inlet water concentration in the desiccant solution to certain levels such as to avoid crystallization of the salt in the solution.

Table number 2.1, 2.2, 2.3 and 2.4 show the summary of operating parameters and the performance of the previous studies statistical data used in various experimental studies for absorber and regenerator performance.

Various kinds of desiccants solutions reported in literature are summarized in table 2.1-2.4 from this table, it can be concluded that

1. Aqueous solution of LiCl is the most widely used liquid desiccant, followed by aqueous solutions of $CaCl_2$ and TEG.
2. Preferred ranges of concentration of liquid desiccant solutions are as follows: LiCl+H2O 30-40%, CaCl2+H2O 35-45%, and TEG 90-96%.
3. Glycol based organic desiccant solutions are less popular in recent study possibly due to their non-zero vapour pressure, thus it is impossible to avoid carryover of the liquid desiccant.

Following Table shows the statistical data used by many researchers in their study with use of different liquid desiccant and different absorber/ regenerator unit.

Author	Desiccant				Air			Air to desiccant ratio M_a/M_l	EF (ε_y)	Remark
	Type	Temp. (°C)	Con. (%)	Flow Rate Kg/s	Flow Rate Kg/s	Temp (°C)	Humidity Kg/kg			
Moon et al [12]	$CaCl_2$	20-45	30-45	0.5-3.5*	0.015-0.026*	24-42	0.033-0.043	0.38-2.4	0.6	CF, 40-120 Pa/m, 608m^2/m^3, MRR=0.00112, EF= 0.6
Fumo et al [10]	LiCl	@24-38	33-35	4.5-8*	0.8-1.5*	28-42	0.014-0.022	0.15-0.25	0.74-0.85	WC, CF, packing density=210m^2/m^3,
Gandhidas an p. [11]	LiCl	30	35	3-6.5*	1.5*	35	0.018			Studied the Effect of HX EF on Water condensation rate. Rate=0.013 kg/s/m^2
Yin et al [16]	LiCl	@25-30	38-40	0.1042**	0.074**	28.5-34.5	0.0118-0.0185	0.71		Studied the effect of 20 and 28% LiCl on mass transfer co-efficient =4 g/m^2 s

Table 2.1 Summary of experimental works on packed bed dehumidifier

Author	Desiccant				Air			Air to desiccant ratio M_a/M_l	EF (ε_y)	Remark
	Type	Temp. (°C)	Con. (%)	Flow Rate Kg/s	Flow Rate Kg/s	Temp (°C)	Humidity Kg/kg			
Fumo et al [14]	LiCl	#58-72	32.5-35.	5-8*	0.325-0.355*	28-42	0.014-0.022	0.15-0.25	0.74-0.85	WC, CF, 210m^2/m^3.
E. Elsarrag [10]	TEG	70-80	90-98	0.6-1.6*	1-1.25*	NA	0.0181-0.0242	0.64-1.1	0.25-0.40	440m^2/m^3, EF, EVR.
Yin et al [9]	LiCl	50-100	30-40	0.001-0.035**	0.001-0.025	20-40	0.0115			PF, η_r. M_r. Internally heated regenerator

Table 2.2 Summary of experimental works on packed bed regenerator

Author	Desiccant				Air			Air to desiccant ratio M_a/M_l	EF (ε_y)	Remark
	Type	Temp. (°C)	Con. (%)	Flow Rate Kg/s	Flow Rate (Kg/s)	Temp (°C)	Humidity (Kg/kg of dry air)			
Qi et al [22]	LiCl	15–45	36	0.05-2.50**	0.05-2.50**	15–45	0.012		0.36	Parametric study on enthalpy effectiveness, moisture Effectiveness and temperature effectiveness
A. Rahamah et al [24]	$CaCl_2$	@20-30	30-40	0.0035-0.01+	0.008-0.0188	25-40	0.015-0.025	1.6-2.5		FF, PF, mathematical modeling of parallel flow falling film
Yin Y et al [18]	LiCl	@20-30	39	0.1036**	0.048-0.096**	30.9			0.36-0.96	Compared the internally cooled dehumidifier and regenerator with adiabatic.

Table 2.3 Summery of experimental works on falling film dehumidifier

Ronghui Qi et al [27]	LiCl	25–60	25–35	0.02–0.2	0.05–2.50	20–40	0.00920–00.0987		3.5	Study Wetted area, film thickness, internally heated regenerator
Rahamah et al [24]	$CaCl_2$	#27-40	#27-40	0.004-0.01+	0.015-0.025	0.004-0.01+	0.015-0.025	1.6-2.5		FF, PF, mathematical modeling of parallel flow falling film

Table 2.4 Summery of experimental works on falling film regenerator

+kg/s-m, **kg/s, ©=m^3/s, *Kg/s-m2, WC= Water Condensation Rate, SP= Structure packing, EF= effectiveness, EVR=Evaporation rate, PF= parallel flow, ɵ= Contact angle, MRR= moisture removal rate, η_r. =regeneration thermal efficiency, M_r= Regeneration rate, HX=heat exchanger, PFHX= plate fin heat exchanger (dehumidifier/regenerator) CF= Cross flow.

2.4 Performance Enhancement Technique

Conventionally metals are used as solid surface in regenerator and absorber towers of chemical plants and the same is followed by the previous researchers in their experimental study. Metals had been obvious choice due to its high wetness and high temperature workability. But, liquid desiccant systems operates at very moderate temperature and unlike commercial chemical plants it is not possible to change solid surfaces of falling film towers on frequent basis (due to corrosive nature of desiccant solution). Polymer could be the possible alternative to metallic surfaces due to inert nature toward inorganic salt solutions. Use of plastic as gas liquid contacting solid surface is limited by the poor wetness characteristics of plastics in comparison to metallic surfaces. To ensure proper dehumidification of air and minimizing the pumping cost; proper wetting of plastic surfaces is mandatory in case plastics are chosen as gas liquid contacting surfaces. Wetting of surface is depends upon contacting surface roughness, liquid property and liquid distribution system. To increase the wetting of the surface several techniques has been adapted like addition of surfactant and modification of surfaces etc.

Gonda et al. [25] studied the falling film evaporation on a corrugated plate of stainless steel of surface area 0.267m^2. They found that stability of falling film on non-wetted area is the common issue; they accredited it in favor of surface tension of liquid. They analyse the flow in increasing and decreasing manner found that for same flow rate the wetted area is about 90% during the case of decreasing flow rate while 50% wetted area during increasing flow rate. They proposed a new heat transfer correlation for the turbulent flow.

Mohamed [26] carried experiments over horizontal plane and fluted surface (pitch of fluted surfaces 7, 5, and 3 mm) tubes to analyse the effect of fluted surface on the heat and flow characteristic of liquid failing film. They observed that more heat transfer occurs at the lowest pitch value) and reported 45 % improvement in heat transfer coefficient corresponding to 3 mm pitch.

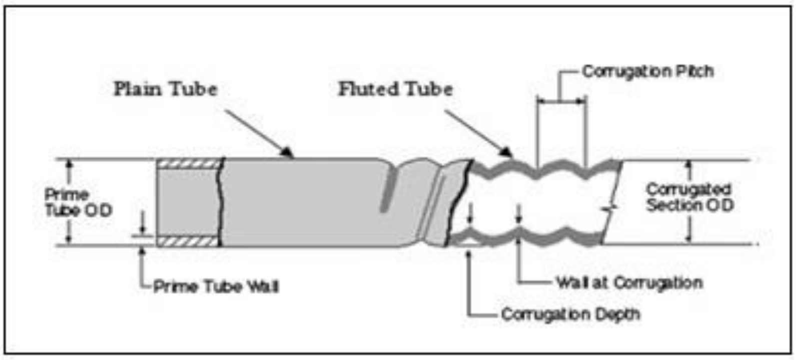


Fig. 2.2 Geometry of plain and fluted tube [26]

Qi et al. [27] studied the effect of slit opening on the wetted area and film thickness for falling film liquid. The experiments were carried out on internally heated regenerator mode. They found that increase in slit opening from 1.0 to 1.25 mm decreased the wetted area by 51% due to increase in film thickness. They found that contact angle reduces with solution temperature and high solution velocity, which significantly reduces the contact time between air and liquid desiccant. They further concluded that decrease in heat and mass transfer area and contact time causes decrease in moisture removal rates. Therefore, the increase of wetted area or wetting factor improves the mass transfer performance, while the performance of the system reduces with increasing thickness of falling liquid film.

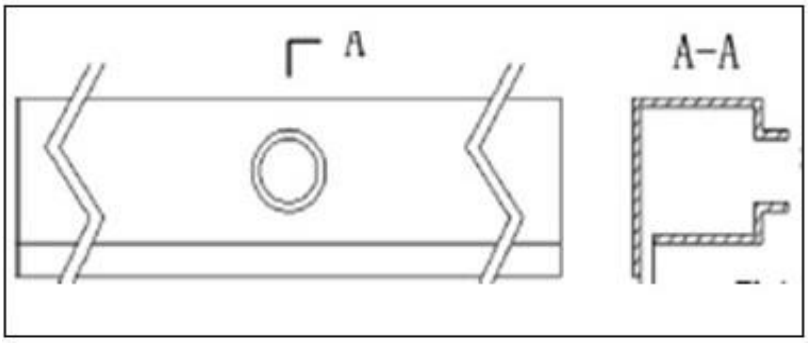


Fig. 2.3 Geometry of liquid slit opening [27]

Patil et al. [7] studied wetting enhancement of polypropylene plate for falling film tower application by adding surfactant (sodium lauryl sulfate-SLS) and surface modification (opposite inclined grooves of 0.5mm, 1.5mm, and 3mm). They found average wetting enhancement of 80.4% and 50% with surface modification method and surfactant addition method respectively. They also compared the wetness of plain plastic with metallic aluminum surface.

