A STUDY OF DEHUMIDIFICATION AND REGENERATION PROCESSES IN A HYBRID COOLING SYSTEM

BY

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Dedicated to

My Beloved Parents

Whose constant prayers, sacrifice, and

inspiration

Led to this accomplishment.

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Abstract

Name: Mohammed Salman Abdul Gaffar

Title: A Study of Dehumidification and Regeneration Processes in a Hybrid Cooling System

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A hybrid liquid desiccant based vapor compression system has been experimentally studied in humid environment. $CaCl_2$, LiCl and mixtures of both have been tested as desiccants in the hybrid system. The ambient air is dehumidified in the dehumidifier and then the air is sensibly cooled in the evaporator before sending it into the conditioned space. The weak desiccant, which absorbs the moisture from the humid air in the dehumidifier, is regenerated using the waste heat from the condenser. The effects of various parameters like packing height, desiccant concentration, temperature and flow rates of the desiccant and air that influence the hybrid system have been investigated. The performances of the hybrid system are evaluated using various performance indices such as effectiveness of the dehumidifier and regenerator and coefficient of performance. The economic analysis for the hybrid system has also been carried out in detail.

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ملخص الاطروحة

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فى هذاالبحث تم اجراء دراسة معملية لاختيارجهاز تبريد مهجن يعمل بضغط البخار وسائل مجفف فى جو رطب. و استحدم كلوريد الكالسيوم و كلوريد الليثيوم ومزيجيهما فى الجهاز المهجن كسوائل مجففة. تم امتصاص رطوبة الهواء الخارجي فى مجفف الهواء ومن ثم تم تبريده فى المبخر قبل ارساله الى الحيز المكيف. تم اعادة تركيز السائل المجفف الذى امتص الرطوبة من الهواء الرطب باستخدام الحرارة الناتجة من المكثف، كذلك تم التحقق من تاثير عدد من المتغيرات على اداء الجهازمثل سماكة مادة الحشو، تركيز السائل المجفف،درجات الحرارة ومعدلات السريان لسائل التجفيف والهواء. و تم تقويم اداء الجهاز المهجن باستخدام معاملات الكفاءة المختلفة مثل كفاءة المجفف ومعامل كفاءة المسترجع ومعامل كفاءة الاداء و كذلك تم اجراء دراسة تحليلية اقتصادية عن اداء الجهاز المهجن .

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Nomenclature

A	- total saving for a year, SR/year
$F^{\cdot}$	- salvage value, SR
i	- interest rate, %
m	- mass flow rate, kg/s
P	- pressure, mm Hg
P_i	- initial investment, SR
Q	- volumetric flow rate, l/min or l/h
RH	- relative humidity, %
SF	- savings factor, %
Sg	-Specific gravity
T	- temperature, °C or K
T_G, T_L	- temperature for air and liquid, respectively, °C
$w_1, w_2, \ldots, w_n$	- uncertainties in the independent variables
w_R	- uncertainty in the result
Z	- height of packing from the bottom, m

Greek letters

ε	- effectiveness
ε'	- average effectiveness

ξ - concentration of the desiccant by weight, %

ω - absolute humidity, kg of water/kg of dry air

ψ - concentration weight fraction or volume fraction

Superscripts

l - liquid

o - at reference state

Subscripts

con - conventional unit

D - *dehumidifier*

R - *regenerator*

F - fan

G - air

ha - humid air

i or in - inlet

id - ideal

L - desiccant

max - maximum value

o or out - outlet

P - pump

ref - reference state

ε - effectiveness

CHAPTER 1

INTRODUCTION

Air conditioning is an energy intrinsic process, especially in hot, humid climates such that existing in the Eastern province of Saudi Arabia. Statistics revealed that 30% of the total energy consumption in Saudi Arabia is consumed in air conditioning [1]. Hence, a new approach to air conditioning is required due to growing concern for conservation of energy, improved comfort and environmental control, and increased ventilation requirements.

The air conditioning load consists of latent (dehumidification) and sensible (temperature control) loads. The conventional air conditioning usually cools and dehumidify simultaneously in a high-energy intensive process. If humid air is cooled below its dew point temperature, condensation of moisture will occur resulting in the air dehumidification as shown in Fig. 1.1. Usually the air has to be reheated to a comfortable condition temperature before it is introduced into the conditioned space in order to avoid excessive sensible cooling. Although this is generally done by using free waste heat or by mixing with return air, the cooling process itself requires more energy. Since the evaporator in the vapor compression system normally operates at a lower temperature than what is required to meet the sensible cooling load, coefficient of performance is low.

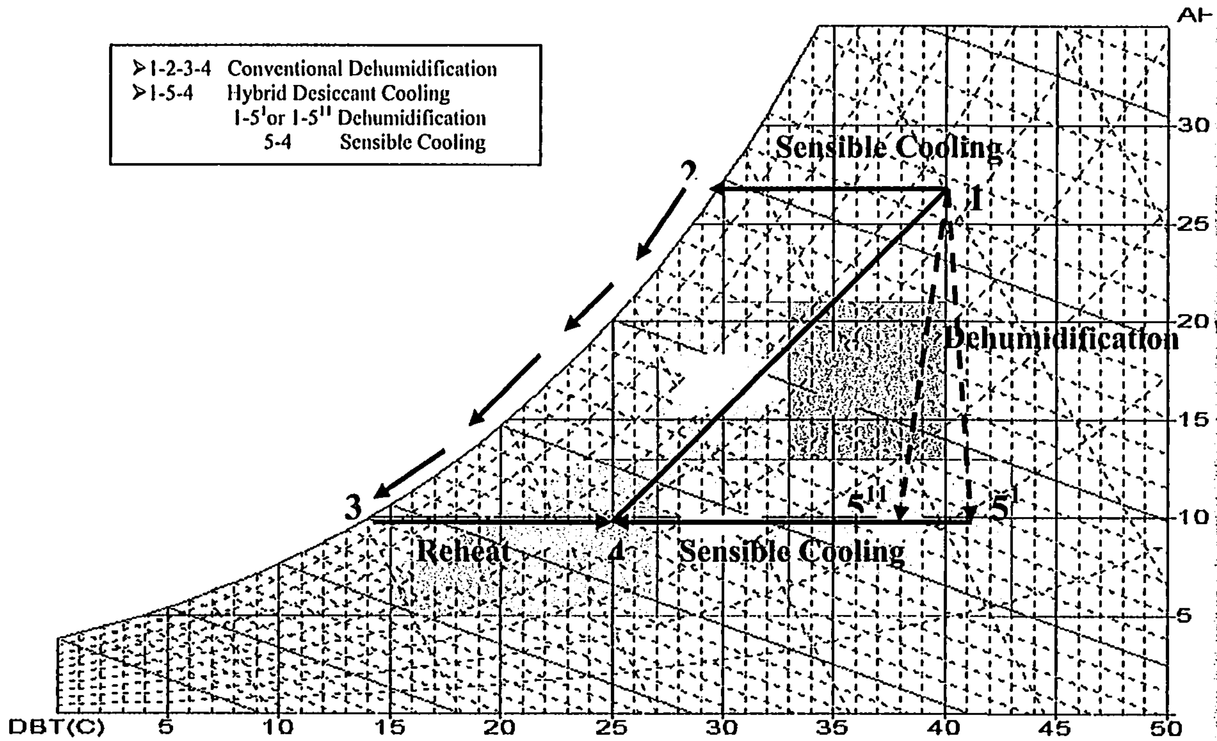


Figure 1.1: Psychrometric chart depicting dehumidification methods.

Moreover, energy efficient vapor compression systems operating at higher evaporator temperatures, are unable to maintain the indoor relative humidity within a comfortable range in hot and humid climates [2]. In humid climates cooling can be accomplished by non-conventional methods also. The air to be conditioned is first dehumidified by means of a suitable desiccant followed by adiabatic evaporative cooling [3-6].

Desiccant technology has excellent potential for cost-effective application in buildings located in hot, humid climates to make major contributions to energy conservation, improve indoor air quality through reduced microbial growth and by removing air pollutants [7]. Latent cooling load is removed by desiccant and conventional air conditioners are used to provide sensible cooling. Desiccant dehumidifier offers alternative to the systems now in common use especially in humid climates. The dehumidifier/regenerator column can be packed either randomly or with structured packing. Structured packing represents the newest development in high efficiency, high capacity packing for mass and heat transfer that has been introduced recently in contrast to the traditional packing.

Desiccant systems offer significant potential for energy savings and reduced consumption of energy. In addition desiccant systems reduces or eliminate the use of CFCs if it is used in conjunction with vapor absorption units or reduced if integrated with vapor compression units. Air dehumidification with liquid desiccants has some significant advantages over the solid desiccants. The regeneration temperature required for liquid desiccants is lower than solid desiccants. In liquid desiccant system part of weak desiccant can be re-concentrated and then mixed with remaining liquid. Also, liquid desiccants can be used as a heat transfer medium in a heat exchanger to be pre-cooled or pre-heated as required. The ability to pump the liquid makes it possible to connect several small dehumidifiers to one large regeneration unit [8]. Indoor air quality is improved because of higher ventilation and fresh air rates associated with desiccant systems. Such systems also offer lower humidity control levels and the capability to remove airborne pollutants. With desiccant systems, air humidity and temperature are controlled separately, enabling better control humidity. Dehumidifying with a liquid desiccant usually scrubs the air stream, not only providing conditioning but also cleaning and disinfecting the air.

Rising energy costs are making desiccant equipment even more attractive for a wide range of air-conditioning applications including comfort-air conditioning systems as well as industrial and process air conditioning systems.

1.1 Present Study

In the present study hybrid liquid desiccant cooling system combines a structured packing liquid desiccant dehumidifier with a vapor compression unit is investigated. The system utilizes a liquid desiccant to remove the latent load and a vapor compression unit to provide the sensible cooling. The schematic of the proposed cooling system is shown in Fig. 1.2. The major parts of the hybrid system consist of a 5-ton conventional vapor compression unit, a packed bed dehumidifier, a packed bed regenerator, pumps for the desiccant, auxiliary heater, two blowers and a heat exchanger. The ambient air enters the gauze type structured packing dehumidifier as shown in Figure 1.2. After the dehumidification process, the warm, dry air is not suitable for comfort conditions.

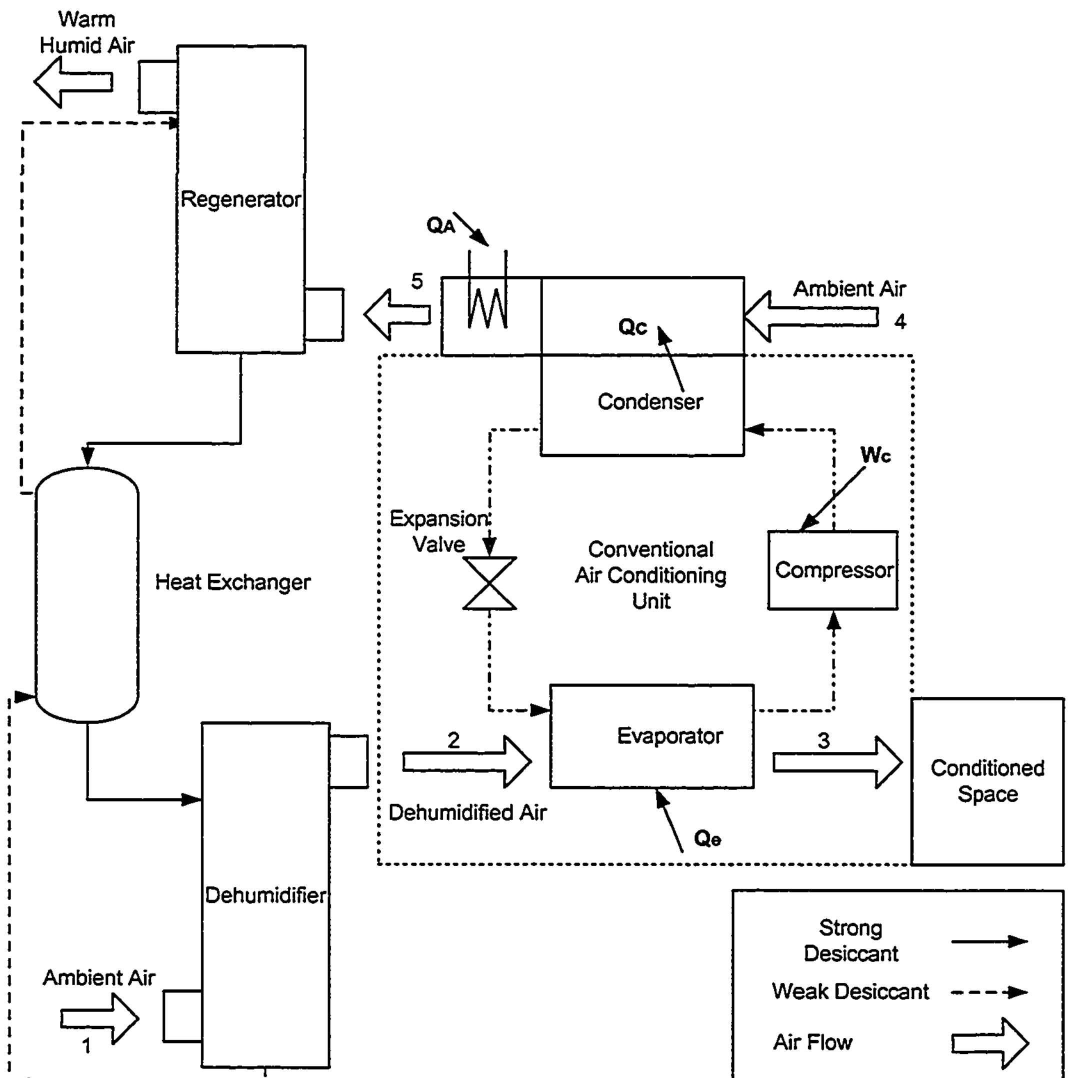


Figure 1.2: Schematic of the hybrid cooling system

Hence, after removing the latent-cooling load in the dehumidifier, the dehumidified air is passed over the evaporator coil in the conventional vapor-compression unit. The air is sensibly cooled and the conditioned air is then delivered to the conditioned space. The weak desiccant leaving the dehumidifier is heated in a desiccant-to-desiccant heat exchanger before it is send to the regenerator. The blower in conjunction with heater is installed on the top of the condenser in such way that the air coming out from the condenser can be easily made to pass through the regenerator inlet. The weak desiccant is sprayed into the regenerator and it is made into contact with the hot air in the packing material in counter flow direction. The air absorbs water from the desiccant as it trickles down the tower. The desiccant leaving from the regenerator is cooled in a heat exchanger before it is again send to the dehumidifier.

1.1.1 Objectives

The main objective of the thesis is to carry out an experimental investigation to study the performance of hybrid cooling system using calcium chloride, lithium chloride and their mixtures. The study of air dehumidification and desiccant regeneration process is carried out by varying important parameters includes like desiccant concentration, desiccant inlet temperature and flow rates, air humidity ratio and packing height.

The performance of desiccant cooling system is compared to conventional system using coefficient of performance. Economic analysis and uncertainty of the system is also carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 Desiccants

Liquid desiccant systems have emerged from their 50-year old heritage in industrial dehumidification to take a more prominent role in air conditioning. The systems are to provide improved air quality and enhanced occupant comfort with a reduced operating cost. In this chapter, a detailed literature review related to liquid desiccant cooling system is presented in the form of tables for easy comparison with key variables.

In the liquid desiccant systems, the moisture from the air is removed by the desiccant and then the air is cooled in an air conditioning unit. The driving potential for the dehumidification process is the difference in the vapor pressure of the air and the desiccant. The vapor pressure of a liquid desiccant is a function of its temperature and concentration. In addition to low vapor pressure, desiccants should have low viscosity, good heat transfer characteristics, and non-corrosive, odorless, non-toxic, nonflammable, stable and inexpensive. The liquid desiccants commonly used in air conditioning systems are lithium bromide, lithium chloride, calcium chloride and Triethylene glycol. A literature search was conducted [9] to obtain relevant data so that figures of merit could be developed for the screening of candidate desiccants.

The figures of merit used are safety, corrosion, heat and mass transfer potential, heat of mixing, and cost of desiccant, parasitic power losses. Review of the material safety data sheet for all the four desiccants indicates that none of the chemicals poses a health hazard when used in the system to dehumidify air. The viscosity of the solutions is important in determining the pumping power required for circulation of the desiccant. Lithium chloride and lithium bromide are less viscous liquids and the Tri ethylene glycol is the most viscous liquid. In most applications the general properties that are required are not fully answered by any single desiccants, but after making some compromises liquid desiccants can be mixed in different proportions to obtain mixtures with improved properties and of low cost. Several experiment and theoretical investigation of thermal systems using single desiccant have been reported. However, a very few have emphasized the analysis of a thermal system employing a mixture of desiccants. Findings from the previous studies have been summarized in Table 1. Ertas et al. [10] compared the heat and mass transfer coefficients of calcium chloride, lithium chloride and mixture of both and found out that the CELD (mixture of 50 % calcium chloride and 50 % Lithium chloride) greatly improved the mass transfer characteristics compared to $CaCl_2$. Desiccant mixtures have been proposed in order to combine the advantages of the individual components and to improve the overall characteristics of the desiccant.

Table 2.1: Desiccant literature survey.

Author	Desiccant	D/R/C*	Additional Comments	Experimental
Dai et al. [11]	$CaCl_2$	C	VCS, VCS + dehumidification and VCS + dehumidification + evaporative cooling is investigated.	Experimental
Kinsara et al. [12]	$CaCl_2$	C	Mathematical modeling of various components; fluid properties are undertaken to study the performance under different conditions.	Analytical
Gandhidasan et al. [13]	$CaCl_2$	D	Inlet air temperature doesn't have effect on the height of the packing.	Numerical
Elsayed et al. [14]	$CaCl_2$	D, R	Raschig rings of 25 mm nominal size are used.	Numerical
Khan [15]	LiCl	D, R	Detailed sensitivity analysis of heat and mass transfer is carried out.	Numerical
Lof et al. [16]	LiCl	R	1-inch Raschig rings sizes are used.	Experimental
Oberg [17]	TEG	C	The liquid flow rate and air temperature did not have a significant effect.	Experimental
Ertas et al. [18, 19]	CELD *	D, R	Regeneration efficiency decreases with higher inlet air humidities.	Experimental
Donald et al. [20]	CELD	D	Performance correlation is given	Numerical
Chung [21, 22, 23]	LiCl & TEG	D	A correlation of column efficiency for different packings and desiccant solutions is developed in this study.	Experimental
Kavasogullari et al. [24]	$CaCl_2$ & LiCl	D	Ceramic raschig rings are used.	Numerical
Pesaran et al. [25]	LiCl & TEG	C	The cooling performance of the heat pipe system using TEG is about 10 % less than LiCl.	Experimental

* D: Dehumidifier, R: Regenerator, C: Cooling system,
CELD: Cost Effective Liquid Desiccant (50 % $CaCl_2$ and 50 % LiCl).

2.2 Hybrid Cooling Systems

In hybrid cooling system the latent load is taken care by the dehumidifier and only sensible cooling is met in the conventional air conditioning. The possible combinations of hybrid cooling systems are presented by Waugaman et al. [26] depending upon the type of desiccant and air conditioning unit. Hybrid air conditioning systems can be classified as follows:

1. Hybrid vapor-absorption/solid desiccant air conditioning system.
2. Hybrid vapor-absorption/liquid desiccant air conditioning system.
3. Hybrid vapor-compression/solid desiccant air conditioning system.
4. Hybrid vapor-compression/liquid desiccant air conditioning system.

Hybrid liquid desiccant cooling systems require two air contact equipments: dehumidifier and a regenerator. In both the contact process heat and mass transfer with large heat effects is involved.

2.2.1 Dehumidifiers

Desiccant dehumidifier is a device that employs a desiccant material to produce dehumidification effect. The process involves exposing the desiccant material to a humid air stream; the desiccant absorbs water vapor in the air because the cool and strong desiccant has a low vapor pressure than water. The desiccant falls down through the dehumidifier because of gravity while the air moves upwards due to the pressure difference created by the blower. There is a considerable pressure drop in the air phase, whereas for liquid phase the only power requirement is for pumping the liquid up to the top of the dehumidifier. The dehumidifier column can be packed either randomly, as mentioned earlier or with structured packing. Structured packing permits improve control of mass transfer by the use of a fixed orientation of transfer surfaces. In a packed bed dehumidification strong, cool desiccant is distribute from the top and allowed to trickle down through the tower in a thin film covering the packing material surfaces. Different kinds of packing material such as structured packing, Raschig rings, Lessing rings, Partition rings, Berl saddles, Intalox saddles, Tellerettes, Pall rings, etc. are commercially available. Among these packing material Raschig rings, flexi rings and Berl saddles are widely used for the dehumidification of air in a packed tower. This research deals with structured packing material used for liquid desiccant systems and the various parameters that are studied by different researchers are presented in Table 2.2.

Analysis of heat and mass transfer between a desiccant-air contact system in packed tower has been studied by Gandhidasan et al. [13] employing calcium chloride as desiccant. The various parameters such as the effect of liquid concentration and temperature, air temperature and humidity and the flow rates of air and liquid affecting the tower performance have been discussed. It is found out that to obtain the same air outlet humidity, the strong liquid at the inlet requires a lesser packing depth than does the weak liquid. The inlet temperature of the air stream does not have any effect on the height of packing, but the outlet temperature of the air may be warmer or cooler depending on the other operating parameters.

Table 2.2: Packed bed dehumidifier performance.

Author	Desiccant	Independent Variables							Type of study
		Q_L	ξ_{in}	$T_{L,in}$	Q_G	$T_{G,i}$	ω_{in}	Z	
		kmol/m^2 s	(%)	^0C	kmol/m^2 s	^0C	kg/kg	m	
Gandhidasan et al. [13]	$CaCl_2$	0.01 –0.13	40-45	30-35.5	.004 –. 064	25-34	0.022 & 0.0227	0.4-1.5	Numerical
El sayed et al. [14]	$CaCl_2$	1-4 kg/s m^2	38-40	20-35	0.3-.7 Kg/s m^2	20-40	-	0-2	Numerical
Ullah et al [27]	$CaCl_2$	0.06	40-45	27-30	0.03-0.066	25-45	-	0.4-1.0	Numerical
Tsair-Wang Chung [21]	LiCl	2-3.5 gpm	30 & 40	13.1-22.89	25-56 CFM	23-26.1	0.0107-0.0139	0.42	Experimental
Kavasogulla-ri et al [24]	$CaCl_2$ or LiCl	0.04 –0.1	40	29-46	0.239	29-41	0.0365	0-2	Analytical
Ertas et al [19]	CELD	1-8.2 gpm	40& 45	26.67-43.3	1091 CFM	30-36	0.017-0.024	0.3-1.52	Experimental

The effectiveness of moisture removal for an adiabatic counter flow packed tower absorber operating with $CaCl_2$ - air contact system was studied by Ullah et al. [27]. The tower effectiveness was expressed as a function of the air inlet temperature and humidity ratio, liquid inlet temperature and concentration and it was found that effectiveness increases with lower liquid temperatures and higher inlet concentrations. The air flow rate has considerable effect on the tower performance for a given height of tower packing and liquid flow rate.

Elsayed et al. [14] developed a finite difference model to calculate the effectiveness of heat and mass transfer in packed beds at various bed heights, various concentrations of calcium chloride solution at the bed entrance to predict the outlet conditions of air and solutions from the beds.

A correlation of column efficiency for different packing heights and desiccant solutions was developed by Tsair-Wang Chung [21,22,23] using lithium chloride and triethylene glycol. Solutions of 30% and 40% LiCl are used. The correlation involves the air and liquid flow rates, air and liquid inlet temperatures, column packing dimensions, and the equilibrium vapor pressure of the desiccant solution. The average value of the errors between predicted and experimental data was about 7 %.

Kavasogullari et al. [24] studied the performance of $CaCl_2$ and LiCl in a dehumidifying packed tower. The heat and mass transfer coefficients have been evaluated and the derived transfer coefficients are used to analyze the performance of the dehumidifier. The effect of various parameters on the performance on the dehumidifier is studied and the results clearly indicate that lithium chloride performed better than calcium chloride but the cost of the former is high.

Ertas et al [19] experimentally studied the performance of a packed bed dehumidifier using new cost effective desiccant mixture of lithium chloride and calcium chloride. The effect of different independent variables on the performance of the dehumidifier was investigated for various climatic conditions and it was found that the air inlet humidity and temperature, and the desiccant inlet temperature and concentration have significant effect on the performance. The dehumidifier worked effectively for high humid conditions and experimental results demonstrate that the CELD is a promising desiccant for cooling and drying operations.

2.2.2 Regenerators

Regenerators are used to concentrate the weak desiccant during the process by removing the water content. The water content will be transferred from the desiccant to the air due to the desiccant high vapor pressure compared to that of water. The simultaneous heat and mass transfer between the air and the desiccant have a large impact on the regenerator performance. The regenerators can be broadly classified depending upon the type of auxiliary heat used for regeneration viz., solar energy, waste energy and the method of regeneration- heating the air, heating the desiccant and both. The regenerator similar to dehumidifier can be packed either randomly or with structured packing. In this study a structured packing tower will be used for regeneration purpose. The weak desiccant is regenerated in a structured-packing tower by means of heating the air and desiccant.

Khan [15] studied the packed type regenerator at partial load operating conditions by sensitivity analysis method. The humidity and enthalpy effectiveness during the regeneration process were found to depend strongly on the solution spray temperature at the regenerator inlet. The very small maximum-minimum spread for both the humidity and the enthalpy effectiveness signifies their weak dependence on air inlet humidity and its temperature.

Al Farayedhi et al [28] studied the heat and mass transfer in a structured packing liquid desiccant regenerator. The effectiveness of the regenerator in terms of concentration is used as performance criteria to study the effects of desiccant concentration, temperature, flow rates of desiccant, packing height and air temperature.

Ertas et al. [18] experimentally studied the performance of a packed bed regenerator using CELD (Cost effective desiccant mixture of lithium chloride and calcium chloride). The effects of desiccant inlet temperature, inlet concentration, and flow rate on the regeneration tower performance were investigated. The results of experiments were found to be accurate with less than 8 % error.

2.2.3 Hybrid Systems

The definition of coefficient of performance reported varies among the authors depending upon the type of hybrid system. Therefore the Coefficient of performance for the vapor compression system plays an important role in evaluating the performance of the system. The studies conducted on hybrid liquid desiccant cooling system are summarized in Table 2.3 and the various parameters used to compare is also presented.

Table 2.3 Hybrid Desiccant System Performance Parameters.

Author	Desiccant	Performance Parameter's	Type of Study
Dai et al [11]	$CaCl_2$	Cooling production, cooling load, electric COP, thermal COP, COP, VCOP, effectiveness of dehumidification and latent load	Experimental
Kinsara et al [12]	$CaCl_2$	$COP_{Hybrid}/COP_{Conventional} = 0.5\text{-}3.0$	Numerical
Sanjeev Jain et al [29]	-	COP =Specific cooling effect / Regeneration heat	Numerical
Oberg [17]	TEG	EER =Cooling effect/wattage	Experimental /Numerical
Gari et al [30]	$LiBr\text{-}H_20$	COP = Cooling effect/Heat input	Analytical
Edward et al [31]	$NH_3\text{-}H_20$	COP = Cooling effect/Energy input	Numerical
Marsala et al. [32]	LiCl	$COP = (Q_{cool}/Q_{bed})_{avg} = 0.5\text{-}0.58$	Experimental
Kettleborough et al. [33]	CELD	$COP = (Q_{cool}/Q_H) = 0.35$	Theoretical
Albers et al [34]	LiBr	$COP = (Q_{cool}/Q_{bed}) = 1.4$	Experimental
Yadav et al. [35, 36]	LiBr	$COP = (Q_{cool}/Q_{E,TOT}) = 3.1\text{-}3.3$	Numerical

A complete Hybrid air conditioning system was studied experimentally Dai et al [11], which consist of desiccant dehumidification, evaporative cooling and vapor compression air conditioning. The experiments were carried out at ARI conditions for the three cases and it was found out that the desiccant system has nearly 20-30 % more cooling production than vapor compression system. Various performance indexes were defined for the hybrid system like electric coefficient of performance, thermal coefficient of performance, coefficient of performance of vapor compression system and effectiveness of the dehumidification. The benefits are represented by lower electricity consumption of the compressor, higher COP of the system, less flow rate of condensation air, and reduced size of vapor compression system, etc.

Kinsara et al [12] proposed an energy efficient desiccant system consists mainly of two packed beds, a heat pump, air washers and a cooling coil. The mathematical model was studied under different operational conditions. The ratio of the coefficient of performance is introduced to compare the two systems and it was found that if this ratio is greater than one, the proposed system using liquid desiccant is more energy-efficient than the conventional A/C system.

Sanjeev Jain et al [29] studied the psychrometric evaluation of seven potential cycles for achieving standard comfort conditions and found that the liquid desiccant systems have the advantage of a lower pressure drop and simultaneous cooling during dehumidification.

Oberg [17] studied the packed bed absorber/regenerator both experimentally and numerically and a performance simulation of this solar hybrid shows that the desiccant dehumidifier providing over 90 % of the latent cooling requirement saves 80 % electrical energy as compared to conventional cooling techniques. Design variables like air flow rate, humidity, desiccant temperature concentration and packing height are found to have the largest impact on the performance of the packed bed dehumidifier and regenerator. The liquid flow rate and the air temperature did not have significant effect. The results obtained from the finite difference model showed in good agreement with the experimental findings.

A mathematical analysis of an integrated absorption desiccant air conditioning system was done by Gari et al. [30]. An overall COP of 1.21 was obtained which is 50 % higher than that of the absorption chiller alone.

Edward et al. [31] studied the combination of air desiccant system combined with an absorption system using a thermodynamic design model. The required heat for the desiccant regenerator was supplied by the absorption cycle absorber and condenser and the combined system had a higher COP than that of the two individual systems.

CHAPTER 3

HYBRID COOLING SYSTEM

A number of hybrid air conditioning systems using desiccants have been proposed by different researchers and some are experimentally tested. Although the concept is the same, the means of providing a contact area for heat and mass transfer between the desiccant and the air for dehumidification and regeneration differ. Two types of desiccants namely solids and liquids can be used for dehumidification of air and two types of conventional air conditioners namely vapor-absorption and vapor-compression units can be used for sensible cooling.

In hybrid vapor-compression/liquid desiccant air conditioning system, the latent load is taken care by a dehumidifier and then vapor compression unit provides the sensible cooling. The heat rejected from the condenser can be used as regeneration energy.

3.1 Desiccants Used

Desiccants are substance, which have a high affinity for water vapor. Two major categories of desiccants are known absorbents and adsorbents. Absorbents experience a chemical change as they attract and retain water vapor. Adsorbent materials hold water molecules in pores at their surface without any chemical changes. Absorbents generally can attract and hold greater quantities of water per unit mass.

3.1.1 Solid Desiccants

Solid desiccants include activated alumina, molecular sieve, deliquescent briquette, montomorillonite clay, active bed support tabular support and silica gel is used for producing dehumidified air. Different types of dehumidifiers and regenerators are available for solid desiccant. Solid packed tower, rotating horizontal bed, multiple vertical bed and rotating Honeycomb are examples. Solid desiccants systems can operate at lower regeneration temperature, but require large volumes of desiccant and also entail significant operating costs for the parasitic systems of blowers required to circulate both the air to be conditioned and the hot air for regeneration. Further as time progress, efficiency of the desiccant bed can be reduced due to dust and foreign matter deposited in the pores. To avoid this, additional air filtering can be added but only at the cost of additional air pressure drop through the system. These drawbacks make the solid desiccant system less attractive, hence liquid desiccant system is chosen for the present study.

3.1.2 Liquid Desiccants

Liquid desiccant include lithium chloride, calcium chloride, lithium bromide and triethylene glycol. The application of the proper desiccant in hot, humid climates would improve the dehumidification effectiveness. The most important property of desiccant is vapor pressure because it's the driving potential for the dehumidification process. The vapor pressure of a liquid desiccant is a function of its temperature and concentration. The properties of the liquid desiccants, which are commonly used, are shown in Table 3.1.

The cost of the desiccants varies from SR 2/kg (for calcium chloride) to SR60/kg (for lithium bromide).

3.1.3 Desiccant Mixtures

Experiments have been done with desiccant solutions of two or more salts in an effort to find a combination, which would produce maximum depression in the properties [37]. By combining different liquid desiccants improved characteristics can be expected as well as a considerable reduction in cost. Some available desiccants have high costs and some other possess poor properties. To stabilize these desiccants and to lower the high cost, and to improve the properties of the desiccants, they can be mixed in different combinations. In most of the applications the general properties that are required are low vapor pressure, high elevation of boiling point, high latent heat of condensation and dilution heat, low crystallization point for the easy handling at low temperature, and low cost. The liquid desiccants can be mixed in different proportions to obtain mixtures with improved properties and of low cost.

There are general mixing rules or equations for each class of mixtures and one must select the proper type of equation for accurate estimation of any given property.

Table 3.1: Properties of liquid desiccants at 25 ^0C

Properties	$CaCl_2$ [38]	LiCl [39]	TEG [17]
Sp. Gravity	1.416	1.2515	1.1
Surface Tension, dyness/cm	93	97.46	46
Viscosity centipoises	7.435	8.7	28
Cp (kJ/kg ^0C)	2.5	2.5	2.3

One must also know what information is required in addition to the corresponding property of the components and their concentrations in order to make valid estimates of the properties of the mixture.

It would be desirable to be able to predict easily the properties of the mixtures from just the corresponding properties of the components and their concentrations. However, in general additional information must be known about the nature of the mixture if accurate prediction of properties is to be made. This information includes interactions between the constituents, particle size and shape, and nature of the packing found in the mixture [40]. The simplest mixture rule is often called, the rule of mixture, it is given as,

$$E = E_a \psi_a + E_b \psi_b \tag{3.1}$$

The concentration terms may be either weight fraction or volume fraction depending upon the kind of property being measured. Another equation which also predicts the properties of the mixture with good accuracy is the inverse rule of mixtures, and is gives as,

$$\frac{1}{E} = \frac{\psi_a}{E_a} + \frac{\psi_b}{E_b} \tag{3.2}$$

The above two equations require that one only needs to know the value of the given property for each component and their concentration. The concentrations are related as,

$$\psi_a + \psi_b = 1.0 \tag{3.3}$$

In this research, simple mixing rules with and without interaction parameter are used to determine the thermophysical properties, such as vapor pressure, density, and viscosity of the desiccant mixtures. Desiccants considered in this study are lithium chloride and calcium chloride.

Vapor pressure of a solution is the pressure of the vapor that is in equilibrium with the solution at a given temperature. By using the data for lithium chloride and calcium chloride from Uemura [39] and Dow Chemical [40] respectively, the vapor pressure of the mixture of lithium chloride and calcium chloride is determined for different concentrations using the simple mixing rules. The calibration curve for calcium chloride and lithium chloride are respectively shown in Fig 3.1 and 3.2.

The equilibrium curves plotted on a psychrometric chart (Fig 3.3) shows that the lithium chloride is having low vapor pressure compare to that of calcium chloride i.e., it can absorb more moisture from the air and vapor pressure of 40% mixture of both is almost equal to that of 45 % calcium chloride.

For selecting the suitable desiccants for the proposed system, various desiccants were investigated and finally $CaCl_2$, LiCl and mixture of both are selected.

3.2 Air Dehumidification Process

In a hybrid system the air is made into contact with the desiccant material in the dehumidifier to absorb moisture from the air. The dehumidification can be accomplished using equipment such as finned-tube surface in a column, spray tower or packed tower. The driving force for the dehumidification is the difference in vapor pressure between the air and the desiccant. Dry desiccant has a low vapor pressure and humid air has a higher vapor pressure. Water moves from the air to the desiccant to equalize that pressure difference. As depicted in Fig. 3.4, when the vapor pressure on the desiccant surface is lower than the air (Point 1), water is absorbed by the desiccant from the air. The desiccant vapor pressure and temperature increases and eventually it reaches equilibrium (Point 2).

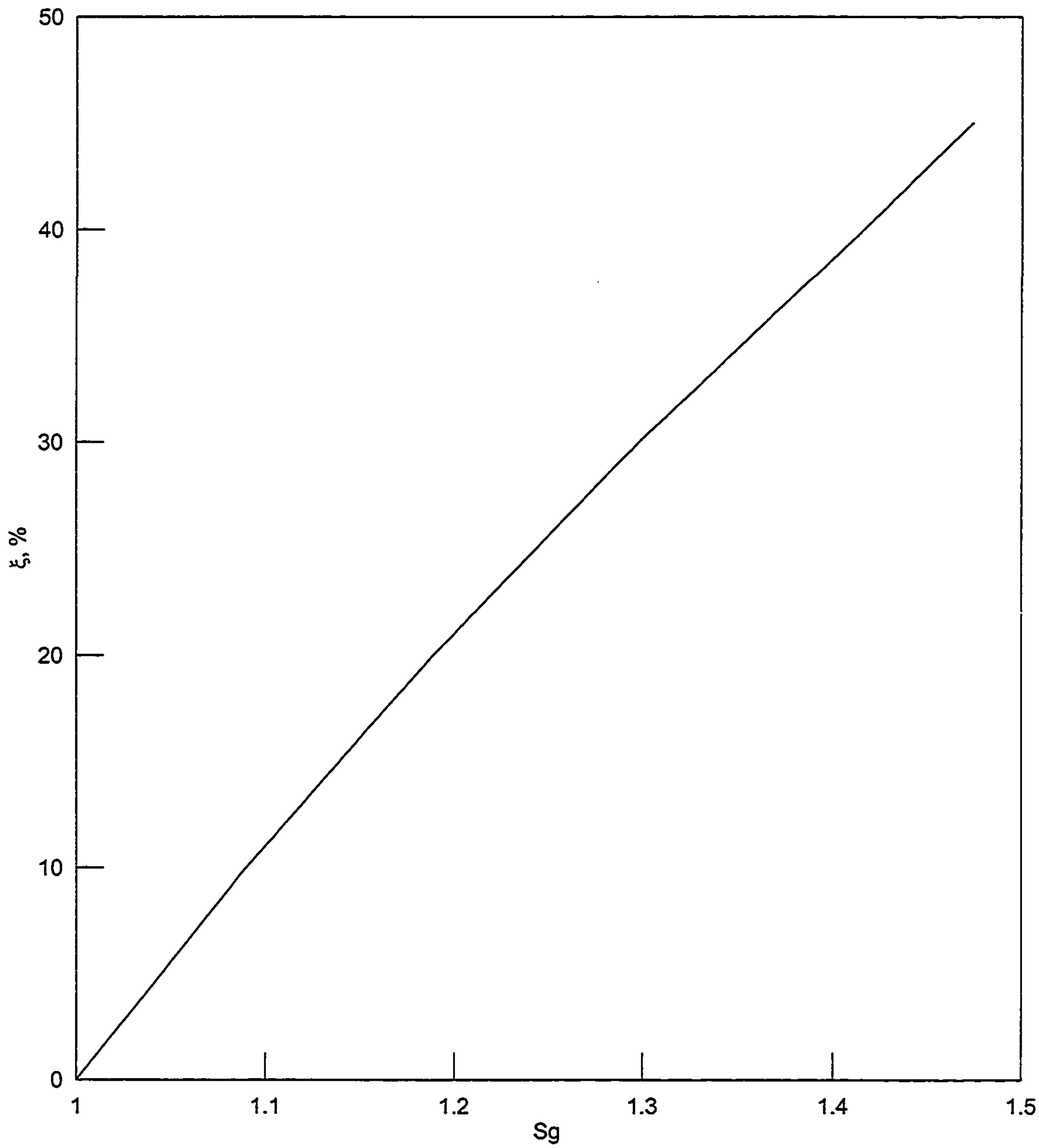


Figure 3.1: Calcium chloride desiccant calibration curve.

