System design and modeling of energy efficient liquid desiccant regeneration system at vacuum condition

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**SYSTEM DESIGN AND MODELING OF ENERGY EFFICIENT
LIQUID DESICCANT REGENERATION SYSTEM AT VACUUM
CONDITION**

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SCHOOL OF ELECTRICAL AND ELECTRONIC ENGINEERING

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SYSTEM AT VACUUM CONDITION**

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Summary

Liquid Desiccant Dehumidification System (LDDS) has been one of the attractive alternatives to replace the conventional mechanical dehumidification system in building air conditioning system due to its higher energy efficiency. LDDS is able to shift the electrical energy towards renewable or low-grade energy and can improve indoor air quality with better humidity control. However, the conventional adiabatic packed-bed regenerator requires higher regeneration temperature which of 60-80°C to regenerate higher desiccant solution concentration. This limits the use of the low-grade or renewable energy as the heat source in the regeneration system of LDDS. Therefore, a novel Absorption-based Liquid Desiccant Regeneration (ALDR) system which operates under vacuum condition is proposed in this work.

A prediction model is first developed to predict the system regeneration performance. Several performance indices which are the Moisture Removal Rate (MRR) and Mass Fraction Increase (MFI) are introduced to represent the regeneration performance of the ALDR system. The prediction model is developed based on the energy and mass balance equations and concept of perfectness. The prediction model is then verified with the experimental data. The experimental results are in good agreement with the predicted results with 94.12% of the points within $\pm 10\%$ deviation and the average deviation is less than 3.37%. The developed prediction model is also used to predict the system regeneration performance under varied operating conditions.

An effective model is developed to simulate the dynamics of the ALDR system. The dynamic model is developed based on internal and external enthalpy balances and mass balances in the various components and it accounts for dynamic behavior due to the heat and mass transfer processes in the components. This approach is simpler as a detailed enthalpy at each state point can be avoided. The developed dynamic model is verified using the data obtained from the experimental platform built in the laboratory. The dynamic response of the simulation results agrees well with the experimental data. This

model is able to predict the relevant parameters such as the temperature, concentration and mass flow of the desiccant solution and also temperatures of the heating and cooling sources when a step change of inlet water temperature is applied to the system. The developed model is useful for designing a controller to control the vacuum pressure in the system so as to achieve the control objective of increasing the regeneration performance of the system. The developed dynamic model can also be adapted to other similar design of regeneration system operating under vacuum condition if the system design data are available.

In the research work, the feasibility of the proposed desiccant regeneration system operating under vacuum condition is of the main concern. Therefore, the system regeneration performance and the regeneration temperature should be determined to validate its feasibility and compared with other existing desiccant regeneration systems. The ALDR system is first designed and built in the laboratory. A Singapore patent application of the proposed ALDR system has been filed. From the experimental results obtained, the regeneration temperature of the ALDR system is found to be around 20-35°C when the operating pressure is between 1000Pa and 2000Pa. This is significantly less than that of the existing desiccant regeneration system which is required to be around 60-80°C. The reduction of regeneration temperature allows the potential use of low-grade or renewable energy source in the regeneration system. The power consumption of the proposed ALDR system is also found to have decreased by 40.66% when compared to conventional liquid desiccant regeneration system which validates its energy saving potential. The reduction of regeneration temperature and power consumption of the proposed ALDR system underlines the main contribution of this work.