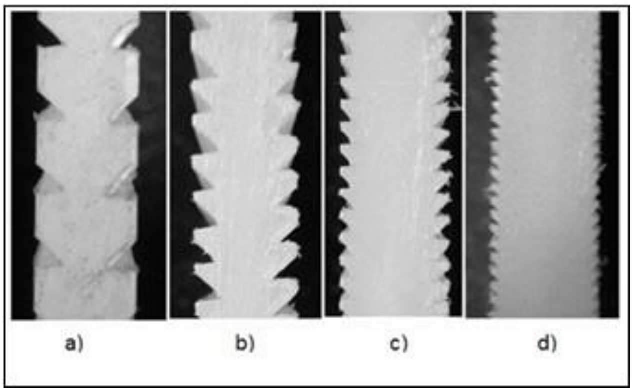


Fig 2.4 Different modified surfaces [7]

Kim et al. [28] developed a new method for wettability measurement and investigated the effect of micro-scale treatment (micro machined tubes) on smooth horizontal tube falling film absorber. They concluded that wettability of a micro hatched tube is more than that of a plain tube. They developed correlations of wettability for the smooth and micro scale treated tubes.

Ali et al. [29] developed a model to investigate the heat and mass transfer between air and falling liquid desiccant solution in parallel and counter flow configurations. They stated that parallel flow configuration provides better dehumidification and cooling than counter flow configuration under presence of nano particle suspensions. They further concluded that low air side Reynolds number enhances the cooling and dehumidification rate, and high Reynolds number enhances the regeneration rate of the liquid desiccant. They also observed that dehumidification and cooling rates increases with increase in volume fraction of nano particles and channel height.

Michel et al. [34] studied performances of grooved plates falling film absorber. They designed grooves to obtain good absorber plate wettability even at low solution flow rate. They characterized the absorption on a LiBr falling film solution for different operating conditions. They investigated the impact of absorber length, cooling water inlet temperature, absorber water vapor pressure, solution inlet temperature, LiBr mass fraction and flow rate. Experimentally the achieved a high absorption rate as high as 7*10^-3 Kg S^-1 m^-2.

2.5 Literature Summary and Objectives of The Project

1. It is clear from the literature summary discussed in this chapter that large number of experimental studies had been reported on the performance of packed bed tower as it provide large heat and mass transfer area, compactness and high efficiency. But, the main drawback of the system is high air side pressure drop and large L/G ratio requirement. Thus, packed bed towers are better suited for large systems. Falling film tower eliminates the drawback of packed tower. However, very limited experimental studies are available on the falling film tower ad still the state of art of above tower is not matured unlike packed towers. Thus, the objective has been identified as carrying out detailed absorption experimentation on falling film tower design.

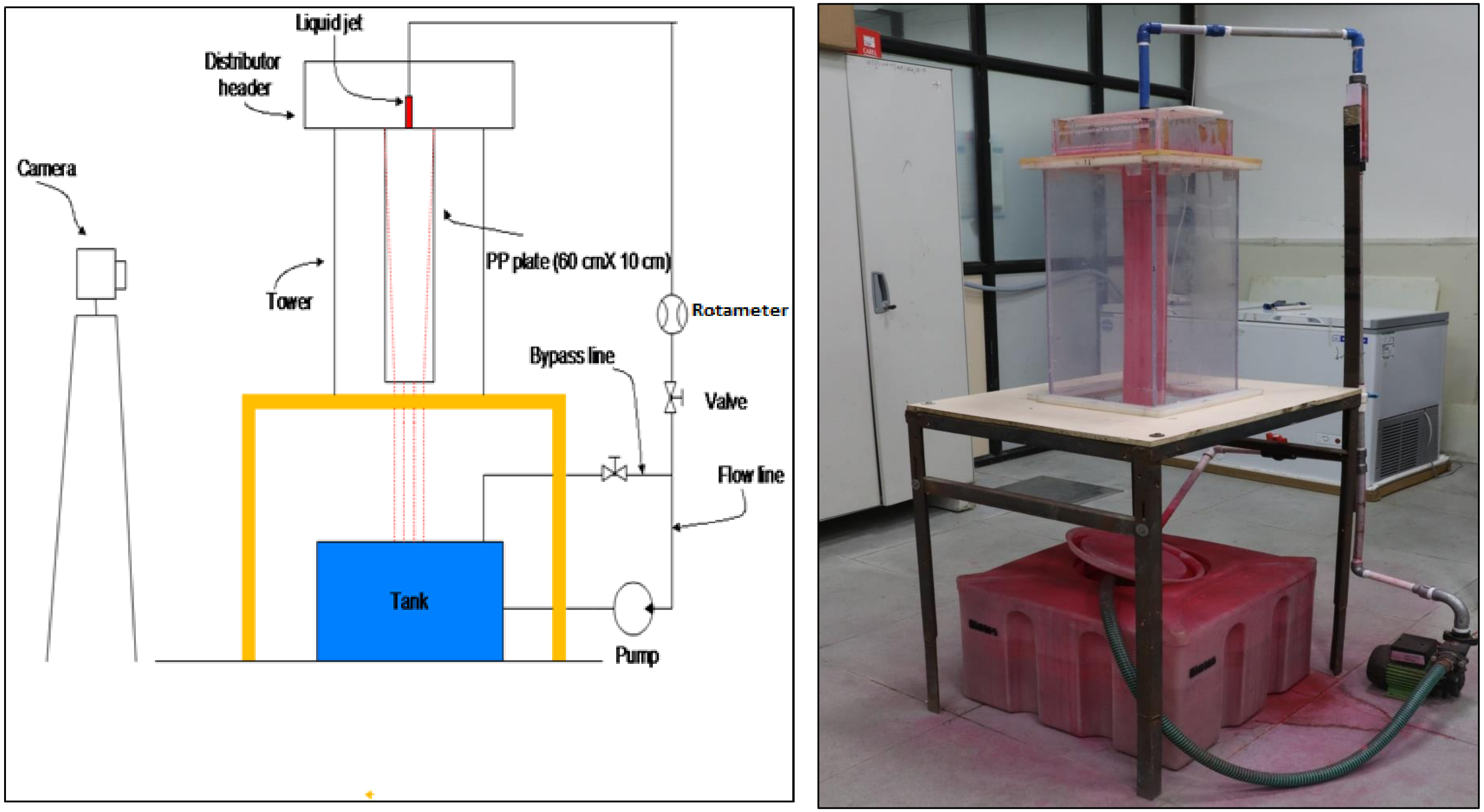
2. The main problems associated with the use of liquid desiccants are corrosion due to inorganic liquid desiccants. In previous studies, metallic surfaces were used as contacting material but the corrosion spoils entire surface after some time. Plastic plates can be used as an alternative to metallic surface, provided wetting characteristics of plastics surface can be elevated up to metallic surface .Plastic surface have excellent corrosion resistance property, low cost and light weight. In the current work, wetting factor of modified polypropylene plates have been experimentally measured for liquid desiccant application. Thus one objective of this project is to develop a highly wetted polypropylene plate for liquid desiccant application.

Single plate vertical falling film tower has been fabricated for the study of the objectives laid in chapter 2. Fabricated falling film tower facilitates easy visualization of desiccant film falling on the solid surface and also enables the study of performance of the absorber and the regenerator both using same setup. The details of the parameter selection, experimental setup and the procedure are discussed in the following sections.