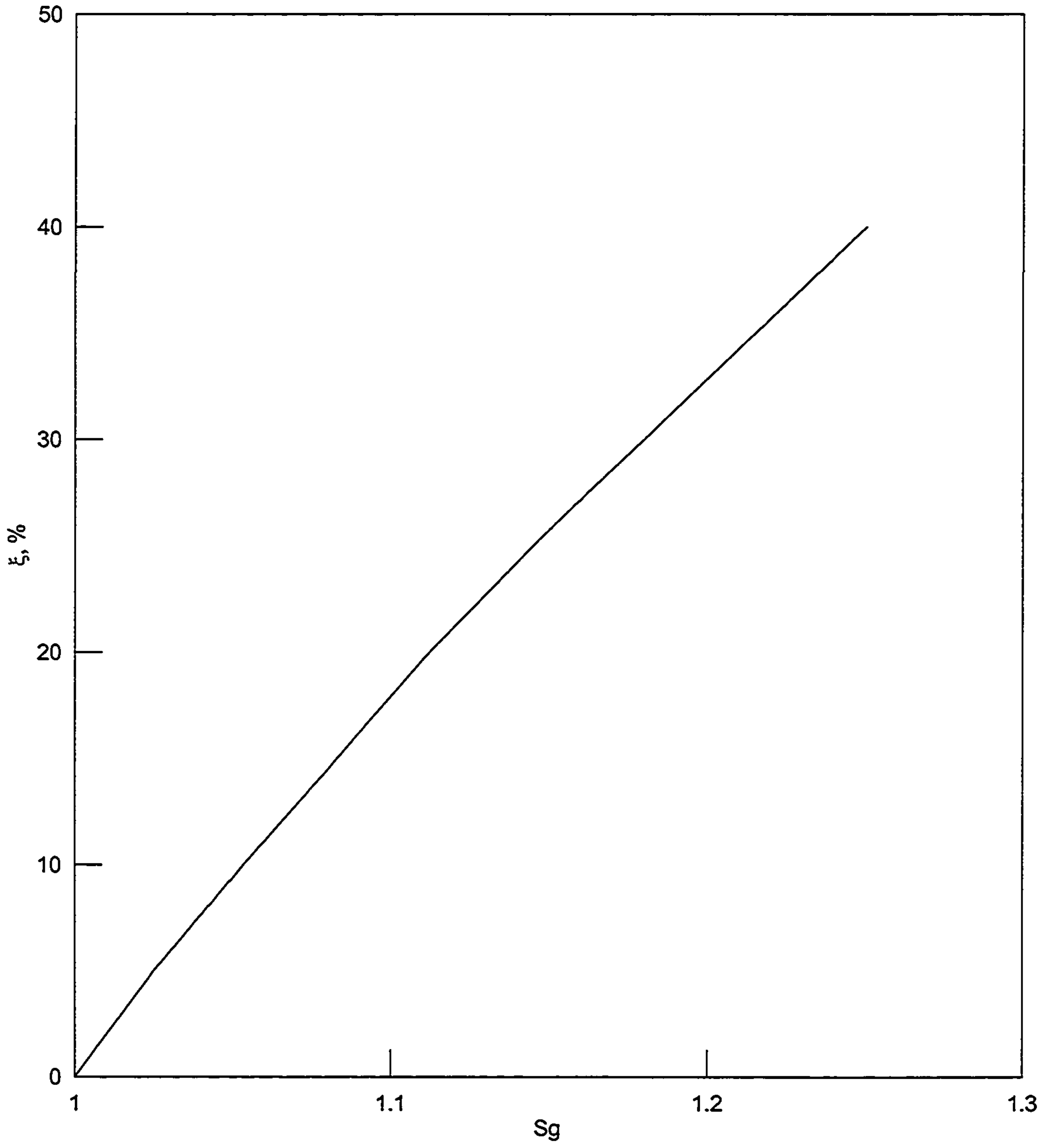


Figure 3.2: Lithium chloride desiccant calibration curve.

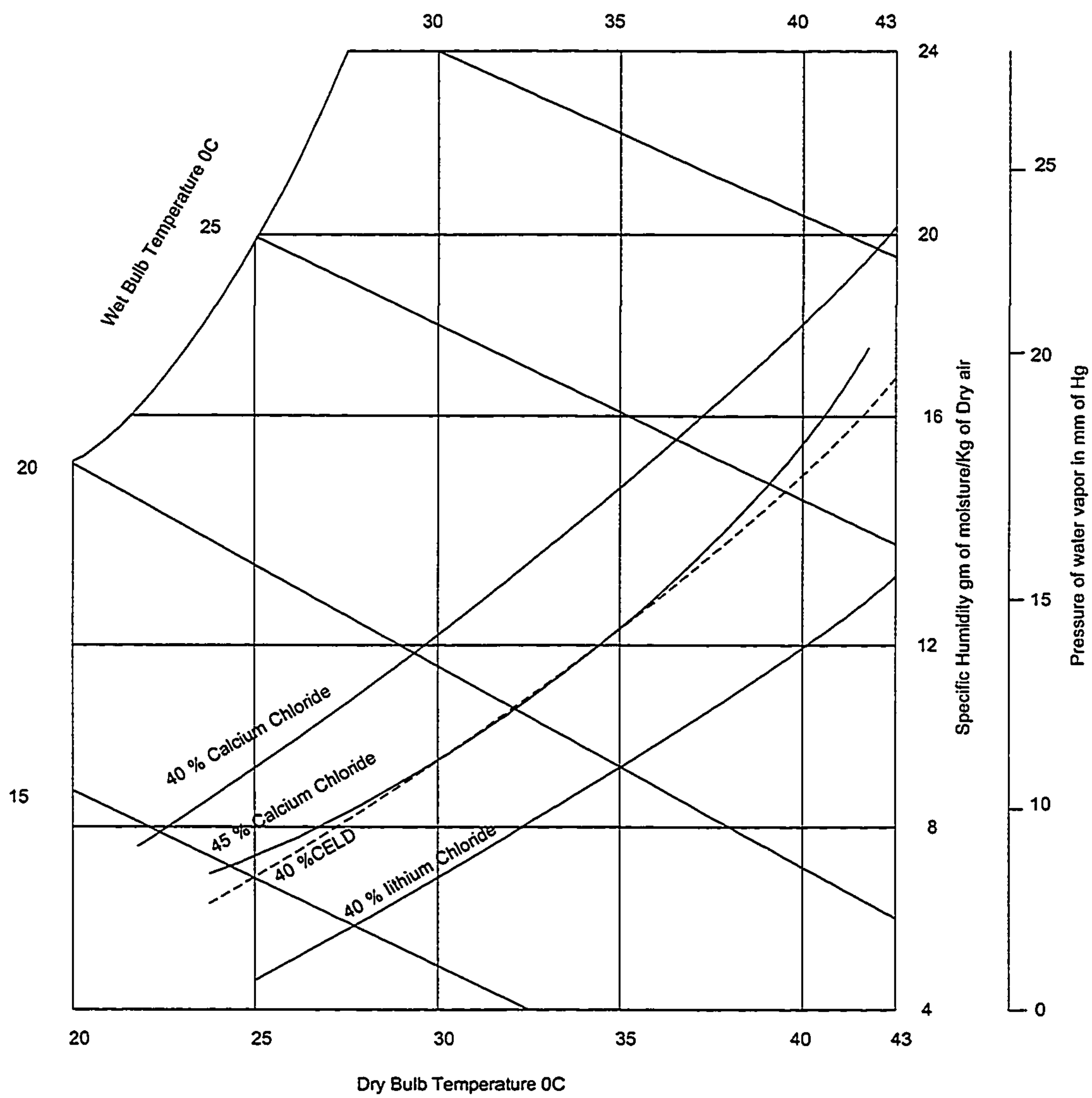


Figure 3.3: Calcium chloride, lithium chloride and CELD equilibrium curves plotted on a psychrometric chart

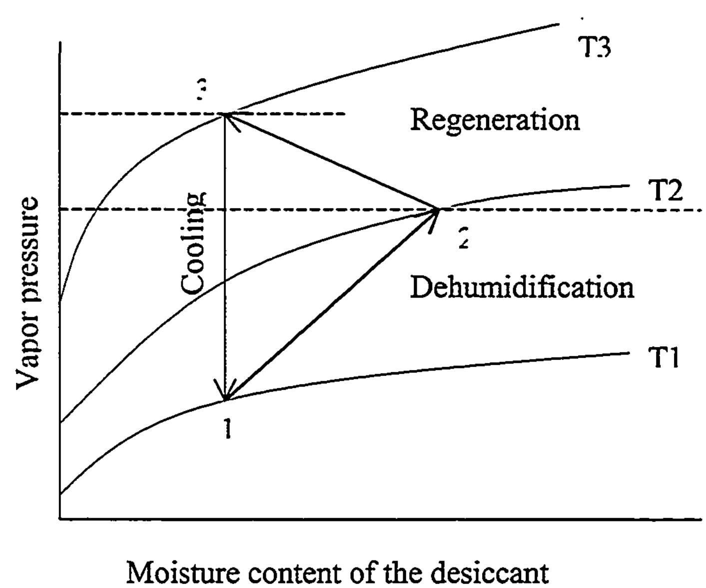


Figure 3.4: Desiccant cycle

The desiccant stops attracting water vapor when the vapor pressure of the desiccant is equal to that of air.

3.2.1 Dehumidifier Effectiveness

The effectiveness of the dehumidifier can be defined as the ratio of the actual change in the humidity ratio to the desired possible change.

$$\varepsilon = \frac{\omega_i - \omega_o}{\omega_i - \omega_e} \tag{3.4}$$

Where ω_e is the humidity ratio in equilibrium with the desiccant solution at the local solution temperature and concentration. Since this value varies with respect to concentration and temperature, for the present study a desired absolute humidity value is chosen as $\omega_e = 0.008$ kg of water/kg of dry air which lies in the human comfort condition. The vapor pressure of $\omega_e = 0.008$ kg of water/kg of dry air is equal to that of 45 % calcium chloride at 30 ^{0}C desiccant temperature for calcium chloride and this corresponds to 40 % lithium chloride at 33 ^{0}C.

The average effectiveness is defined as $\epsilon^i = \sum \frac{\epsilon_n}{n}$. (3.5)

3.3 Desiccant Regeneration Process

Desiccant regeneration is the process of re-concentrating the weak desiccant. The desiccant must be heated to increase its vapor pressure so that the water moves out from the desiccant towards the air, which has lower vapor pressure as it is being re-concentrated. The vapor pressure of the desiccant increases to Point 3 as shown in Fig.3.4. To regenerate the weak desiccant three possibilities exist and they are as follows:

(1) Heat the weak desiccant, which is already preheated in the heat exchanger, using an auxiliary heater and the condenser waste heat. The regenerative air stream is humidified as it passes through the regenerator and then exhausted to the ambient.

(2) The condenser waste heat is used to preheat the ambient air and an auxiliary heater provides further heating. The preheated weak desiccant in the heat exchanger is sprayed in the regenerator.

(3) To provide an auxiliary heater in the air loop as well as in the desiccant loop.

3.3.1 Regenerator Effectiveness

The effectiveness of the regenerator can be defined as the ratio of the actual change in the concentration to the maximum possible change in the concentration of the desiccant.

$$\varepsilon = \frac{\xi_o - \xi_i}{\xi_e - \xi_i} \tag{3.6}$$

Where, ξ_e is the maximum concentration in equilibrium with the air outlet humidity ratio. Since this value varies with respect to the air inlet humidity, for the present study the desired concentration values are chosen as $\xi_e =$ 0.50 for calcium chloride, 0.45 for lithium chloride and 0.475 for CELD.

CHAPTER 4

EXPERIMENTAL SET-UP

4.1 Air Dehumidification System

The dehumidification system is made up of a counter flow packed bed dehumidification tower, a circulation pump, make up tank and a main air blower. The schematic diagram of the dehumidification system is shown in Figure 4.1 and the detailed dimension of the dehumidification tower in Fig. 4.2. The dehumidification tower is made up of fiber glass since it is non-corrosive and light weight. The tower is 2.6 m high and 50 cm in diameter and 0.5 cm thick. The dehumidifier is also equipped with two view windows. An upper one to check the spraying system and lower one to check the level of the desiccant. A stand is designed and manufactured for holding the dehumidifier. A photo of the tower in its final form is shown in Figure 4.3. The dehumidification tower can hold up to 72 cm high and 50 cm in diameter structured packing material. Gauze-type BXPFP structured packing is used, which has high efficiency, light weight and small pressure drop characteristics. A photo of the packing material is shown in Figure 4.4. A polyethylene tank with a capacity of about 60 gallons is used as make-up tank.

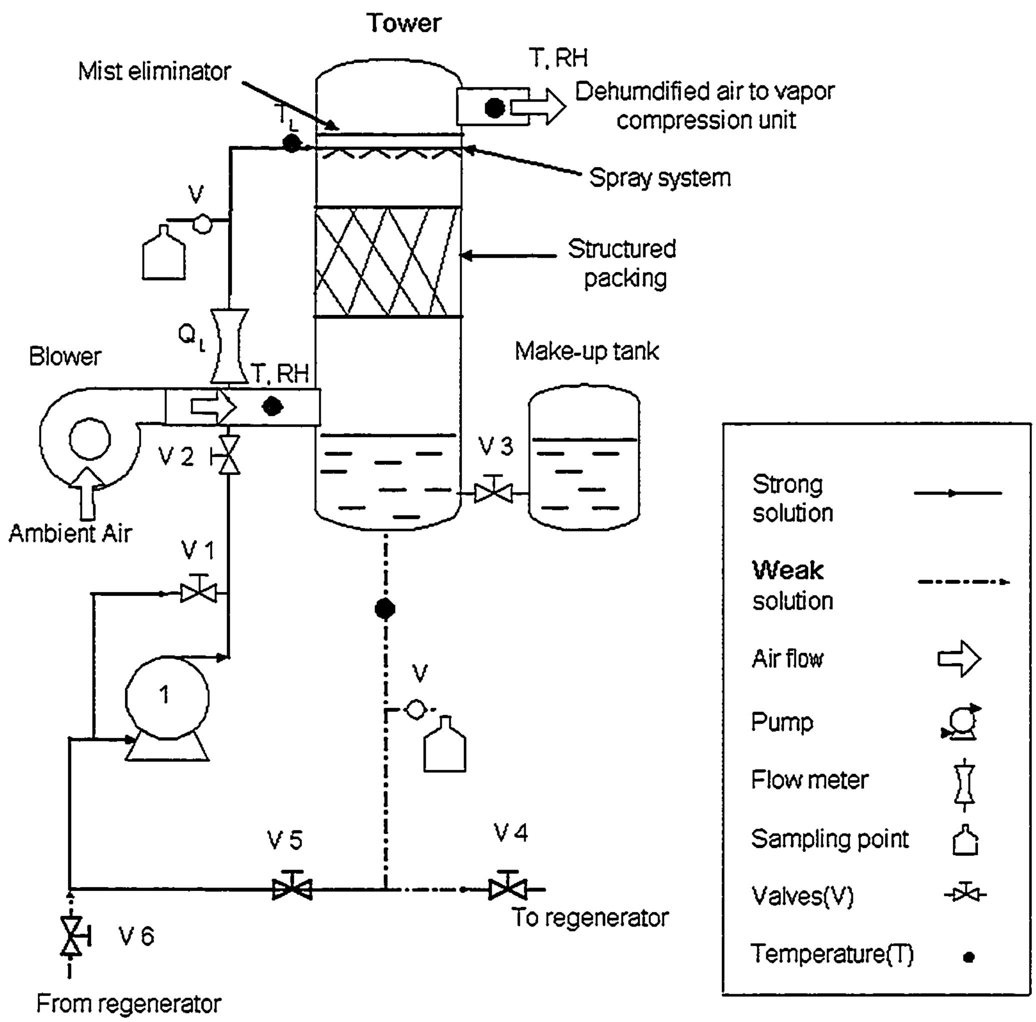


Fig 4.1: Schematic diagram of the experimental apparatus for air dehumidification.

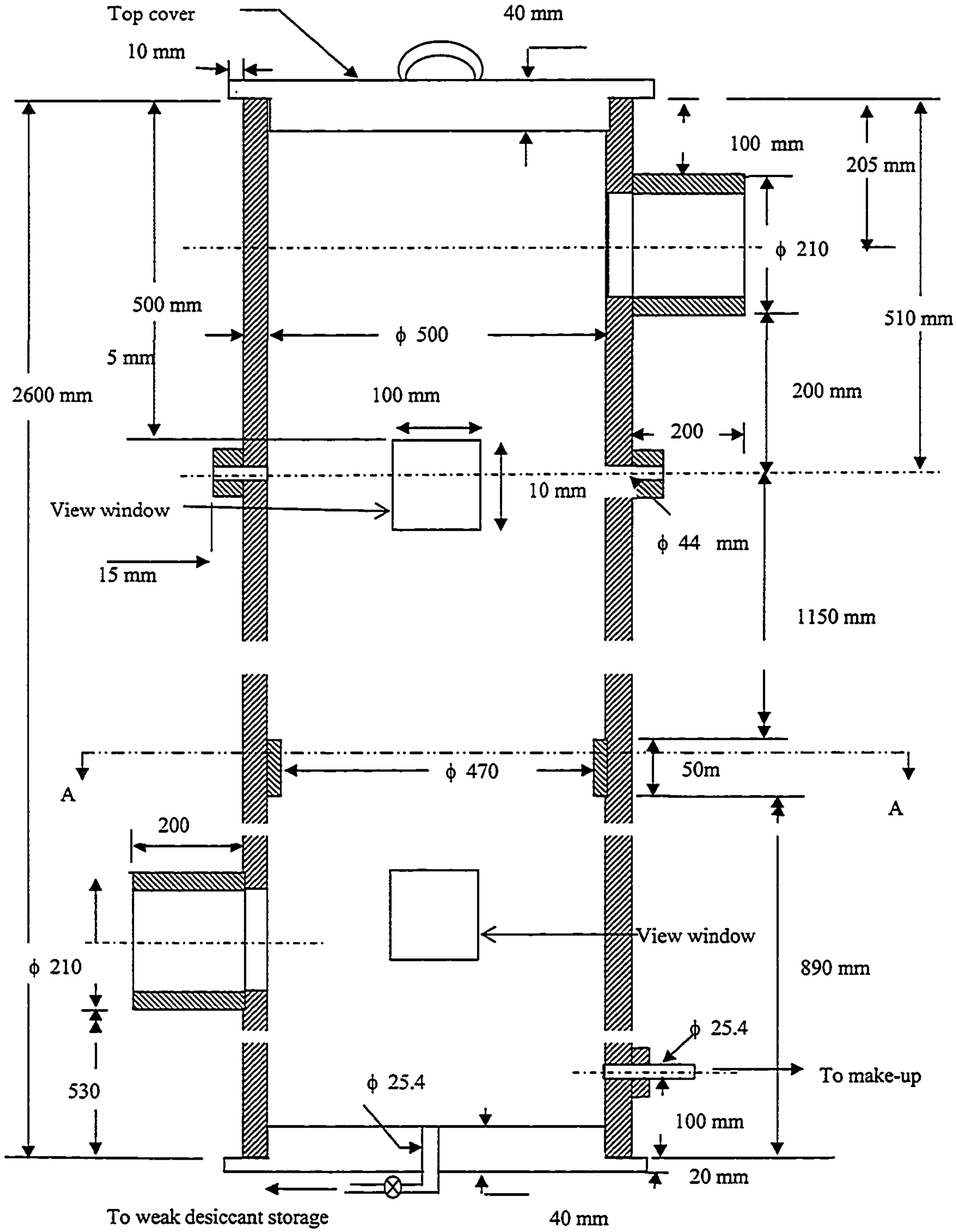


Fig. 4.2 Detailed dimensions of the dehumidfiier

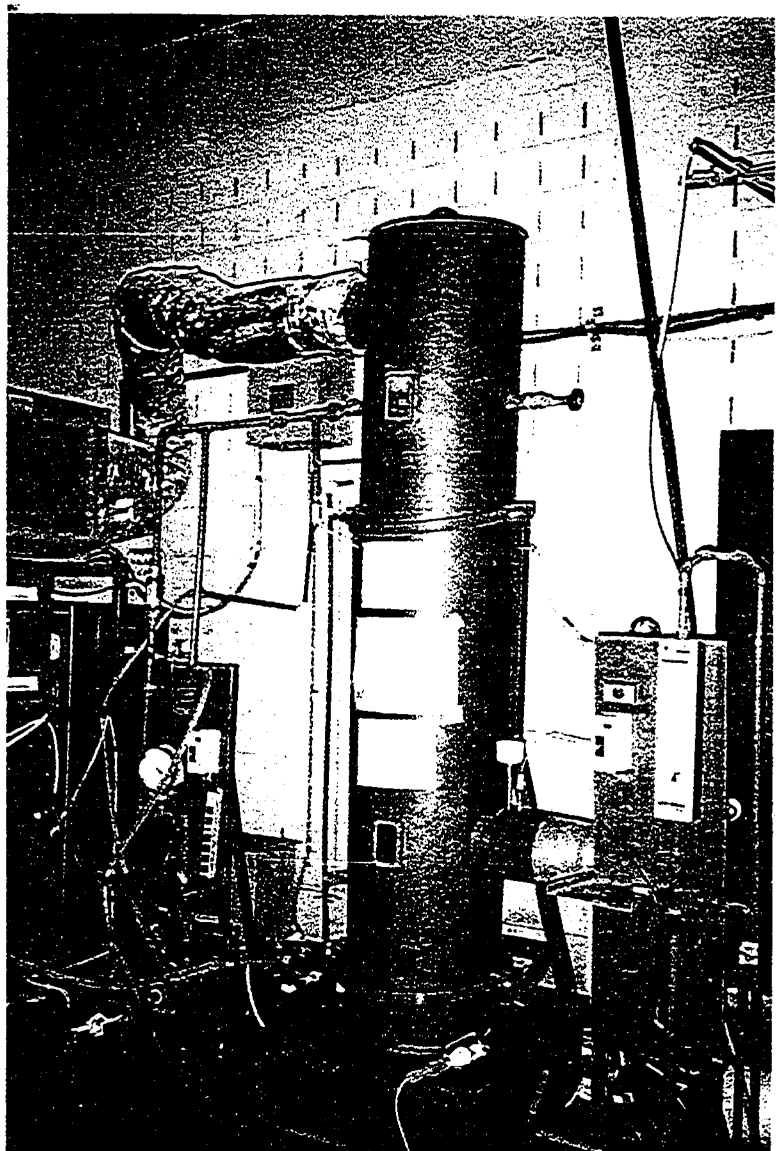


Figure 4.3: Air dehumidification set-up

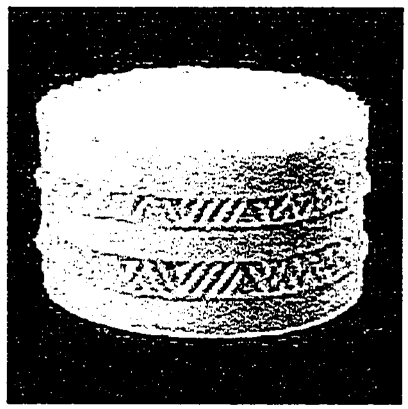


Figure 4.4: Gauze-type BXPFP structured packing material

A custom spray system was designed and fabricated where the distance between the nozzles is 1 cm while the nozzle diameter is 1 mm to insure uniform desiccant spraying on the structured packing. This system was tested and even desiccant distribution was obtained. A mist eliminator was placed on top of the spraying system to prevent mist leaving with the dehumidified air. An insulated flexible air duct of 20 cm diameter is used to supply the ambient air to the dehumidifier from the blower. The airflow rate and its temperature and relative humidity were measured with a Velocity Calc probe. The temperature at different locations are measured with a K-type of thermocouples connected to digital display having an accuracy of 0.1^0 C. Desiccant flow rate was measured by an axial flow meter. Sampling points were provided at the inlet and outlet of the dehumidification tower for measuring desiccant concentration. A 6m long insulated flexible hose is connected from the dehumidifier to the air blower to withdraw fresh ambient air. The piping system is designed in such a way that allows the desiccant in the dehumidifier to circulate independent of the regenerator and/or the desiccant to circulate in the dehumidifier and the regenerator simultaneously. This apparatus allows studying the performance of dehumidification of air by varying different parameters.

4.1.1 Procedure for Air Dehumidification

1. A 45 % concentrated $CaCl_2$ solution is prepared and the specific gravity is measured using a hydrometer to determine its concentration.
2. The dehumidification tower is filled with the desiccant solution (approximately 80 liters) and it is packed with 34 cm height structured packing material.

3. The desiccant is pumped into the dehumidifier using a stainless steel pump and it is sprayed inside the dehumidifier using a conventional sprayer.
4. The air is blown into the dehumidifier in a counter flow direction and it is made to contact with the desiccant in the structured packing.
5. The airflow rate, temperature and its humidity are measured at the inlet and outlet of the dehumidifier using Velocity Calc.
6. The desiccant absorbs water from the air as it trickles down the packing material and gets diluted.
7. A sample of desiccant is taken at inlet and outlet of the dehumidifier for temperature and concentration determination.
8. If the desiccant concentration is weak at the outlet of the dehumidifier it is send to the regenerator or else it is recirculated back again.

4.2 Desiccant Regeneration System

An experimental set-up consisting of a structured packing regeneration system in conjunction with vapor-compression system has been designed and constructed. The schematic diagram of the regeneration system is shown in Fig. 4.5 and 4.6. The regeneration system consists of a counter-flow structured packing regeneration tower, a circulation pump, a make-up tank and a main blower in conjunction with a 10 kW electric heater to regulate the air inlet temperature. The tower is made up of fiberglass, 2.6m high, 50cm in diameter and 0.5cm thick. The detailed dimensions of the tower are shown in Fig. 4.7. It is designed to house up to four packing elements, each approximately 17 cm thick. The regenerator is also equipped with two view windows.

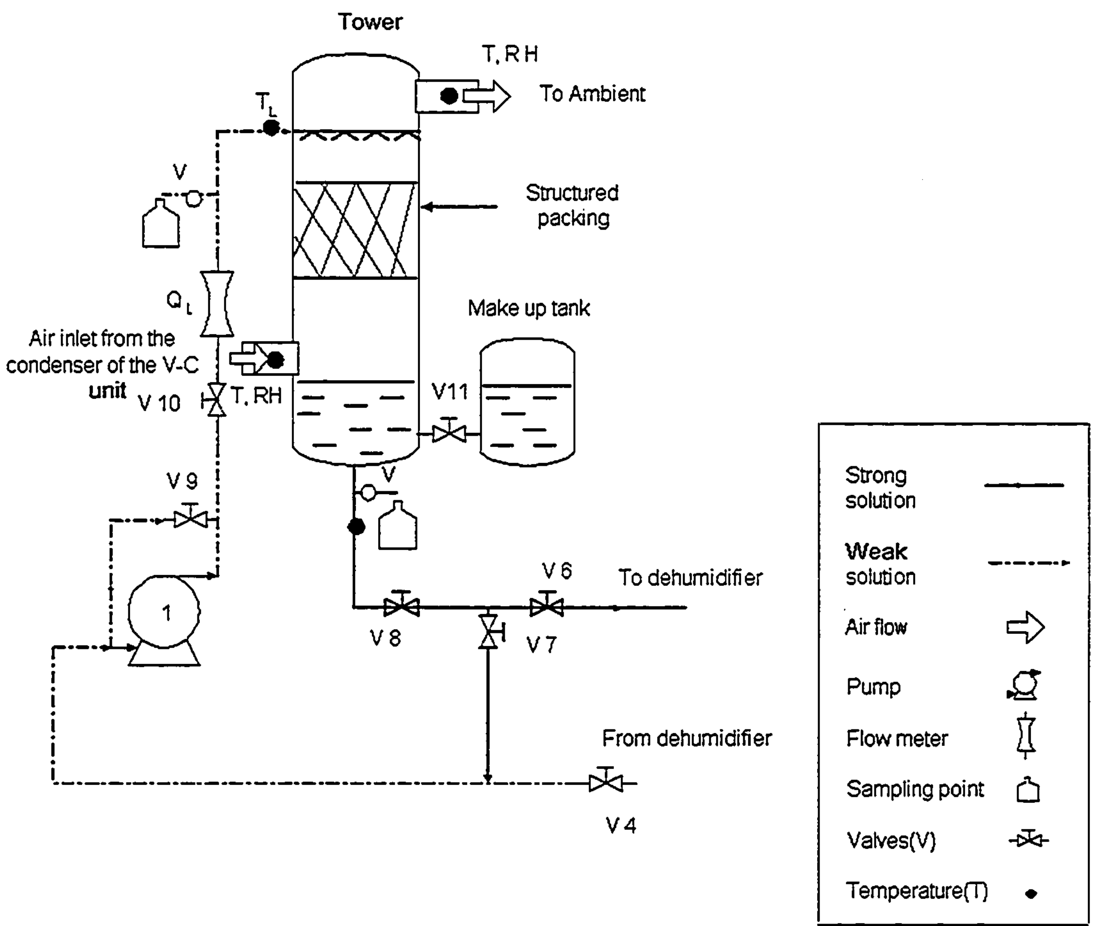


Figure 4.5: Schematic of the experimental apparatus for desiccant regeneration.

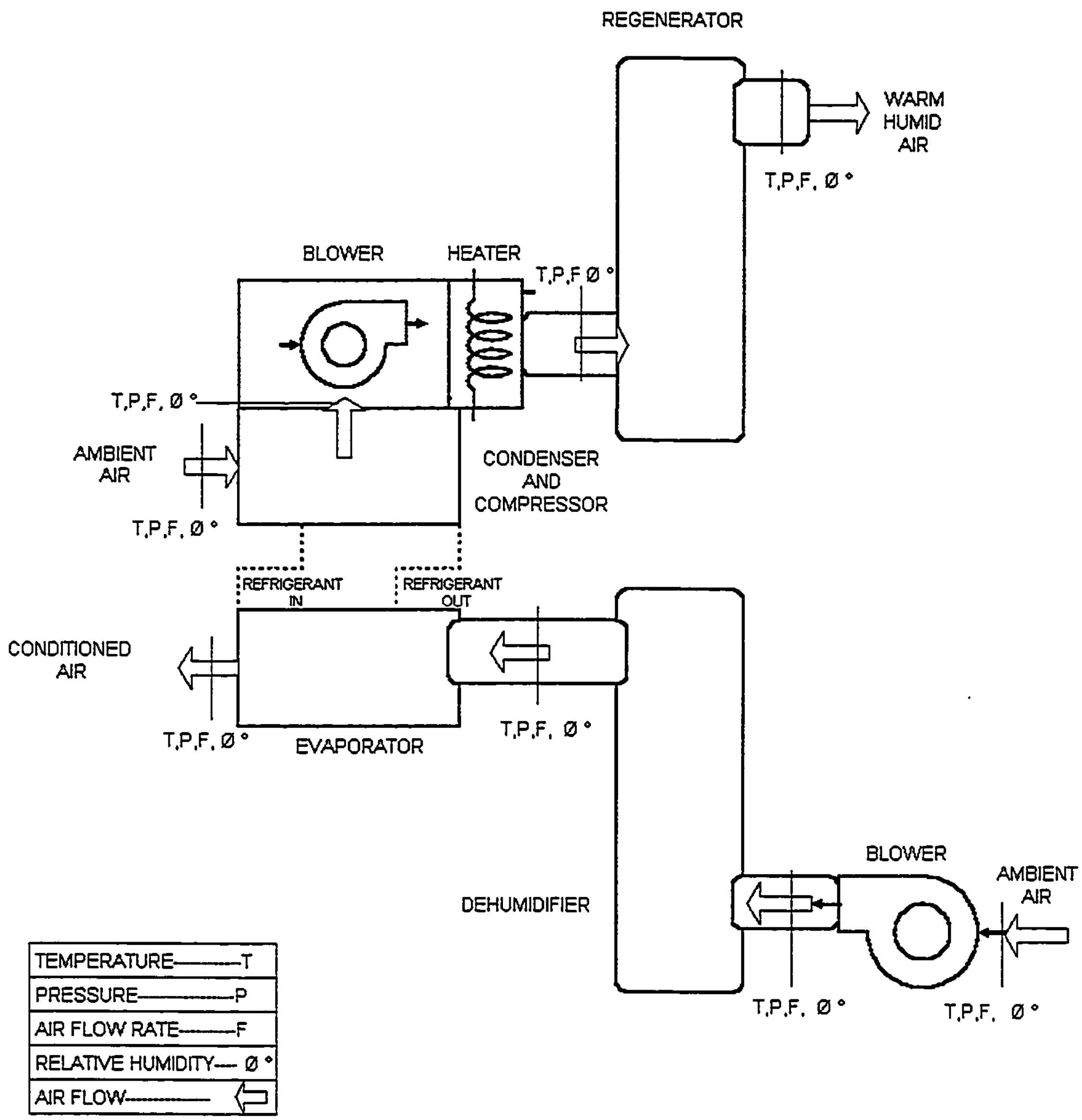


Figure 4.6: Schematic of the air loop for regeneration system

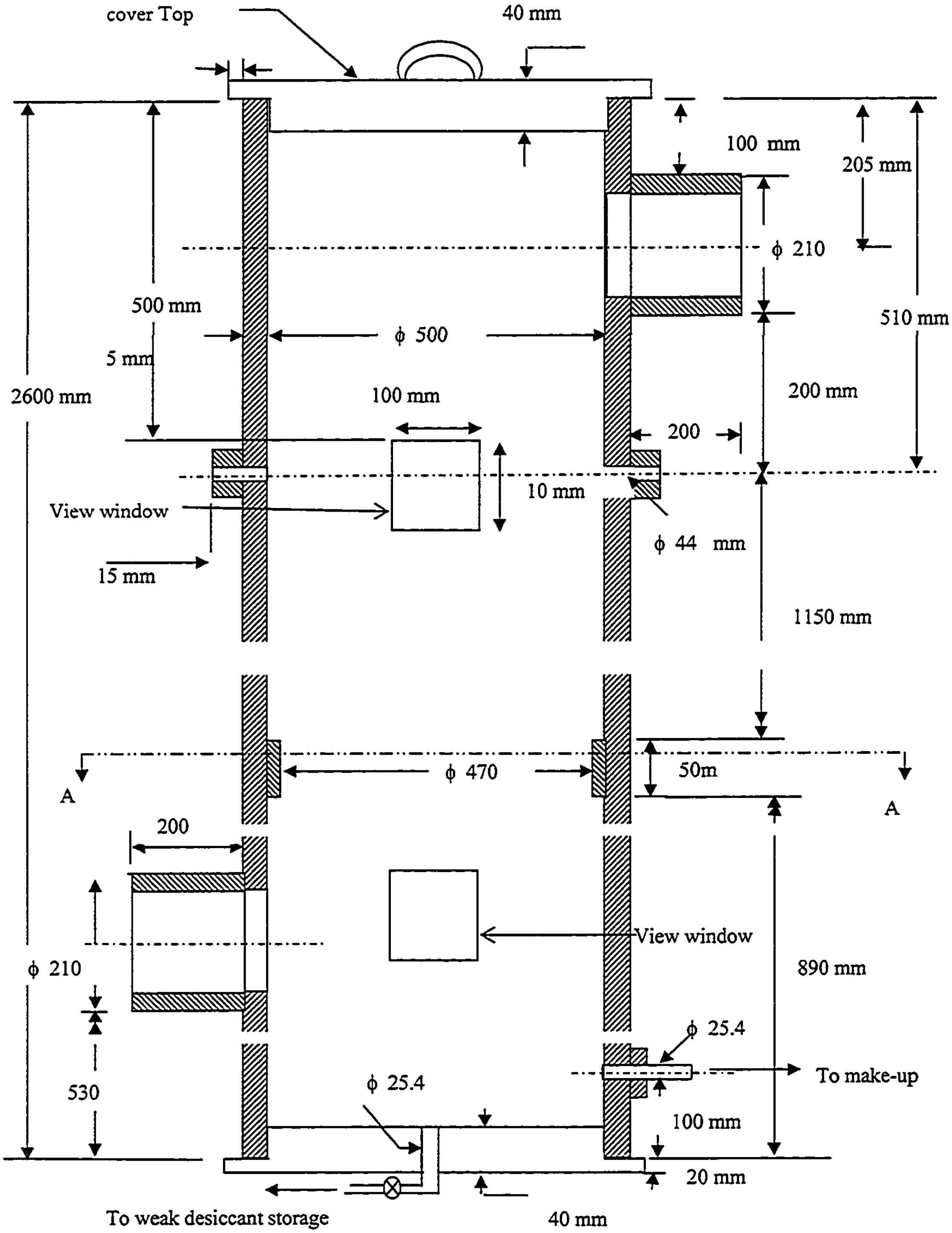


Fig. 4.7 Detailed dimensions of the regenerator

An upper one to check the spraying system and lower one to check the level of the desiccant. A stand is designed and manufactured for holding the regenerator and a photo of the tower in its final form in Fig. 4.8. Sulzer gauze-type steel (AISI 316L) structured packing is used. A photo of the packing material is shown in Figure 4.9 A custom spray system was designed and fabricated where the distance between the nozzles is 1 cm while the nozzle diameter is 1 mm to insure uniform desiccant spraying on the structured packing. A polyethylene tank with a capacity of about 60 gallons is used as make-up tank. The airflow rate and its temperature and relative humidity were measured with a Velocity Calc probe. The temperature at different locations are measured with a K-type of thermocouples connected to digital display having an accuracy of 0.1^0 C. Desiccant flow rate was measured by an axial flow meter. Sampling points were provided at the inlet and outlet of the regenerator tower for measuring desiccant concentration.

An insulated flexible air duct of 20cm diameter is used to supply the airflow from blower to the regenerator. The blower in conjunction with heater is designed, constructed, and installed on the top of the condenser in such way that the air coming out from the condenser can be easily made to pass through the regenerator inlet. A themostat regulates the air inlet temperature to the regenerator. The piping system is designed in such a way that allows the desiccant in the regenerator to circulate independent of the dehumidifier and/or the desiccant to circulate in the dehumidifier and the regenerator simultaneously. This apparatus allows studying the performance of regenerator by varying different parameters.

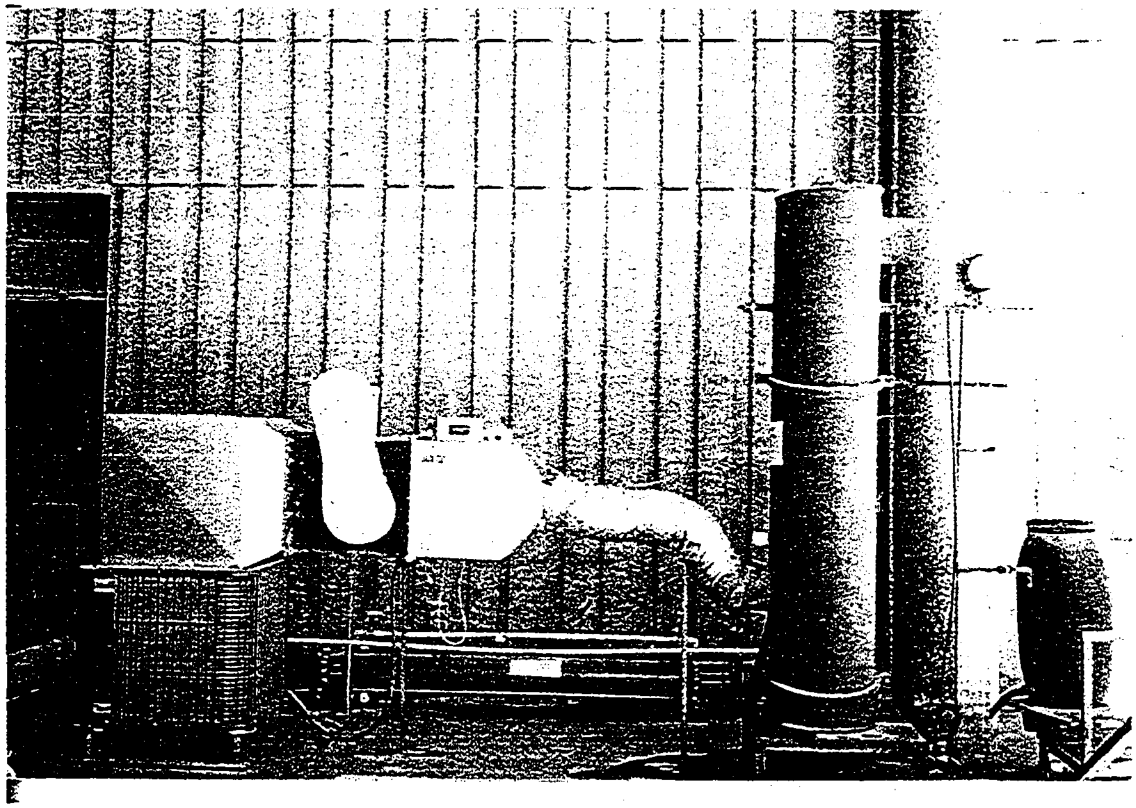


Figure 4.8: Desiccant regeneration set-up

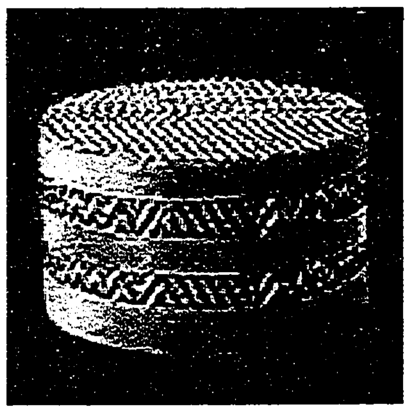


Figure 4.9: Sulzer gauze-type steel (AISI 316L) structured packing material.