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Nomenclature

Variables

A	Area (m^2)
c_p	Specific heat capacity ($\text{Jkg}^{-1}\text{K}^{-1}$)
d	Humidity ratio (gkg^{-1})
D	Diameter of tube (m)
E	Power consumption (W)
F	Fouling factor (m^2KW^{-1})
g	Gravity constant (ms^{-2})
h	Enthalpy (Jkg^{-1})
K	Ratio of practical to ideal system performance
k	Thermal conductivity ($\text{Wm}^{-1}\text{K}^{-1}$)
l	Specific heat of solution (Jkg^{-1})
M	Mass (kg)
MFI	Desiccant Mass fraction increase (%)
MRR	Moisture removal rate (kgs^{-1})
$\dot{m}$	Mass flow rate (kgs^{-1})
N	Number of horizontal heat exchanger tubes
n	Desiccant mass fraction (%)
P	Pressure (Pa)
Pr	Prandtl number
$\dot{Q}$	Heat flux (W)
r	Latent heat of vaporization (Jkg^{-1})
R	Gas constant ($\text{Jkg}^{-1}\text{K}^{-1}$)
Re_D	Reynold's number
T	Temperature (K)
t	Time (s)

th	Thickness of heat exchanger tube (m)
U	Heat transfer coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)
V	Volume (m^3)
$\dot{V}$	Volume flow rate (m^3s^{-1})
X	Concentration

Indices

<i>air</i>	Air
<i>ALDR</i>	ALDR system
<i>con</i>	Condenser
<i>cond</i>	Condensed
<i>cw</i>	Cooling water
<i>deh</i>	Dehumidification
<i>evap</i>	Evaporation
<i>exp</i>	Experiment
<i>ext</i>	External
<i>f</i>	Film
<i>gen</i>	Generator
<i>hex</i>	Heat exchanger
<i>hw</i>	Hot water
<i>ideal</i>	Ideal
<i>in</i>	Inlet
<i>int</i>	Internal
<i>out</i>	Outlet
<i>packed – bed</i>	Packed-bed regeneration system
<i>prac</i>	Practical
<i>pred</i>	Predicted
<i>reg</i>	Regeneration
<i>s</i>	Surface
<i>sat</i>	Saturation

<i>sol</i>	Solution
<i>v</i>	Vapor
<i>w</i>	Water

Greek letters

α	Internal heat transfer coefficient ($\text{Wm}^{-2}\text{K}^{-1}$)
μ	Dynamic viscosity ($\text{kgm}^{-1}\text{s}^{-1}$)
ρ	Density (kgm^{-3})

Chapter 1 Introduction

1.1 Background

The energy consumption by Air-Conditioning and Mechanical Ventilation (ACMV) systems is approximately half of the total building electrical energy consumption. The overcooling and reheating process in the conventional mechanical dehumidification system makes the system very energy intensive. The dehumidified air by this method is cooler than the required comfort condition and hence it is a waste because of the need for extra reheating energy. Hence, there should be energy-efficient air conditioning system for energy conservation. Liquid Desiccant Dehumidification Systems (LDDS) as shown in Figure 1.1 has been proved to consume relatively less energy in removing moisture in the process air as compared to the conventional mechanical dehumidification system and provides a better humidity control [1-3].

Figure 1.1: Conventional packed-bed type liquid desiccant regenerator in LDDS [1]

LDDS also offers energy savings for ACMV systems for its potential use of low grade or renewable energy in the desiccant regenerator. The water component in process air is removed by using the desiccant solution which has high affinity for water vapor instead of overcooling and reheating process. The liquid desiccant regenerator is one of the main components in LDDS where the diluted desiccant solution is concentrated so

that it can be reused in the dehumidifier. The liquid desiccant regenerator plays a vital role in the performance of LDDS as the major energy consumption in LDDS is the heat energy supplied to the liquid desiccant regeneration system.

The high regeneration temperature of around 60-80°C [4-6] has been one of the main concerns in the adiabatic packed-bed regenerator in LDDS. The removal of moisture in the process air is due to surface vapor pressure difference between the air and solution streams. Therefore, higher regeneration temperature is required to regenerate higher concentration of desiccant solution and this limits the use of low grade energy or renewable energy as the heat source. As a result, this will increase the energy consumption in LDDS. Thus, a new structure of liquid desiccant regenerator operating under vacuum condition with the purposes of reducing the regeneration temperature and increasing the energy efficiency is proposed as shown in Figure 1.2.