Chapter 3 Experimental Setup and Procedure

3.1 Experimental Setup and Procedure to Develop Highly Wetted Polypropylene Plate

In this project single plate falling film tower set up has been used. The set up consist of distributor header, vertical tower, solution tank, flow line, bypass line .distributor header and vertical tower is made from acrylic sheet for clear visualization of liquid film. The distributor header is a hollow square (L*B) (26 cm*26cm) cylinder of H=9.5cm.the top side of distributor has been kept open for regular cleaning of slit opening around test plate. Slit opening has been kept 1 mm both side of plate which provides uniform liquid distribution. Vertical tower (L*B*H) (26cm*26cm*63cm) is hollow cylindrical structure. Red colour added water has been used as the working fluid. Red colour has been used for clear visualization of wetted area. Solution line consist of consists of flow line, bypass line. Monoblock pump (Kirloskar, 0.5HP) has been used to circulate the liquid across supply loop. Camera (Canon, 550 D) and light source have been used to capture images of flow pattern. Desired flow rate through the supply line has been set with the help of two ball valves (one ball valve in flow line and another ball valve in bypass line) and monitored with the help of rota meter. Before doing experiment the water has been remixed with red die colour for 20 min. Flow line ball valve has been closed and bypass line ball valve has been opened for remixing of water with red colour. Images of both side of plate are captured by camera. Post processing of these images for wetted area estimation has been carried out using Image software

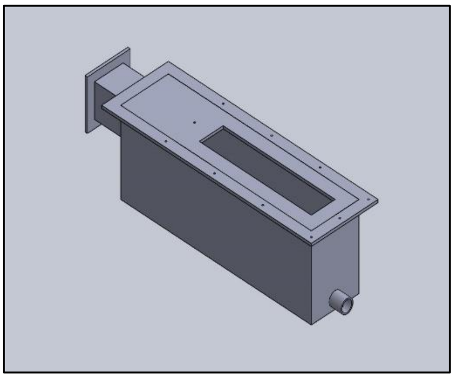


(a) (b)

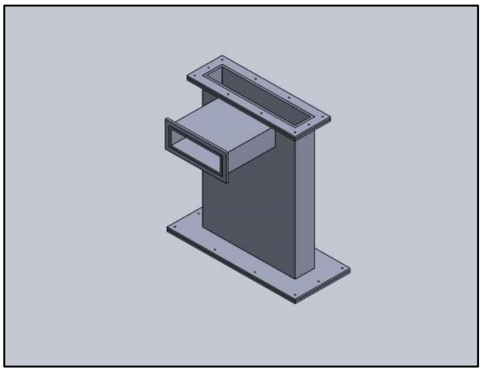
Fig. 3.1 (a) Schematic diagram of experimental setup (b) Experimental setup

3.2 Experimental Setup and Procedure to Study Liquid Desiccant Application

Vertical falling film tower has been fabricated for the study of the objectives laid in chapter 2. Fabricated setup facilitates easy visualization of desiccant film falling on the solid surface and also enables the study of performance of the absorption and the regeneration both using same setup. Design of falling film tower has been made using solid works software .The details of the parts of falling film tower and the procedure are discussed in the following sections.



(a)



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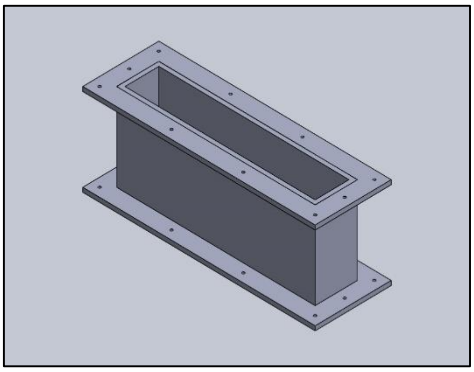
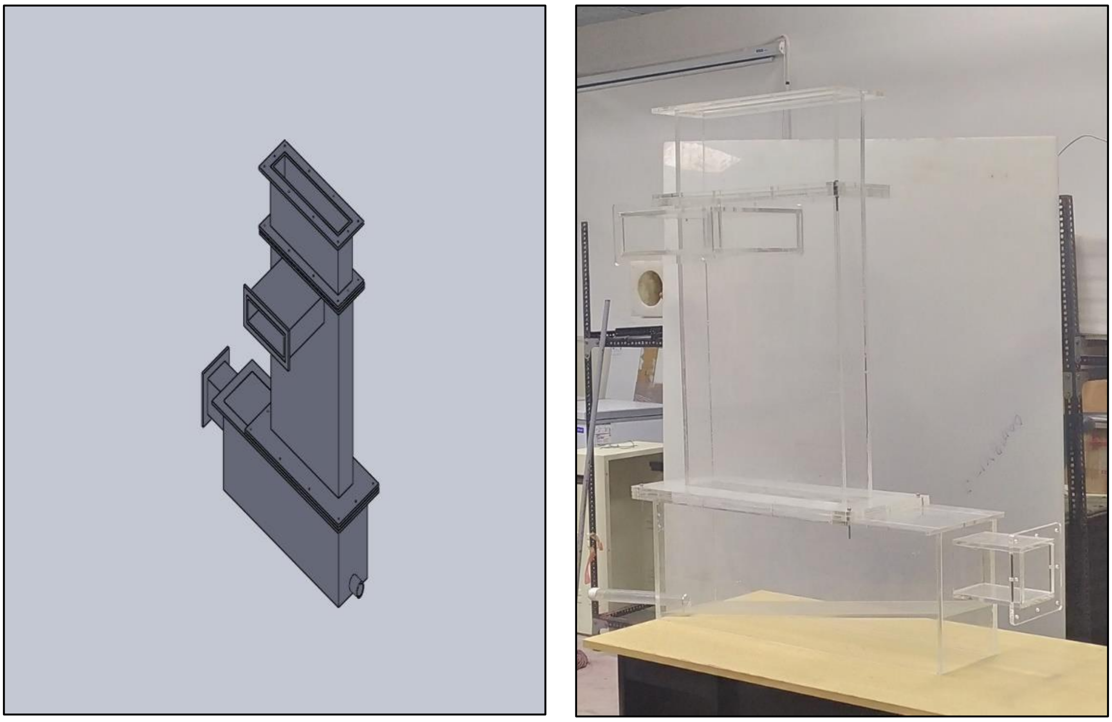


(c)

Fig. 3.2 Schematic diagram of (a) Bottom tank (b) Central part of tower (c) Distributor header



(a) (b)

Fig. 3.3 (a) Schematic diagram of falling film tower (b) Falling film tower

Different parts of vertical falling film tower has been fabricated by laser cutting machine and added with the help of chloroform. The falling film tower has not been connected with solution tank, supply line, blower etc. due to the time limitation of project.so the absorption experiments has been carried out on existing setup in applied thermodynamic lab.

The details of the parameter selection, existing experimental setup and the procedure are discussed in the following sections.

3.3 Experimental Design Guideline and Parameter Selection

The performance of the desiccant system depends on the efficient dehumidifier and regenerator unit, with reference to previous study the operating variables that affect the system performance need to understand. Mainly following factor affect the system performance

1. The liquid to air flow rate ratio.
2. The air flow rate, air inlet temperature

3. The desiccant temperature, concentration of desiccant and desiccant flow rate.

Thus proper selections of operative parameters are of major concern. Selections of operative parameters are discussed from reference listed in literature study.

3.3.1 The Liquid to Airflow Rate Ratio

The liquid to air flow rate ratio is important to improve the performance of the liquid desiccant system. The liquid to air ratio in various study varies from 0.06-5 [6], proper selection of this ratio must be important to wetting of the surface in tower used for dehumidification and regenerator purpose, but higher the liquid to air ratio causes the carryover of the liquid to ambient or in conditioned space it may create the occupant health problem. Thus lower liquid to air ratio are preferred to reduce carryover of liquid, also the system performance reduced as this ratio greater than 2 [8].

3.3.2 Air Flow Rate

The moisture removal rate increases with increasing air flow rate directly proportional to it. Higher air flow rate increases the mass transfer coefficient between the desiccant solution and the air stream, but reduces the contact time. The equilibrium vapour pressure of solution tends to increase due to higher moisture removal thus humidity gradient reduces as air flow rate increases [8]. The air flow rate range is selected from 0.03-0.15 kg/s from previous study [27] to avoid the liquid carryover, generally liquid carryover was found at velocity 4m/s [23].

3.3.3 Desiccant Inlet Temperature

Effect of air inlet temperature for dehumidification and regenerator studied practically [8], [10], [12]. Increase in air temperature vapour pressure of air increases moisture shifts more from air to desiccant, but high increase in air temperature reduces the performance of system due heat transfer from air to liquid due to heat release during condensation of water vapour. In the literature the desiccant inlet temperature range varies 25-35^{o}C for dehumidification and 50-100^{o}C for regeneration.

3.3.4 Desiccant Flow Rate

Desiccant flow rate to attain inside space condition calculate from optimum liquid to air ratio. High solution flow rate ensures good contact between the air and the desiccant and also increases the heat and mass transfer coefficients due to increase in wetting of surface, but increases the hydrodynamic resistance to air flow increases the air side pressure drop [9], [10], [12]. So proper selection of desiccant flow rates is important.

3.3.5 Desiccant Concentration

Partial vapour pressure of desiccant depend on the concentration of desiccant solution, with increase in concentration vapour pressure decreases and absorption capacity increases, but increase of surface tension property of desiccant it reduces the wetting of surface taking part in dehumidification and regeneration. Mostly LiCl, CaCl2 and TEG are used in literature as desiccant in the range of 38-40%, 30-45%, 90-95% respectively. For present work lithium chloride is selected as desiccant with concentration of 39%.

3.4 Experimental Setup Description

The experimental setup for falling film tower shown in Fig. 3.4 and Fig 3.5 mainly consist of air blower, two liquid desiccant receivers of 200 liter capacity each, a rota meter for measuring the desiccant flow rate, PID control, magnetic drive chemical pump and polypropylene plate (working surface) of dimension 400mm×10mm×700mm (length×width×height). Polypropylene used as working surface because of its excellent corrosion resistance properties. The falling film absorption and regeneration tower is constructed from acrylic sheet (t = 9.5 mm) of cross section 450 mm×80 mm (length × width) and 700mm in height to allow for flow visualization. . Distributor's bottom header is provided with 1 mm of slit opening on both side of solid plate. This arrangement is designed to get uniform distribution of solution along the complete width of plate. The liquid after falling through the tower collects inside the used solution tank 6'.