4.2.1 Procedure for Desiccant Regeneration

1. A weak concentrated $CaCl_2$ solution is prepared and the specific gravity is measured using a hydrometer to determine its concentration.
2. The regenerator tower is filled with the desiccant solution (approximately 80 liters) and it is packed with 34 cm height structured packing material.
3. The desiccant is pumped into the regenerator using a stainless steel pump and it is sprayed inside the tower using a conventional sprayer.
4. The condenser waste heat is blown into the regenerator in a counter flow direction and it is made to contact with the desiccant in the structured packing.
5. The airflow rate, temperature and its humidity are measured at the inlet and outlet of the regenerator using Velocity Calc.
6. The inlet air absorbs water from the desiccant as it passes over the packing material.
7. A sample of desiccant is taken at inlet and outlet of the regenerator for temperature and concentration determination.
8. If the desiccant concentration is strong at the outlet of the regenerator it is send to the dehumidifier or else it is recirculated back again.

4.3 Hybrid Cooling System

The principal elements of hybrid system are vapor compression unit, structured packing dehumidifier and regenerator. A 5-ton conventional vapor compression cooling system is assembled with the dehumidifier in such a way that the air coming out of the dehumidifier tower can be easily passed into the vapor compression unit for sensible cooling. A desiccant-to-desiccant heat exchanger is added to pre-cool the hot desiccant leaving the regeneration tower while pre-heating the desiccant leaving the dehumidification tower. A photo of the heat exchanger in its final form is shown in Figure 4.10. Another water-to-desiccant heat exchanger is used to cool the strong desiccant before entering the dehumidifier. A photo of the heat exchanger in its final form is shown in Figure 4.11. The air flow rates, temperature and its humidity are measured with a Velocity Calc. Sampling points where valves are fitted to enable to take a sample of the desiccant solution to measure its concentration. A 4-m long insulated flexible hose is connecting the dehumidifier with vapor compression unit to send the dehumidified air into the evaporating coil. The consumption of the electricity is measured by a power meter and a thermostat is provided to regulate the air outlet temperature from the evaporator. The schematic diagram of the hybrid cooling experimental system is presented in Fig.4.12.

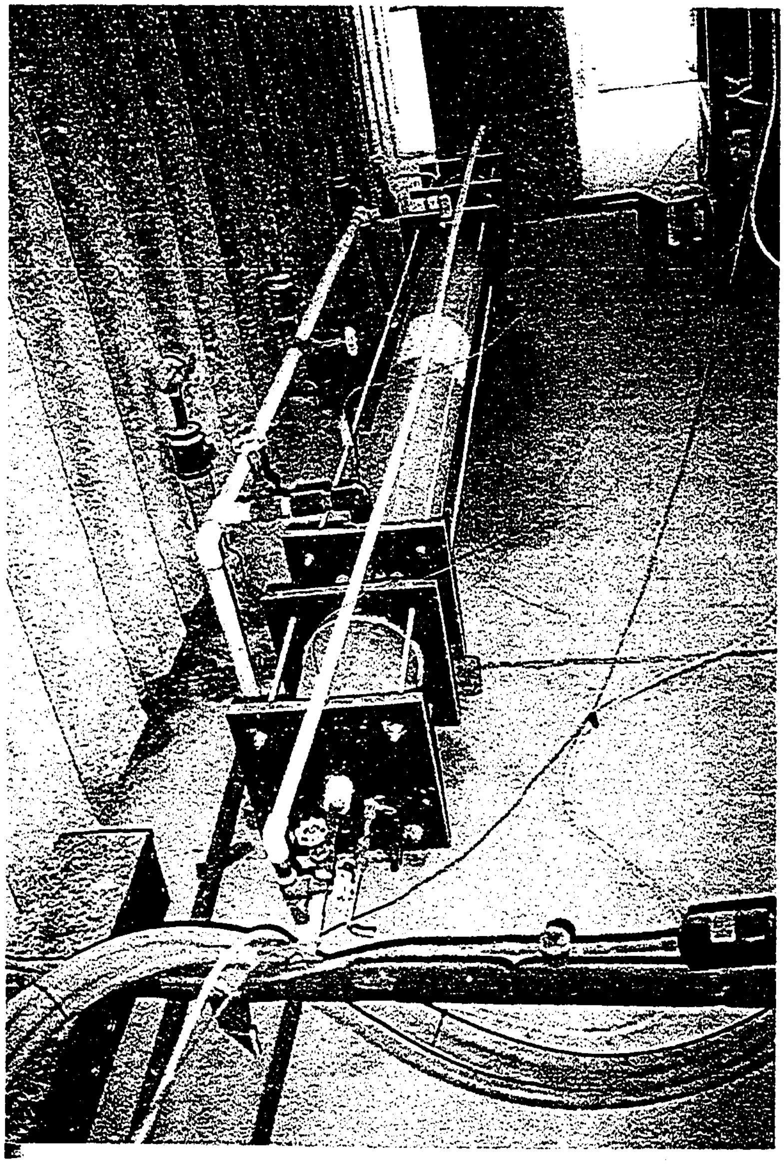


Figure 4.10: Desiccant-desiccant heat exchanger

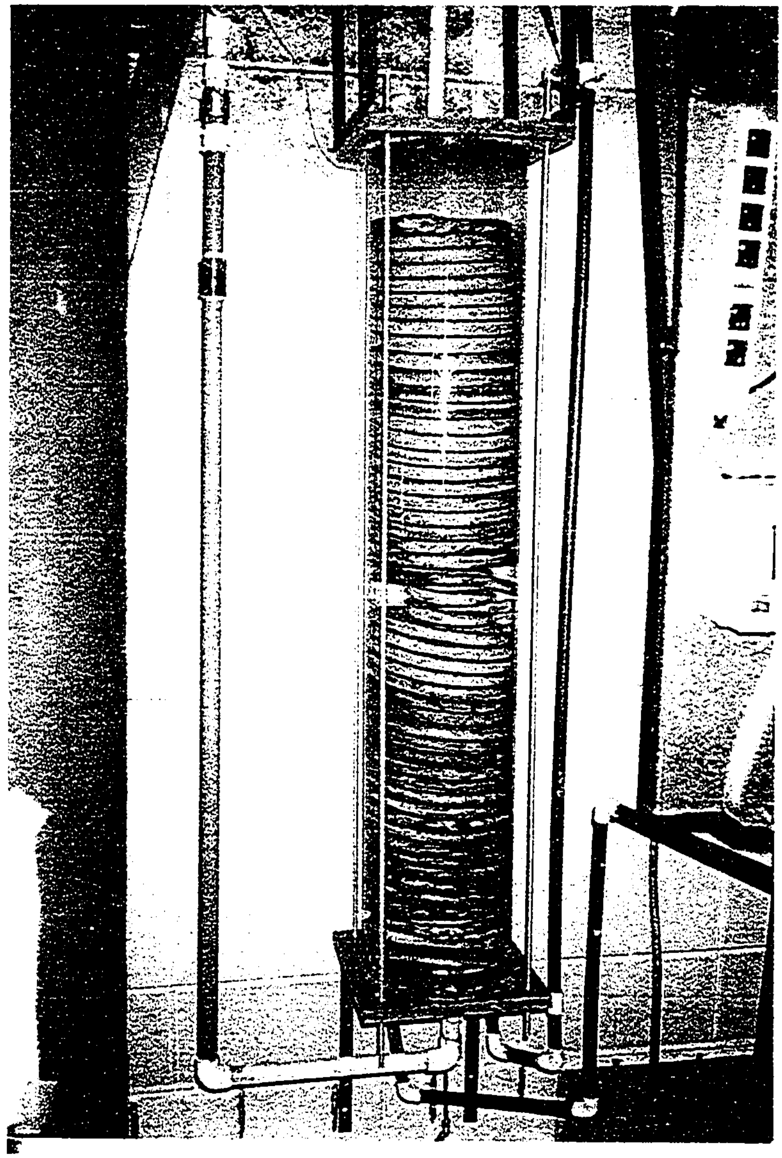


Figure 4.11: Water-desiccant heat exchanger

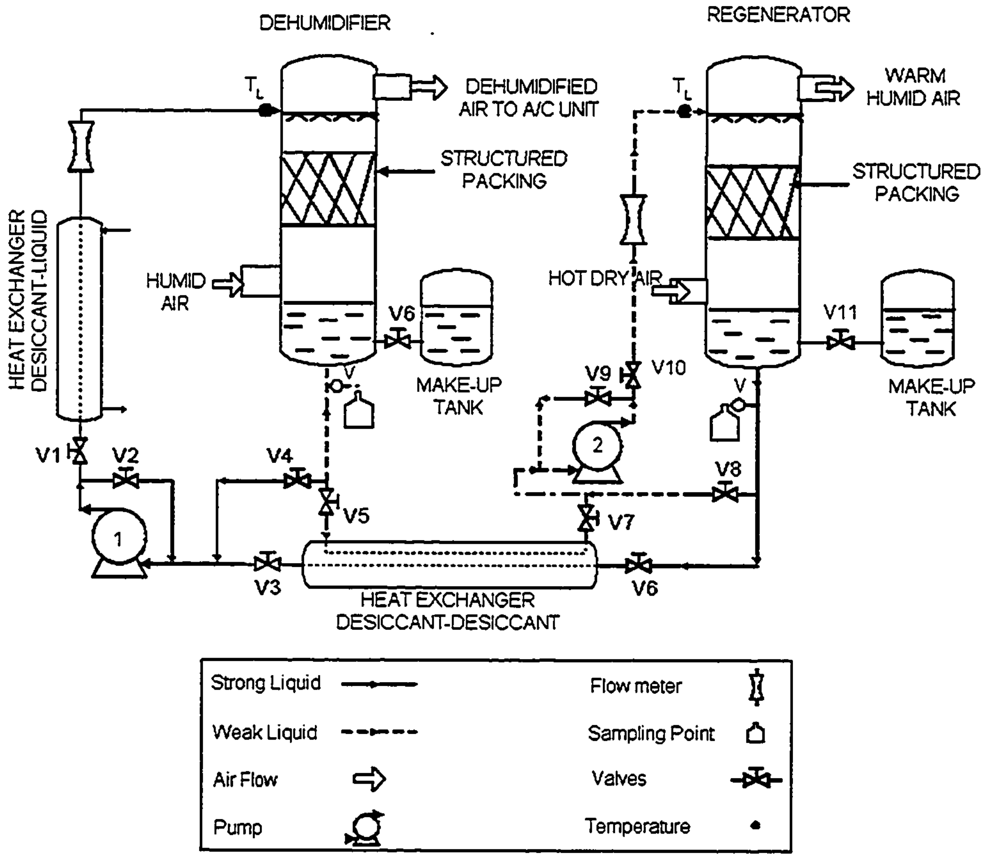


Fig.4.12: Schematic of the desiccant loop in the hybrid cooling system.

4.3.1 Procedure for Hybrid System

1. A concentrated desiccant solution is prepared and the specific gravity is measured using a hydrometer to determine its concentration.
2. Both the towers are filled with the desiccant solution (approximately 200 liters) and it is packed with structured packing material.
3. The desiccant is pumped into the dehumidifier using a stainless steel pump and it is sprayed inside the tower using a conventional sprayer.
4. The air is blown into the dehumidifier in a counter flow direction and its made to contact with the desiccant in the structured packing.
5. The desiccant absorbs water from the air as it trickles down the packing material and gets diluted.
6. The dehumidified air is sent to the evaporator coil for sensible cooling and the compressor power is measured by power meter.
7. A sample of desiccant is taken at inlet and outlet of the dehumidifier for temperature and concentration determination.
8. The airflow rate, temperature and its humidity are measured using Velocity Calc.
9. If the desiccant concentration is weak at the outlet of the dehumidifier it is send to the regenerator or else it is recirculated back again.
10. The weak solution coming out of the dehumidifier is send to the regenerator using a desiccant-desiccant heat exchanger where it is heated up with the exchange of hot solution coming out from the regenerator.
11. Then it is sprayed into the regenerator using a conventional sprayer.

12. The condenser waste heat is blown into the regenerator in a counter flow direction and its made to contact with the desiccant in the structured packing.
13. The hot concentrated solution is cooled in the heat exchanger by exchanging heat with the solution coming out of the dehumidifier. After passing through the heat exchanger, the warm solution is further cooled by the coil-type heat exchanger and it is sprayed again in the dehumidifier.

CHAPTER 5

RESULTS AND DISCUSSIONS

The effects of various parameters like packing height, desiccant concentration, temperature and flow rates of the desiccant and air that influence the air dehumidification and desiccant regeneration in a hybrid system will be discussed.

The climatic conditions of Dhahran, Saudi Arabia were simulated as the ambient conditions for the hybrid system. The variation of temperature and humidity per hour in Dhahran, Saudi Arabia is shown in Fig 5.1. Usually during the night maximum relative humidity recorded is 100 % and the temperature is usually around 32-34 ^{0}C but as the day progresses the air temperature increases resulting in the decrease of relative humidity and usually when the temperature is above 40 ^{0}C the humidity usually around 30 %. Therefore in this study a moderate humid, humid and high humid climates were used as the ambient conditions.

Results will be discussed separately in different sections according to each topic.

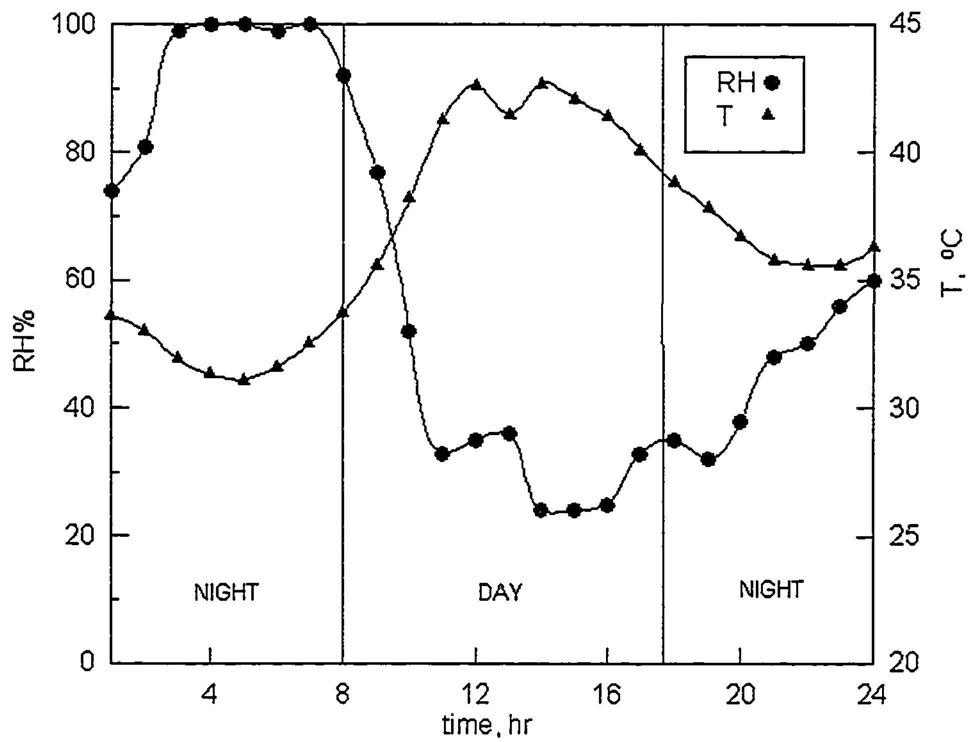


Fig. 5.1: Variation of temperature and relative humidity of a very hot and humid day in Dhahran, Saudi Arabia.

5.1 Dehumidifier

A set of experiments were conducted using the dehumidification set-up to investigate the performance of the gauze-type structured packing dehumidifier using calcium chloride as the desiccant. Two elements of the BXPFP structured gauze type packing were used. The strong desiccant was sprayed in the dehumidifier at different flow rates for a particular flow rate of air, namely 3200 m^3/h. The effects of various parameters on the air dehumidification process will be discussed.

The experimental results of the dehumidification system for the desiccant flow rate of 10 l/min are shown in Fig. 5.2 to Fig. 5.5. The variation of the desiccant concentration and temperature in the dehumidifier is shown in Fig 5.2. The desiccant concentration continuously decreases with time as it absorbs water vapor from the air and its temperature decreases. The potential for mass transfer at the beginning of the run is high due to the higher concentration of the desiccant and hence the removal of moisture is faster and as the desiccant becomes weaker the mass transfer rate decreases. The temperature of the desiccant decreases gradually as time increases but the rate of decrease is less than the rate of concentration decrease. Despite the heat generated by moisture absorption, which tends to increase the desiccant temperature, the heat transfer from the air (due to the large temperature difference between the desiccant and air) decreases the desiccant temperature slightly.

The variation of air outlet temperature and relative humidity with time is shown in Figs. 5.3. The figure indicates that the air outlet temperature is almost constant at 35 ^{0}C and greater than the inlet air temperature due to the heat transfer from the desiccant to the air.

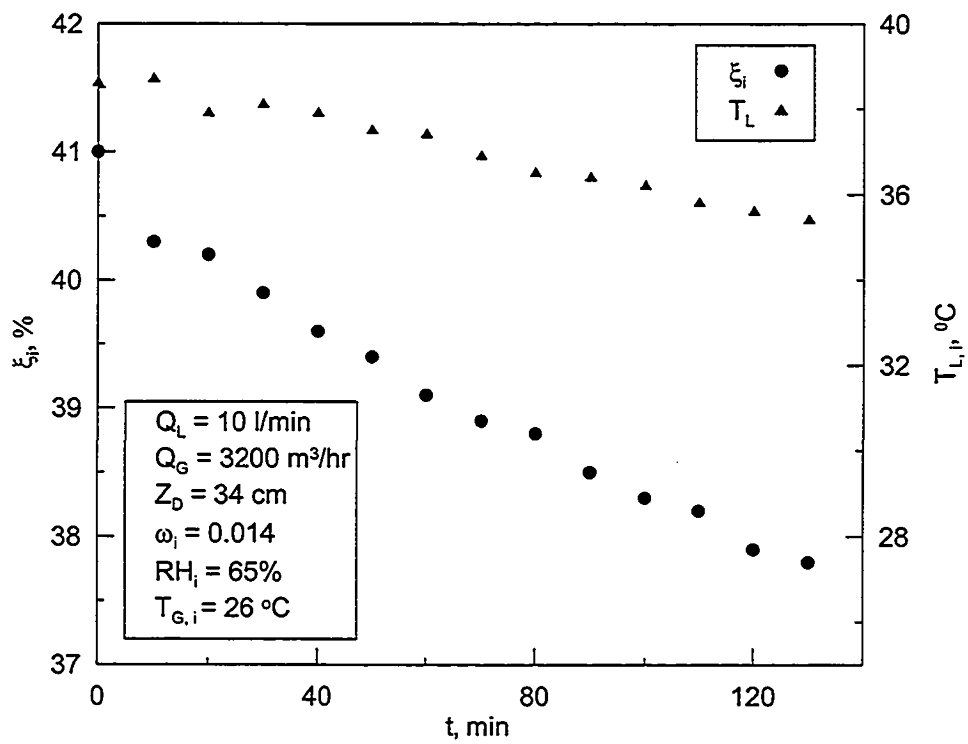


Figure 5.2: Time variation of concentration and desiccant temperature for Q_L = 10 l/min in the dehumidifier.

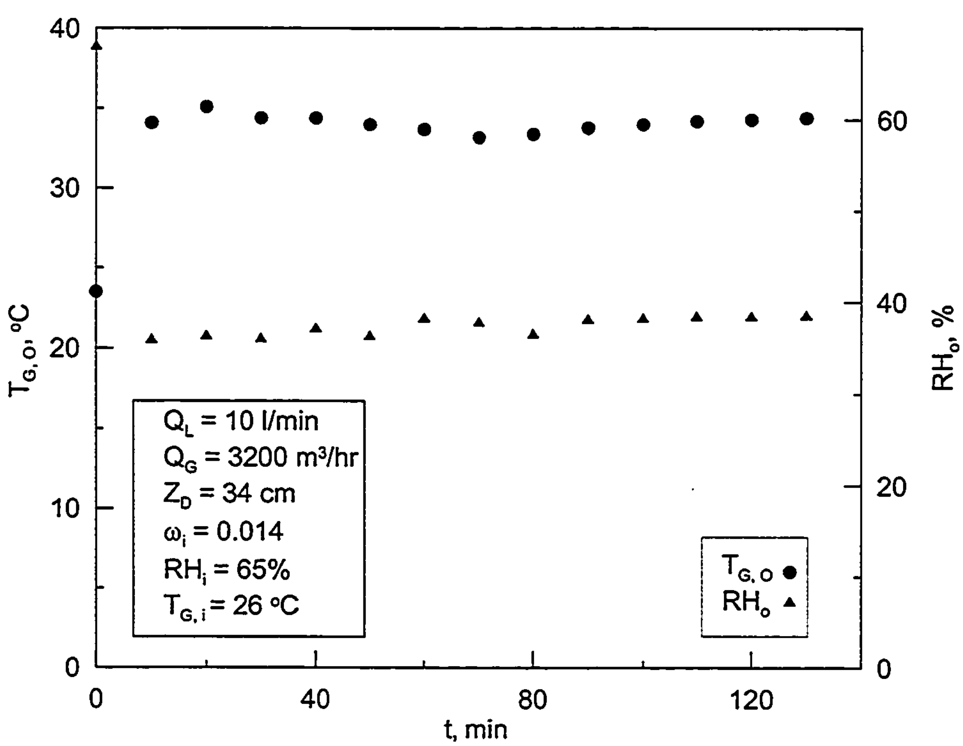


Figure 5.3: Time variation of outlet temperature and humidity for Q_L= 10 l/min in the dehumidifier.

The air outlet relative humidity decreases at the beginning and then slightly increases as desiccant becomes weaker but it is always less than the inlet absolute humidity. The variation of the outlet and ratio of absolute humidity of air with time is shown in Fig 5.4. The air outlet absolute humidity decreases in the beginning and then slightly increases when the desiccant becomes weak. The effectiveness of the dehumidifier is plotted versus time as shown in Fig 5.5. In the start of the run the effectiveness is high but as the vapor pressure of the desiccant increases with time, the dehumidifier effectiveness decreases.

5.1.1 Effect of Desiccant Flow rate

The effect of the desiccant flow rate on the performance of the dehumidifier is studied. Fig 5.6 shows that as the desiccant flow rate increases, the concentration of the desiccant at the outlet of the dehumidifier decreases for a particular flow rate of air. The absolute humidity of the air at the outlet of the dehumidifier decreases as the desiccant flow rate increases due to the fact that air is exposed to a large quantity of desiccant, which increases the potential for mass transfer. However, it is found that as the desiccant flow rate reaches a certain maximum value in this case 22 l/min, the effect of the desiccant flow rate decreases. This is due to the excessive flow of the desiccant on the packing material, which causes flooding in the dehumidifier. The average effectiveness of the dehumidifier increases with the flow rates of the desiccant as shown in the Fig. 5.7

5.1.2 Effect of Desiccant Inlet Temperature

The effect of desiccant inlet temperature on the dehumidifier performance is shown in Fig. 5.8 for a given set of operating conditions.

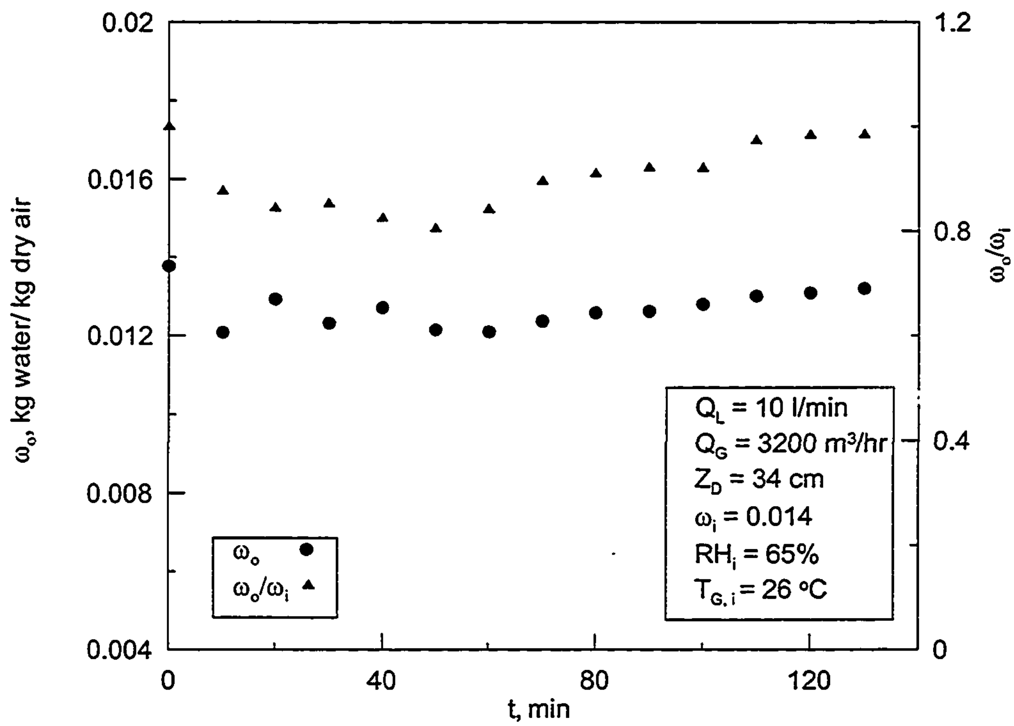


Figure 5.4: Time variation of outlet absolute humidty and ratio of outlet to inlet absolute humidty for Q_L = 10 l/min in the dehumidifier.

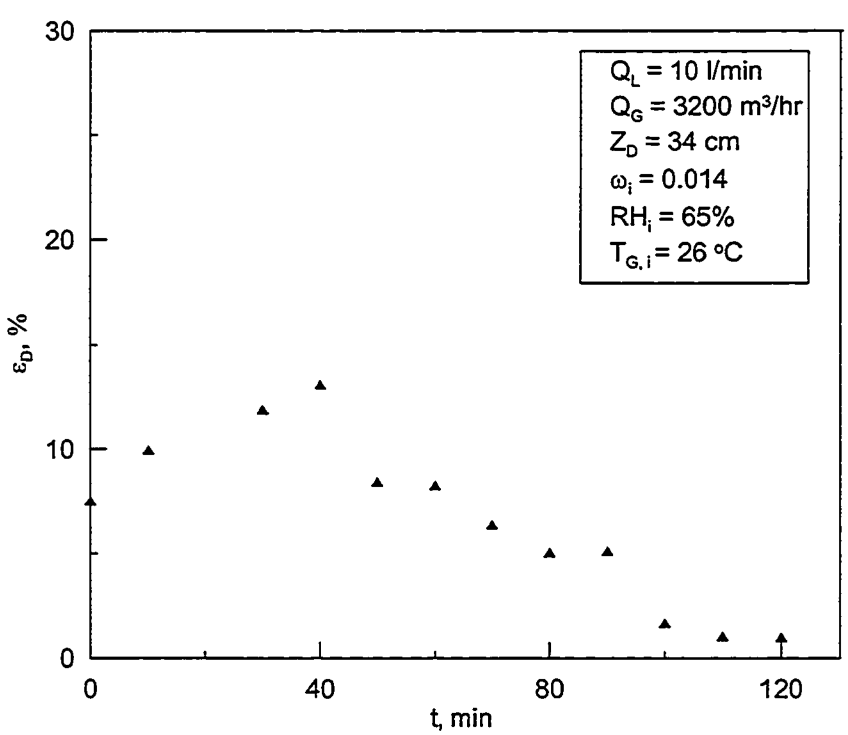
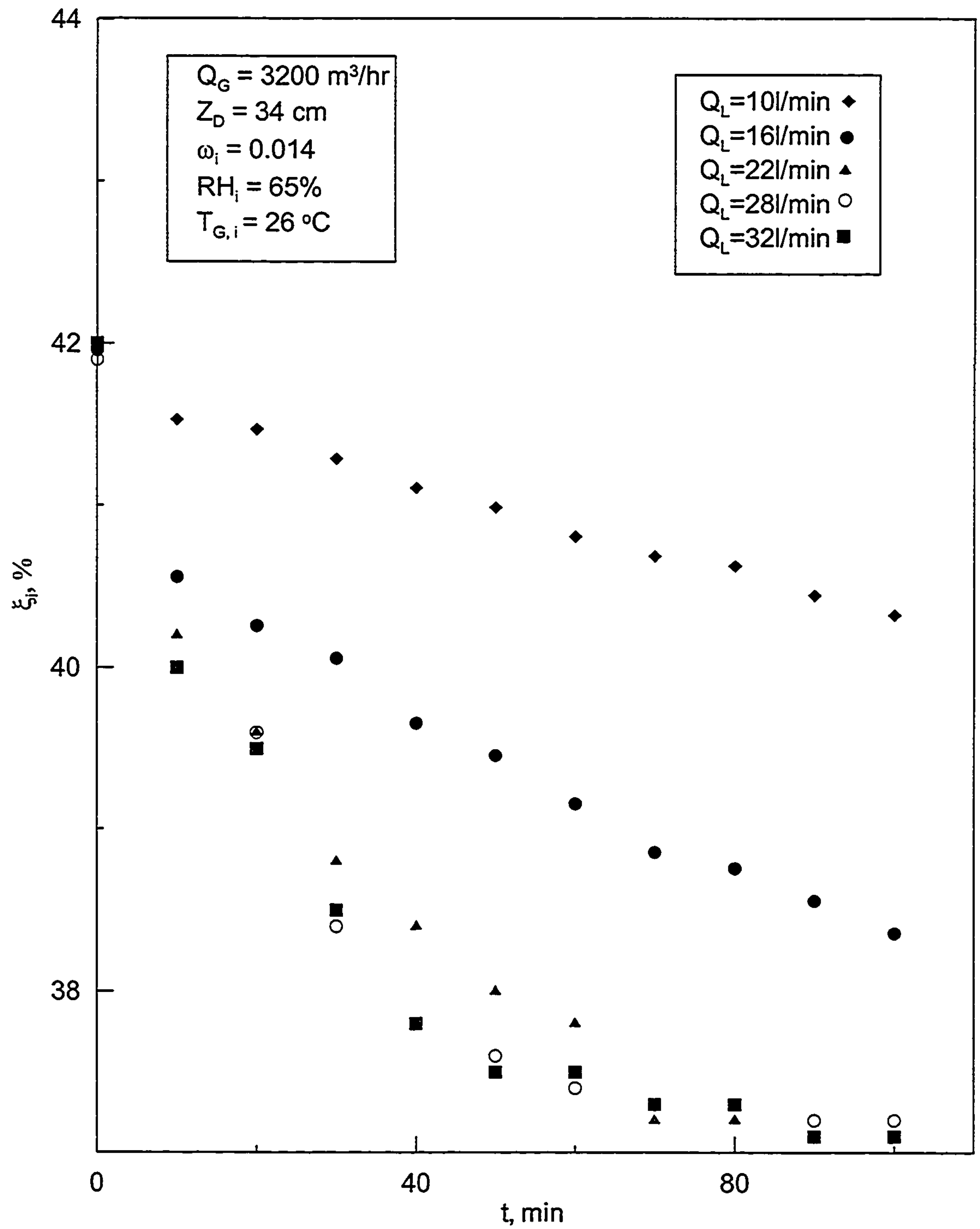


Figure 5.5: Effectiveness of the dehumidifier with time for Q_L= 10l/min.



Fiqure 5.6: Variation of concentration with time for different desiccant flow rates in the dehumidifier.

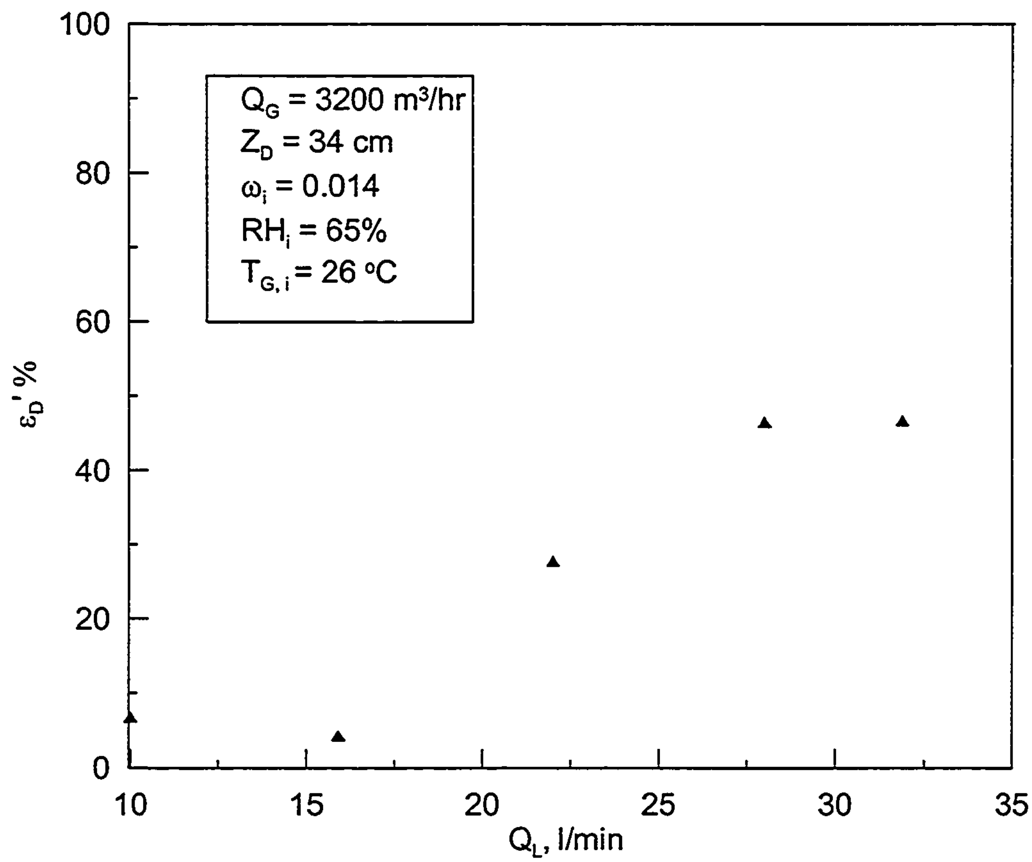


Figure 5.7: Average effectiveness of the dehumidifier with time for various flow rates.

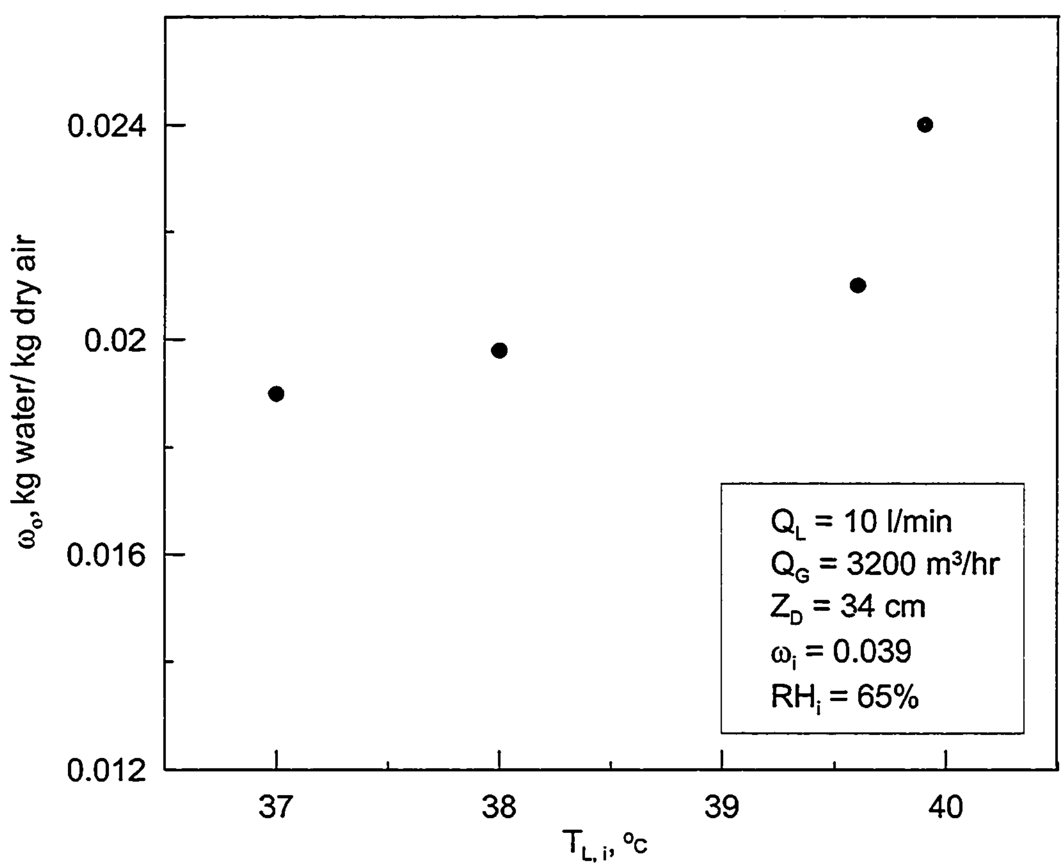


Figure 5.8: Effect of desiccant inlet temperature on the change in air absolute humidity in the dehumidifier.

The increase in inlet desiccant temperature tends to increase the air outlet absolute humidity resulting in the decrease in the effectiveness of the dehumidification. This is due to the fact that at higher temperatures the desiccant has a higher vapor pressure, and there is a decrease in the vapor pressure difference between the desiccant and the air. As the potential for mass transfer decreases the desiccant absorbs less moisture from the air and the air outlet absolute humidity increases.

If the desiccant temperature is less than the air temperature, it gets heated up after the dehumidification resulting in the increase in the vapor pressure whereas if the desiccant temperature is more than air temperature it gets cooled resulting in decrease in vapor pressure, which increases the effectiveness of the dehumidifier.

5.1.3 Effect of Desiccant Inlet Concentration

The effect of desiccant inlet concentration on the dehumidifier performance is shown in Fig. 5.9. As the desiccant concentration increases the air outlet absolute humidity decreases which results in increase of the dehumidification effectiveness. The stronger desiccant has a lower vapor pressure, which increases the potential for mass transfer. Hence a stronger desiccant absorbs more moisture from the air and the air outlet absolute humidity further increases.

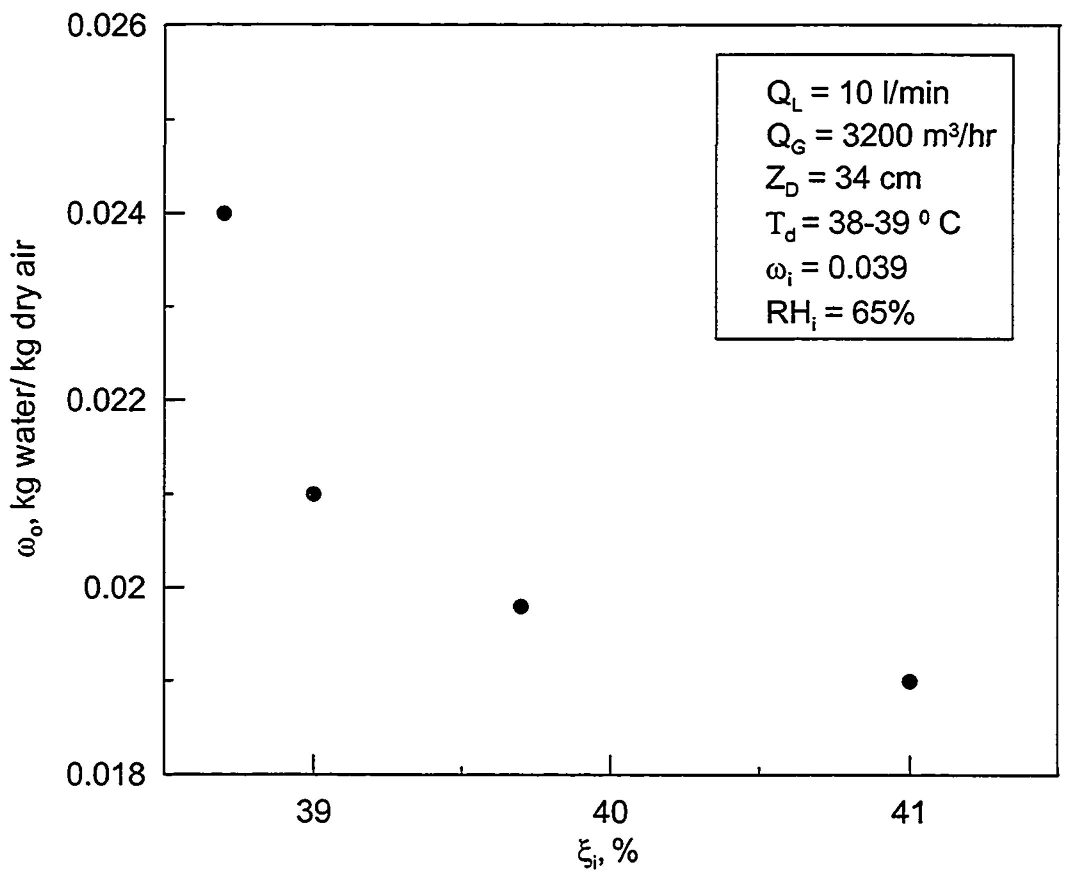


Figure 5.9: Effect of desiccant concentration on the dehumidifier performance in the dehumidifier.