Figure 1.2: The proposed ALDR system in LDDS [1]

The newly proposed Absorption-based Liquid Desiccant Regeneration (ALDR) system which operates under vacuum condition is able to reduce the boiling point of the diluted desiccant solution. The system offers the following benefits: 1) the reduction in boiling point of desiccant solution results in the decrease in the regeneration temperature, enables the system to use low grade energy or renewable energy as the heating source for energy savings; 2) the water composition in the liquid desiccant is removed by boiling it into water vapor form where it is a faster process than that in the adiabatic

packed-bed regenerator; and 3) no air stream is exploited in the ALDR system and hence fan is not required in this system and solution carryover is avoided.

In order to validate the feasibility of applying vacuum condition in regenerating desiccant solution, the system is designed based on the concepts and ideas explained before. The experimental platform of the proposed system will also be set up to test for its feasibility. The novelty of the proposed system compared to the conventional regeneration system is vital to be pointed out. Besides the system's feasibility, the regeneration performance of the proposed system is important to be determined as well. Since this is a new topic to be discovered, a reliable and accurate regeneration performance prediction model is important to predict the system performance without having to carry out the experiment. In addition, a dynamic model which is able to describe the dynamic behavior of each component in the system will be developed so that it can be used for the control and optimization purpose in the future. The regeneration temperature and power consumption of the proposed system are also determined experimentally to highlight the contribution of this research work.

1.2 Objectives

The objectives of this research work are outlined as below:

1. Design and develop a new liquid desiccant regenerator in LDDS to improve the system performance and increase the energy efficiency.

As explained in Section 1.1, the regeneration temperature of the current liquid desiccant regeneration systems is high and it prohibits the potential use of renewable energy source in the regenerator of LDDS. Therefore, a novel desiccant regeneration system operating under vacuum condition will be designed and a system experimental platform will be built for this purpose. The details of the design and development of the proposed system will be discussed in Chapter 3.

2. Develop a performance prediction model to predict the regeneration performance of the proposed system and investigate the regeneration performance under varied operating conditions.

In order to predict the performance of the proposed regeneration system without the need of carrying out the experimental tests, a performance prediction model will be developed. Then, the developed prediction model will be validated with the experimental results. The development of the performance prediction model and the performance investigation using the model developed will be discussed further in Chapter 4.

3. Develop a model for the ALDR system to describe the dynamic behavior of the system.

The description of dynamic behavior in each component of the proposed system is vital to understand the change of relevant parameters in the system with time. The desiccant regeneration system often operates outside the vicinity of the users. Thus, a dynamic model that simulates the transient performance of the system is important here. A dynamic model based on a simplified approach will be developed in Chapter 5.

4. Analyze the system performance of the proposed liquid desiccant regenerator experimentally.

Following the development of the first prototype of the system, several experimental tests will be carried out to test for the feasibility of the system in Chapter 6. The experimental results will be carried out under varied operating conditions to investigate the performance of the regeneration system. The regeneration temperature will also be determined and compared with that of other desiccant regeneration system from literature.

5. Compare the system characteristics and energy consumption of the proposed liquid desiccant regeneration system with that of the conventional adiabatic packed-bed regenerator in LDDS.

In order to highlight the contribution of the proposal of energy efficient liquid desiccant regeneration system, the parameters and energy consumption of the proposed liquid desiccant regeneration system will be compared with the packed-type regenerator available in the literature. In Sections 6.5 and 6.6, the comparison of both the system characteristics and energy consumption will be described in detail.

1.3 Organization of the thesis

There are a total of 7 chapters in this thesis. Chapter 2 reviews the background and previous work of the LDDS and liquid desiccant regenerator in LDDS. The reviews of the current available liquid desiccant regeneration systems will lead to the motivation of developing a novel liquid desiccant regeneration system that is able to solve the current high regeneration temperature issue in the system. This chapter also covers the work done on the modeling of relevant systems and air conditioning systems. Since the proposed system is a newly developed system, therefore relevant systems in different fields of research and air conditioning systems will be taken as the references here.