Two 200 liter capacity tanks made up of PP (12 mm thickness) are used as fresh solution tank and used solution tank to store fresh unused liquid desiccant and used lithium chloride solutions respectively. RTD"s (Resistance temperature detector) PT-100 temperature sensors of ± 0.1 ^{0}C accuracy are used for the measurement of DBT and WBT.

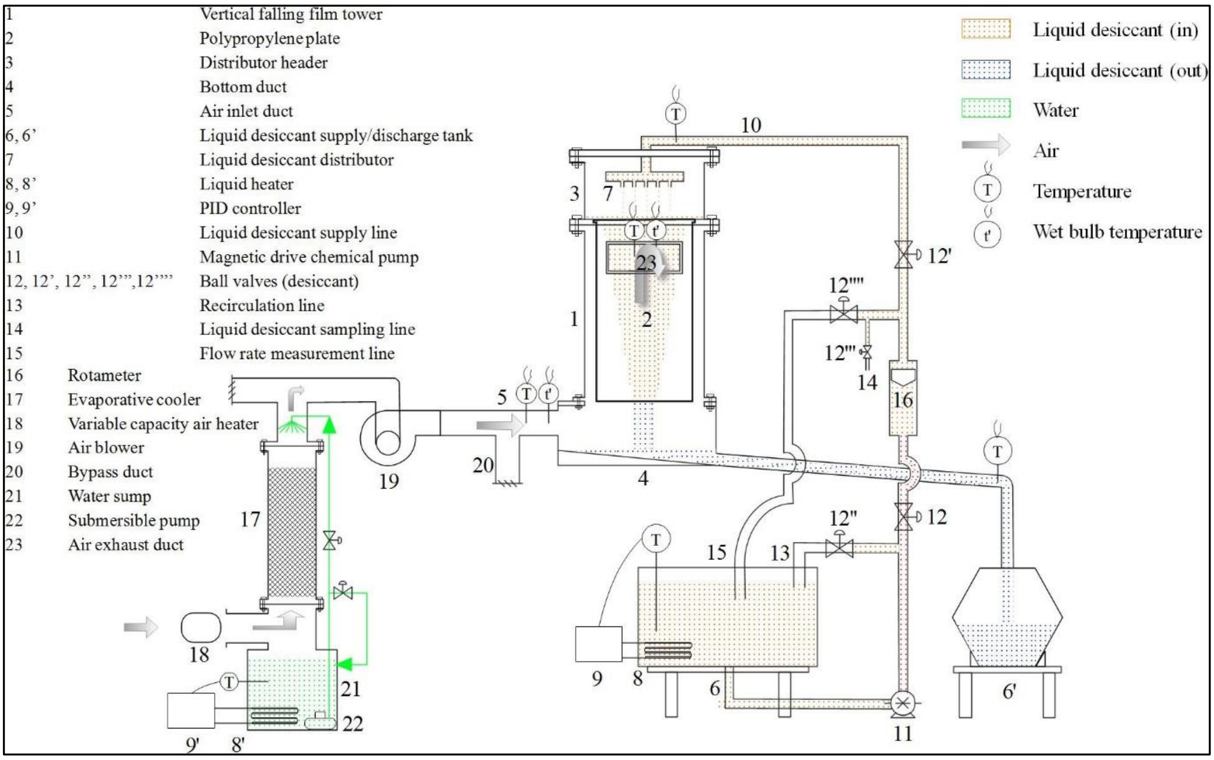


Fig. 3.4 **Schematic diagram of experimental setup [35]**

. A magnetic drive chemical pump ((150 watt, MP-60 pump of Machbow Company). is used to pump liquid desiccant solution from supply tank. The maximum volumetric flow capacity of the Pump is 30 LPM at the head of 7 meters height. The flow rate is measured & controlled by the ball valve rotameter coupled line. The pump impeller is made up of non-corrosive PVDF material. A 3 phase 0.25 HP air blower (max. air flow rate of 280 cfm) is used for driving air inside main unit. The inlet of air blower is connected to air heater coupled evaporative cooling tower, which helps in achieving the required level of temperature and Humidity desired for carry out the experiments. The outlet of blower is connected to the air duct through which excess air is thrown outside setup through bypass line and required mass flow of air is allowed to flow through main unit

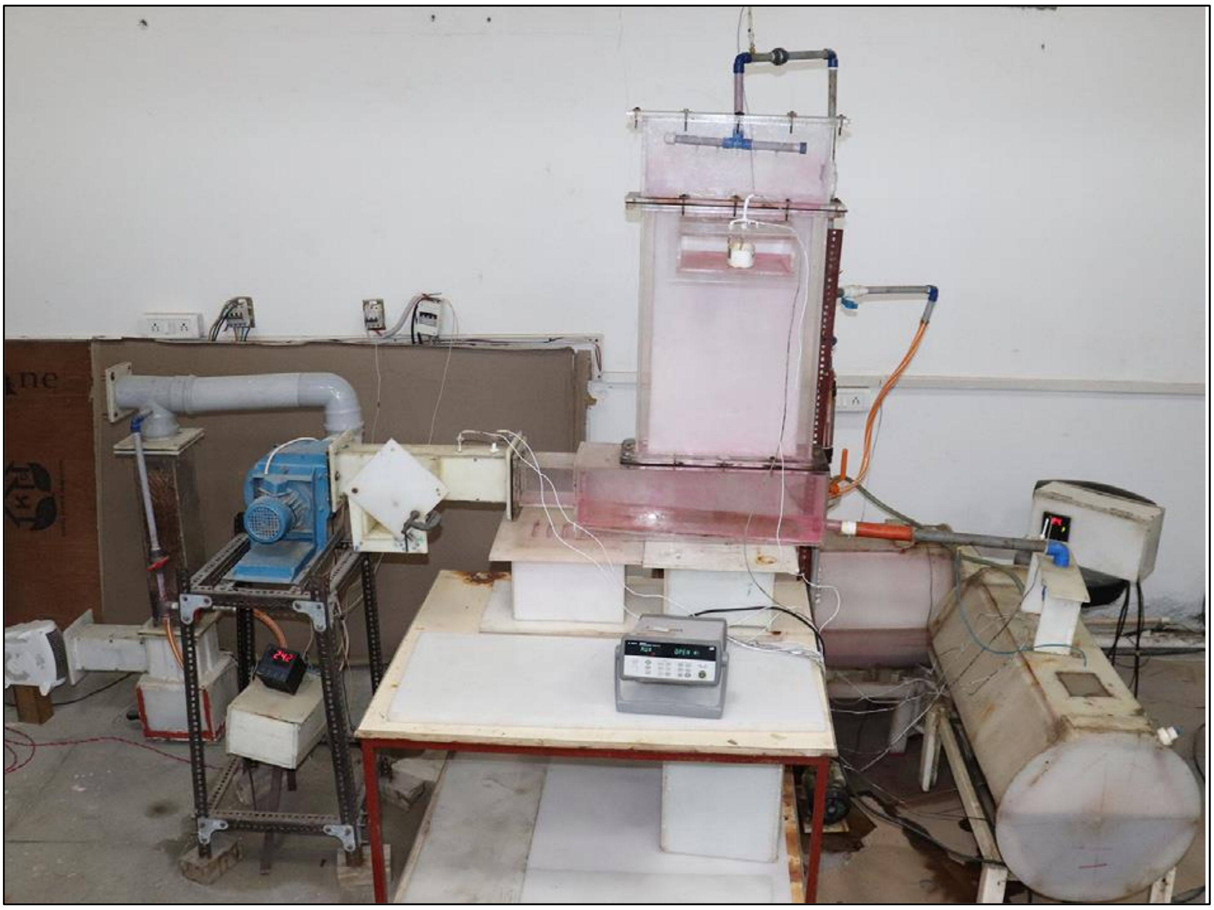


Fig. 3.5 Experimental setup [35]

To evaluate the performance of the dehumidification and regeneration process, it is necessary to measure the flow rate, temperatures of desiccant solution and temperatures of air (DBT and WBT) at inlet and outlet duct. The instruments used for these parameters are as follow:

1. Four wires RTDs PT-100 are used to measure temperature of desiccant solution and air conditions at the inlet and the outlet positions. To measure WBT woven sleeve with water bottles are fixed in air ducts. The air specific humidity is calculated from the measured values of DBT and WBT. One more PID controller with J type thermocouple is used to regulate inlet water temperature of evaporative cooler.

2. Variable flow Rotameter of range 0-15 LPM is used to measure the volume flow rate of liquid desiccant. One by pass solution line is provided prior to rotameter. On the outlet of rotameter; one ball valve is installed to regulate the flow of liquid desiccant across main unit. One outlet line is provided (at rotameter outlet) for the measurement of mass flow rate corresponding to each experimental run. A data acquisition system; Agilent 34972A is used to

monitor and record different parameters. Total 8 RTDs are connected to DATA logger with scanning interval of 3 sec. duration.