5.2 Regenerator

A Set of experiments were conducted using the set-up to investigate the performance of the gauze-type structured packing regenerator using calcium chloride as the desiccant. Two elements of the Sulzer gauze-type steel (AISI 316L) structured packing were used. The weak desiccant was sprayed in the regenerator at different flow rates for a particular flow rate of air, namely 1200 m^3/h. The effects of various parameters on the desiccant regeneration process will be discussed. In this study the performance of the regenerator is studied alone without dehumidification system. The desiccant is made to recirculate in the regeneration loop only. The effect of various parameters on the performance of the regenerator is studied under dry as well as in humid conditions.

The experimental results of the regeneration system for the desiccant flow rate of 600 l/hr and air inlet temperature of 60 ^{0}C are shown in Fig. 5.10 to Fig. 5.13. It can be seen from Fig. 5.10 that, as time increases the desiccant concentration as well as its temperature increase. The increase in the desiccant concentration is due to mass transfer of the water vapor from the desiccant to the air. The desiccant gets concentrated from 34 % to 45 % in about 10hr and the desiccant temperature is increased from 39 ^{0}C to 43 ^{0}C .

From Fig 5.11 shows the variation of air outlet temperature and humidity with time. The air outlet temperature increases for some time and then there is no significant increase in air outlet temperature and it is at around 48 ^{0}C for this case whereas the air outlet relative humidity always decreases as time increases. The absolute humidity as well as ratio between the absolute humidity of the air leaving the regenerator to that of

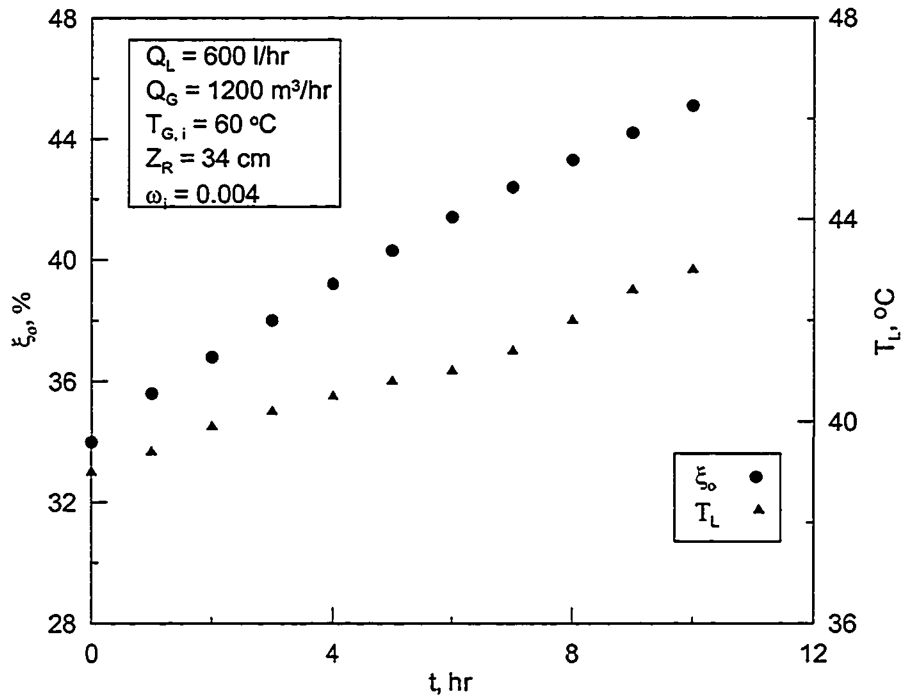


Figure 5.10: Time variation of concentration and desiccant temperature for Q_L = 600 l/hr and $T_{G,i}$ = 60 °C in the regenerator.

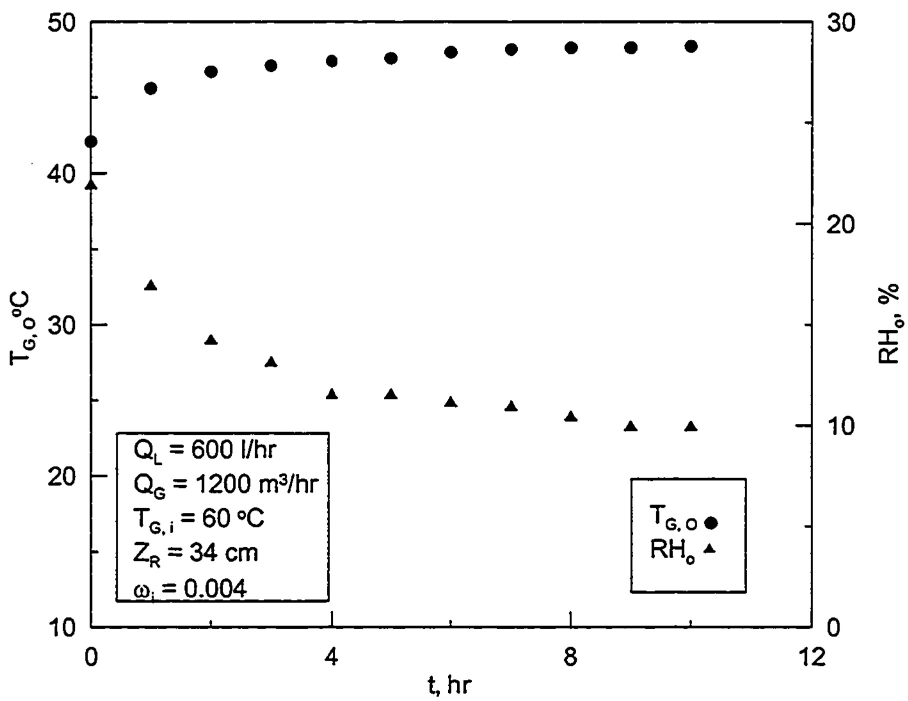


Figure 5.11: Time variation of outlet temperature and humidity for Q_L= 600 l/hr and $T_{G,i}$ = 60 °C in the regenerator.

the inlet condition is shown in Fig. 5.12. The figure shows that both the absolute humidity and the ratio between the absolute humidity of the air at exit to that at the inlet are decreasing with time. However, the value of ω_o is always greater than the inlet absolute humidity because of the moisture transfer from the liquid desiccant to the air. As the desiccant becomes stronger with time the moisture content of the desiccant decreases resulting in decrease in outlet humidity with time. The Figure 5.13 depicts the regenerator effectiveness with time. As time elapsed, the effectiveness increases due to the decrease of the vapor pressure of the air leaving the regenerator.

5.2.1 Effect of Desiccant Flow rates:

The effect of the desiccant flow rate on the performance of the regenerator is studied. Keeping the other parameters constant, i.e., $T_G = 60\ ^0C$, $Q_G = 1200\ m^3/hr$ and Z = 34 cm the desiccant flow rate is varied from 600 to 1000 l/hr. Fig 5.14 shows that as the desiccant flow rate increases, the concentration of the desiccant increases because the air is exposed to a large quantity of desiccant which increases the potential for mass transfer. However it is found that as the desiccant flow rate reaches a certain maximum value the effect of the desiccant flow rate decreases. This is may be due to the excessive flow of the desiccant on the packing material, which causes flooding in the regenerator. Similar trends were observed for different air temperatures 70 ^0C and 80 ^0C and the results are shown in Fig 5.15 and Fig. 5.16. However, it is found that to obtain the same required concentration, the desiccant flow rate 600 l/hr takes longer time than other runs of Q_L = 800 l/hr and 1000 l/hr

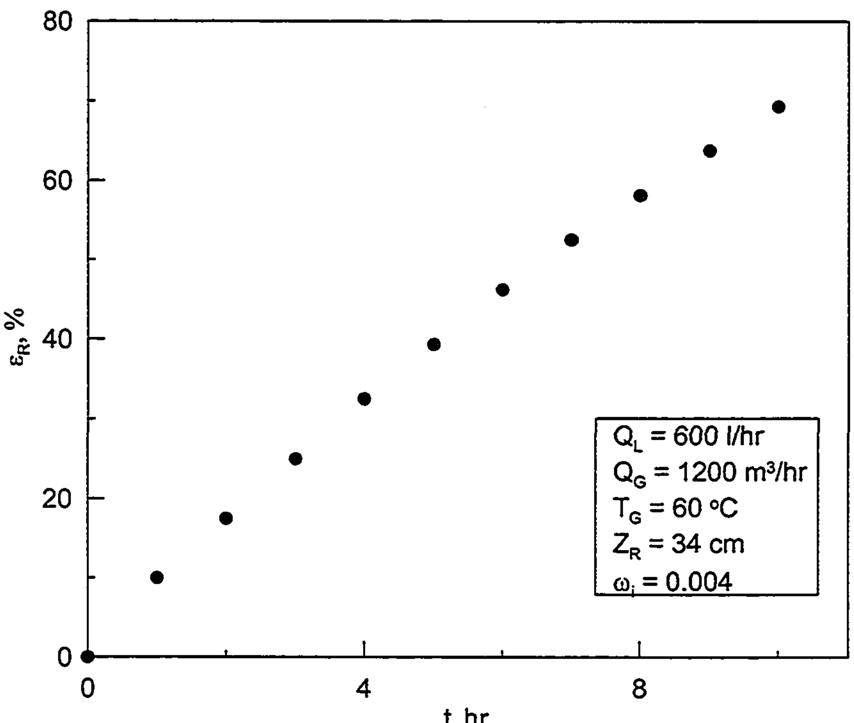


Figure 5.12: Effectiveness of the regenerator with time for Q_L = 600 l/hr and $T_{G,i}$ = 60 °C in the regenerator.

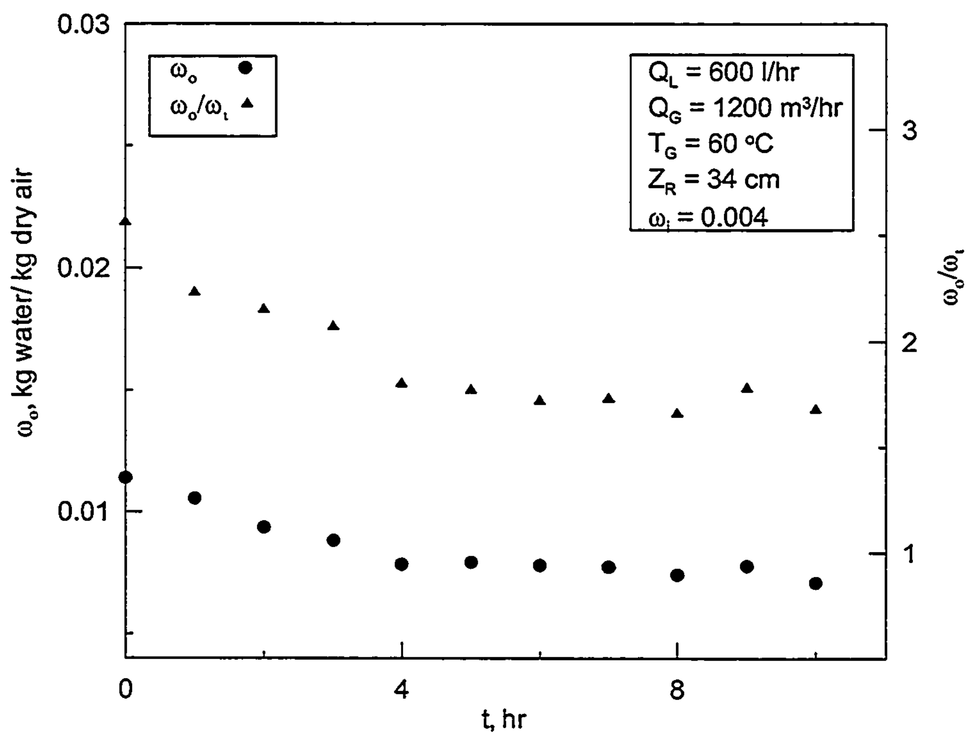


Figure 5.13: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for Q_L = 600 l/hr and $T_{G,i}$ = 60 °C in the regenerator.

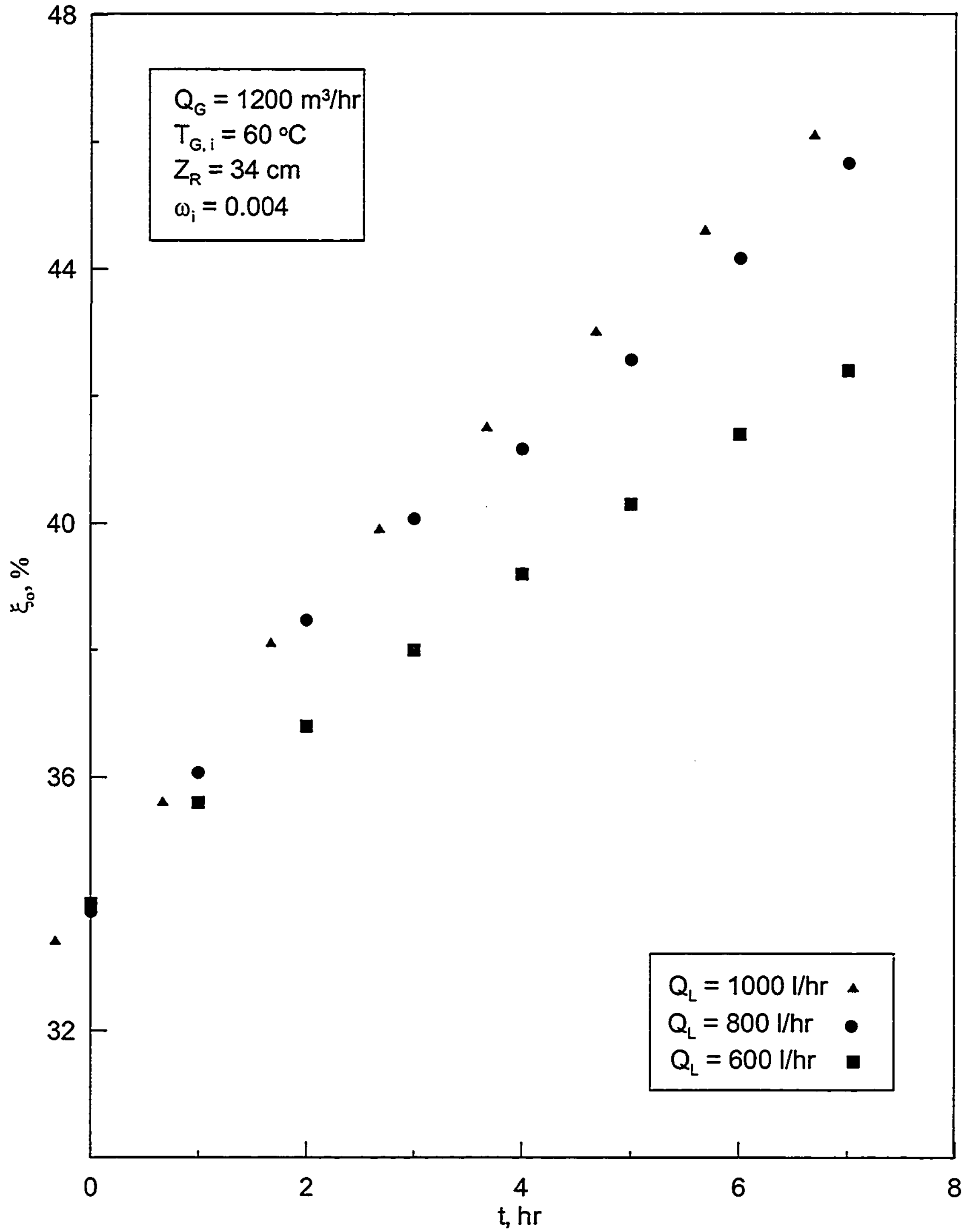


Figure 5.14: Variation of concentration with time for different desiccant flow rates at 60^{0}C air inlet temperature in the regenerator.

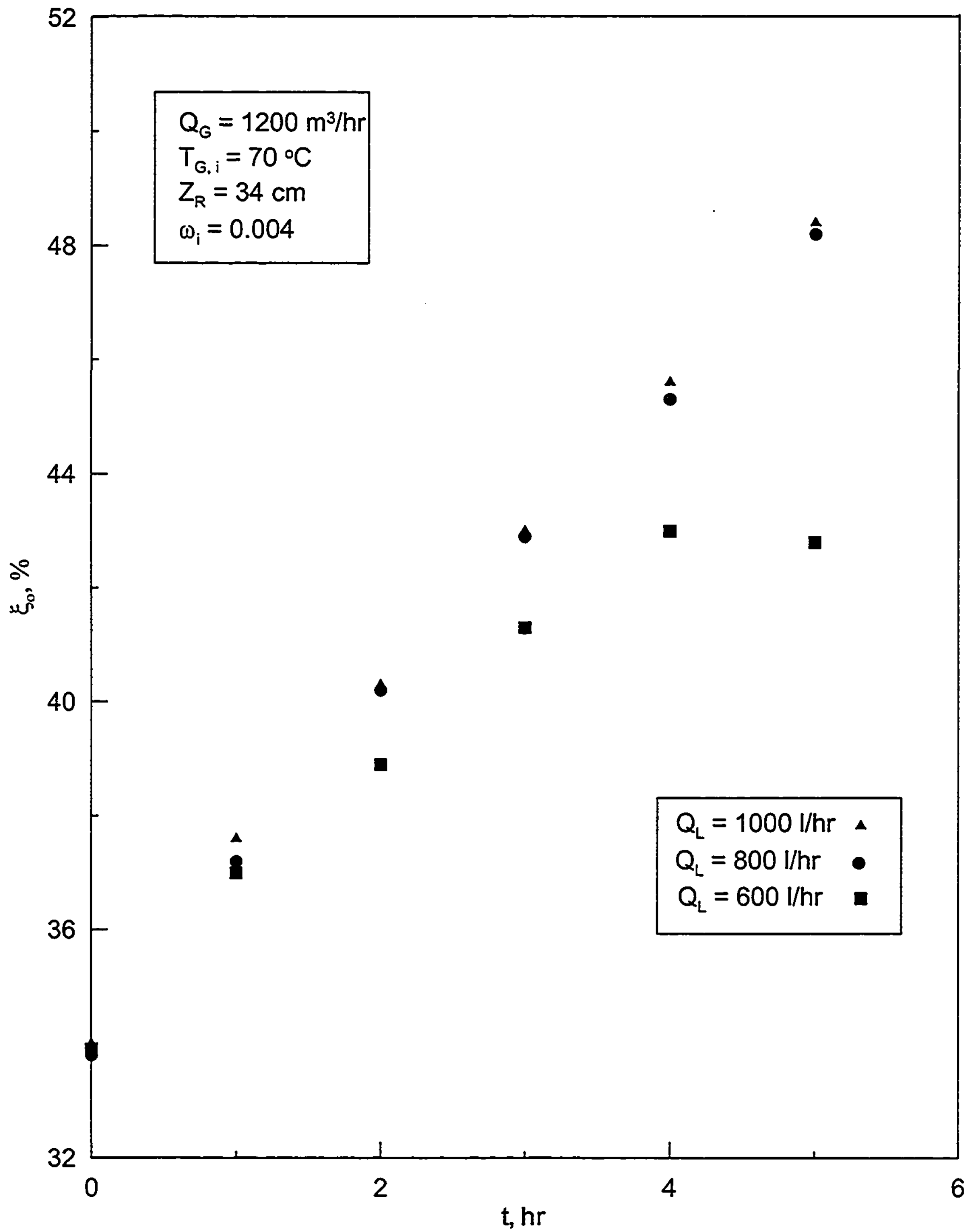


Figure 5.15: Variation of concentration with time for different desiccant flow rates at 70°C air inlet temperature in the regenerator.

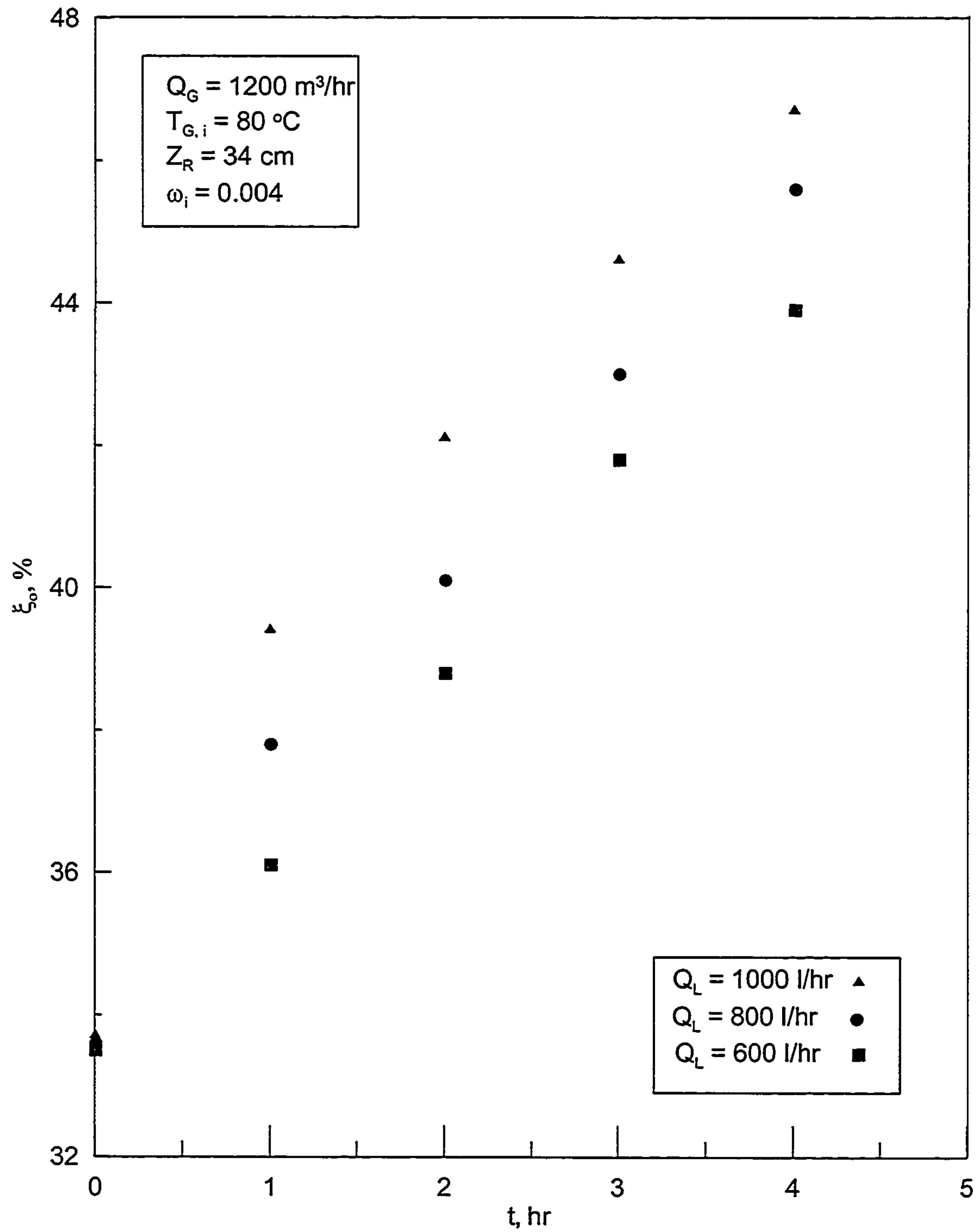


Figure 5.16: Variation of concentration with time for different desiccant flow rates at 80°C air inlet temperature in the regenerator.

5.2.2 Effect of Air Inlet Temperature:

The effect of air inlet temperature on the time taken to obtain the required concentration of the desiccant is shown in Figs. 5.17, 5.18 and 5.19 for three desiccant flow rates; 800l/hr, 1000l/hr and 1200 l/hr, respectively. From the figures it is clear that higher inlet temperature takes less time to obtain the required concentration since higher air temperature results in higher desiccant temperature and hence increased potential for mass transfer.

The effectiveness of the regenerator for the effect of desiccant flow rate and the effect of air inlet temperature is shown in Figs. 5.20 to 5.25 which clearly shows that the effectiveness increases with increase in desiccant flow rate and air inlet temperature.

5.2.3 Effect of Ratio of Air to Desiccant Flow rate

The effect of Q_G/Q_L on the regenerator performance is shown in Fig. 5.26. It can be seen from the figure that the desiccant concentration at the outlet of the regenerator increases with Q_G/Q_L due to increase in water evaporation from the desiccant and then decreases. This may be due to the fact that the increased wetting of the structured packing material with increasing Q_G/Q_L. At a particular ratio of Q_G/Q_L, maximum wetting of the packing is obtained and further increase in Q_G/Q_L will not improve the wetting, as shown in the figure and hence the desiccant concentration at the outlet decreases.

5.2.4 Effect of Desiccant Inlet Temperature

The response of the regeneration system to varying the desiccant inlet temperature is shown in Fig. 5.27. As the desiccant inlet temperature increases, the desiccant

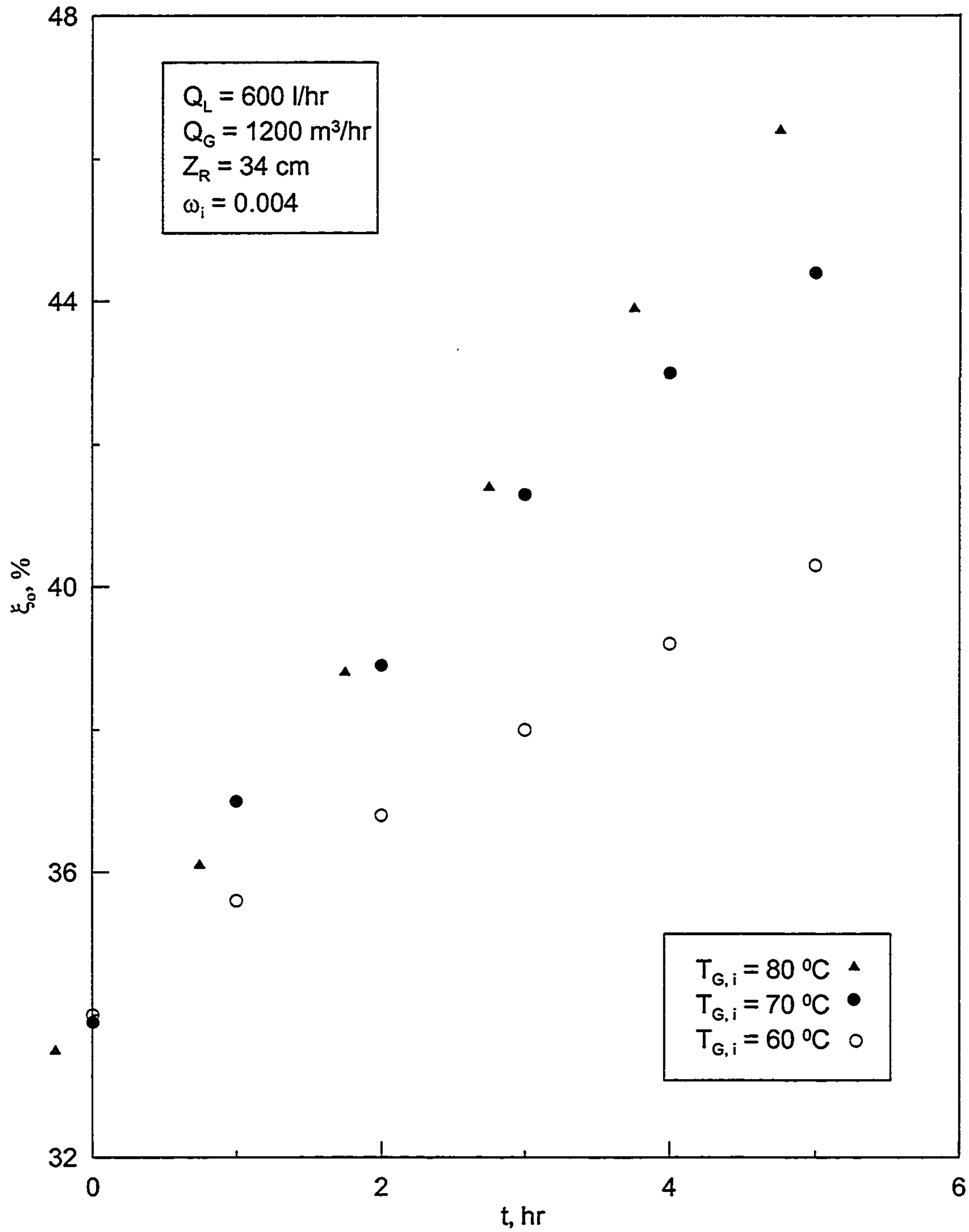


Figure 5.17: Variation of concentration with time for different air inlet temperatures at 600l/hr desiccant flowrate in the regenerator.

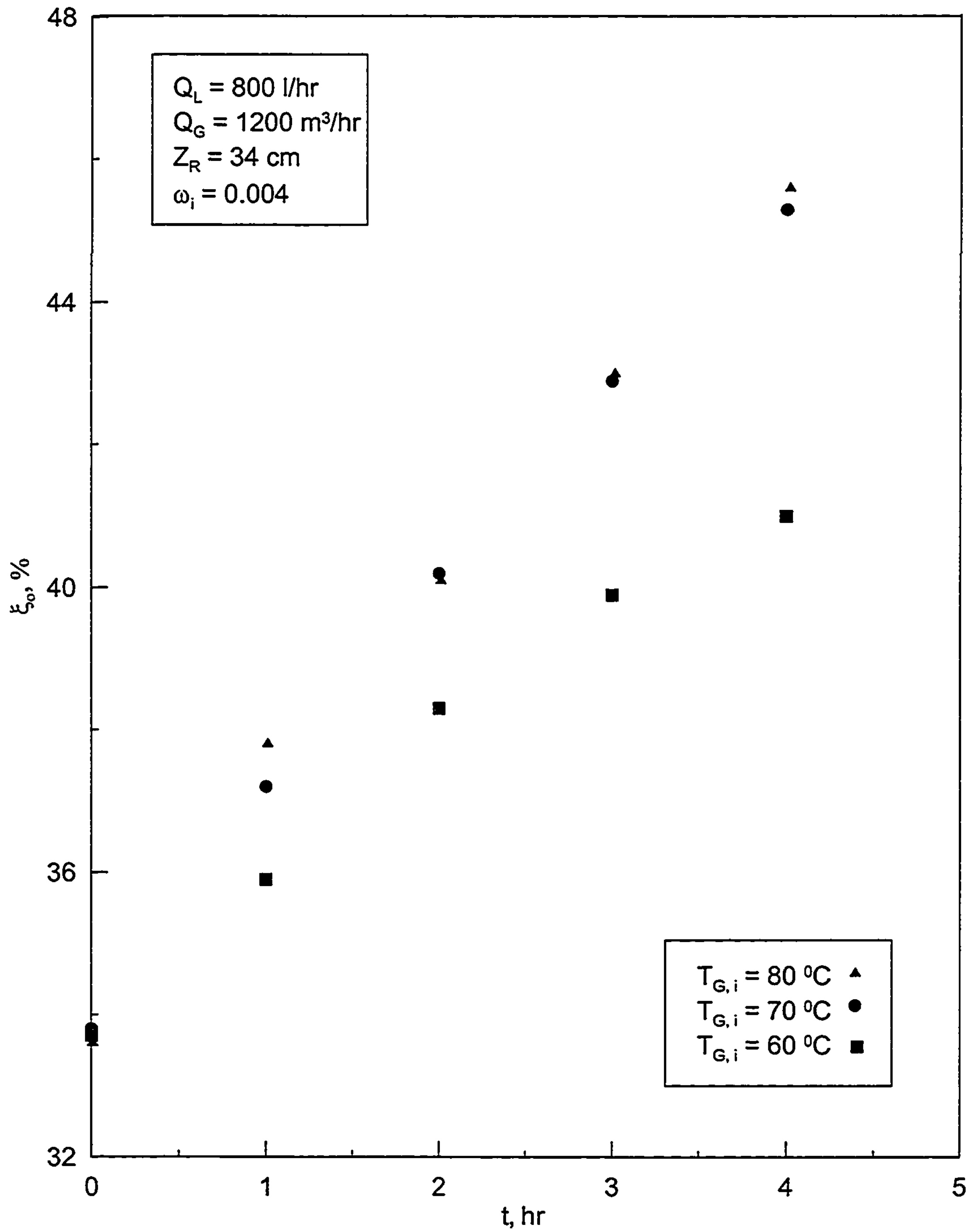


Figure 5.18: Variation of concentration with time for different air inlet temperatures at 800l/hr desiccant flowrate in the regenerator.

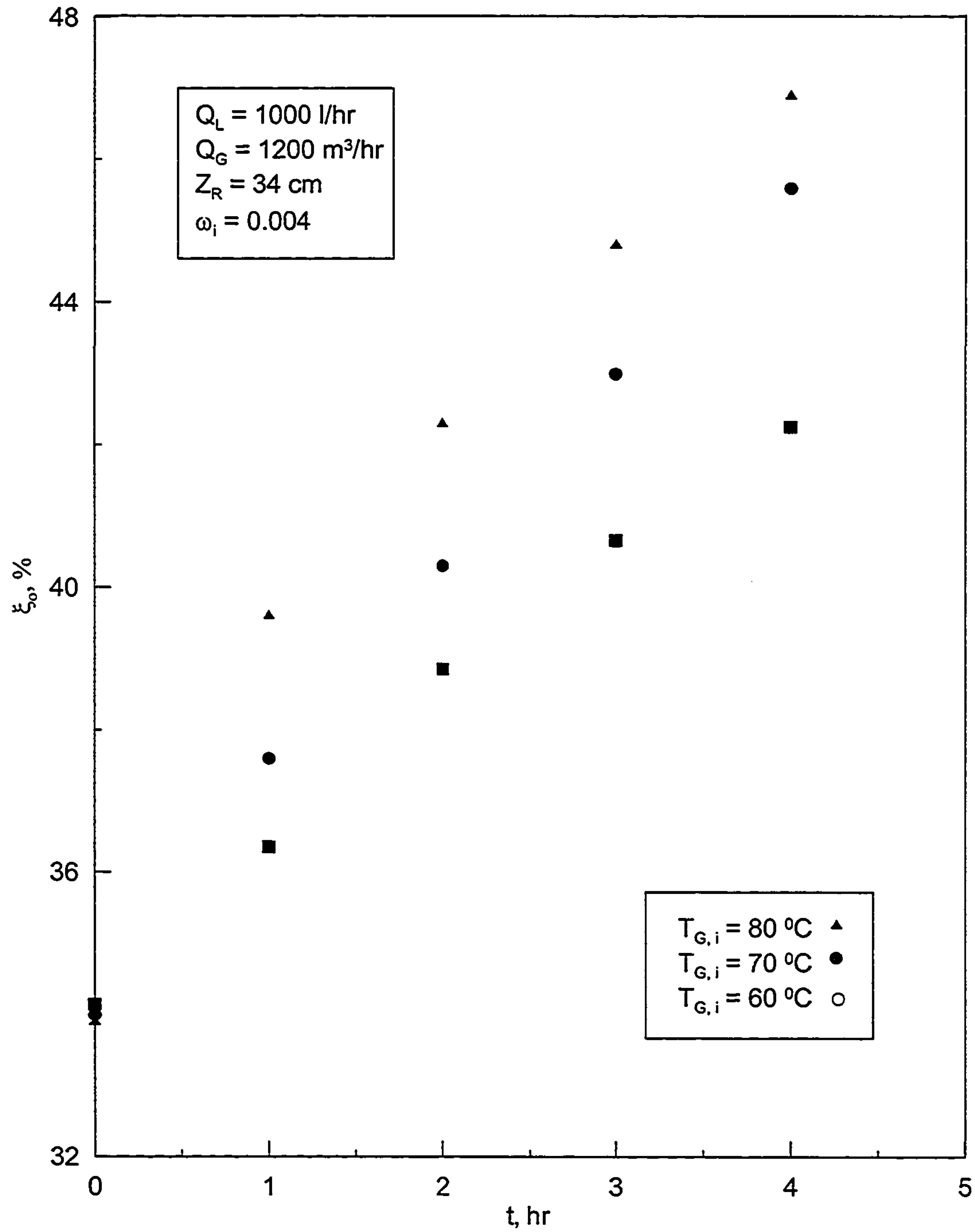


Figure 5.19: Variation of concentration with time for different air inlet temperatures at 1000l/hr desiccant flowrate in the regenerator.

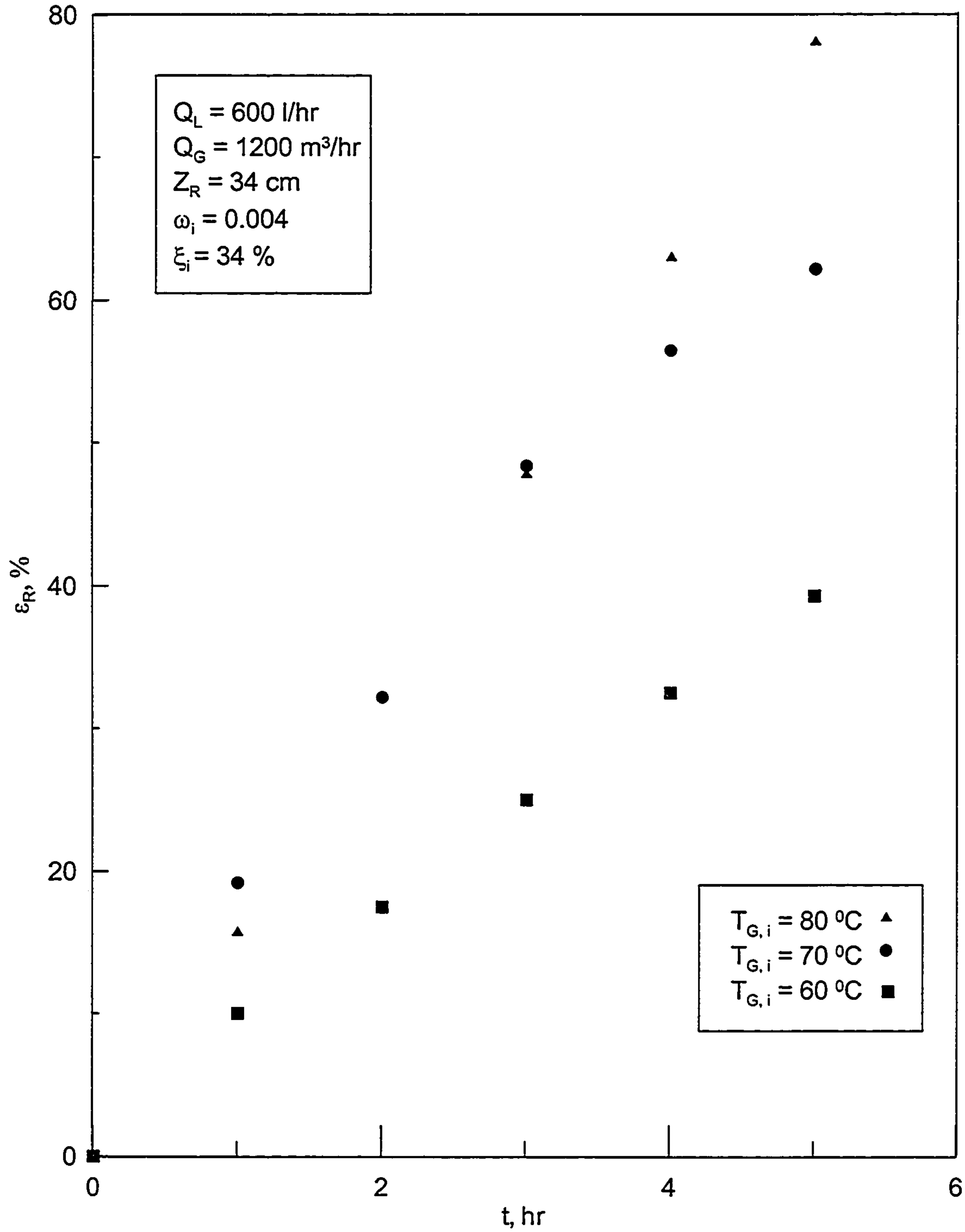


Figure 5.20: Effectiveness of the regenerator with time for Q_L = 600 l/hr for different air temperatures.