In Chapter 3, the system design of the proposed ALDR system is described. All the main components in the proposed system and processes occurred during the regeneration process will also be explained. The working principle of the ALDR system will also be described in detail in this chapter. Besides that, this chapter also includes the points of novelty claimed for the proposed ALDR system. In addition, the development of the experimental platform of the proposed system together with the components and sensors installed will also be included in this chapter.

Chapter 4 describes the development of a performance prediction model to predict the regeneration performance of the proposed system. Another important index will also be introduced in this chapter. The governing equations involved will be first developed based on the energy and mass balance equations. Furthermore, the validation of the developed prediction model using the experimental results is discussed and the regeneration performance is then investigated under various operating conditions.

The development of dynamic model for the ALDR system is shown detailed in Chapter 5. The beginning of the chapter will introduce the governing equations developed in each main component of the system. The models of the main components comprise of the generator, the condenser and the heat exchanger models. The governing equations are developed based on the internal and external energy and mass balance equations. The developed dynamic model is then validated with the experimental results to prove that the dynamic model is good enough to predict the transient performance of the ALDR system. Consistency examination is also carried out by inserting a step change of inlet temperature into the system model and the transient performance of the system is then analyzed.

Chapter 6 presents the experimental results of the developed system to understand the standard operating conditions of the system. Several testing sets will be listed and the regeneration performance for each test will be analyzed. Useful regeneration performance indices are introduced in this chapter. The regeneration temperature of the proposed system is determined through the experimental tests. Next, the characteristics and parameters of the proposed ALDR system are compared with the conventional packed-bed regenerator in LDDS available from the literature to emphasize the novelty of the proposed ALDR system. Lastly, the power consumption of both regeneration systems is compared to prove the energy saving potential of the ALDR system.

The final chapter, Chapter 7 will conclude the thesis with a summary of the key contributions. Some future research directions will also be recommended in this chapter.

The suggestions include the continuation work on system modification, system integration with the dehumidifier in LDDS and design of the system controller in the future.

1.4 Contributions

1. A novel and energy-efficient liquid desiccant regeneration system operating under vacuum condition is developed in this work.

The proposed liquid desiccant regeneration system is able to reduce the regeneration temperature to around 20-35°C which is much lower than other liquid desiccant regenerators available in the literature by operating the regeneration process under vacuum pressure of within 1000Pa and 2000Pa. The regeneration temperature of mostly conventional packed-bed regenerator is more than 60°C. The power consumption of the proposed system is also proved to be reduced by around 40.66% compared to that of the conventional packed-type regenerator in Chapter 6. The reduction of regeneration temperature allows the potential use of low-grade or renewable energy source in the regenerator of LDDS. The heat source may comprise any one of the condenser in a heat pump cycle, solar energy, waste heat from industry, etc. On the other hand, the cooling source can comprise any one of chilled water from the chiller, cooling sea water, cooling water from cooling tower, chilled plant condensed water, cooling water or an evaporator in a heat pump cycle. The points of novelty claimed of the proposed ALDR system are emphasized in Chapter 3. A Singapore patent application of the proposed ALDR system has been submitted and filed.

2. A simple and accurate performance prediction model is developed for the proposed liquid desiccant regeneration system.

The proposed system is a new liquid desiccant regeneration system operating under vacuum condition and it has never been discussed in any literature. The performance prediction model is developed based on the energy and mass balance equations of this newly developed system and the concept of perfectness which is commonly discussed in other researchers' work. This research work modifies this approach and validates the use of this concept in developing the performance prediction model for the proposed system. The developed regeneration performance model is proved to be able to predict the regeneration performance of the system with 94.12% of the points within $\pm 5\%$ error. In Chapter 4, the regeneration performance of the proposed system is investigated and analyzed. A journal paper based on these results has been published in Applied Energy.