The flow rates of air are calculated by measuring air velocity at outlet using vane probe anemometer having measuring rang within 0.8-30m/s an accuracy of ± (2%+0.2m/s), a resolution of 0.1m/s (MODEL: AM-4210). Air velocity measured at various points exit to air outlet duct of cross section 25cm×7.5cm and average values were used to calculate air mass flow rate. Mass flow rate of liquid desiccant measured after completion each experiment by adjusting valve 12'''' and 12' such that rota meter shows same reading that was set during experiment by adjusting valve 12 and 12''. Through sampling line liquid desiccant collected in vessel for 120s. Mass of collected liquid is calculated by dividing liquid collection time to get mass of flow rate of liquid desiccant. Solution is transported back to the supply tank with help of submerged pump.

3.5 Experimental Procedure

3.5.1 Salt Preparation

Liquid desiccant solution is prepared from the laboratory grade dehydrated lithium chloride salt (99.6% purity) available in 2 kg pack of Neogen Chemical Company. The reason for choosing the laboratory grade is to avoid the effect of other impurities on the performance of the experimental runs. RO water has been used for preparing the final salt solution.

The salt solution is prepared inside 20 liter barrel tank and manual stirring is carried out until homogeneous solution forms.

3.5.2 Basic Preparation

The following activities are carried out before starting the experiment.

1. 30 ml Borosil sample bottles for collecting the liquid desiccant samples at inlet and outlet of the falling tower are washed with RO water and dried. This activity is carried out in order to ensure that concentration of the samples is not affected by the impurities present in the sample bottles.

2. Small bottles water sink used for wetting the wicks of WBT sensors are filled with RO water. Further, the wicks of the WBT sensors (RTDs) are cleaned with hot RO water after every 2-3 days to wash away any dust particles collected over the surface of wicks due to impurities of atmospheric air. It is observed that this exercise helps in accurate measurement of WBT.

3. Before the experiment; water level in WBT water sink is maintained at proper level by filling RO water. This helps in avoiding any undesired error in WBT measurement due to less evaporation of water.

4. Air flow rate is set at desired condition by controlling it with bypass duct. Initially, air is only allowed to flow through falling film tower until steady state conditions (same DBT and WBT at inlet and outlet) are achieved.

5. Sampling lines are cleaned before start of each experiment. It is observed that left over solution in the sampling line crystallizes and chokes sampling points especially under cold conditions.

3.5.3 Experimental Procedure for Absorption Case

Experimental conditions for the absorber study are given in Table 3.1.

Sr. No.	Parameter	Initial value
1	Inlet air temperature (^{0}C)	31
2	Inlet air flow rate (kg/s)	0.052
3	Inlet air humidity (g/kg of dry air)	25
4	Inlet liquid desiccant temperature (^{0}C)	25
5	Inlet liquid desiccant flow rate (kg/s)	0.077
6	Inlet liquid desiccant concentration (%)	39

Table 3.1 Experimental conditions for absorber study

1. During the absorption process, the temperature of the liquid desiccant solution is generally low. As no cooling arrangement has been given inside the tank 6, hence, solution temperature is controlled by taking out part of the salt solution out of the receiver tank and cooling it inside the deep freezer. Vice versa heating requirement is fulfilled by heating the solution inside the tank 6 through solution heater.

2. Rest of the experimental procedure remains the same as in the absorption mode (described in the previous section 3.5.2).

3.5.4 Concentration Measurement

Samples of liquid desiccant from the inlet and outlet lines are collected through sampling line in 30ml glass bottle to know the inlet and outlet concentration of liquid desiccant. Density of collected samples is measured by using density meter (Rudolph Research Analytical DDM 2911 PLUS Density Meter) with accuracy of 0.00001 g/cm^3. The solution concentration is calculated by density correlation given by Conde [32]. Before measurement of density, U tube of density meter is rinsed with water and soap solution at 50 ^{0}C. The calibration of machine is carried out by measuring density of air. Then, sample is injected with help of 5 ml syringe. Density of the injected sample appears on monitor. Each sample density is measured twice in order to ascertain accurate concentration.

Chapter 4 Results and Discussion

4.1 Results and Discussion to Develop Highly Wetted Polypropylene Plate

Experiment has been done on four different polypropylene plate having width of grooves 2mm, 3mm, 4mm and 5.5mm respectively to get highly wetted polypropylene plate. The grooves are designed on plate to obtain good wettability even at a low solution flow rate. Four different size of vertical groove on plain plate surface has been proposed based on capillary length phenomenon.

Capillary Length (Ca) = $\sqrt{\frac{\sigma}{\rho g}}$

Where σ = surface tension, ρ=density, g= 9.8 m/s^2

Capillary length for water is 2.69mm

Hence to get the optimized channel width, wetting behavior of four different plates has been experimentally investigated.

Test plate	Width(w in mm)	Depth (d in mm)	Fin width(f in mm)
1	2	0.5	1
2	3	0.5	1
3	4	0.5	1
4	5.5	0.5	1

Table 4.1 Dimensions of grooved plates

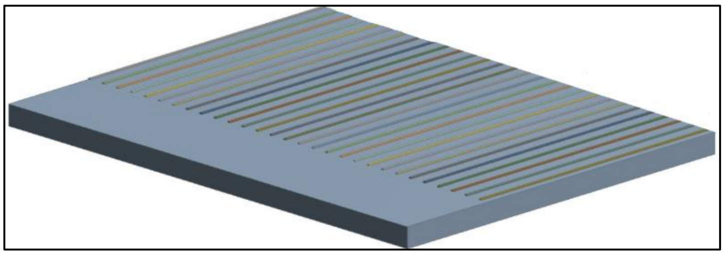
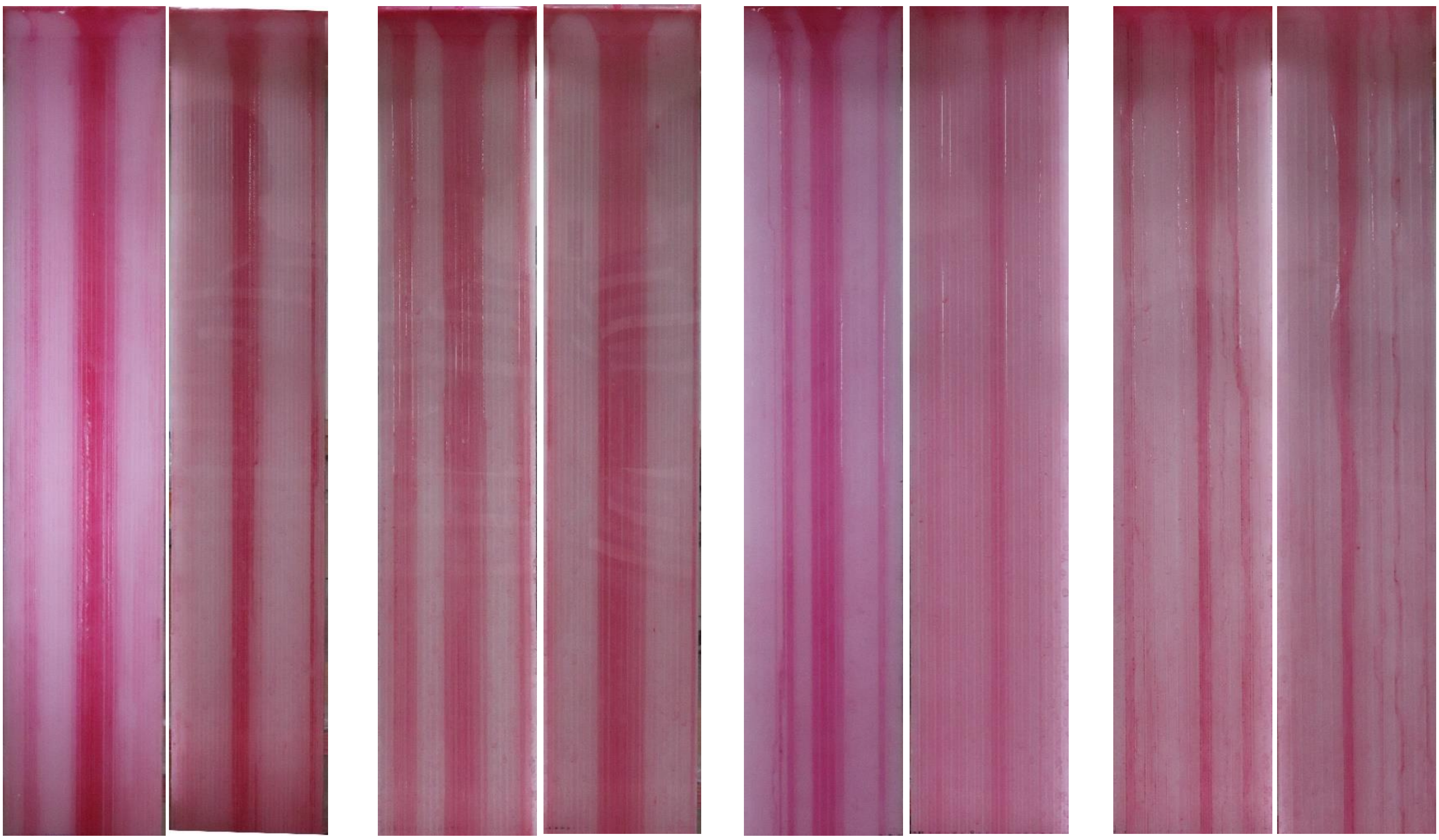


Fig. 4.1 Plate with vertical grooves



(a) (b) (c) (d)

Fig. 4.2 Flow pattern on plates having groove width (a) 2mm (b) 3mm (c) 4mm (d) 5.5mm at 0.015 kg/s

Experimental test shows that when width of groove is less than the capillary length then solution flows outside of the grooves because of more surface tension effect. When the width of groove is greater than the capillary length then solution wet the base of the grooves because of less surface tension effect. When the width of groove are too wide compared to the capillary length (w≥ 2Ca) then solution does not wets the entire base of the grooves for the flow range studied.