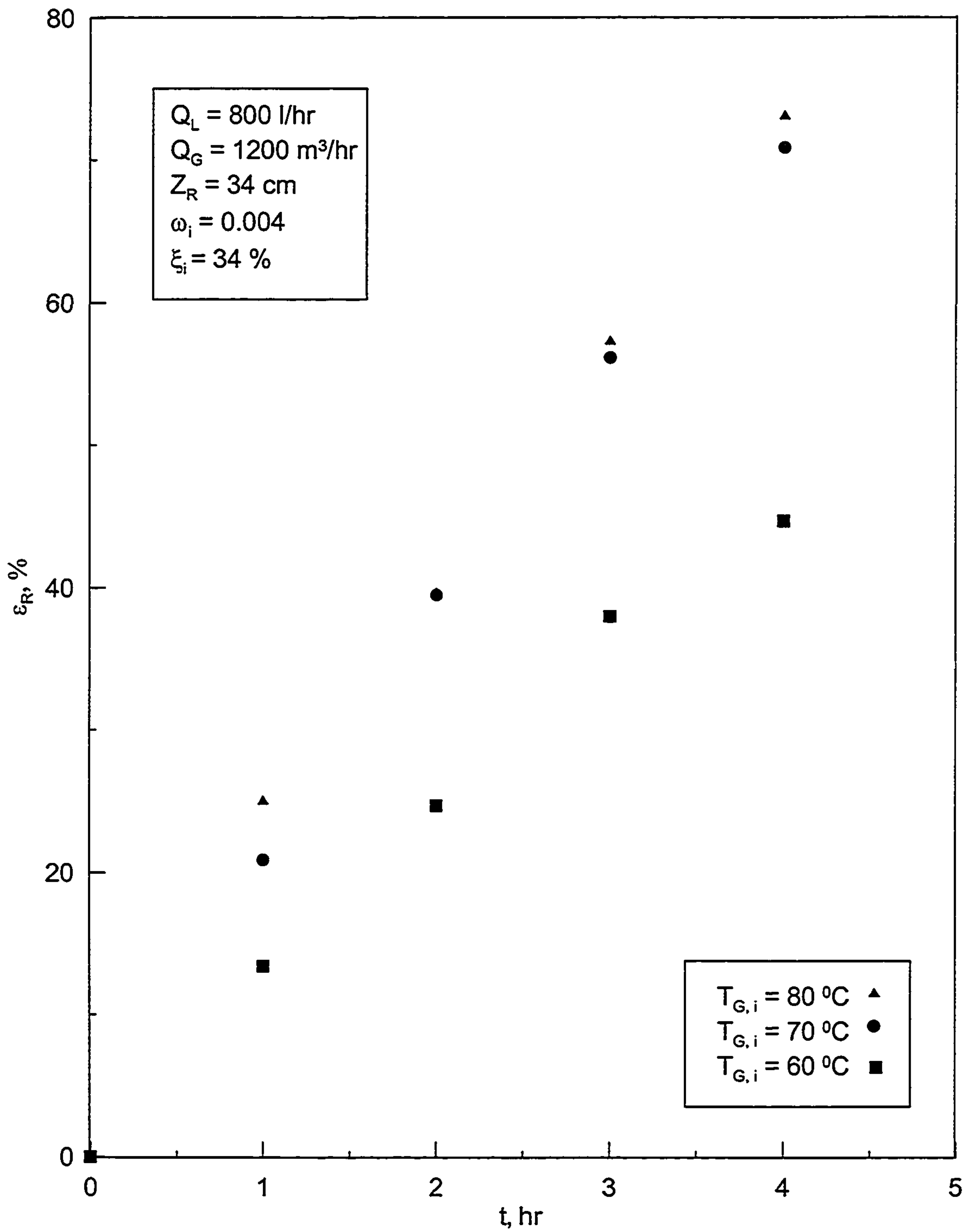


Figure 5.21: Effectiveness of the regenerator with time for Q_L = 800 l/hr for different air temperatures.

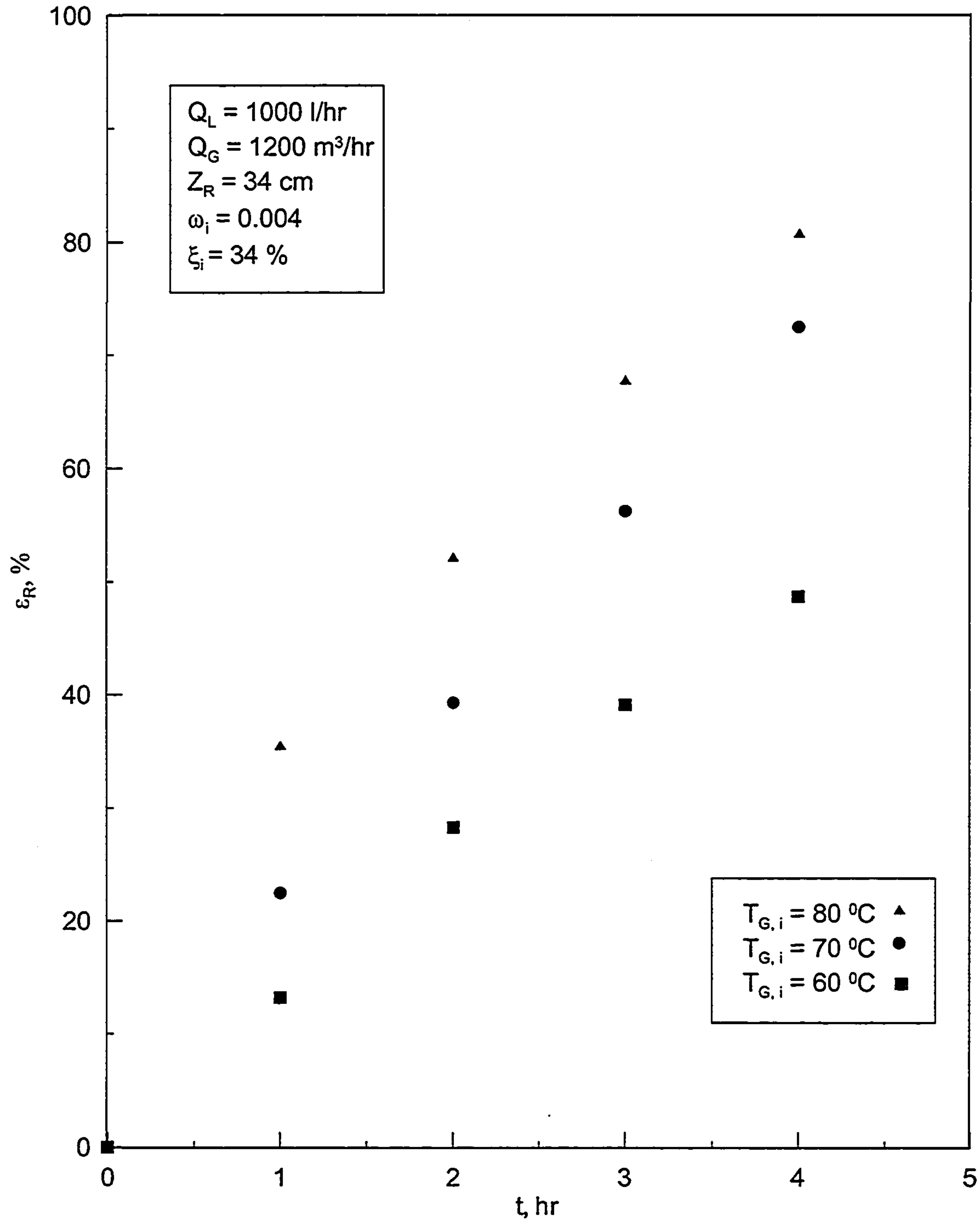


Figure 5.22: Effectiveness of the regenerator with time for Q_L = 1000 l/hr for different air temperatures.

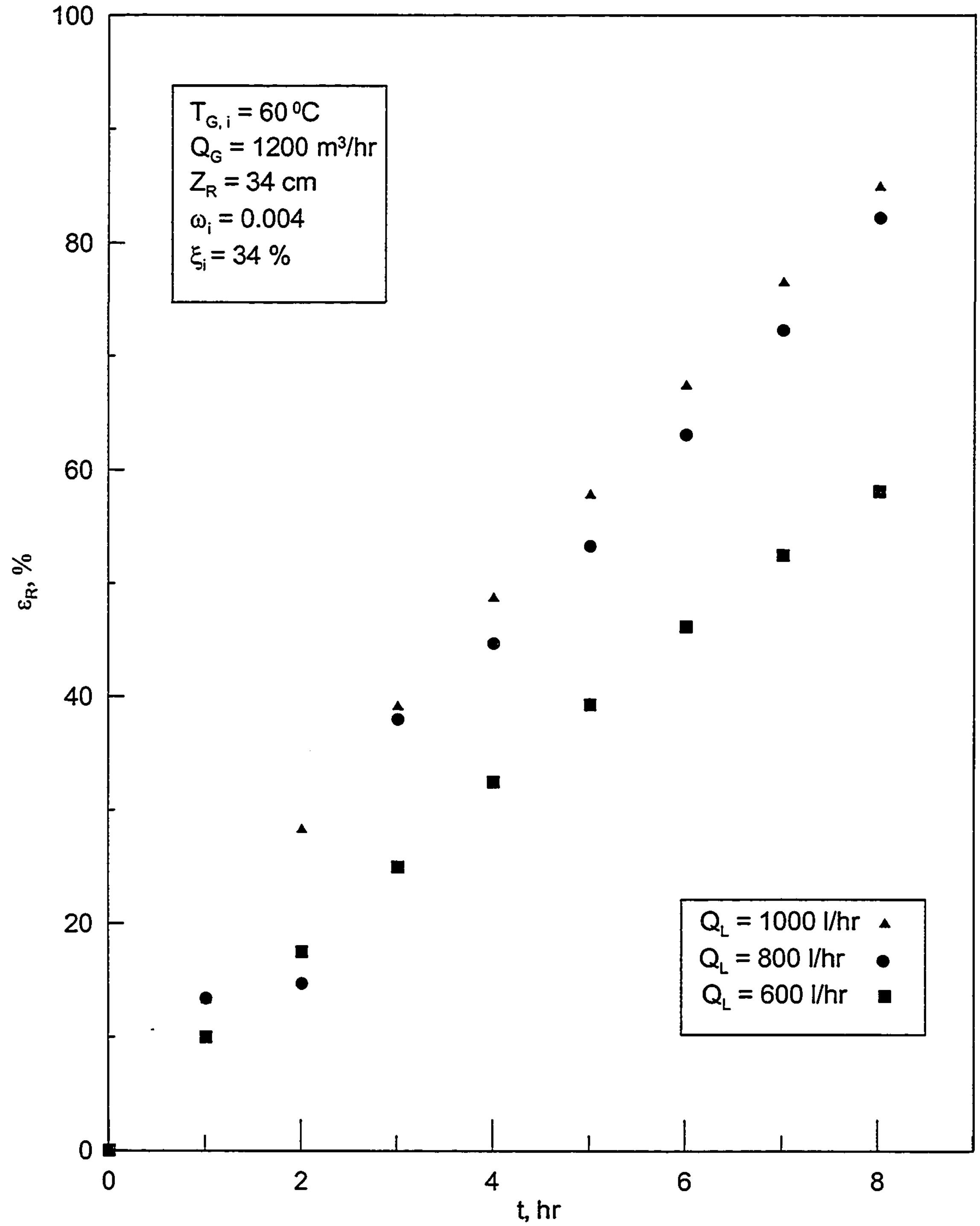


Figure 5.23: Effectiveness of the regenerator with time for $T_{G,i} = 60\,^0C$ for different desiccant flow rates.

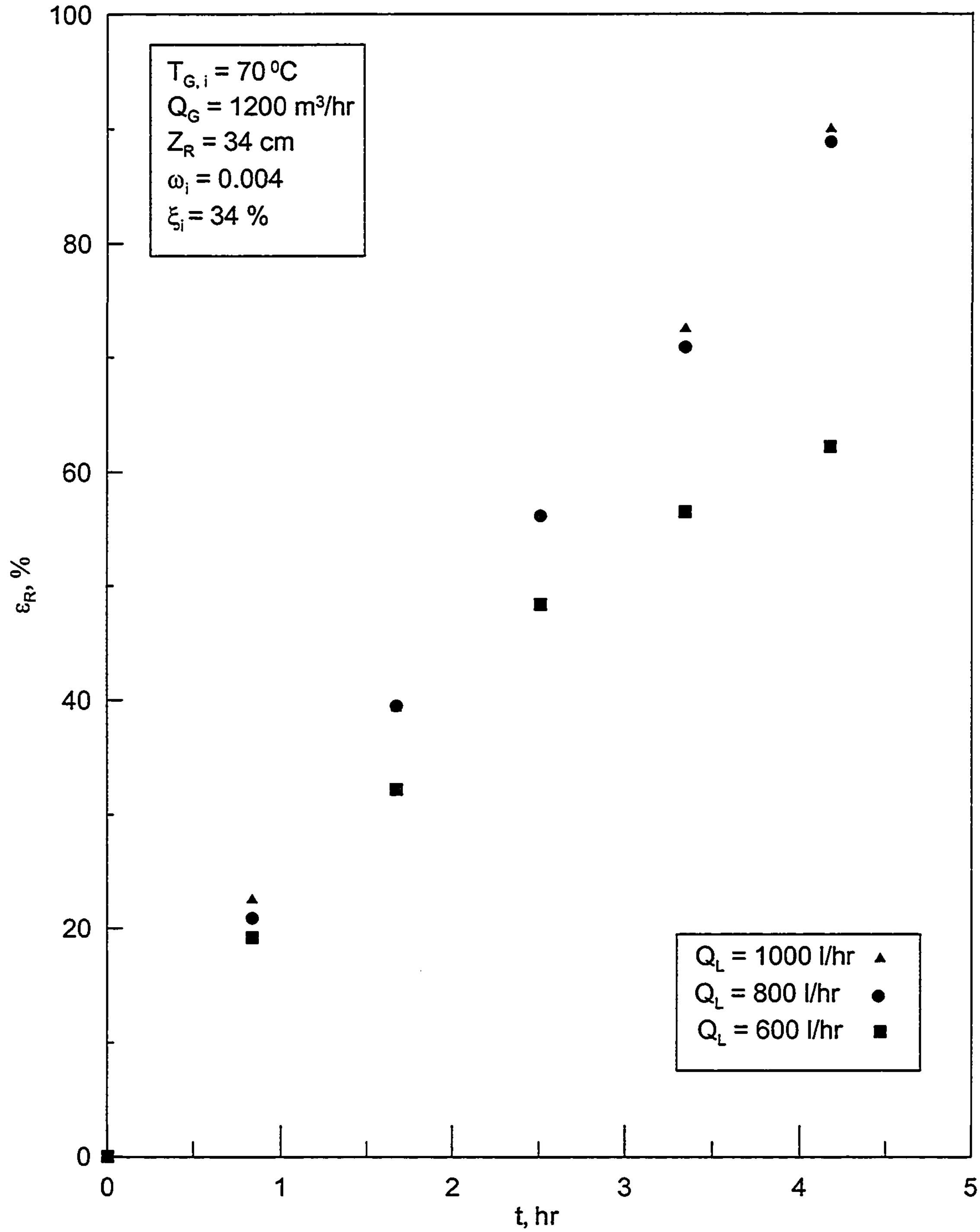


Figure 5.24: Effectiveness of the regenerator with time for $T_{G,i} = 70\,^0C$ for different desiccant flow rates.

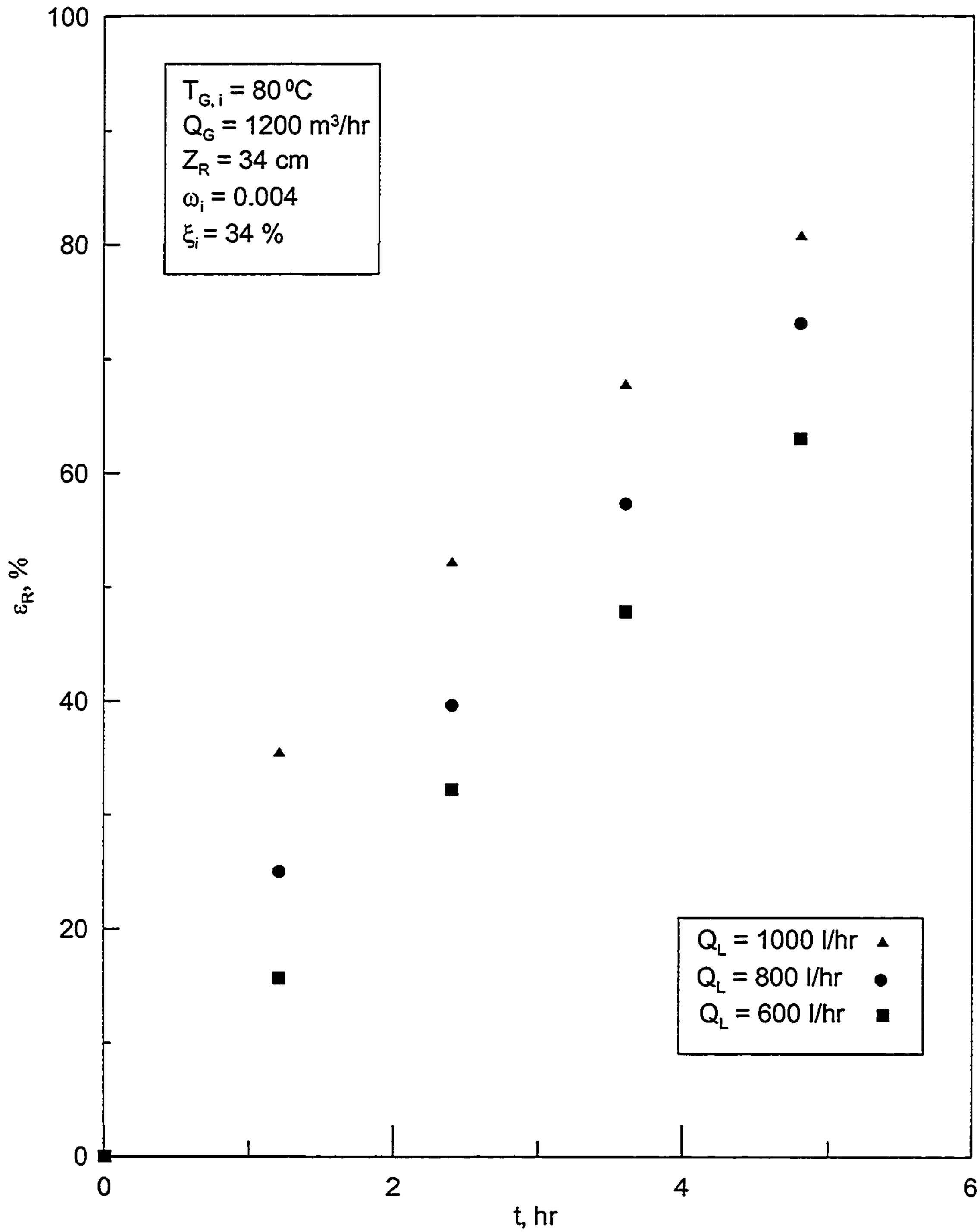


Figure 5.25: Effectiveness of the regenerator with time for $T_{G,i}$ = 80 °C for different desiccant flow rates.

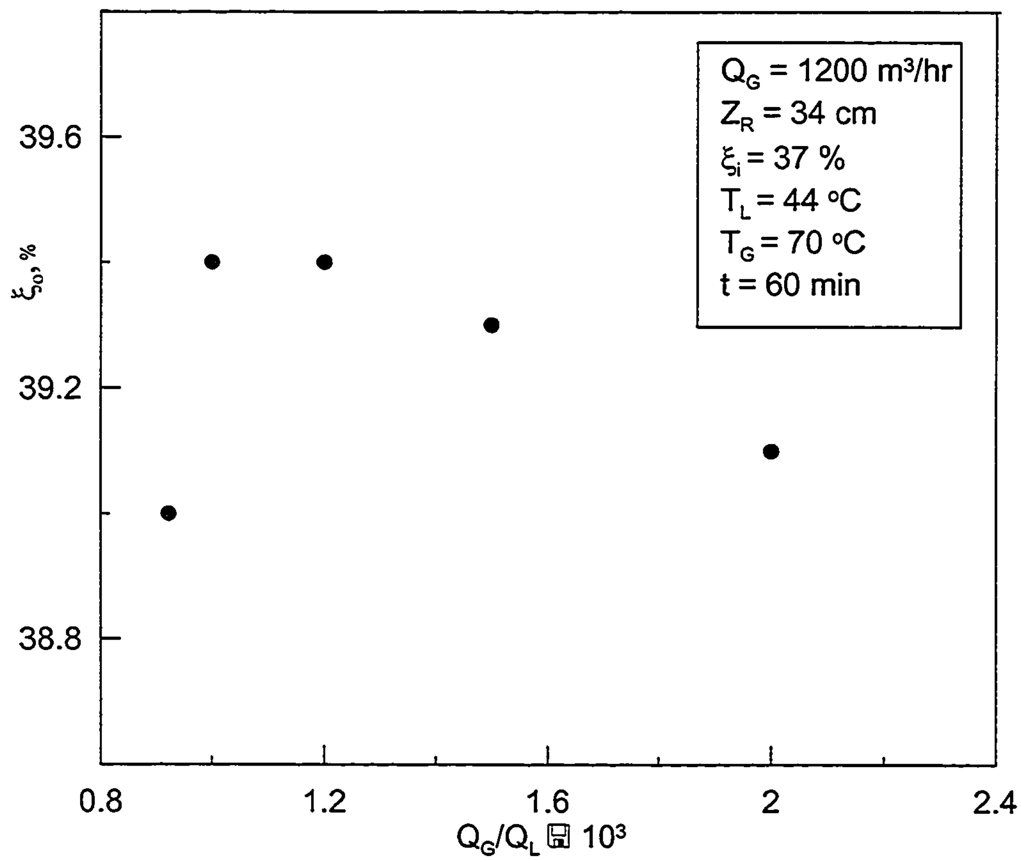


Figure 5.26: Effect of the ratio of air to desiccant flow rate on the outlet concentration in the regenerator.

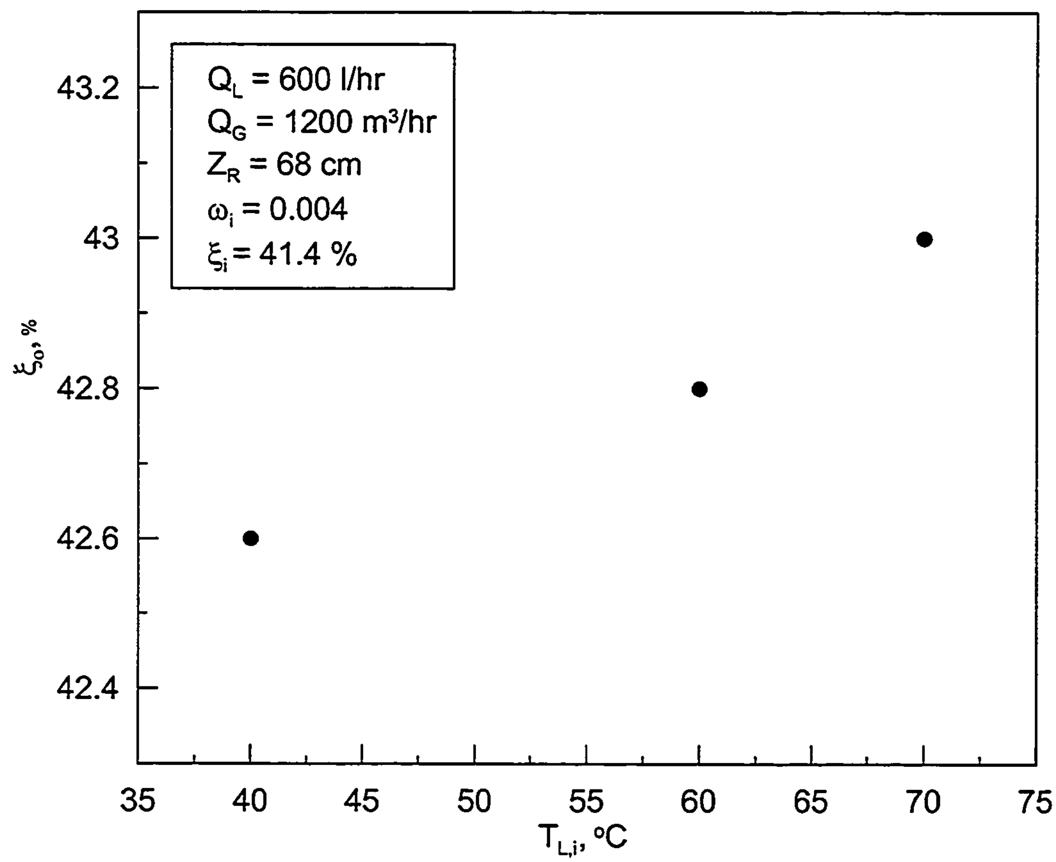


Figure 5.27: Effect of desiccant inlet temperature on the outlet concentration in the regenerator.

concentration at the outlet increases due to an increase in the vapor pressure difference between the desiccant and the air. As the potential for mass transfer increases, the desiccant evaporates more water to the air, hence the desiccant concentration at the outlet increases.

The effect of the air inlet temperature on the performance of the regeneration system is shown in Fig. 5.28. The water evaporation rate from the weak desiccant increases with increasing air inlet temperature due to increase in vapor pressure of the desiccant, which is the potential for mass transfer, and hence the concentration of the desiccant at the outlet increases.

5.2.5 Effect of Air Inlet Humidity Ratio

In order to investigate the effect of air inlet humidity ratio on the outlet desiccant concentration, experiments are conducted in the regenerator, for the packing height of 68 cm, for different desiccant inlet temperatures. The air inlet temperature is maintained at 70 °C and the desiccant inlet temperature is varied from 45 to 70 °C using an auxiliary heater. The inlet desiccant (calcium chloride solution) concentration is maintained at 37% and the experimental results are shown in Fig. 5.29. As expected, the water evaporation rate decreases with the increase in inlet air humidity ratio for any given desiccant inlet temperature. A higher humidity ratio implies higher air vapor pressure and consequently lower potential for mass transfer. The water evaporation rate increases with the inlet desiccant temperature since desiccant vapor pressure is highly dependent on the temperature that increases the potential for mass transfer.

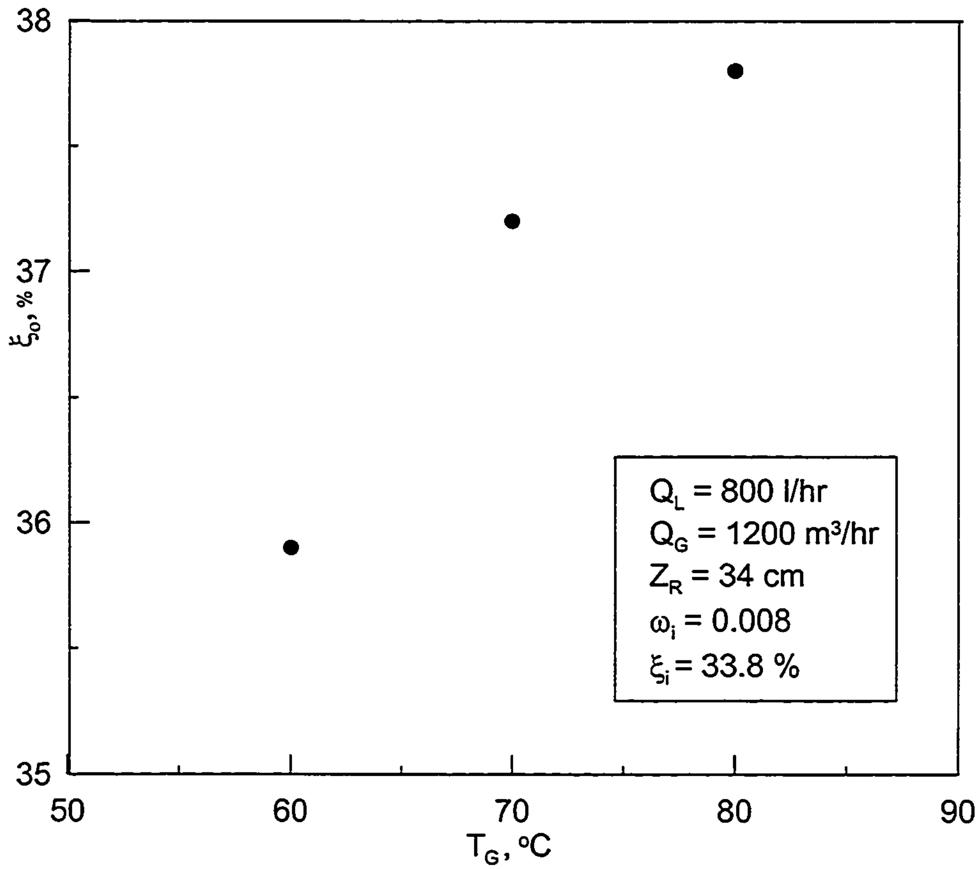


Figure 5.28: Effect of air inlet temperature on the outlet concentration in the regenerator.

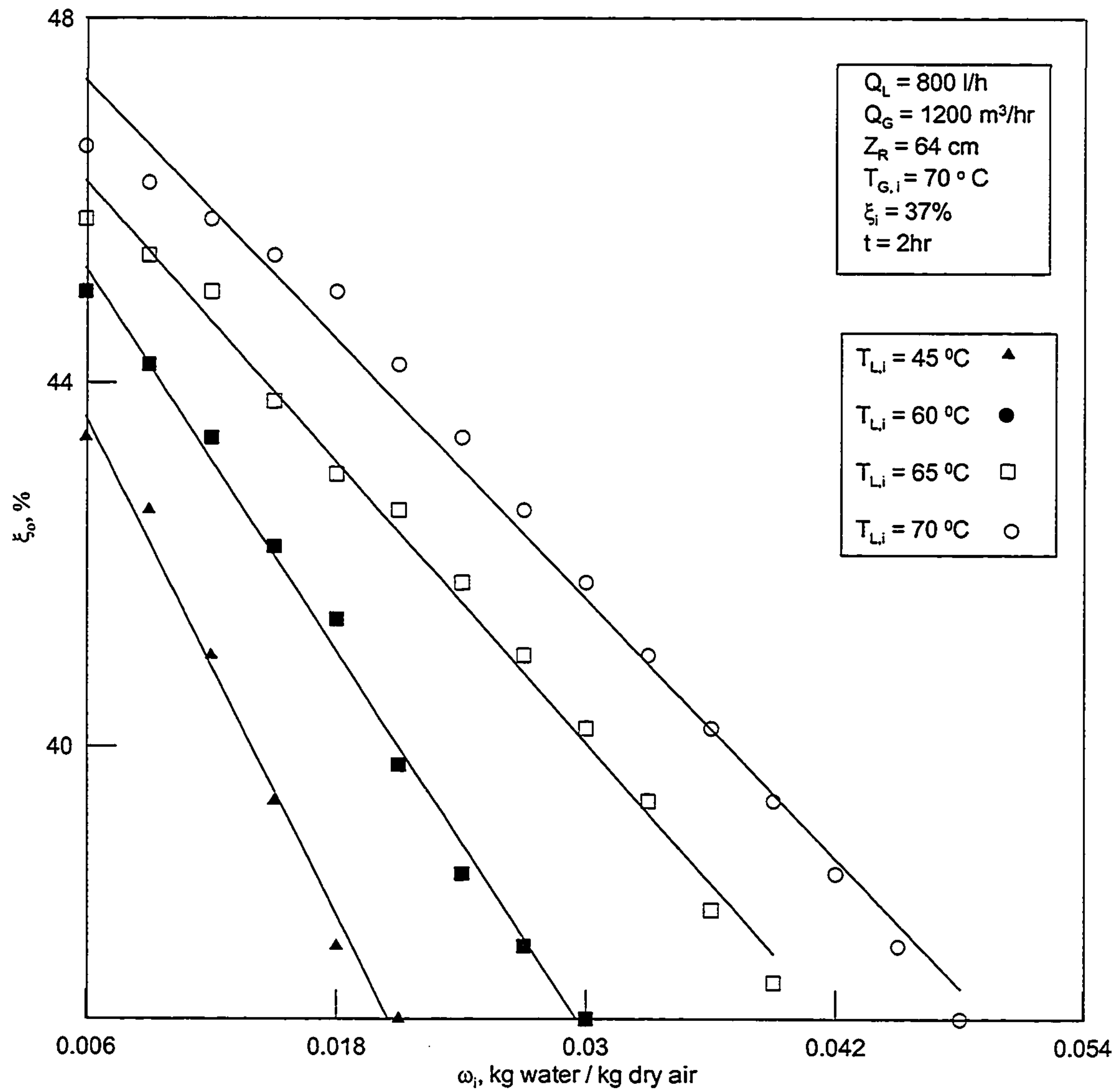


Figure 5.29: The effect of air inlet humidity ratio on the outlet desiccant concentration in the regenerator for various desiccant inlet temperature.

From the figure it is clear that the desiccant can be regenerated at lower desiccant temperature if the regeneration air contains low humidity ratio. However, for high humid conditions, the desiccant can be regenerated at higher desiccant temperatures. For example, the desiccant is regenerated from 37% to 38.6% with the desiccant inlet temperature of 45 °C when the air inlet humidity ratio is 0.006 kg water/kg dry air, which is dry air. In order to concentrate the desiccant for the same level when the inlet humidity ratio is 0.024 kg water/kg dry air, the desiccant must be heated to about 70 °C. This clearly indicates that the regenerator performs well even in humid conditions but the desiccant must be heated for higher temperature.

5.3 Hybrid System

The effects of various parameters on the dehumidification and regeneration processes in a hybrid liquid desiccant cooling will be discussed using $CaCl_2$, LiCl and mixtures of both as desiccants. From the experiments conducted for dehumidifier and regenerator, it is found that the maximum desiccant flow rate for the dehumidifier is 14 l/min and for the regenerator is 800 l/h. Hence experiments are conducted for these optimum flow rates for the hybrid system.

5.3.1 Calcium Chloride Results

Experiments are conducted for the hybrid system using $CaCl_2$ as desiccant. Two elements of the structured gauze type packing in dehumidifier and four elements in the regenerator are used. The strong desiccant is sprayed in the dehumidifier at flow rate of 14 l/min for a particular flow rate of air, namely 3200 m^3/h and in the regenerator the strong desiccant is sprayed at flow rate of 800 l/hr for a particular flow rate of air, namely 1200 m^3/h. The ambient condition is selected as 40 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air. The air inlet to the regenerator is heated to 70 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air

Figure 5.30 shows the time variation of concentration and desiccant temperature in the dehumidifier for the hybrid system. Since the desiccant absorbs water vapor from the air its concentration decreases significantly at the beginning but after approximately 20 minutes it reaches a steady state condition at 41.6 % because the regenerator re concentrates the desiccant simultaneously. The desiccant inlet temperature is maintained at 36 to 38° C with use of the heat exchangers. Figure 5.31 shows the time variation of air outlet temperature and its relative humidity from the dehumidifier. The air outlet temperature reaches a temperature of 36° C because of the high desiccant inlet temperature.

Figure 5.32 shows the time variation of outlet absolute humidity of air and the ratio of absolute humidity of air in the dehumidifier for the hybrid system. It is to be noted that the air entering the dehumidifier is very humid as mentioned earlier and the air absolute humidity at the outlet approaches a steady state value of 0.025. Figure 5.33 shows the effectiveness of the dehumidifier for the hybrid system with time. The dehumidifier effectiveness decreases with time due to the increase in the desiccant vapor pressure.

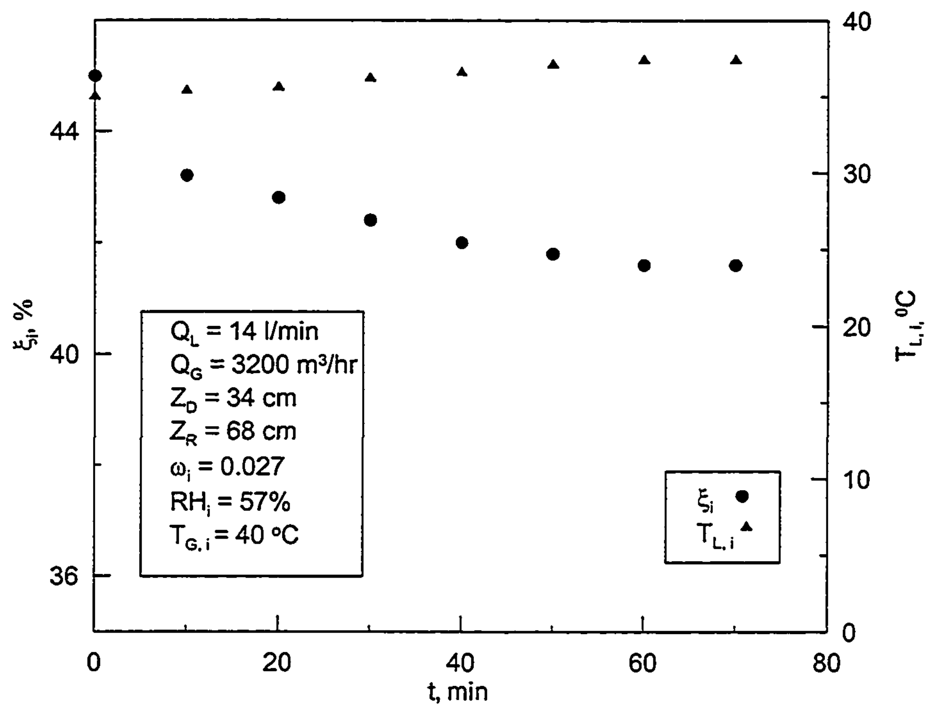


Figure 5.30: Time variation of concentration and desiccant temperature for 34 cm packing height in the dehumidifier and 68 cm in the regenerator while the hybrid system is running.

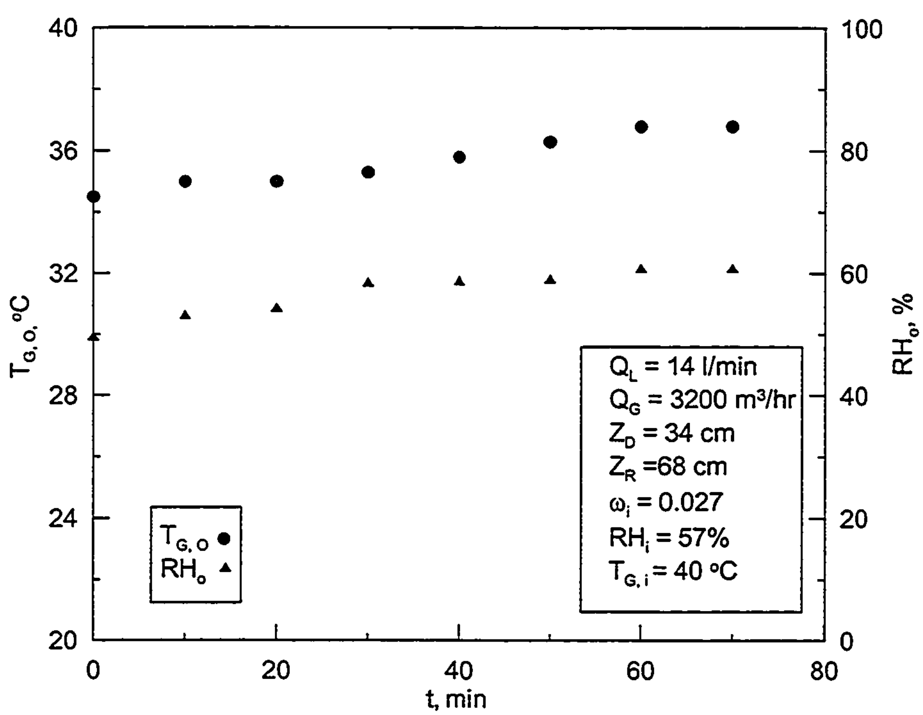


Figure 5.31: Time variation of outlet air temperature and humidity for 34 cm packing height in the dehumidifier and 68 cm in the regenerator while the hybrid system is running.