Wettability of the filler surface is mainly manifested by the wetting factor which is defined as follow:

Wetting Factor ($\in_w$) = $\frac{A_w}{A_b}$

Where Aw is Projection area of liquid film on the plate and Ab is the area of plate

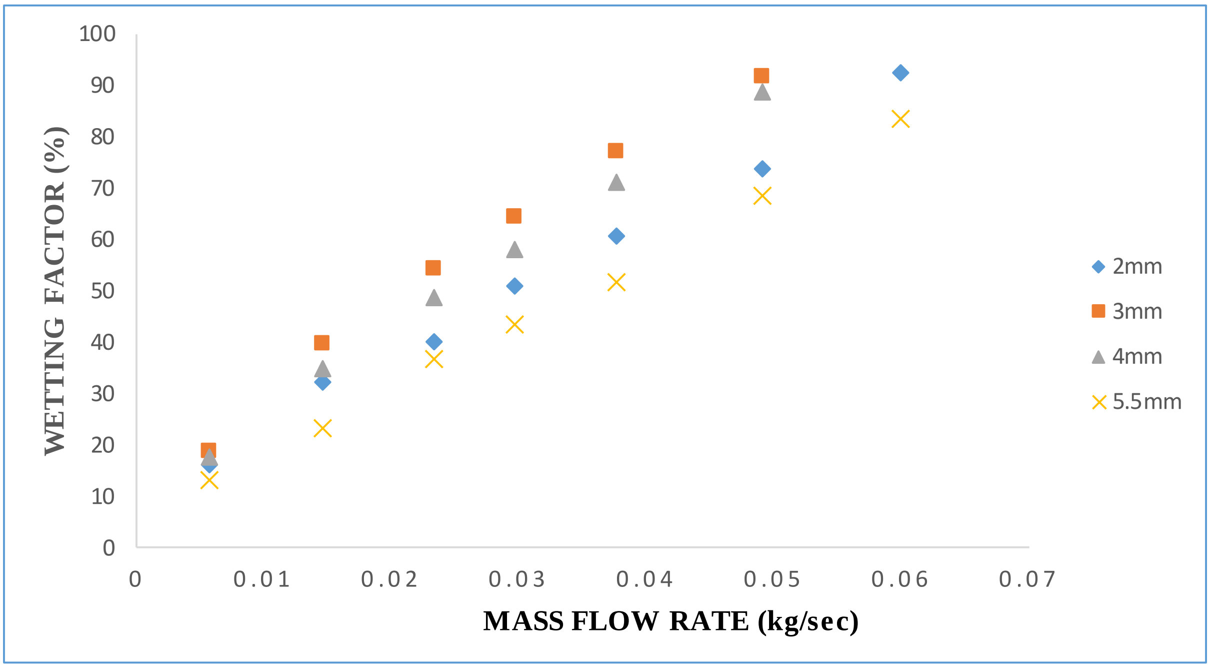


Fig. 4.3 Comparison of wetting factor for four different plates having groove width 2mm, 3mm, 4mm, 5.5mm respectively.

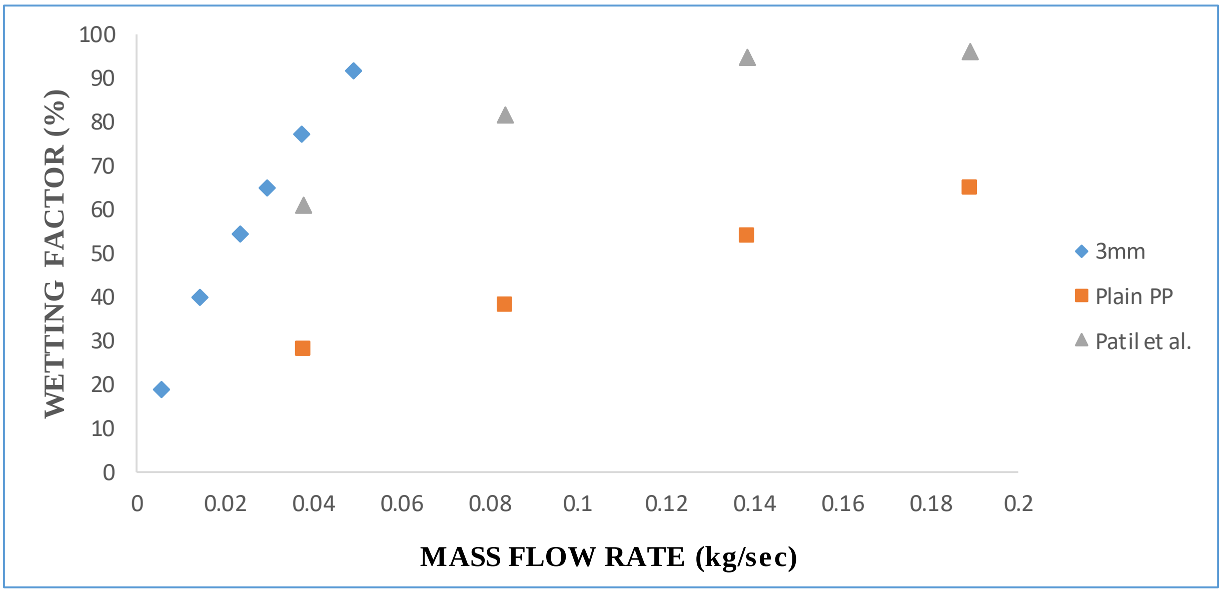


Fig. 4.4 Comparison of wetting factor for 3mm plate, plain PP and Patil et al.

Fig. 4.3 shows that wetting factor of plate having groove width 3mm is more than plates having groove width 2mm, 4mm and 5.5mm respectively at low and high flow rate. Average wetting factor for plate having 3mm groove width is 26.31% and 8.4 % higher than plates having groove width 2mm and 4mm respectively.

Fig 4.4 shows that wetting factor of plate having 3mm width is more than modified Patil et al. plate.

4.1.1 Wetting Factor Correlation

From patil et al. 2016, correlation for wetting factor is as follow:

$$\epsilon_w = \frac{10.17\ (Re)^{0.24}\,(\gamma)^{0.03}\,(\frac{A_{ext}}{A})^{0.42}}{(\frac{\sigma_l}{\sigma_w})^{0.55}}$$

Where Re= Reynolds number, γ = Surface energy, A_{ext}=Extended surface area of modified surface,σ_l =Surface tension of liquid, σ_w= surface tension of water

Where Re=$\frac{4m_l}{\mu W}$

μ= viscosity of liquid, m_l=mass flow rate, W=width of plate

$$\text{MAPE (\%)} = \frac{100}{N}\sum_{i=1}^{N}\left|\frac{\epsilon_{experiment,i}-\epsilon_{prediction,i}}{\epsilon_{experiment,i}}\right|$$

Plates	MAPE (%)
2mm	31.55
3mm	33.30
4mm	32.10
5.5mm	39.10

Table 4.2 MAPE for all four plates

MAPE is above 30% for all four plates so new wetting factor correlation is developed for vertically grooved plates.

New wetting factor correlation is as follow:

$$\epsilon_w = 2.50(Re)^{0.73}(\gamma)^{0.69}(\frac{A_{ext}}{A})^{4.09}(Bo)^{0.18}$$

Where Bo=$(\frac{w}{Ca})^2$, Bo is defined as bond number

Where w = width of groove

MAPE for new wetting factor correlation is as follow:

Plates	MAPE (%)
2mm	11.15
3mm	20.47
4mm	3.85
5.5mm	16.27

Table 4.3 MAPE for new wetting factor correlation for different plates

Table 4.3 shows that average MAPE is 13% for new wetting factor correlation which is better than previous correlation.

4.2 Results and Discussion for Absorption Study

Selection of experimental parameter has been discussed in section 3.5.1. Experimentation is done on the setup with varying in operating parameter such as solution flowrate, inlet desiccant temperature, inlet air humidity. For evaluating the effect of each independent parameter on the system performance, one of the parameters is varied, while others are kept constant. Three or four independent sets of readings have been taken for each individual parameter in order to understand its effect on performance of the system.

4.2.1 Performance Index

The performance of the absorption depends on the following factor:

1. Maximum possible contact between liquid and air.
2. Efficient heat transfer.

This above factor can achieved in a falling film absorber in which both gas to be absorbed and absorbing liquid flow downward. The liquid flows at such a rate that the surface do not flow full of the liquid but instead, run down by gravity along the surface as a thin film. This produces a much greater linear velocity for a given flow rate than could be obtained in packed tower absorber.

Effectiveness of absorption is most commonly studied as performance index of the absorption. It is the ratio of the actual change in the moisture content of air taking place in the desiccant-air contacting equipment to the maximum possible change in the moisture content at given operating conditions [6].

$$\varepsilon = \frac{(Wa,in - Wa,out)}{(Wa,in - Wa,eq)}$$

Wa, in= Moisture content in air initially

Wa, out= Moisture removal from air during process

Wa, eq = Moisture at equilibrium condition for an insulated absorber, the maximum possible difference in humidity ratio of air is obtained when air is in equilibrium with the inlet desiccant solution, i.e. when the partial pressure of water in the air is equal to the vapour pressure of the inlet desiccant solution and the driving force for mass transfer is zero.

$$W_{eq} = 0.622\frac{Psol}{P - Psol}$$

Where Psol is vapour pressure of solution which is the function of solution concentration and temperature. Psol increases with increase in solution temperature and decreases with increase in solution concentration.

Absorption rate of absorber gives the transfer of more vapour as possible from inlet air to the desiccant solution. Absorption rate is used to determine the amount of vapour removed from inlet air in an absorber is given as below.

$$m_{abs} = m_a(\Delta W)$$

Where $\Delta W = ABS(W_{a,in} - W_{a,out})$ is change in absolute air humidity and m_a is air flow rate.

4.2.2 Performance Analysis of Absorption

(1) Effect of Desiccant Flow Rate

The mass flow rate of liquid desiccant is varied by changing the set value on the rota meter. It can be seen from figure 4.5 (a), (b) and(c) that change in specific humidity, dehumidification effectiveness and absorption rate increase as the mass flow rate of liquid desiccant increased. High solution flow rate ensures good contact between the air and liquid desiccant and also increases the heat and mass transfer coefficients due to increase in wetting of surface. Higher solution flow rate also helps in maintaining low equilibrium vapour pressure of solution throughout the absorber, which improves the overall mass transfer and change in specific humidity occurring inside the absorber. Therefore, the performance of the system improves.

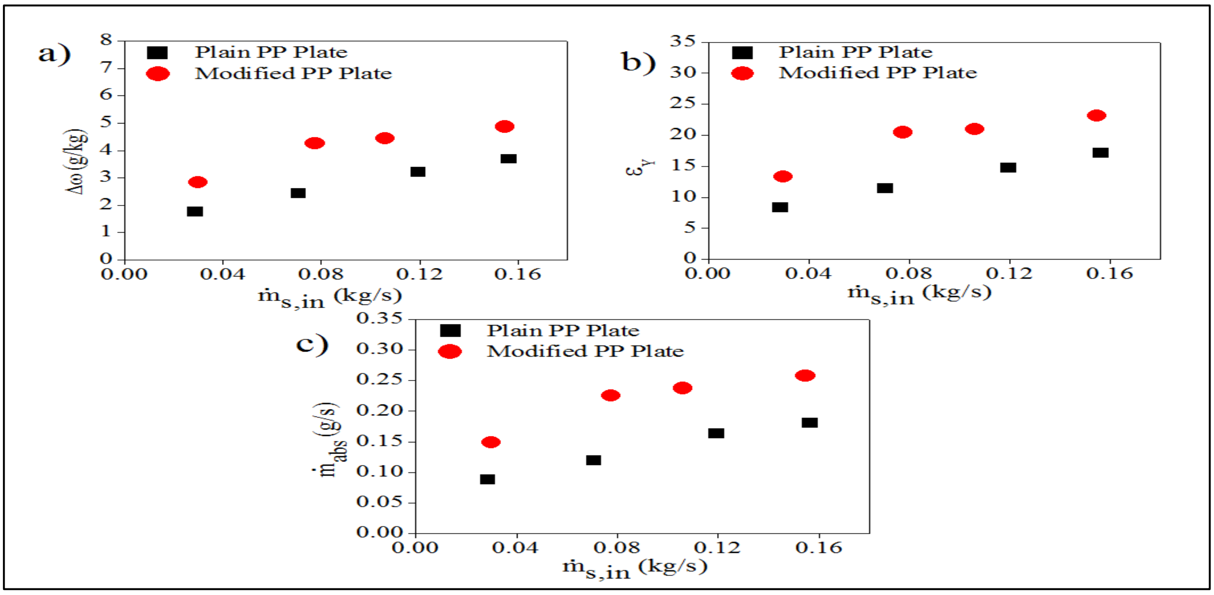


Fig. 4.5 Effect of the mass flow rate of the liquid desiccant on (a) Change in specific humidity (b) Dehumidification effectiveness (c) Absorption rate

(2) Effect of Desiccant Temperature

The inlet temperature of the solution is increased by heating the liquid desiccant solution inside the storage tank. As the liquid desiccant inlet temperature is increased, the change in specific humidity, dehumidification effectiveness and absorption rate of air decrease. In general, equilibrium vapour pressure of the liquid desiccant increases with increase in its temperature; it reduces the overall mass transfer occurring inside the absorber. Therefore, rate of moisture transfer and change in specific humidity decrease with increase in inlet solution temperature.

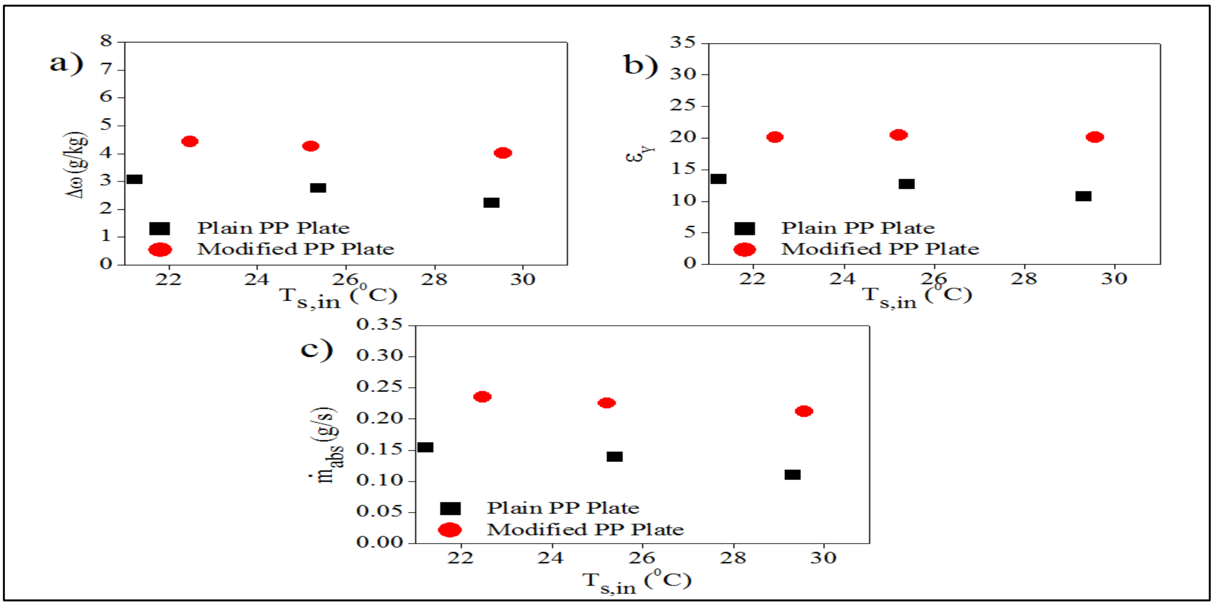


Fig. 4.6 Effect of the liquid desiccant inlet temperature on (a) Change in specific humidity (b) Dehumidification effectiveness (c) Absorption rate

(3)Effect of Inlet specific humidity

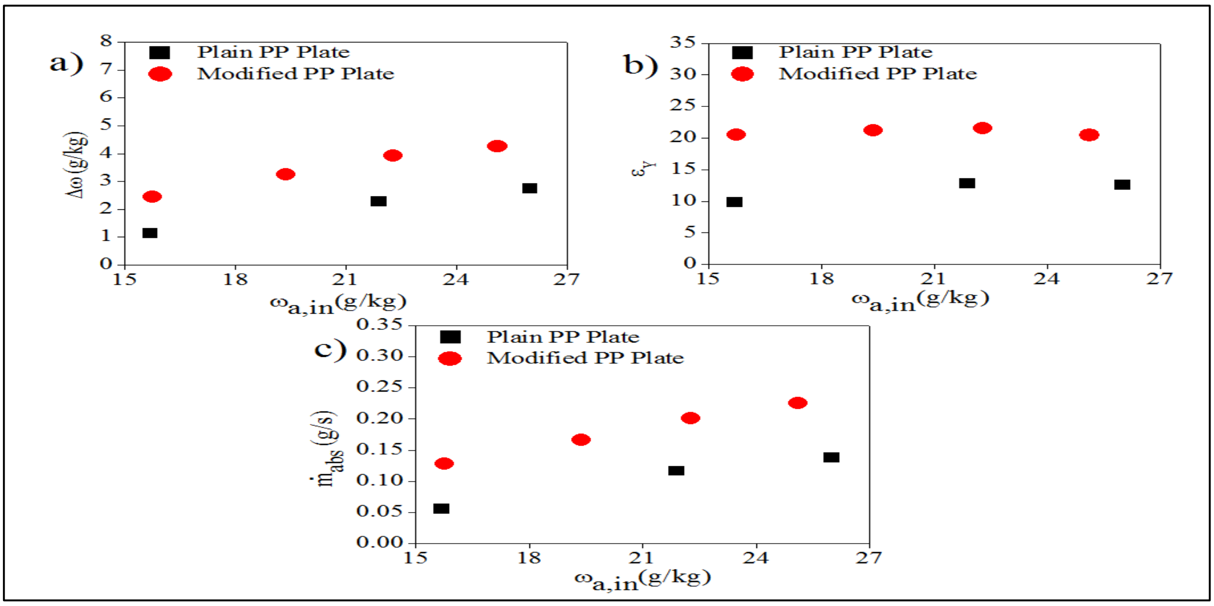


Fig .4.7 Effect of the inlet air specific humidity on (a) Change in specific humidity (b) Dehumidification effectiveness (c) Absorption rate

It is noticed from figure 4.7 (a), (b) and (c) that as the inlet specific humidity of air is increased, change in specific humidity, Dehumidification effectiveness and moisture removal rate of air increases. The above trend can be attributed to the fact that as the inlet specific humidity of air increases, it increases the potential of mass transfer.