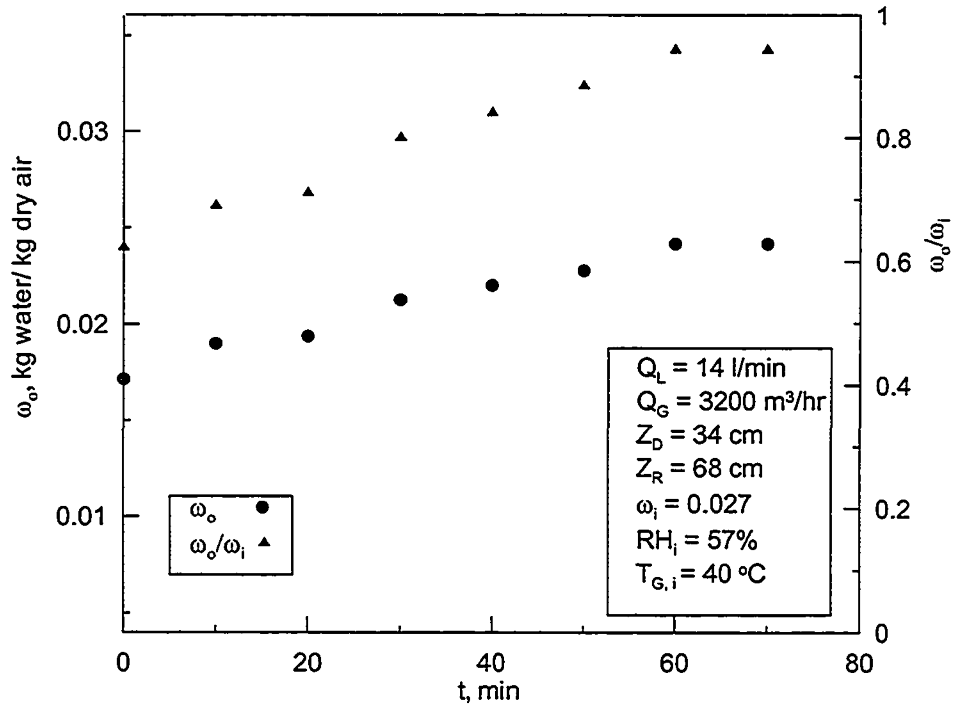


Figure 5.32: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for 34 cm packing height in the dehumidifier and 68 cm in the regenerator while the hybrid system is running

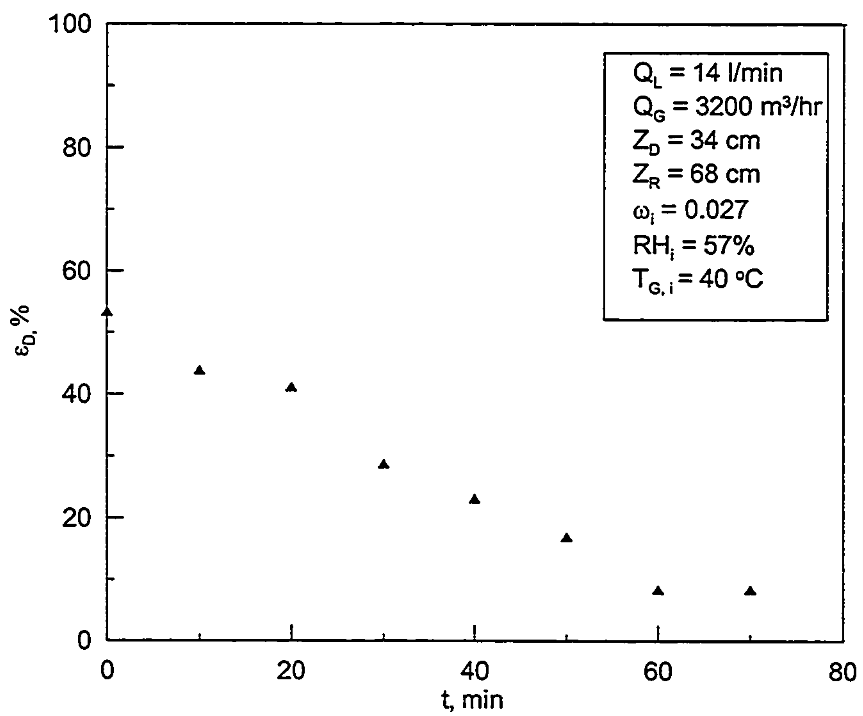


Figure 5.33: Effectiveness of dehumidifier with time for 34 cm packing height in the dehumidifier and 68 cm in the regenerator while the hybrid system is running

Since at the beginning of the experiments the desiccant concentration is high (about 45%), the air is dehumidified rapidly and then the outlet absolute humidity of air is almost constant since the inlet desiccant concentration is constant at 41.6 %. The results indicate that the dehumidifier is performing well with the regenerator in the hybrid system.

The weak desiccant from the dehumidifier is reconcentrated simultaneously in the regenerator after being preheated in desiccant-to-desiccant heat exchanger. The time variation of inlet and outlet desiccant concentrations in the regenerator is shown in Fig. 5.34 for the hybrid cooling system. It can be seen from the figure that the desiccant concentration before entering the regenerator is maintained at a steady state value of about 41.1% and it is regenerated simultaneously to 41.6%. Figure 5.35 shows the effectiveness of the regenerator versus time. The regenerator is working steadily with an effectiveness of about 6%.

5.3.2 Effect of Air Humidity Ratio

Experiments are conducted for the very high humid inlet conditions of the air before entering the dehumidifier at about 47 to 48° C with humidity ratio of 0.048 kg of water per kg of dry air. The condenser waste heat is used to preheat the regeneration air and an electrical heater is used for increasing the air temperature to 70° C. The hot air entering the regenerator is relatively dry with the absolute humidity of 0.015 kg of water per kg of dry air. The experiments are conducted with the same amount of packing heights in both units. The results for the packing height of 34 cm (that is, two packing elements) in dehumidifier as well as in the regenerator are shown in Figs. 5.36 to 5.41.

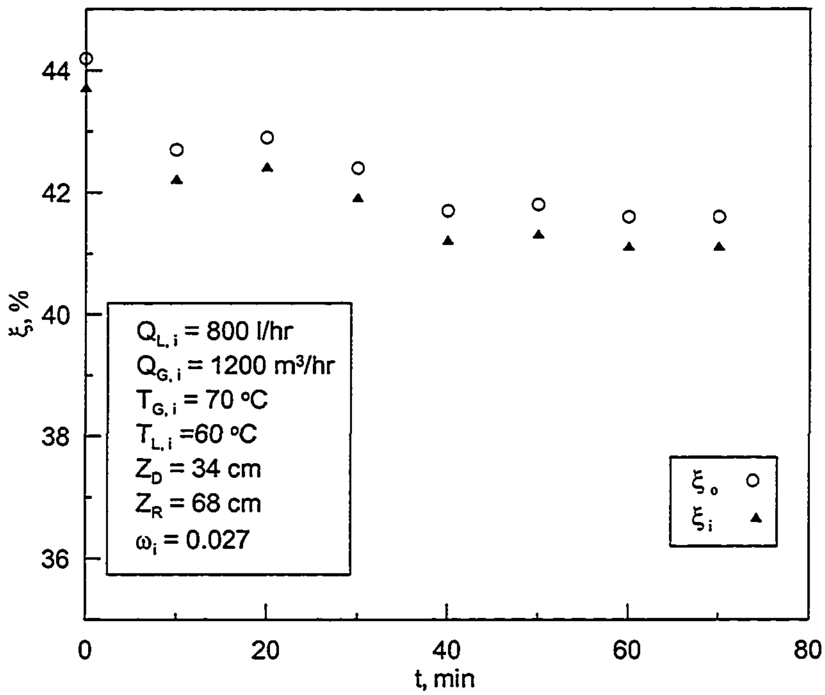


Figure 5.34: Time variation of inlet and outlet concentration for 68 cm packing height in the regenerator and 34 cm in the dehumidifier while the hybrid system is running.

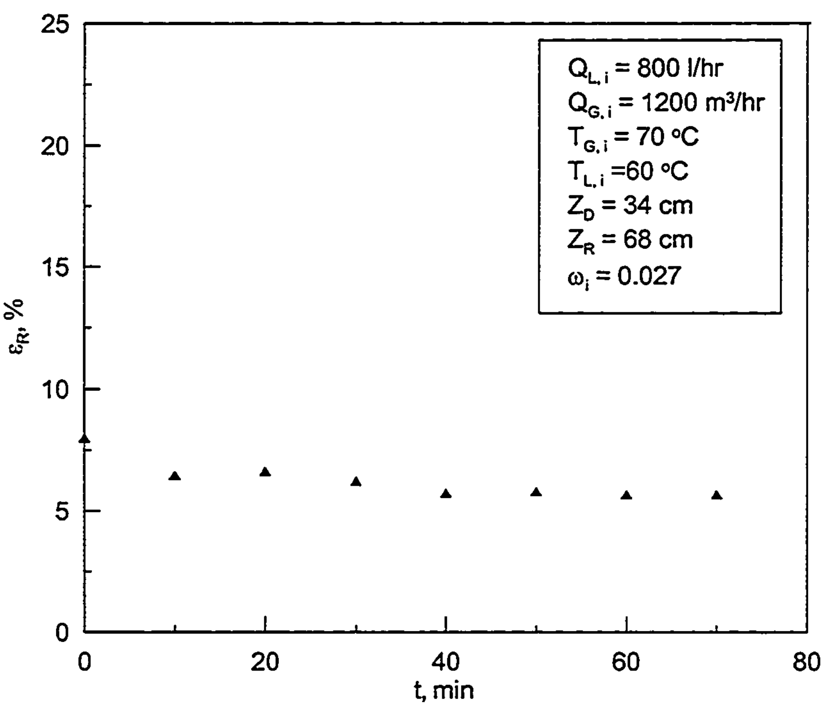


Figure 5.35: Effectiveness of regenerator with time for 68 cm packing height in the regenerator and 34 cm in the dehumidifier while the hybrid system is running.

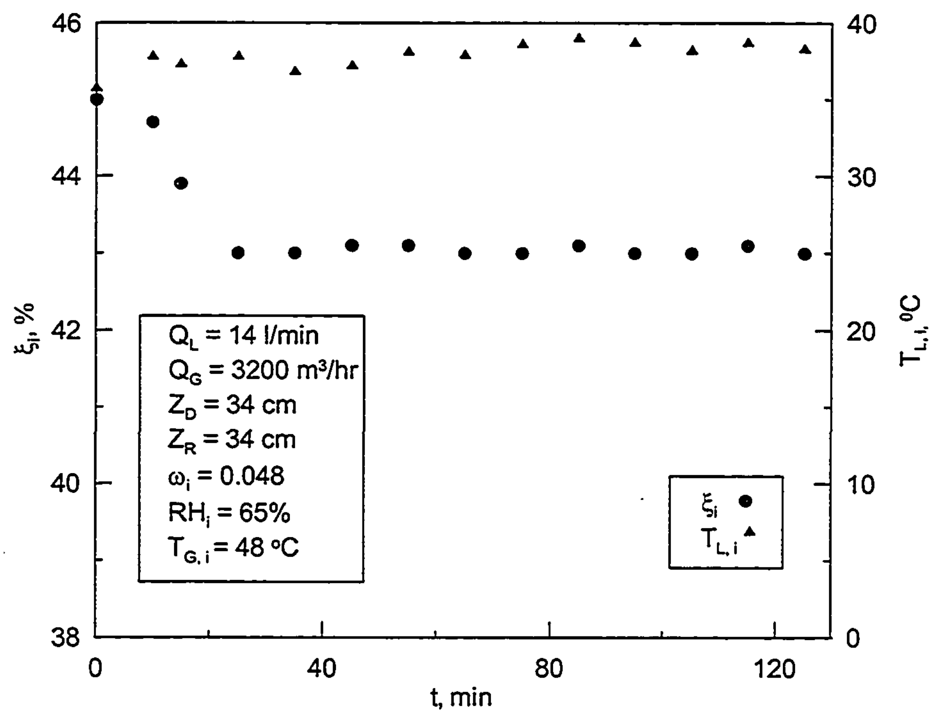


Figure 5.36: Time variation of concentration and desiccant temperature in the dehumidifier for humid condition in both towers while the hybrid system is running

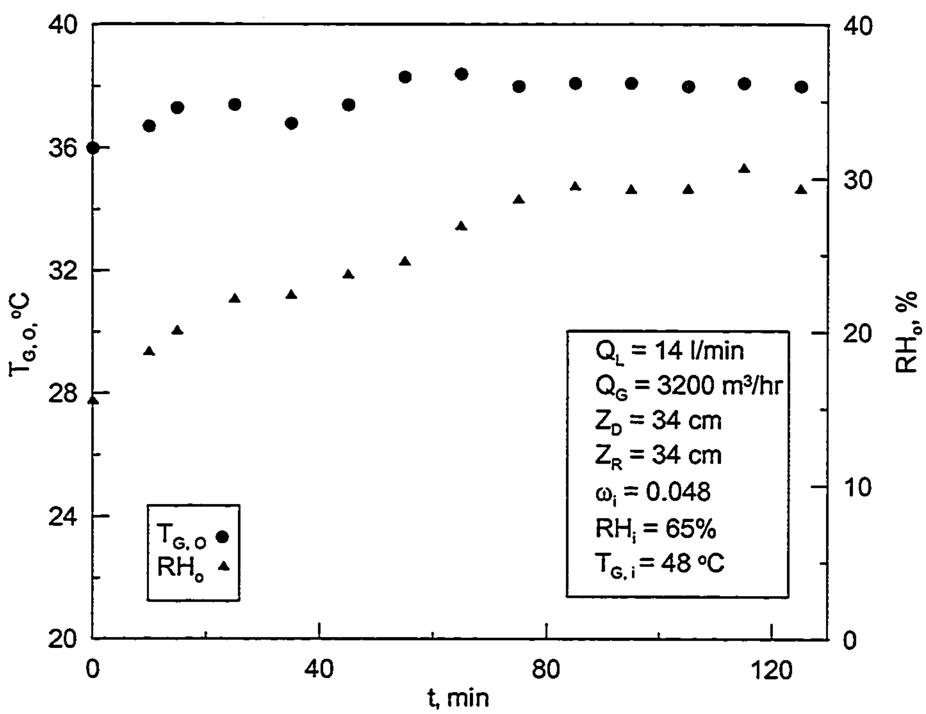


Figure 5.37: Time variation of outlet air temperature and humidity in the dehumidifier for humid condition while the hybrid system is running.

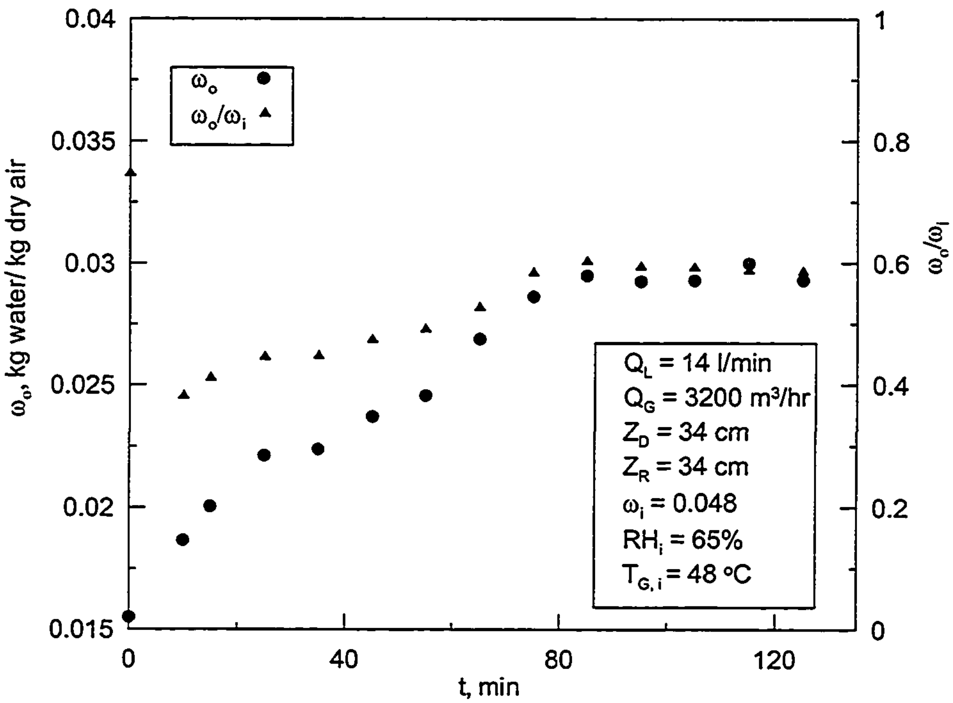


Figure 5.38: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity in the dehumidifier for 34 cm packing height in both towers while the hybrid system is running

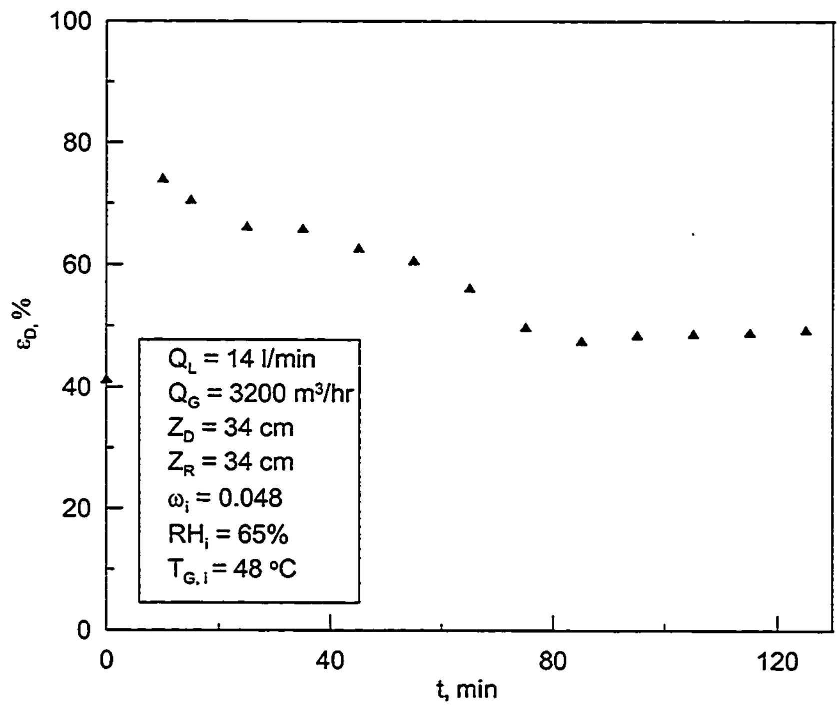


Figure 5.39: Effectiveness of dehumidifier with time for 34 cm packing height in both towers while the hybrid system is running

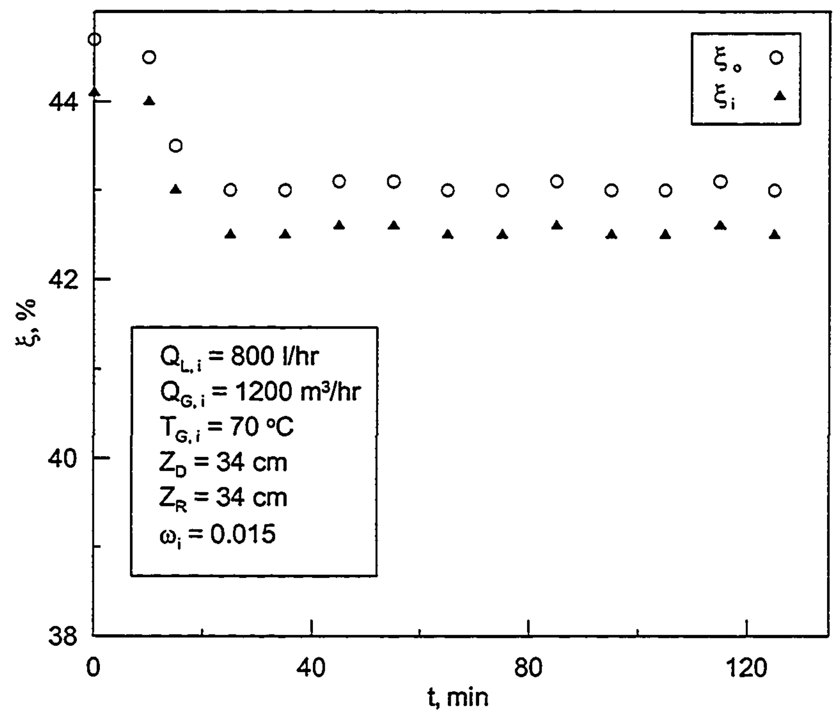


Figure 5.40: Time variation of inlet and outlet concentration in the regenerator for humid condition while the hybrid system is running.

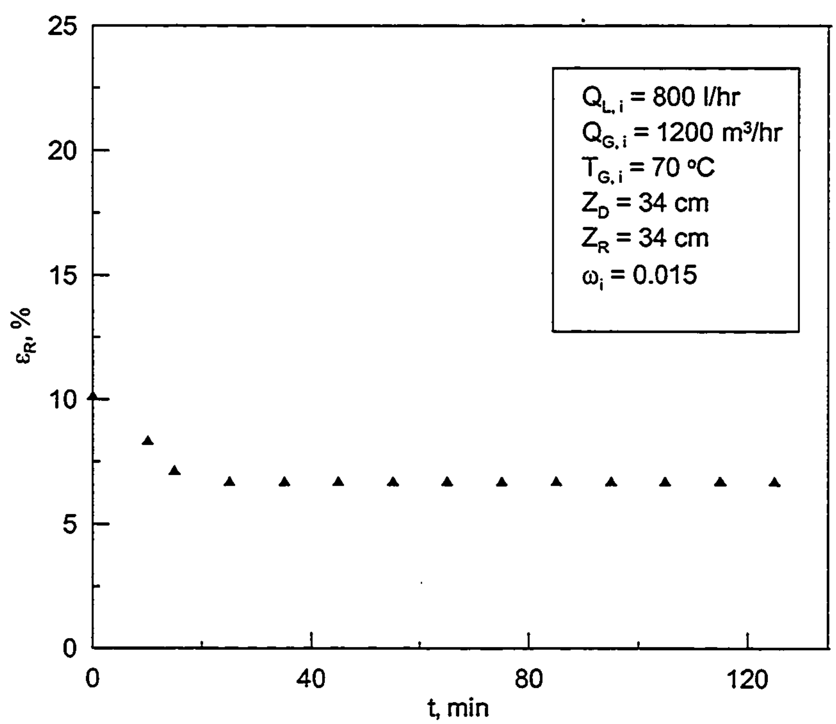


Figure 5.41: Effectiveness of regenerator with time humid condition in both towers while the hybrid system is running

Figure 5.36 shows the time variation of concentration and desiccant temperature in the dehumidifier for the hybrid system. Since the desiccant absorbs water vapor from the air its concentration decreases significantly at the beginning but after approximately 20 minutes it reaches a steady state condition at 43 % since the regeneration process maintains the desiccant concentration, which indicates that the regeneration process is effective. Using the two heat exchangers, the desiccant inlet temperature is maintained at 36 to 38° C as shown in the figure. Figure 5.37 shows the time variation of air outlet temperature and its relative humidity from the dehumidifier. The air outlet temperature reaches a temperature of 38° C because of the high desiccant inlet temperature and the air outlet relative humidity is about 30% while it enters the dehumidifier with a value of 65 %.

Figure 5.38 shows the time variation of outlet absolute humidity of air and the ratio of absolute humidity of air in the dehumidifier for the hybrid system. It is to be noted that the air entering the dehumidifier is very humid as mentioned earlier and the air absolute humidity at the outlet approaches a steady state value of 0.028. Since at the beginning of the experiments the desiccant concentration is high (about 45%), the air is dehumidified rapidly and then the outlet absolute humidity of air is almost constant since the inlet desiccant concentration is constant at 43%. The results indicate that the dehumidifier is performing well with the regenerator in the hybrid system. Figure 5.39 shows the effectiveness of the dehumidifier for the hybrid system with time. The dehumidifier effectiveness decreases with time due to the increase in the desiccant vapor pressure.

The weak desiccant from the dehumidifier is reconcentrated simultaneously in the regenerator after being preheated in desiccant-to-desiccant heat exchanger. The time variation of inlet and outlet desiccant concentrations in the regenerator is shown in Fig. 5.40 for the hybrid cooling system. It can be seen from the figure that the desiccant concentration before entering the regenerator is maintained at a steady state value of about 42.5% and it is regenerated simultaneously to 43%. Figure 5.41 shows the effectiveness of the regenerator versus time. The regenerator is working steadily with an effectiveness of about 7%.

5.3.3 Effects of Packing Height in the Dehumidifier and Regenerator

In order to find the best packing height in both towers trial experiments were conducted. For this study the packing height in the regenerator is 68 cm and the dehumidifier packing height is varied from 34 to 68 cm. The average dehumidifier effectiveness is shown in Fig. 5.42. As the dehumidifier packing height increases, the average effectiveness of the dehumidifier decreases. This is due to the fact that when the dehumidifier packing height is large, the dilution of the desiccant is more due to absorption of more moisture from the air and hence the desiccant re-concentration becomes less effective.

For studying the effect of packing height in the regenerator the packing height of the dehumidifier is kept at 34 cm and the regenerator packing height is varied from 34 to 68 cm. The average regenerator effectiveness is shown in Fig. 5.43. As the regenerator packing height increases, the average effectiveness of the regenerator increases. This is due to the fact that when the regenerator packing height is small, the desiccant is weakly

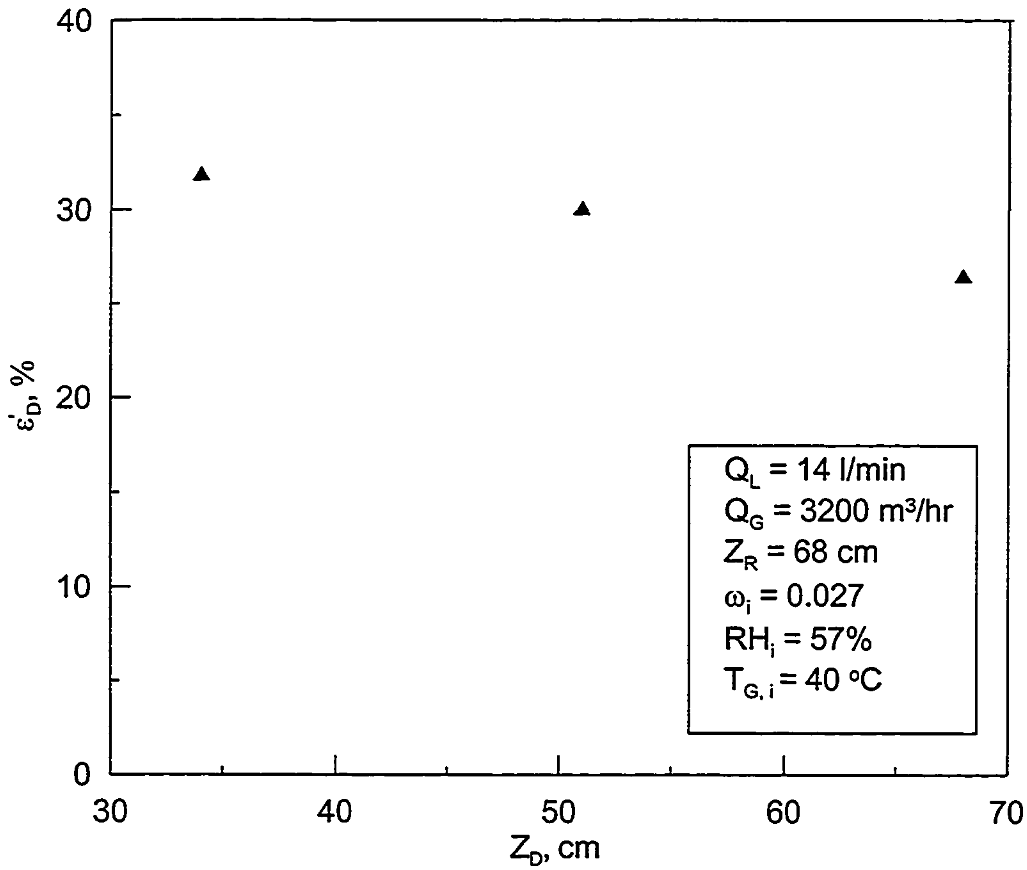


Figure 5.42: Average effectiveness of the dehumidifier with packing height while the hybrid system is running.

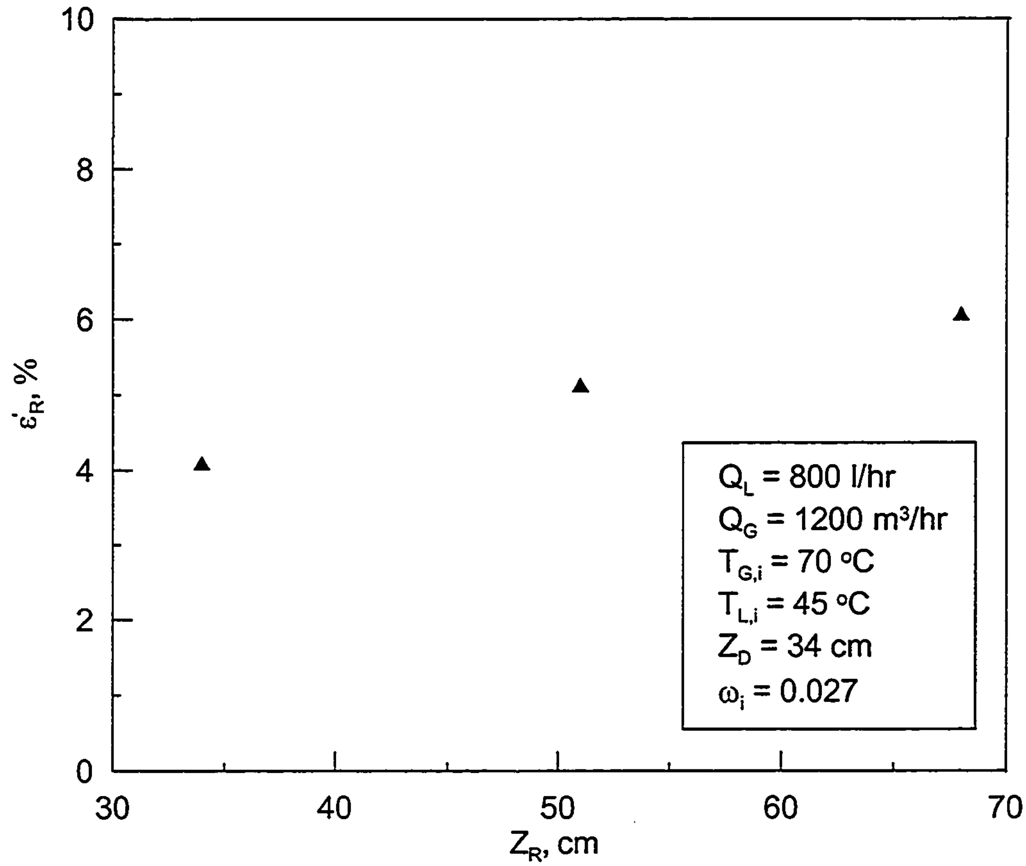


Figure 5.43: Average effectiveness of the regenerator with packing height while the hybrid system is running.

concentrated due to evaporation of less water vapor from the desiccant. When the regenerator packing height is large, the desiccant is strongly concentrated due to evaporation of more water vapor from the desiccant due to longer period of contact and more surface area, and thus the desiccant is fully reconcentrated. From the above study of packing height it is found that the best combination was 34 cm in dehumidifier and 68 cm in regenerator.

5.3.4 Lithium Chloride Results

Experiments are conducted for the hybrid system using LiCl as desiccant. Two elements of the structured gauze type packing in dehumidifier and four elements in the regenerator are used. The strong desiccant was sprayed in the dehumidifier at flow rate of 14 l/min for a particular flow rate of air, namely 3200 m^3/h and in the regenerator the strong desiccant was sprayed at flow rate of 800 l/hr for a particular flow rate of air, namely 1200 m^3/h. The ambient condition is selected as 40 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air. The air inlet to the regenerator is heated to 70 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air. The results are discussed below.

The variation of the lithium chloride solution concentration and temperature with time in the dehumidifier while the hybrid system is running are shown in Fig. 5.44. In the beginning the desiccant concentration is 40% and as the desiccant absorbs water vapor from the air its concentration decreases but it reaches a steady state value of 38.6% since the regeneration process effectively maintains the desiccant concentration. Using the two heat exchangers the desiccant inlet temperature is maintained at 34.6 °C as shown in figure.

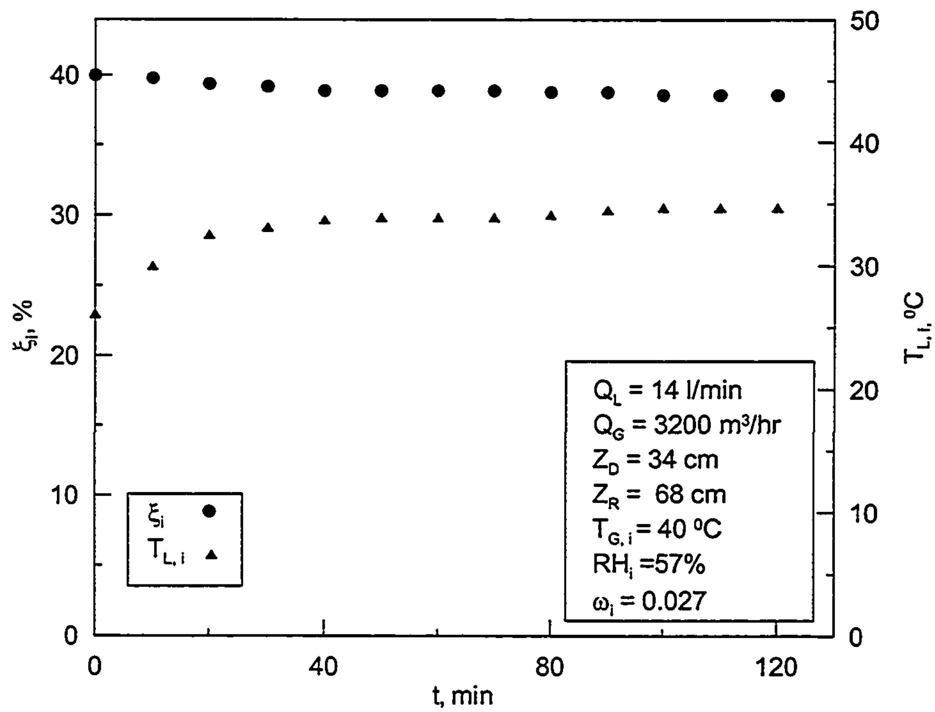


Figure 5.44:Time variation of concentration and inlet temperature for 40% LiCl solution in the dehumidifier while the hybrid system is running.

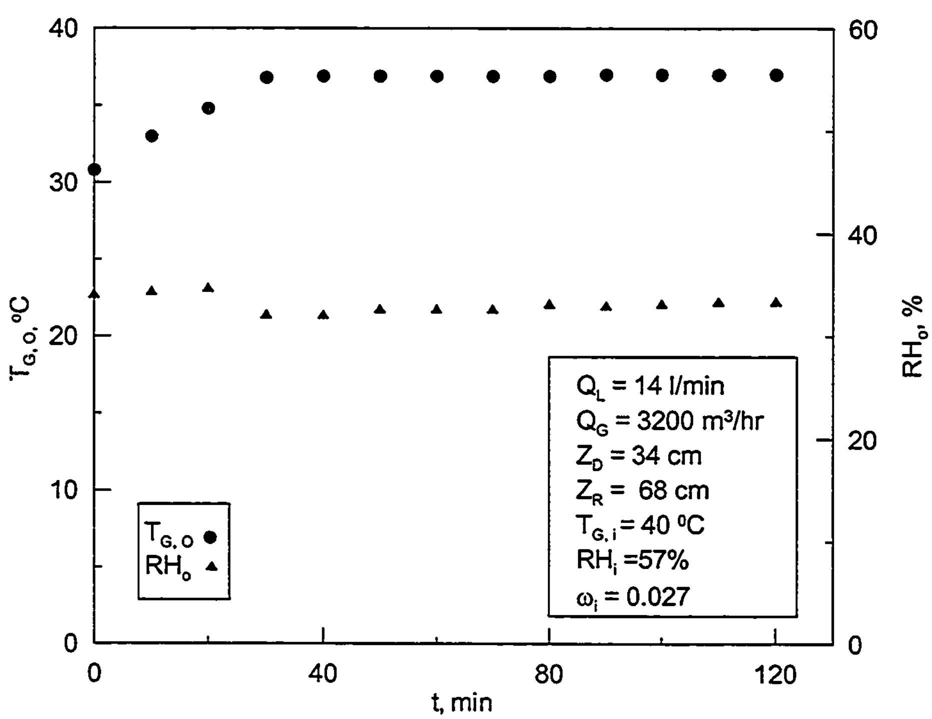


Figure 5.45:Time variation of outlet air temperature and humidity in the dehumidifier for 40% LiCl solution while the hybrid systemis running.

The time variation of air outlet temperature and relative humidity from the dehumidifier are shown in Fig. 5.45. The air outlet temperature reaches a maximum value of 37 °C as shown in figure because of high desiccant temperature. The air outlet relative humidity is about 30 % while it enters with a value of 57%.

The time variation of outlet absolute humidity of air and the ratio of absolute humidity of air in the dehumidifier for the hybrid system is shown in Fig. 5.46. It is to be noted that the air enters with absolute humidity of 0.027 and approaches a steady state value of 0.013 at the outlet of the dehumidifier. At the beginning the air is dehumidified rapidly due to higher inlet desiccant concentration that increases the potential for mass transfer. The effectiveness of the dehumidification process with time is shown in the Fig. 5.47. The dehumidifier effectiveness decreases at the beginning of the operation and once the regenerator reaches the steady state, the dehumidifier effectiveness is maintained at about 70%.

The dehumidifier is working continuously with an effectiveness of about 70 % compared with an effectiveness of about 10 % for calcium chloride as the desiccant.

The time variation of the inlet and outlet desiccant concentrations in the regenerator is shown in Fig. 5.48. For this operation, the desiccant inlet temperature is maintained at about 70 °C and the desiccant is reconcentrated in the regenerator steadily from 37.5% to about 39%. Effectiveness of the regenerator with time for the lithium chloride solution concentration of 40% is shown in the Fig. 5.49.

The regenerator is working continuously with an effectiveness of about 20% compared with an effectiveness of about 7% for calcium chloride solution as the desiccant in the regenerator.

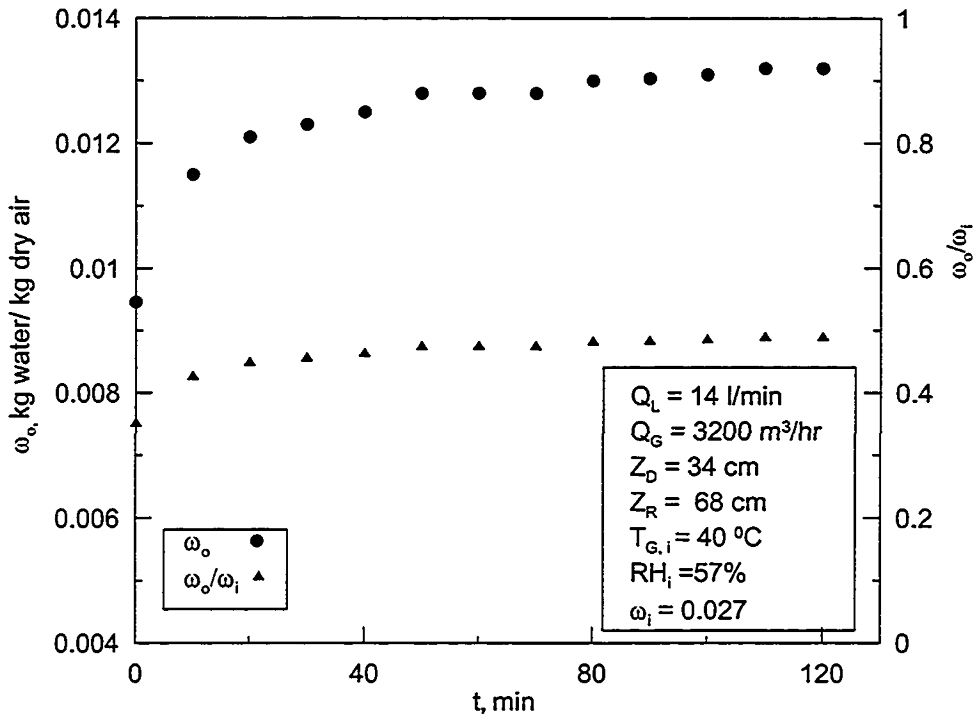


Figure 5.46: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for 40% LiCl solution in the dehumidifier while the hybrid system is running.