Chapter 5 Conclusions and Future Scope

The main objective of the present work was to develop highly wetted polypropylene plate for liquid desiccant application, to develop correlation for vertically grooved plates, fabrication of falling film tower and absorption study. The issue of carry over and corrosion, commonly associated with liquid desiccant systems were removed by replacing metallic surface with the polymer (polypropylene) due to inert nature toward desiccant. Following conclusion has been drawn from the experimental study.

5.1 Conclusions from Wetting Experiments

1. The plate surface with 3mm groove width shows consistent performance at low and high flow rate.

2. Average wetting factor for plate having 3mm groove width is 26.31% and 8.4 % higher than plates having groove width 2mm and 4mm respectively.

3. The proposed correlation shows superior performance as compared to previous model and it predicts the current datasets with MAPE of 13%.

5.2 Conclusions from Absorption Study

1. The modified plate shows superior performance for all parameters in the studied range, the average increment in absorption rate for change in mass flow rate, change in solution temperature and change in specific humidity is 55%, 68% and 88% respectively.

2. Out of analyzed parameters, mass flow rate of solution shows noteworthy impact on moisture effectiveness.

3. The study is useful for designing liquid desiccant system operating at low flow rate conditions.

5.3 Future Scope

1. Need to identify the noncorrosive desiccant.
2. Incomplete wetting of the contact surfaces degrades the performance of system thus finding of good contacting surface with high surface energy and good thermal property is necessary.

References

1. Review of Liquid Desiccant Technology for HVAC Applications Andrew Lowenstein, PhD.
2. Lesson 29 Inside And Outside Design Conditions, Version 1 ME, IIT Kharagpur, *nptel.ac.in/courses/112105129/pdf/R&AC%20Lecture%2029.pdf*
3. J. Mishra, P.K. Sahoo, "Performance studies of hybrid solid desiccant–vapor compression air-conditioning system for hot and humid climates", Energy and Buildings, 102 (2015) 284–292.
4. X. Wang, W. Cai, J. Lu, Y. Sun, X. Ding, "A hybrid dehumidifier model for real-time performance monitoring, control and optimization in liquid desiccant dehumidification system", Applied Energy 111 (2013) 449–455.
5. R. Kumar, "Studies on standalone liquid desiccant based air-conditioning systems", Ph.D. Thesis, Mechanical Engineering Department, IIT, Delhi, 2008.
6. S. Jain, P.K. Bansal, "Performance analysis of liquid desiccant dehumidification systems", International Journal of Refrigeration, 30 (2007) 861-872.
7. D. Patil, R. Kumar, F. Xiao, "Wetting enhancement of polypropylene plate for falling film tower application", Chemical Engineering and Processing: Process Intensification, 2016, "In press" doi:10.1016/j.cep.2016.06.005.
8. E. Elsarrag., "Performance study on a structured packed liquid desiccant regenerator", Solar Energy, 80 (2006) 1624–1631.
9. Y. Yin, X. Zhang.,"Comparative study on internally heated and adiabatic regenerators in liquid desiccant air conditioning system", Building and Environment, 45 (2010) 1799-1807.
10. N Fumo and D. Y. Goswami., "Study of an aqueous lithium chloride desiccant system: air dehumidification and desiccant regeneration", Solar Energy, 72 (2002) 351–361.
11. Y. Yin, X. Zhang, Z. Chen., "Experimental study on dehumidifier and regenerator of liquid desiccant cooling air conditioning system", Building and Environment, 42 (2007) 2505–2511.

12. C.G. Moon, P.K. Bansal, S. Jain., New mass transfer performance data of a cross-flow liquid desiccant dehumidification system", International Journal Of Refrigeration, 32 (2009) 524 – 533.
13. Y. Yin, X. Zhang, G. Wang, L. Luo., "Experimental study on a new internally cooled/heated dehumidifier/regenerator of liquid desiccant systems", International Journal Of Refrigeration, 31 (2008) 857–866.
14. L. Wang, F. Xiao, X. Zhang, R. Kumar., "An experimental study on the dehumidifier performance of a counter flow liquid desiccant dehumidifier", International Journal Of Refrigeration, 16 (2016).
15. K. Gommed, G. Grossman., "Experimentally investigation of a liquid desiccant system for solar cooling and dehumidification", Solar Energy, 81 (2007) 131-138.
16. K. Gommed, G. Grossman., "Investigation of an improved solar powered open absorption system for cooling dehumidification and air conditioning", International Journal Of Refrigeration, 35 (2012) 676-684.
17. R. Kumar, P.L. Dhar, S. Jain, "Development of new wire mesh packings for improving the performance of zero carryover spray tower", Energy, 36 (2011) 1362-1374.
18. Y. Yin, X. Zhang, "Comparative study on internally heated and adiabatic regenerators in liquid desiccant air conditioning system", Building and Environment 45 (2010) 1799-1807.
19. Kang, K. H. Kim, D. Y. Lee, "Fluid flow and heat transfer on a falling liquid film with surfactant from a heated vertical surface", Journal of Mechanical Science and Technology, 21 (2007) 1807-1812.
20. S. Jain, P.L. Dhar, S.C. Kaushik., "Experimental studies on the dehumidifier and regenerator of a liquid desiccant cooling system", Applied Thermal Engineering, 20 (2000) 252-267.
21. S. Bouzenadaa, C. McNevin, S. Harrison c, A. N. Kaabi., "An experimental study on the dehumidification performance of a low-flow falling-film liquid desiccant air-conditioner", Procedia Computer Science, 52 (2015) 796 – 803.
22. R. Qi, L. Lu, H. Yang, F Qin., "Influence of plate surface temperature on the wetted area and system performance for falling film liquid desiccant regeneration system", International Journal of Heat and Mass Transfer, 64 (2013) 1003–1013.
23. W. Kessling, E. Laevemann and C. Kapfhammer., "Energy storage for desiccant cooling systems component development." Solar Energy, 64 (1998) 4–6 209–221.

24. A. Rahamah, M. M. Elsayed and N. M. Al-Najem., "A numerical solution for cooling and dehumidification of air by a falling desiccant film in parallel flow", Renewable Energy, 13 (1998) 305-322.
25. A. Gonda, P. Lancereau, P. Bandelier, L. Luo, Y. Fan., "Water falling film evaporation on a corrugated plate", International Journal of Thermal Sciences, 81 (2014) 29-37.
26. A. M. I. Mohamed., "Experimental study of heat transfer and flow characteristics of liquid falling film on a horizontal fluted tube", Heat Mass Transfer, 46 (2010) 841–849.
27. R. Qi, L. Lu, H. Yang, F. Qi., "Investigation on wetted area and film thickness for falling film liquid desiccant regeneration system", Applied Energy, 112 (2013) 93–101.
28. D.S. Kim, C.A. I. Ferreira., "Flow patterns and heat and mass transfer coefficients of low Reynolds number falling film flows on vertical plates: Effects of a wire screen and an additive", International Journal Of Refrigeration, 32 (2008) 138 –149.
29. A. Ali, K. Vafai, A.-R. A. Khaled., "Comparative study between parallel and counter flow configurations between air and falling film desiccant in the presence of nanoparticle suspensions", International Journal Of Energy Research, 27 (2003) 725–745.
30. www.kathabar.com/pdfs/Technical_Dat.
31. www.niagarablower.com..com/, www.districenergy.org/assets/pdf.
32. M.R. Conde, "Properties of aqueous solutions of lithium and calcium chlorides: formulations for use in air conditioning equipment design", International Journal of Thermal Sciences, 43 (2004) 367–382.
33. P. Gandhidasan., "A simplified model for air dehumidification with liquid desiccant", Solar Energy, 76 (2004) 409–416.
34. Benoit Michel, Nolwenn Le Pierres, Benoit Stutz, " Performances of grooved plates falling film absorber" Energy, 0360-5442
35. Ritunesh kumar, digvijay patil, Fu Xiao, Tao Lu " Performance intensification of regeneration process for non-corrosive plastic plate vertical falling film tower" Applied thermal engineering, 1359-4311