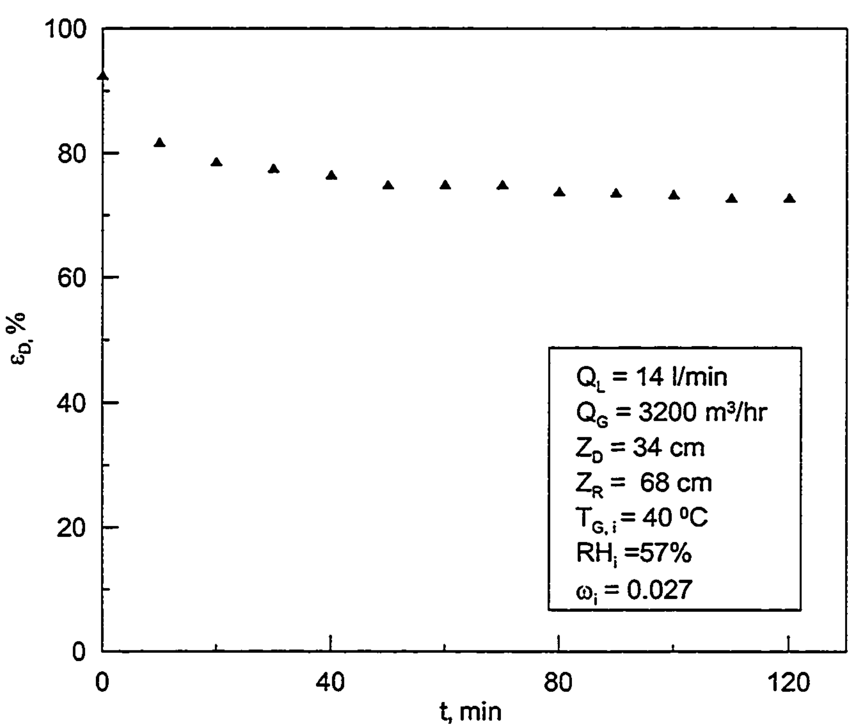


Figure 5.47: Effectiveness of the dehumidifier with time for 40% LiCl solution while the hybrid system is running.

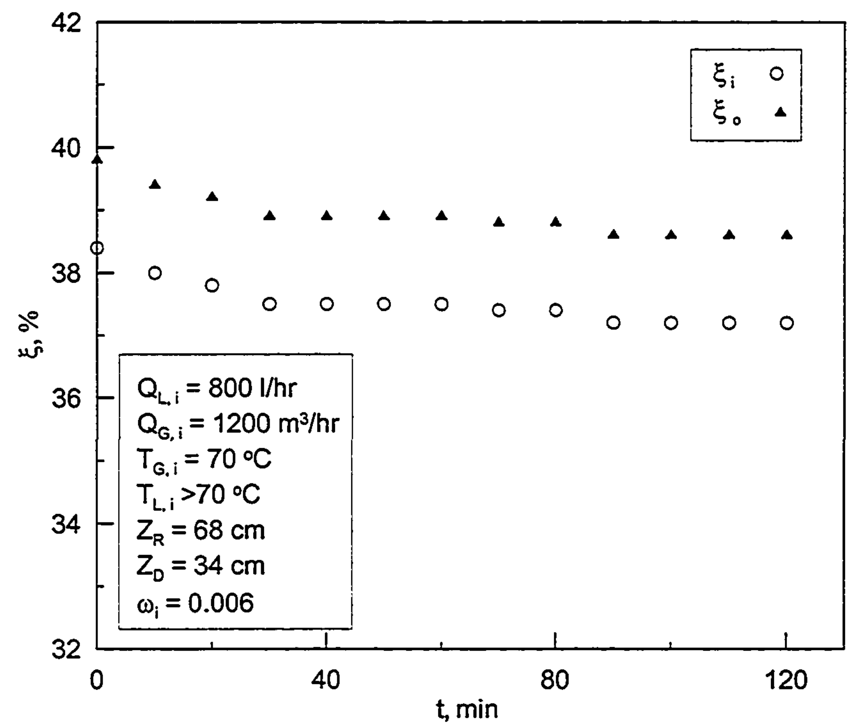


Figure 5.48: Time variation of inlet and outlet concentration for 40% LiCl solution in the regenerator while the hybrid system is running.

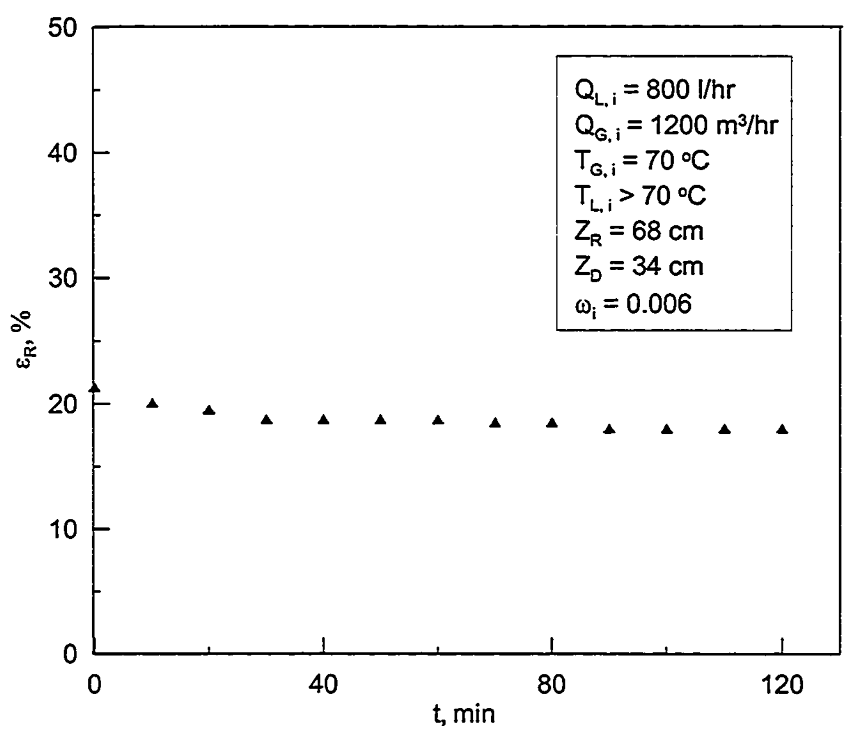


Figure 5.49: Effectiveness of the regenerator with time for 40% LiCl solution while the hybrid system is running.

5.3.5 Effect of Desiccant Mixtures

In order to get a cost effective desiccant calcium chloride and lithium chloride are mixed in different weight combinations. For the desiccant mixture an overall concentration of 40% is maintained. The following weight combinations are carried out in the present study for the hybrid cooling system:

1. 40% $CaCl_2$ by weight. = 40 % overall concentration
2. 32% $CaCl_2$ + 8% LiCl by weight = 40 % overall concentration
3. 20% $CaCl_2$ + 20% LiCl by weight = 40 % overall concentration
4. 8% $CaCl_2$ + 32 % LiCl by weight = 40 % overall concentration
5. 40% LiCl by weight = 40 % overall concentration

The properties (specific gravity, vapor pressure and viscosity) of various mixtures can be calculated using general mixing rule.

The time variation of concentration and inlet temperature for 32% $CaCl_2$ and 8% LiCl by weight mixture in the dehumidifier while the hybrid cooling system is running is shown in Fig. 5.50. At the beginning the desiccant mixture overall concentrations is 40% and the inlet air humidity ratio is maintained at a constant value of 0.027 kg water per kg of dry air. The packing height in the dehumidifier and in the regenerator is 34 cm and 68 cm respectively. As the desiccant absorbs water vapor from the air, the mixture concentration decreases and reaches a steady state value of slightly less than 38%. Although the experiment is started with the desiccant mixture inlet temperature of 32 °C, the desiccant mixture inlet temperature reaches a steady state value of 38 °C after about one hour with the use of two heat exchangers. This temperature increase may be due to the larger quantity of $CaCl_2$ in the solution compared with LiCl and further, $CaCl_2$

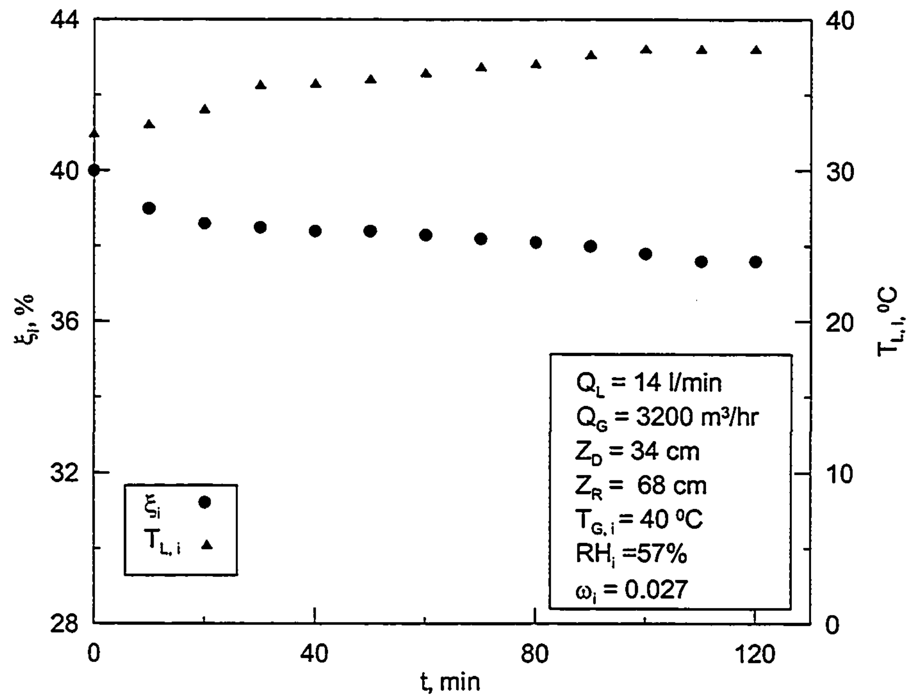


Figure 5.50:Time variation of concentration and inlet temperature for 32% $CaCl_2$ and 8% LiCl solution in the dehumidifier while the hybrid system is running.

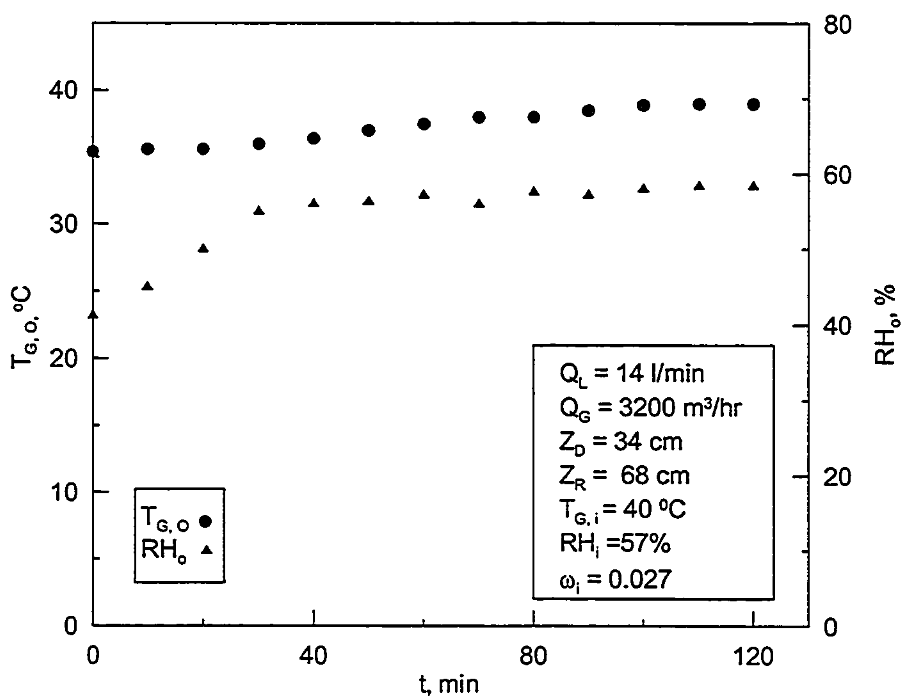


Figure 5.51:Time variation of outlet air temperature and humidity in the dehumidifier for 32% $CaCl_2$ and 8% LiCl solution while the hybrid system is running.

solution has higher thermal conductivity. Figure 5.51 shows the variation of air outlet temperature and relative humidity with time from the dehumidifier. The air outlet temperature reaches a steady state value of about 38 °C. The air outlet relative humidity steadily increases from about 40% to 56% while it enters with a value of 57%.

The time variation of outlet absolute humidity of air and the ratio of absolute humidity of air in the dehumidifier for this desiccant mixture is shown in Fig. 5.52. At the beginning the air is dehumidified rapidly from 0.027 to about 0.015 but steadily it increases to reach a steady state value of about 0.026. The effectiveness of the dehumidifier process for this desiccant mixture is shown in Fig. 5.53.

The dehumidifier effectiveness steadily decreases from about 64% and reaches a steady state value of about 5%.

The time variation of the inlet and outlet desiccant concentration in the regenerator is shown in Fig. 5.54 and the effectiveness of the regenerator with time for this desiccant mixture is shown in Fig. 5.55.

The regenerator is working with an effectiveness value of about 5%, which is very much same as the single desiccant of $CaCl_2$ solution.

Similarly experiments are conducted with 20% $CaCl_2$ and 20% LiCl by weight mixture in the dehumidifier for the hybrid cooling system and the results are shown in Figs. 5.56 to 5.61. The results for the desiccant mixture of 8% $CaCl_2$ and 32% LiCl by weight mixture are shown in Figs. 5.62 to 5.67.The effect of various desiccant mixture compositions on the average effectiveness of the dehumidifier is shown in Fig. 5.68 for the given operating conditions. As the LiCl composition increases in the mixture, the effectiveness of the dehumidifier also increases.

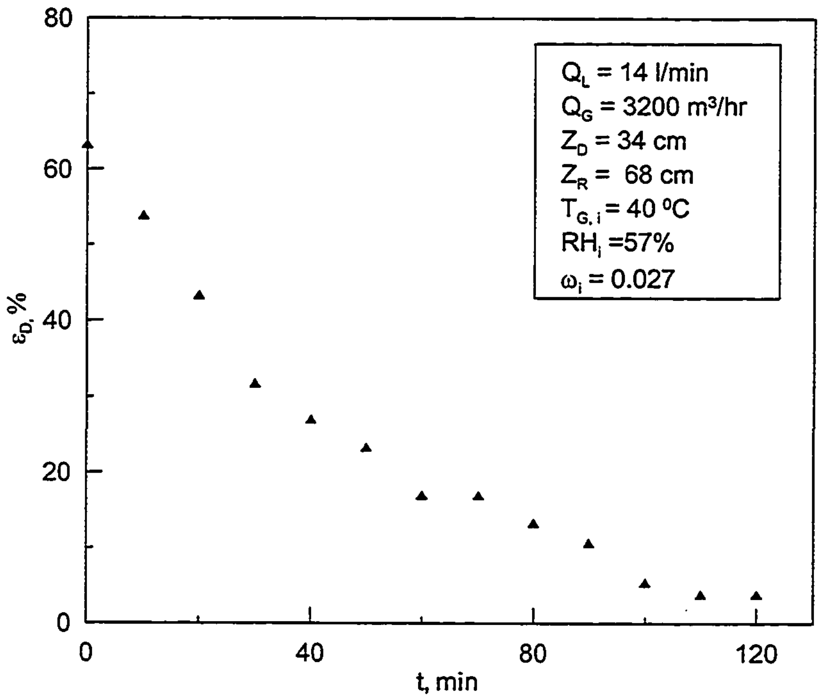


Figure 5.52: Effectiveness of the dehumidifier with time for 32% $CaCl_2$ and 8% LiCl solution while the hybrid system is running.

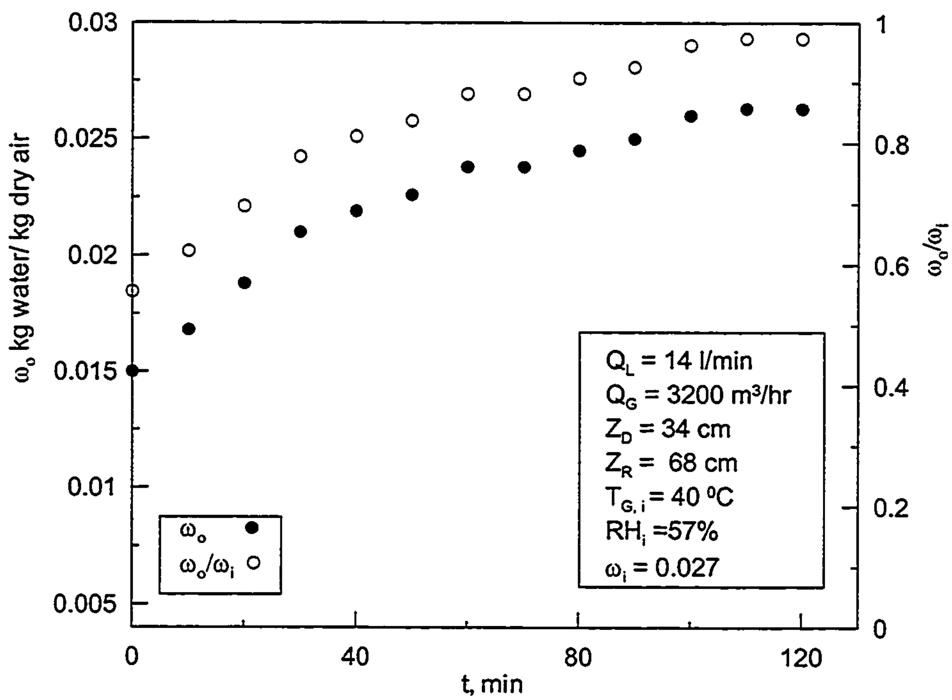


Figure 5.53: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for 32% $CaCl_2$ and 8% LiCl solution in the dehumidifier while the hybrid system is running.

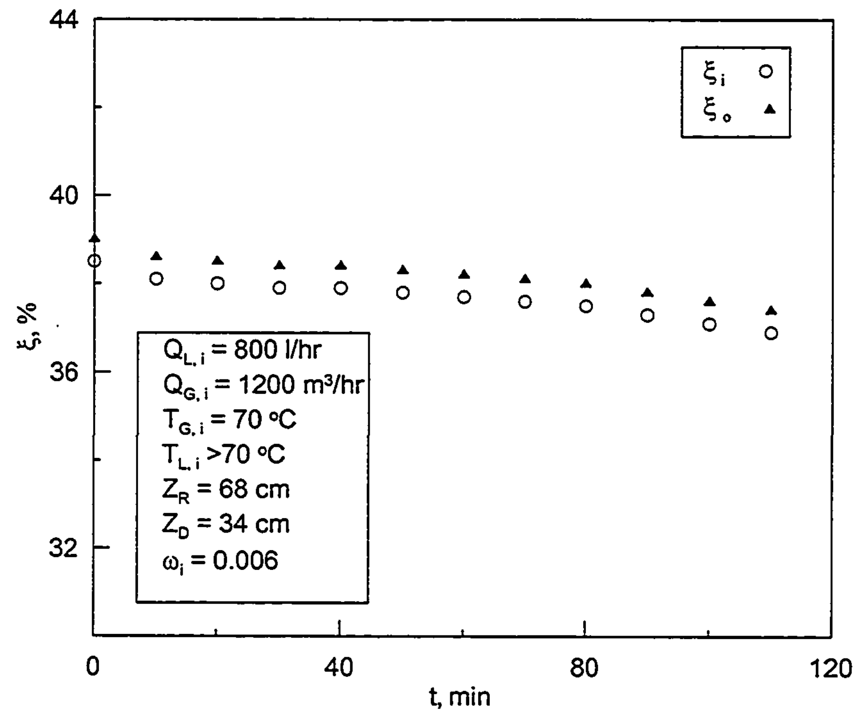


Figure 5.54: Time variation of inlet and outlet concentration for 32% $CaCl_2$ and 8% LiClsolution in the regenerator while the hybrid system is running.

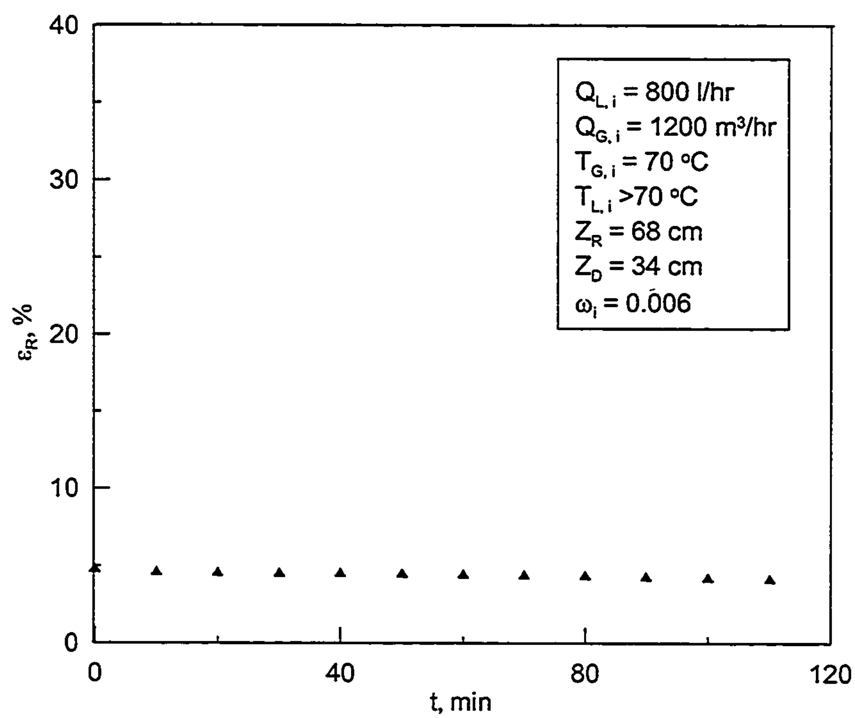


Figure 5.55: Effectiveness of the regenerator with time for 32% $CaCl_2$ and 8% LiCl chloride solution while the hybrid system is running.

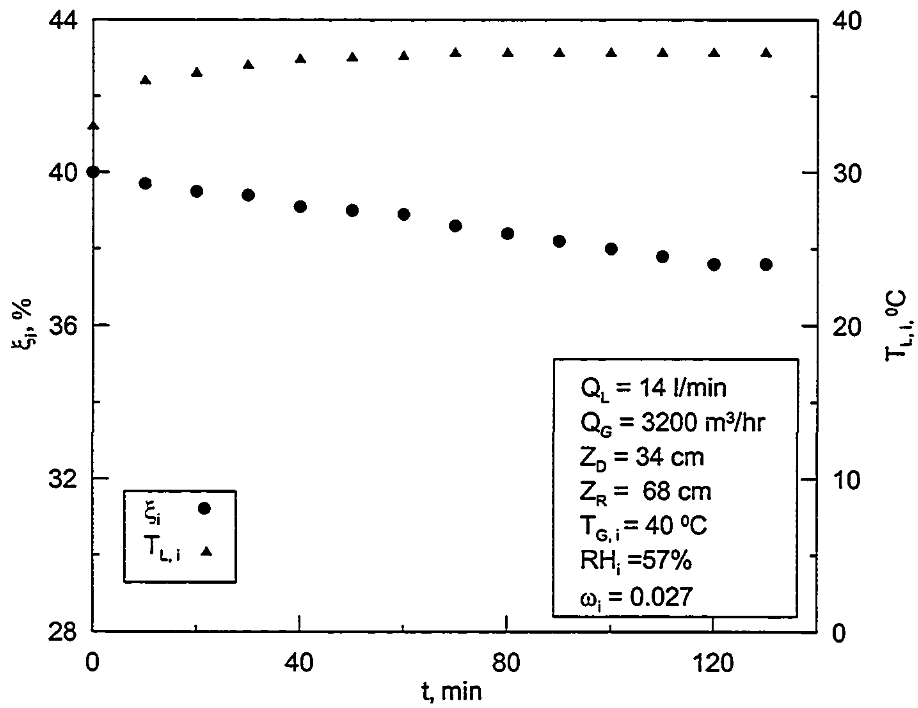


Figure 5.56:Time variation of concentration and inlet temperature for 20% $CaCl_2$ and 20% LiCl solution in the dehumidifier while the hybrid system is running.

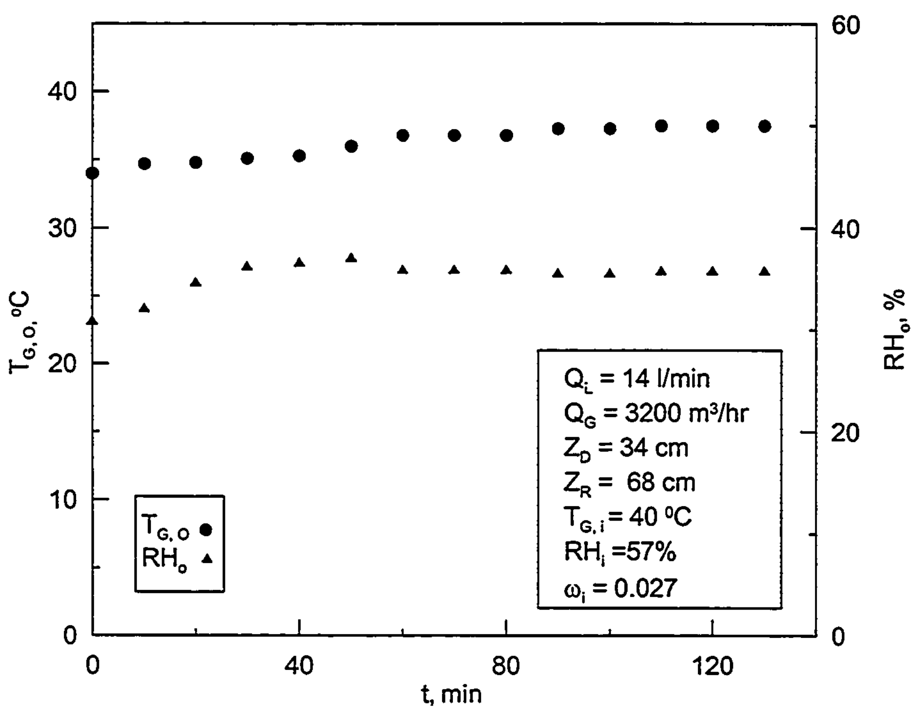


Figure 5.57:Time variation of outlet air temperature and humidity in the dehumidifier for 20% $CaCl_2$ and 20% LiCl solution while the hybrid system is running.

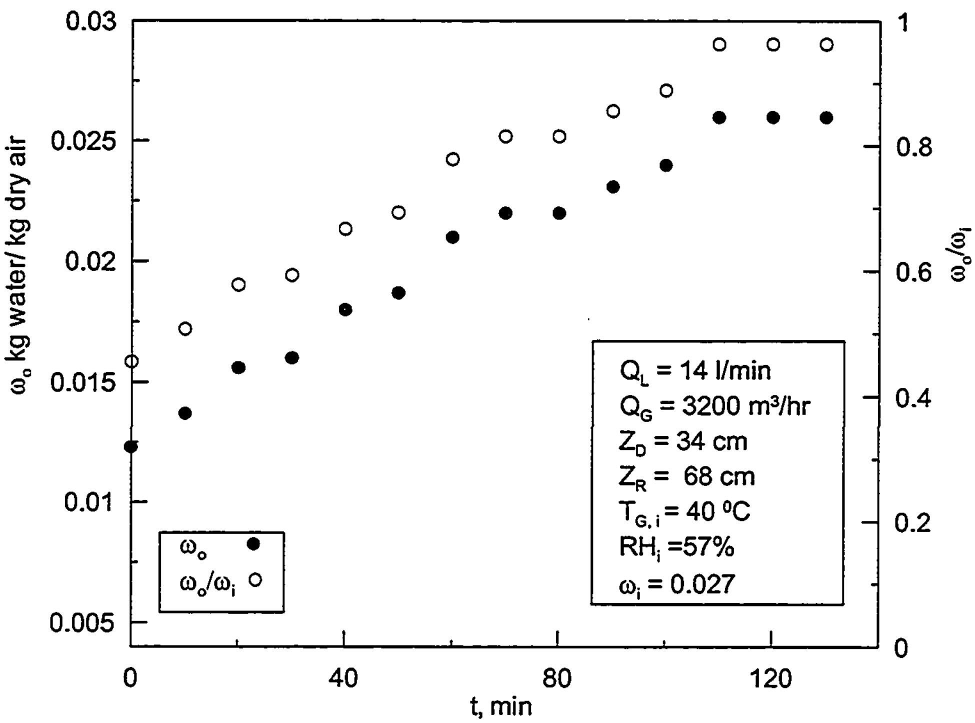


Figure 5.58: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for 20% $CaCl_2$ and 20% LiCl solution in the dehumidifier while the hybrid system is running.

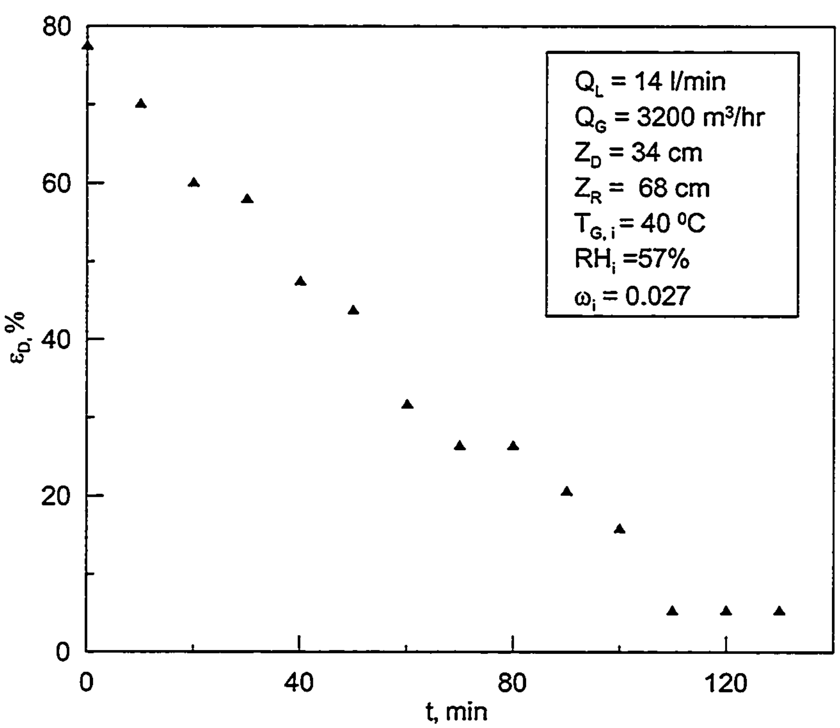


Figure 5.59: Effectiveness of the dehumidifier with time for 20% $CaCl_2$ and 20% LiCl solution while the hybrid system is running.

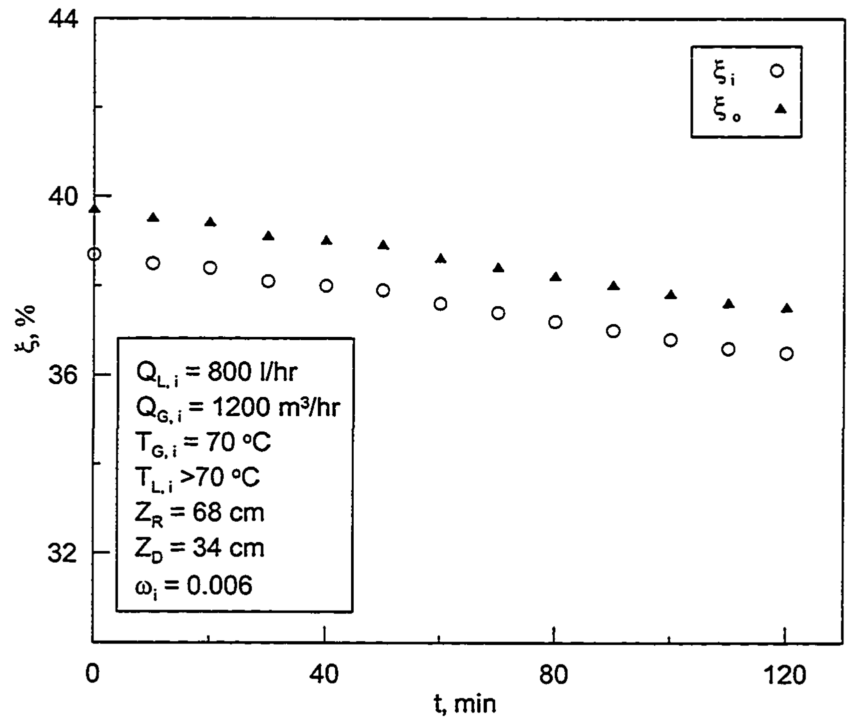


Figure 5.60: Time variation of inlet and outlet concentration for 20% $CaCl_2$ and 20%LiCl solution in the regenerator while the hybrid system is running.

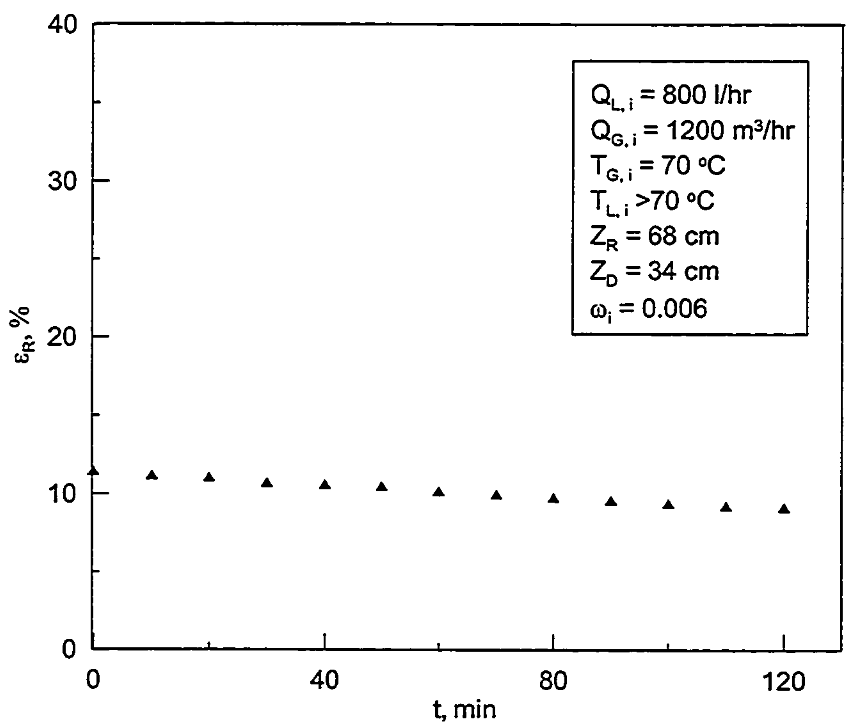


Figure 5.61: Effectiveness of the regenerator with time for 20% $CaCl_2$ chloride and 20% LiCl solution while the hybrid system is running.

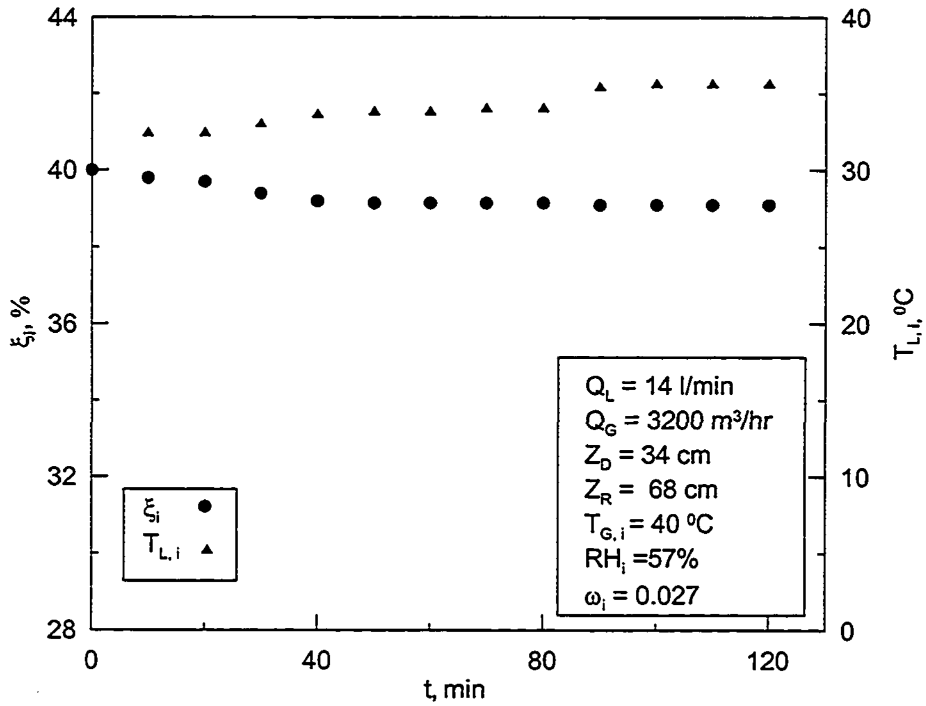


Figure 5.62:Time variation of concentration and inlet temperature for 8% $CaCl_2$ and 32% LiCl solution in the dehumidifier while the hybrid system is running.

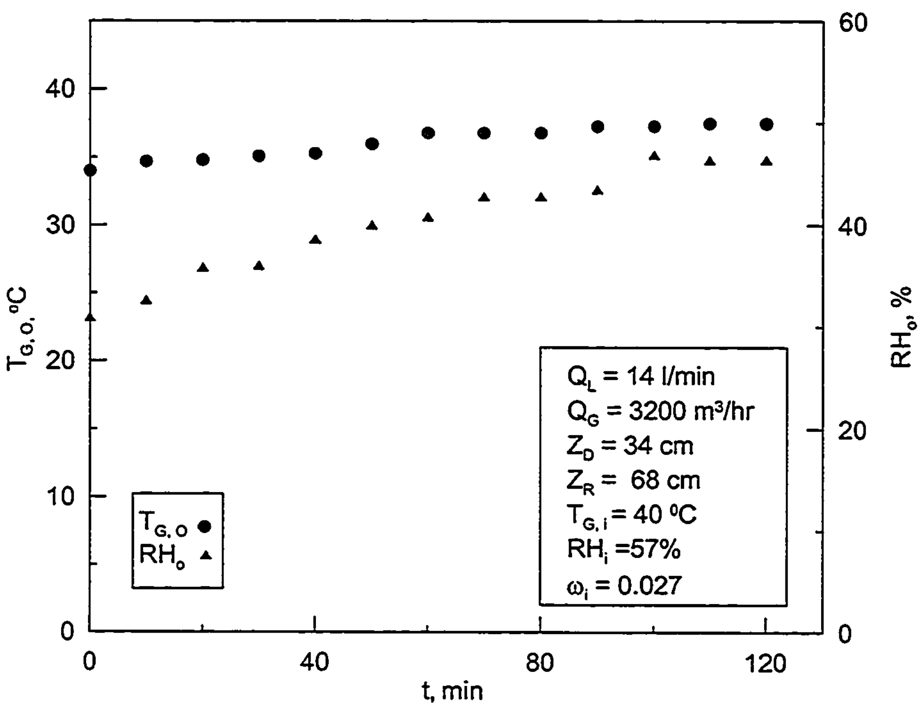


Figure 5.63:Time variation of outlet air temperature and humidity in the dehumidifier for 8% $CaCl_2$ and 32% LiCl solution while the hybrid system is running.

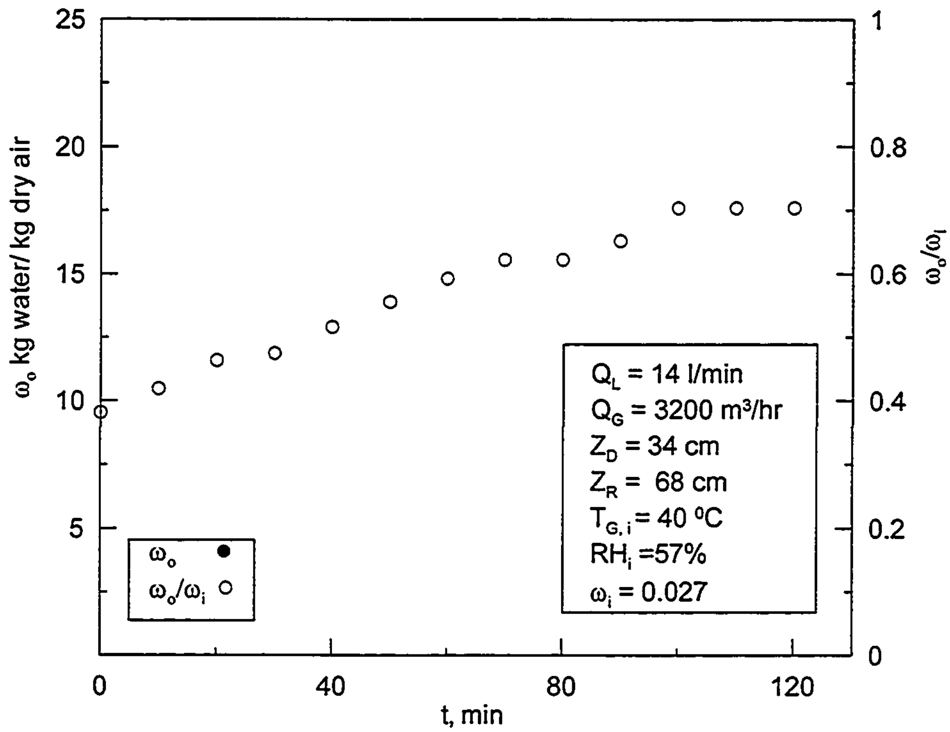


Figure 5.64: Time variation of outlet absolute humidity and ratio of outlet to inlet absolute humidity for 8% $CaCl_2$ and 32% LiCl solution in the dehumidifier while the hybrid system is running.

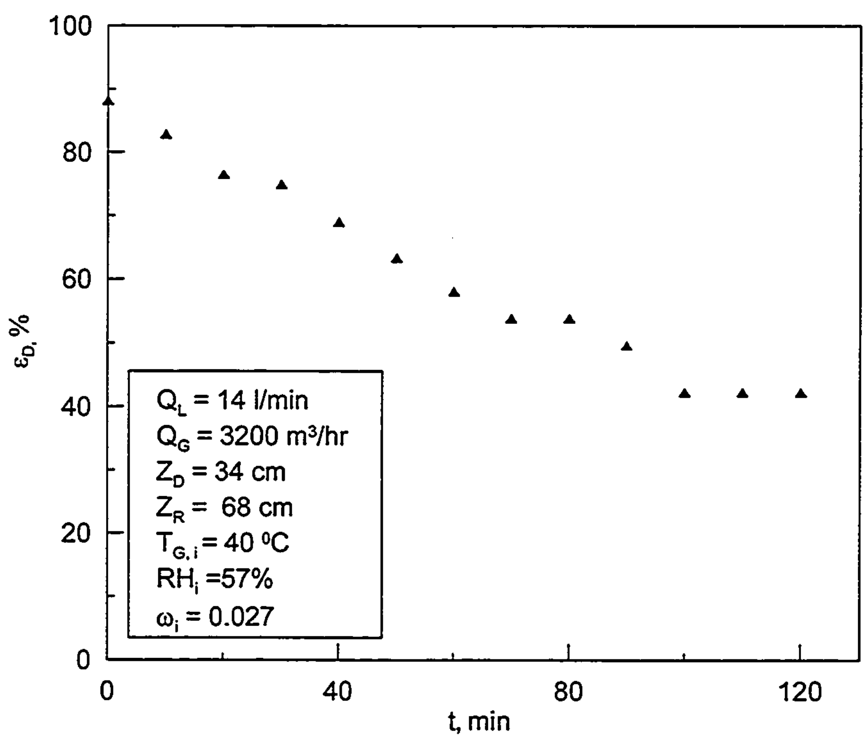


Figure 5.65: Effectiveness of the dehumidifier with time for 8% $CaCl_2$ and 32% LiCl solution while the hybrid system is running.

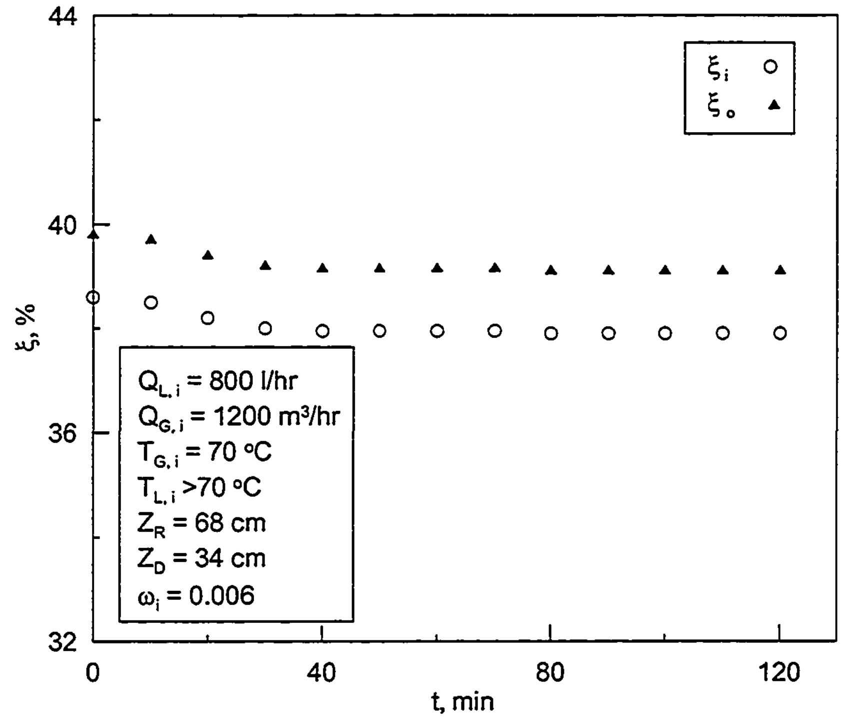


Figure 5.66: Time variation of inlet and outlet concentration for 8% $CaCl_2$ and 32% LiCl solution in the regenerator while the hybrid system is running.

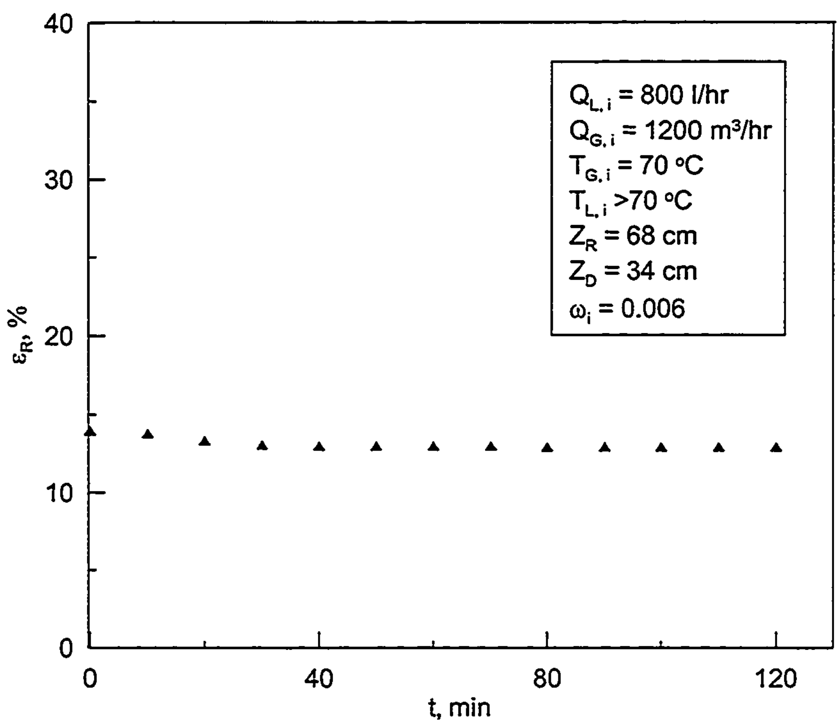


Figure 5.67: Effectiveness of the regenerator with time for 8% $CaCl_2$ chloride and 32% LiCl solution while the hybrid system is running.

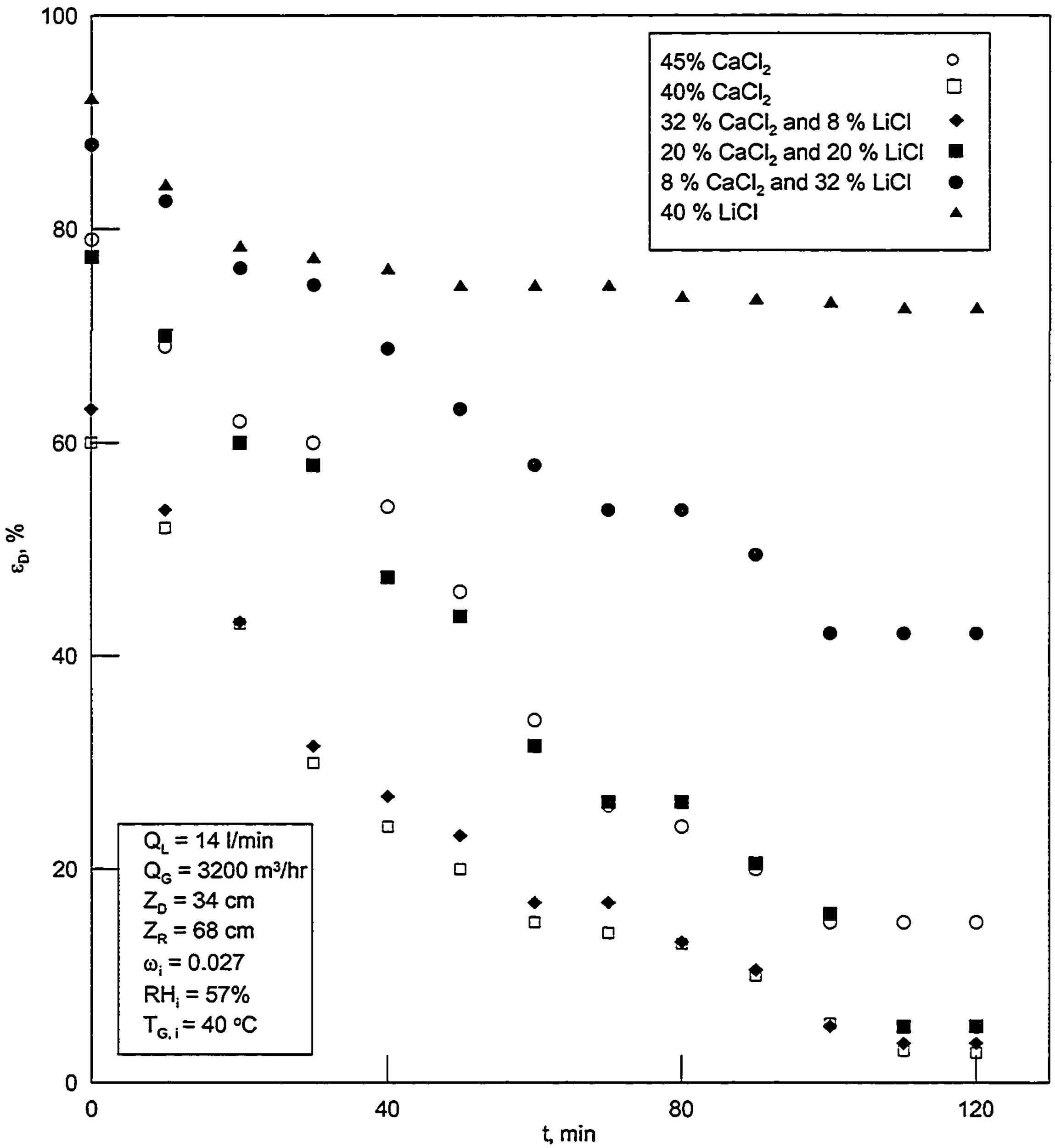


Figure 5.68: The effectiveness of the dehumidifier with time while the hybrid system is running.

The effectiveness increases from about 40% for 20% $CaCl_2$ and 20% LiCl by weight mixture in the dehumidifier for the hybrid cooling system to more than the effectiveness value of 60% for 8% $CaCl_2$ and 32% LiCl by weight mixture. The effect of various desiccant mixture compositions on the average effectiveness of the regenerator is shown in Fig. 5.69 for the given operating conditions. As the LiCl composition increases in the mixture, the regenerator effectiveness also increases but the increase is not significant as in the dehumidifier.

The time variation of the dehumidifier effectiveness for different mixtures is shown in Fig. 5.70. It clearly shows that 40% LiCl solution as the single desiccant outperforms all the other desiccant mixtures and the least performance is obtained with 40% $CaCl_2$ solution as the single desiccant. Although the equal composition of the desiccant mixture (that is, 20% $CaCl_2$ and 20% LiCl by weight) performs well, slightly more LiCl composition significantly improves the dehumidifier performance.

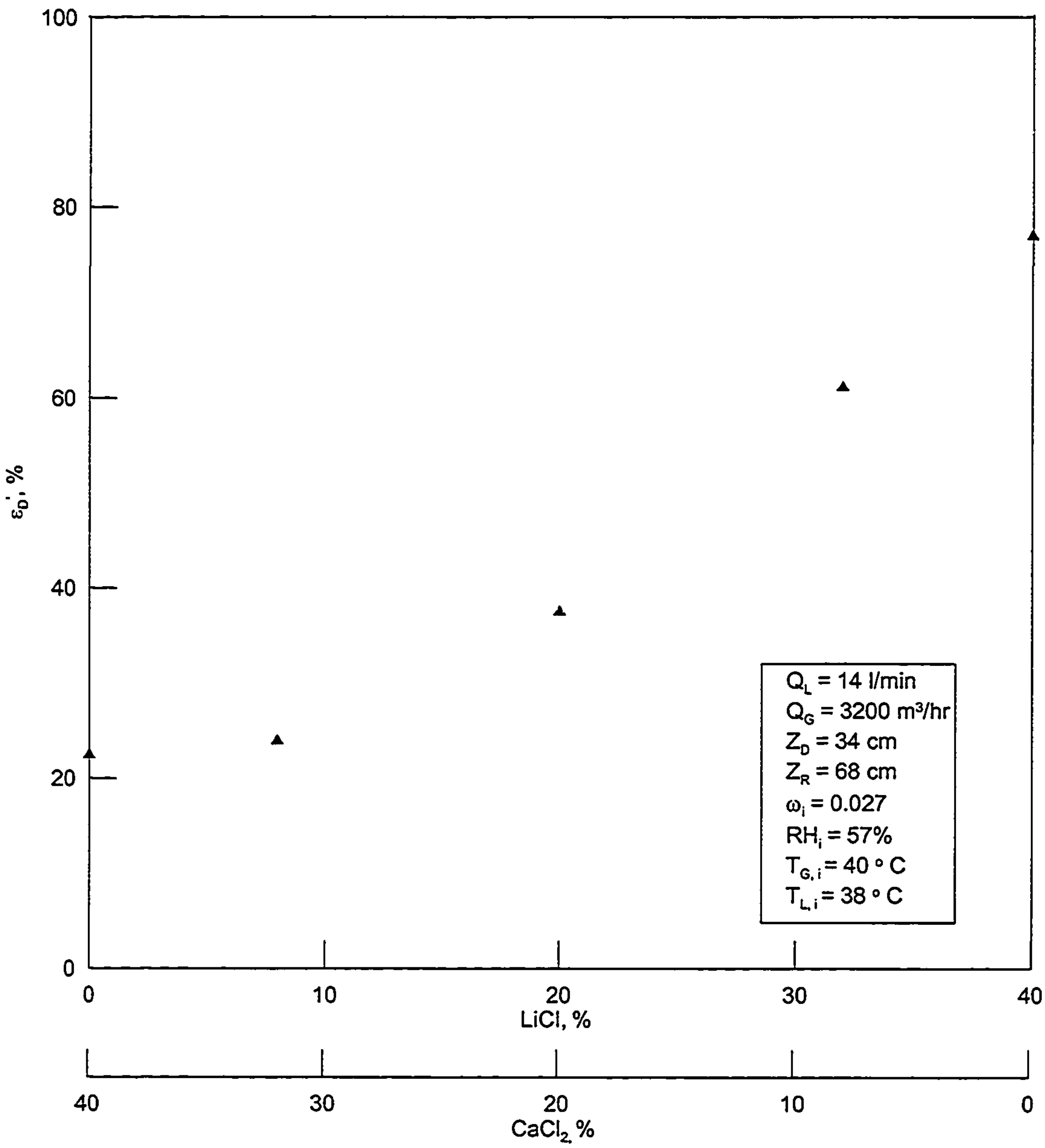


Figure 5.69: The effect of desiccant mixture composition on the average dehumidier effectiveness while the hybrid system is running.

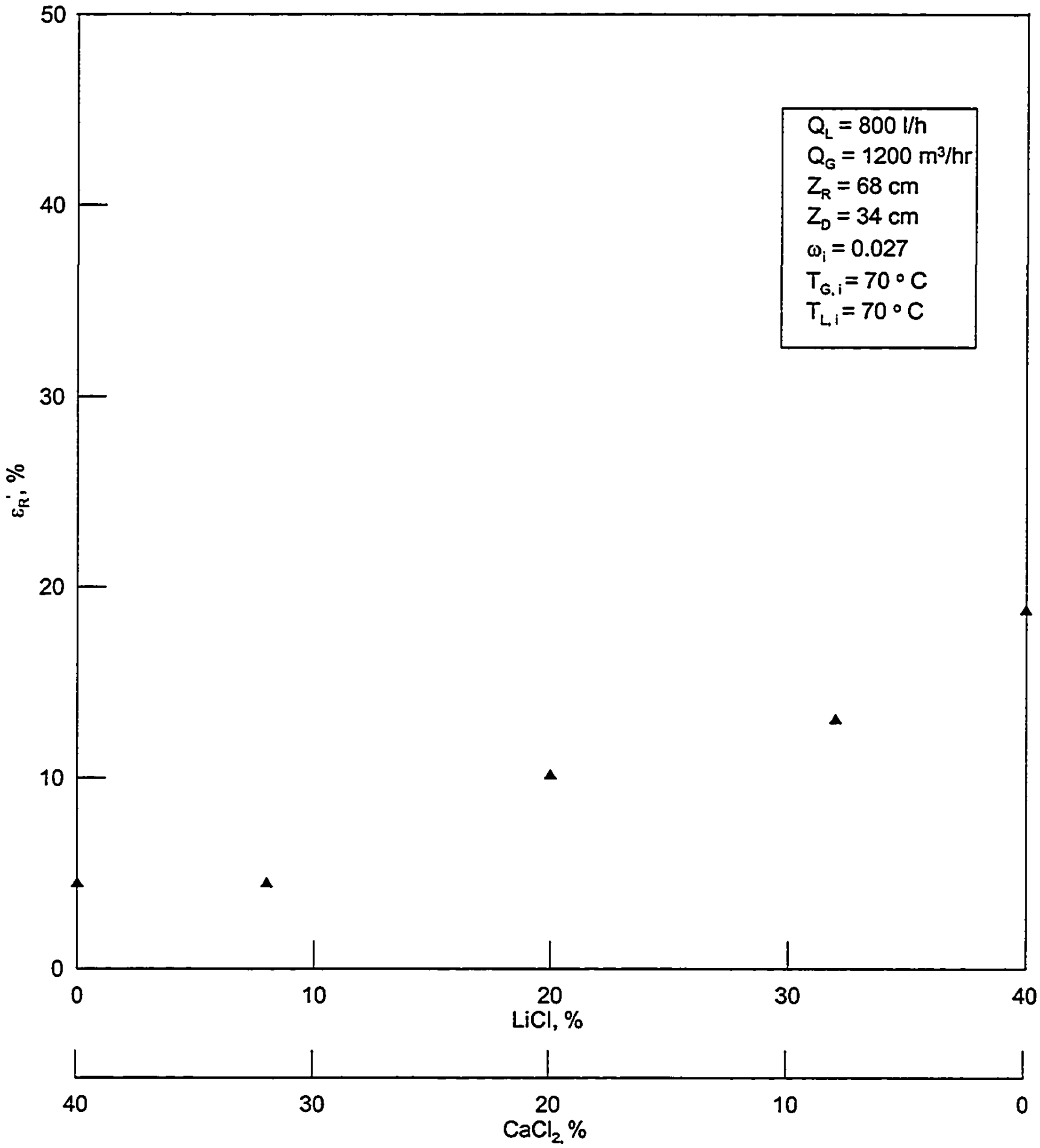


Figure 5.70: The effect of desiccant mixture composition on the average regenerator effectiveness while the hybrid system is running.

CHAPTER 6

PERFORMANCE OF THE HYBRID SYSTEM

The hybrid desiccant systems are cost effective where the thermal energy required for regenerating the desiccant is readily available and the latent fraction is high. The magnitude in saving of energy is directly affected by various factors such as ambient conditions, type of desiccant and air conditioning load. The conventional unit requires large amount of energy to meet the latent cooling load in humid climates. In the present study the performance of the hybrid system is compared with the vapor compression unit by using coefficient of performance. For the sake of comparison the regeneration energy is excluded since it can be provided by different means of waste energy or solar energy.

The coefficient of performance is one of the criteria to assess economical performance of the system. The energy saving analysis can be demonstrated by comparing the conventional and hybrid system. In addition to the yearly saving of money and payback period of the hybrid system, the energy saving factor, is calculated.

6.1 Coefficient of Performance

The coefficient of performance is the ratio of the energy that can be removed from the air-conditioning space, (Q), which consists of latent (Q_L) and sensible loads (Q_S) to that of compressor work (W_C).

$$Q = Q_S + Q_L = m_a\,(C_{pa}+C_{pw}\omega)(T_{in}-T_{out}) \tag{6.1}$$

$$COP = \frac{Q_S + Q_L}{W_C} \tag{6.2}$$

In order to find the coefficient of performance of vapor compression the ambient condition is selected as 40 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air. The outlet temperature of air leaving the evaporator is almost kept constant. The air inlet and outlet temperatures and its humidities are measured using Velocity Calc. The compressor work is measured using a power meter.

The COP of the conventional vapor compression unit is found to be 1.55 and the results show that the COP of the vapor compression unit in hybrid liquid desiccant cooling system under different desiccant mixtures is more than that of the conventional vapor compression system as given in Fig. 6.1. It can be clearly seen that for 40% $CaCl_2$ the COP is approximately 14.8% higher than vapor conventional unit and for 40% lithium chloride it is approximately 39% much higher than that of conventional unit. The reason that the hybrid liquid desiccant is superior in performance lies in the fact that the dehumidification of air in the hybrid system provide more potential to remove the latent load moreover the electricity consumption of the compressor in the hybrid system is less.

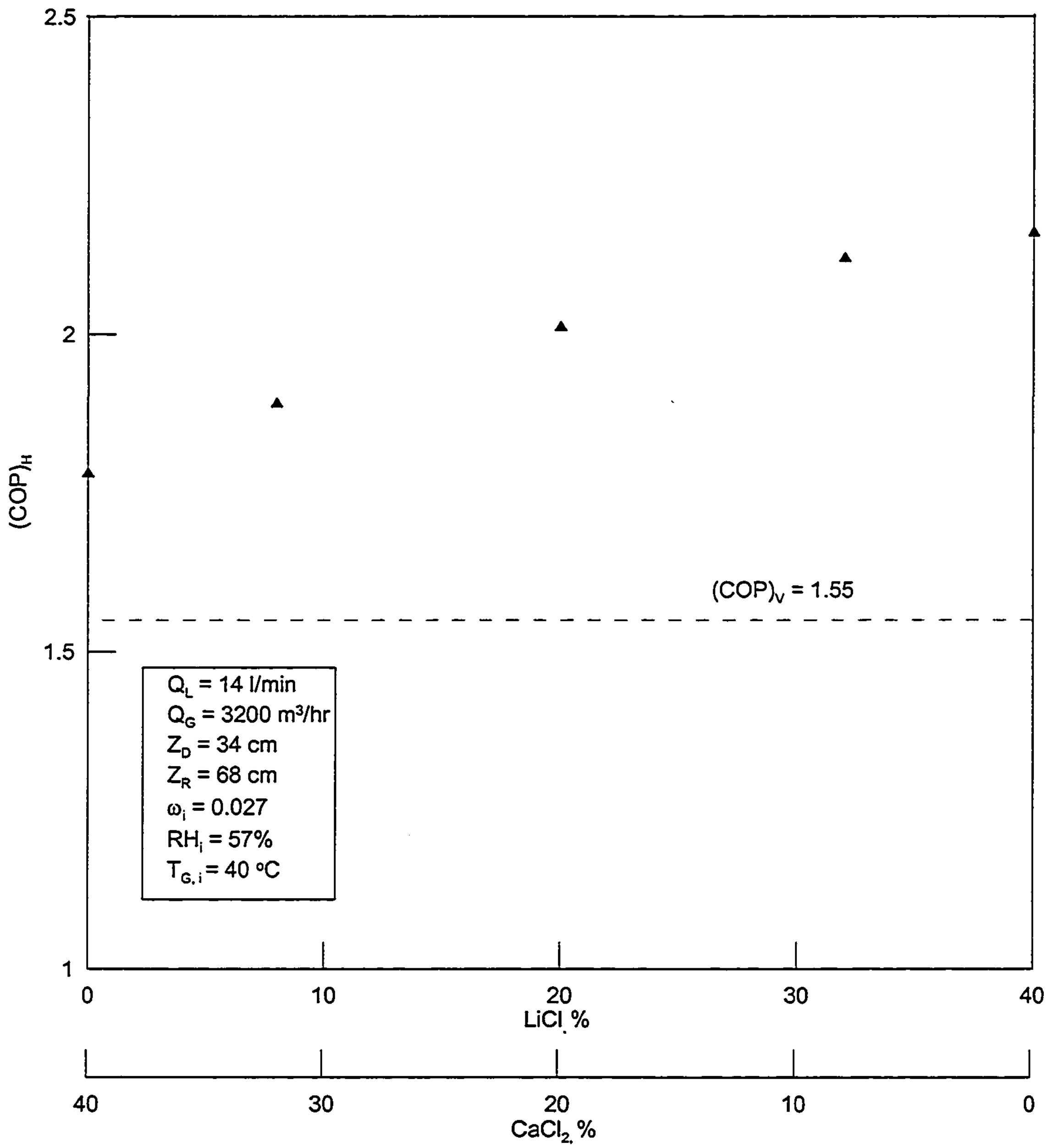


Figure 6.1: The effect of desiccant mixture composition on the coefficient of performance.

The amount of auxiliary energy needed for regenerating the desiccants are shown in Fig. 6.2. The energy needed to heat the desiccant is more than heating the air

6.2 Economic Analysis

A set of experiments were carried out with conventional vapor compression system and hybrid system with ambient conditions as 40 ^{0}C with a humidity ratio of 0.027 kg of water per kg of dry air. The desiccant used in hybrid system is $CaCl_2$. The outlet temperature of air leaving the evaporator is almost kept constant for the sake of comparison of the energy needed.

Energy calculations for the conventional system as well as for the proposed hybrid cooling system is presented as follows:

Energy needed to run the conventional vapor compression system ≡ E_{con} = 9.9 KW

Energy needed to run the vapor compression unit in Hybrid System ≡ E_H = 7.01 kW

6.2.1 Energy Saving Calculations

The savings factor (SF) is the percentage of energy that will be saved with the installation of the hybrid system. Energy saving calculations for vapor compression system can be estimated by:

$$SF = \left(1 - \frac{E_H}{E_{con}}\right) x100 \qquad (6.3)$$

SF = 29.19 %

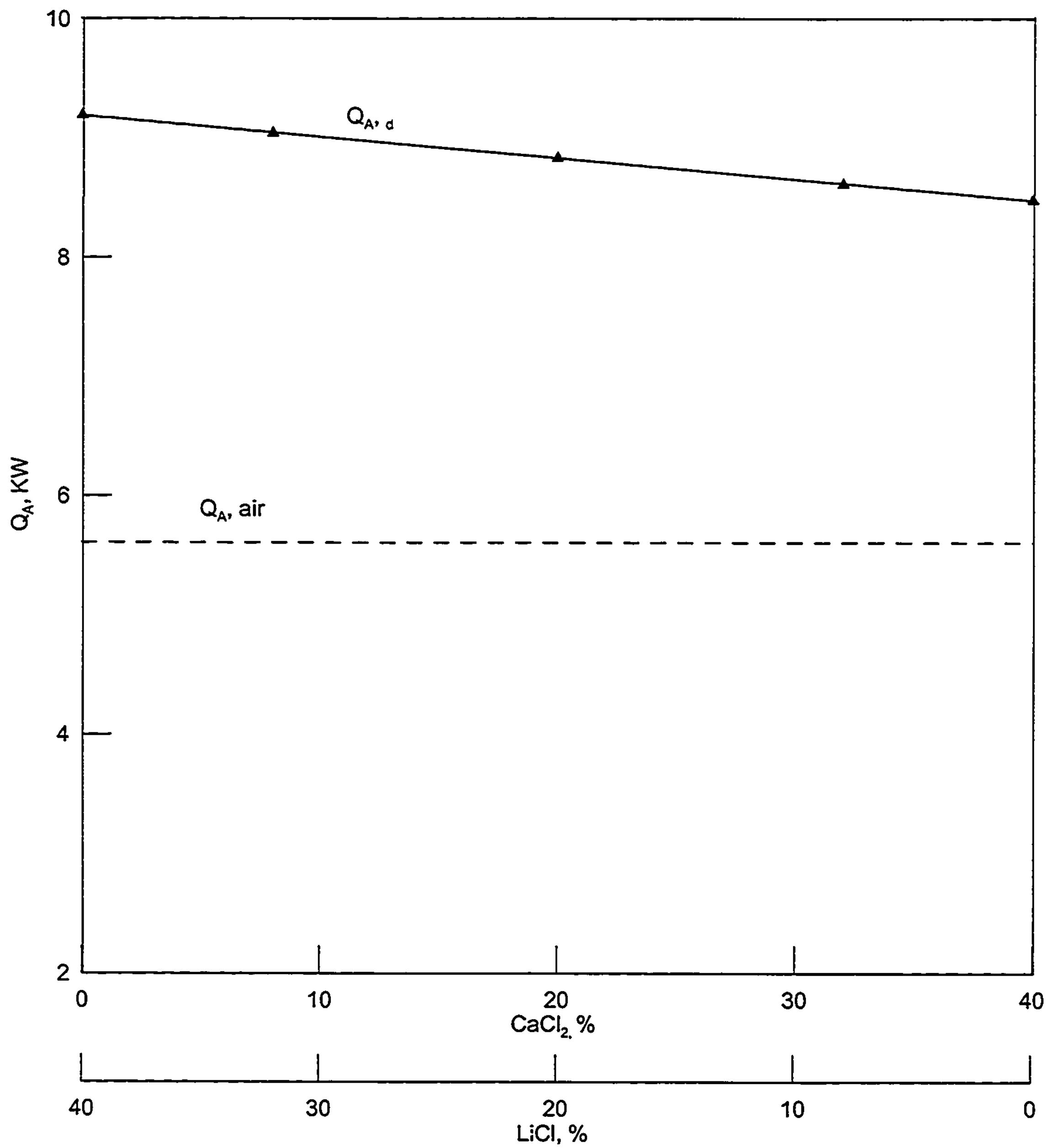


Figure 6.2: The amount of auxillary energy needed for regenerating the desiccant mixtures.

6.2.2 Yearly Cost Savings

The daily saving that the hybrid system will bring can be calculated based on the price of electricity. For the present analysis the price of electricity is taken as SR 0.08/KWh. Power needed to run the vapor compression unit in the hybrid cooling system is 168.24 KWh/day and the cost is SR 13.46/day.

For the conventional system the power needed to run the vapor compression unit and the fans is 237.6 kWh/day and the cost is SR 19.0/day. Thus, the hybrid system will provide saving of SR 5.54/day. Yearly savings can be calculated from the daily savings assuming that the air conditioning unit is operated for eight months from March to October. Therefore total saving, A, is SR 1329.6/year.

6.2.3 Payback Period

Payback period is the length of time required to recover the first cost of an investment from the net cash flow produced by that investment for an interest rate equal to zero. The interest rate during this period and the salvage value of the equipment is taken into consideration. The method used is called "Capital Recovery with Return"[41]. Table 6.1 shows the cost of the hybrid cooling system.

The initial investment for the proposed system, P_i, is SR 11192 from the Table 6.1. The salvage value of the pumps, desiccant tanks and fans is calculated from 20% of the initial costs. The initial total costs of these items are SR 2560, and the salvage value, F', is SR 512.

The payback period can be calculated from the following relation:

$$n_p = \frac{\ln\left[\dfrac{A}{A - i(P_i - F')}\right]}{\ln(1+i)} \qquad (6.4)$$

Where i = interest rate

The total payback period for the hybrid system with 8% interest is 13.36 years or 13 years and 4 months.

Table 6.1: The cost of the hybrid cooling system

Item	Unit	Unit cost SR	Total cost SR
Desiccant pumps	2	810	1620
Towers (Dehumidifier and Regenerator)	2	2250	4500
Fans	2	400	800
Heat exchanger	2	1000	2000
Desiccant tanks	2	70	140
Desiccant material (calcium chloride)	3	85	255
PVC pipes, fittings, valves, etc.		1000	1000
Labor to manufacture (54 h)		SR 25/h	1350
Labor to assemble (20 h)		SR 25/h	500
Total retail cost			12165
From retail to wholesale conversion, 20%			-2433
Wholesale conversion total cost			9732
Assuming 15% profit			1460
Retail sale price			11192

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

A detailed investigation has been carried out to study the performance characteristics of the hybrid cooling system using calcium chloride, lithium chloride and their mixtures. The performance of the dehumidifier is influenced by several factors including the desiccant properties, packing type, packing height, fluid flow rates, the desiccant inlet temperature and concentration and the air temperature and humidity. The experiments are carried out to analyze the dehumidification system for different flow rates as a function of time. The desiccant concentration and its temperature decrease with time when the dehumidifier is working alone since the desiccant continuously absorbs water vapor from the air. The air dehumidification is high at the beginning of the dehumidification process, since the mass transfer potential is high due to the high desiccant concentration. The air outlet temperature increases slightly and then remains constant with time. The rate of air dehumidification is faster for higher desiccant flow rates. The effectiveness of the dehumidifier is used as a performance parameter. The effectiveness of the packed bed dehumidifier is defined as the ratio of the difference in absolute inlet to outlet humidity to the difference between the inlet and desired absolute humidity. It is observed that as the flow rate of the desiccant increases the average effectiveness also increases but at high flow rates it begins to decrease due to flooding of the desiccant.

Decrease in the desiccant inlet temperature results in an improvement of the air dehumidification since the mass transfer rate is increased. This is due to the decrease in desiccant vapor pressure, which is the driving force for the mass transfer process. Moreover, as the inlet desiccant concentration increases, the effectiveness increases because the vapor pressure decreases and thus the potential for mass transfer increases.

The regeneration process is an essential one to recover the concentration of the desiccant in the regenerator in order to reuse it again in the dehumidifier. Heat required for the regeneration process may be supplied by fossil fuel, solar energy or an electric heat source. Using a free source of energy such as waste heat from a plant, solar energy or energy extracted in a cogeneration process provides an ideal energy supply for an economic regeneration process. In the regenerator, the weak desiccant is brought into contact with hot air so as to transfer the moisture from the desiccant to the air. The performance of the regenerator as a function of time is investigated experimentally until steady state condition is reached. The desiccant concentration and its temperature increases with time as a result of the mass transfer of the water vapor from the desiccant to the air and heat transfer from the hot air discharged from the condenser. The time required to obtain the required desiccant concentration in the regeneration process is reduced by increasing the air inlet temperature. The removal of water from the weak desiccant increases with increasing air inlet temperature due to increase in water vapor pressure. The desiccant regeneration process also increases up to a maximum value of the ratio between air to desiccant flow rate ratio (Q_G/Q_L) due to the increase of mass transfer from the desiccant and then decreases as a result of the excessive wetting of the structured packing material (flooding). The maximum generation occurs approximately at Q_G/Q_L =1 m^3/liter. The desiccant regeneration increases as the desiccant inlet temperature increases due to the increase in the vapor pressure difference between the desiccant and the air. Moreover, the regeneration process increases with decreasing the absolute humidity of the entering air. This is due to the decrease in the vapor pressure of the air, which results in increasing the driving force for mass transfer from the desiccant to the air.

The effectiveness of the packed bed regeneration process using heated air is defined as the ratio of actual change in concentration of the desiccant during the regeneration process to the maximum possible change in the concentration of the desiccant. Heating the air for the regeneration process results in an increase in the effectiveness as the air temperature increases. This is because as the air temperature increase, the liquid desiccant is heated and hence its vapor pressure increases leading to an increase in the effectiveness.

In addition, the regeneration effectiveness decreases as the humidity ratio of the inlet air increases. As the humidity of the inlet air increases, higher liquid desiccant temperature is required for the regeneration process.

The effect of calcium chloride solution, lithium chloride solution and different mixture ratios of both on the performance of the hybrid system is investigated. The hybrid system having a combination of 34-cm packing height in the dehumidifier and 68-cm packing height in the regenerator is selected for the study since it provides he best steady operation in simultaneous air dehumidification and desiccant regeneration. An overall solution concentration of 40 % of lithium chloride and calcium chloride with different ratios is studied.

The system is tested using different concentrations of desiccant mixtures of calcium chloride and lithium chloride with the following compositions:

a. 40% and 45% $CaCl_2$ by weight.

b. 32% $CaCl_2$ + 8% LiCl by weight.

c. 20% $CaCl_2$ + 20% LiCl by weight.

d. 8% $CaCl_2$ + 32 % LiCl by weight.

As the lithium chloride content in the solution increases, the effectiveness of the regenerator as well as that of the dehumidifier increases. In addition, as the lithium chloride content increases, the hybrid system performance reaches steady state condition faster. Although the performance of the system using lithium chloride is higher, its cost is about 20 times that of calcium chloride. A 45% solution of calcium chloride has similar performance compared with a solution of 20% Calcium chloride and 20% lithium chloride. A solution of 45% concentration of calcium chloride produced better performance compared to the 40% calcium chloride solution. The average effectiveness of the dehumidifier improved from 22% to 75% by using 40% solution of lithium chloride instead of a 40% solution of calcium chloride.

Moreover, the regeneration of the lithium chloride liquid desiccant is more effective than that of calcium chloride solution. The regeneration process effectively maintains the desiccant concentration continuously for the air dehumidification process for all the desiccant mixtures. The desiccant mixture of 20% $CaCl_2$ and 20% LiCl by weight. (CELD) is found to be the optimum mixture in terms of cost and performance.

Results indicate that, for 40% $CaCl_2$ the COP is 1.77, which is 14.8% higher than that of the vapor compression unit. On the other hand for 40% lithium chloride it is 2.2, which is 39% higher than that of conventional unit.

7.2 Recommendations:

The following recommendations are stated:

1. To improve the performance of a conventional system for humid climates, a hybrid system using liquid desiccants is suggested.
2. It is recommended to use lithium chloride as a desiccant in order to get the best performance.
3. To minimize the cost of desiccant regeneration, it is recommended to use a solar energy or waste heat for regeneration.
4. It is recommended to use a hybrid system using heating the air for regeneration.
5. It is recommended to keep the ratio of air flow rate to desiccant flow rate at approximately 1 m^3/liter.
6. The minimum ratio between the packing height of the dehumidifier to that of the regenerator should not be less than 0.5.
7. All components of the system should be selected from non-corrosive materials such as fiberglass and PVC.
8. During winter seasons, the hybrid system should be drained and rinsed with fresh water and the desiccants should be stored in a warm ($T > 20^{o}C$) place in order to avoid crystallization.

9. The concentration of the desiccants in the hybrid system should not be less than 40 %.

10. It is recommended to use a heat exchanger to heat the week desiccant entering the regenerator and cool the strong desiccant entering the dehumidifier.

APPENDIX

UNCERTAINTY AND ERROR ANALYSIS

1. Direct Measurements (Independent variables)

Direct Measurements	Measured by	Accuracy
Dry Bulb temperature	Thermocouple	$\pm 0.1^{o}C$
Wet Bulb temperature	Thermocouple	$\pm 0.1^{o}C$
Pressure	Pressure gauge	$\pm 1\,psi$
Flow rate (1)	Flow meter	$\pm 25l/h$
Flow rate (2)	Flow meter	$\pm 1l/\min$
Electric power	Power meter	$\pm 0.1kW\,h$
Relative humidity	VelociCalc instrument	± 0.1 %
Specific gravity (and hence concentration)	Hydrometer	±0.02
	Which corresponds to concentration difference of	±0.1

2. Dependent Variables

Variables	e_{max}	e_{min}	% Uncertainty	
			Max.	Min.
Effectiveness (ξ)	0.0168	0.009148	0.061	0.058
Outlet & inlet humidity ratio (ω_0/ω_i)	0.0218	0.1029	2	3.76

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