3. A dynamic model based on a simplified approach is developed for the proposed liquid desiccant regeneration system.

The approach of regenerating desiccant solution under vacuum condition is an under-explored topic and there is no work done at least not reported on the development of dynamic model for the proposed ALDR system. The temperature change of all components is a complex three-dimensional heat transfer problem, thus the dynamic model for the system is developed using a simplified approach which is based on the internal and external energy and mass balance equations. This approach is simpler as the detailed enthalpy calculated at each state point can be avoided. The dynamic model developed is able to predict the transient performance of the proposed system with the error within $\pm 15\%$. The development of the dynamic model is shown in Chapter 5. Based on the results obtained, a journal paper has been published in Energy and Buildings.

Chapter 2 Literature Review

2.1 Introduction

Nowadays, Heating, Ventilation and Air Conditioning (HVAC) systems consume almost half of the energy consumption in buildings. The large energy consumption in an air conditioning system is due to the overcooling and reheating process in the conventional mechanical dehumidification system. Liquid Desiccant Dehumidification Systems (LDDS) have been one of the attractive alternatives to replace the conventional mechanical dehumidification systems for greater energy saving. LDDS has the advantages over the conventional systems in terms of: (1) consuming relatively less energy in the dehumidification process; (2) giving better humidity control; (3) potential use of low grade or renewable energy as the heat source in the desiccant regeneration system [3, 7-11]. The liquid desiccant regenerator is one of the main components in LDDS and it affects the energy efficiency of the system. Therefore, the research reported in the literature on LDDS and the desiccant regeneration systems will be reviewed here.

2.2 Liquid Desiccant Dehumidification System (LDDS)

Liquid Desiccant Dehumidification System (LDDS) has been proposed to replace the conventional air dehumidification system especially in hot and humid climate. The liquid desiccant used can also be Lithium Chloride, Lithium Bromide and Magnesium Chloride which have good characteristics of desiccant and vaporization does not occur at ambient conditions. The thermal properties of the lithium chloride and calcium chloride can be obtained from [12] and [13]. The conventional LDDS consists of dehumidifier and regenerator which compose of packing columns respectively. The dehumidifier removes the moisture in process air whereas the regenerator concentrates the diluted liquid desiccant solution.

The research done on LDDS covered the area of system design [7, 14, 15], experimental investigation [16-19] and performance analysis [20-22]. The heat and mass transfer process were mostly investigated in the research on air dehumidification by LDDS. The three most common modeling approaches are finite difference, effectiveness Number of Transfer Unit (NTU) and empirical models. The finite difference method is the most commonly-used modeling method among the three approaches for its accuracy in performance analysis. This finite difference method is based on the fundamental equations which are solved numerically and validated with the experimental data. Reference [23] developed a differential model to test the columns using lithium bromide solution to predict the performance of a packed bed dehumidifier for solar air conditioning under various operating condition. Experiments showed that preheating of air could enhance the regeneration of desiccant and pressure drop in the packing bed could be lowered by selecting suitable type of packing in the dehumidifier or regenerator.

The finite difference method does not work well for the counter flow configuration as the solution outlet conditions are unknown and iterative computation is needed to obtain convergence in the known inlet conditions. Therefore, simplified models were proposed in several literature. A differential model was developed to evaluate the effectiveness of heat and mass transfers in the packed beds of liquid desiccant system at various design and operating conditions [24]. Charts of effectiveness of heat and mass transfers presented could be used for predicting the solution and air outlet conditions from the bed. Reference [25] developed a computationally-efficient effectiveness model for the liquid desiccant heat and mass exchangers. The developed effectiveness model agreed well with the finite difference model and experimental data.

Reference [26] proposed an analytical solution of adiabatic heat and mass transfer process in packed-type liquid desiccant equipment in both parallel and counter flow configurations based on the finite difference model. The predicted performance in the model showed good agreement with the experimental data. Two-dimensional theoretical model was developed depending on NTU to predict the parameters of air and solution

inside the adiabatic cross flow dehumidifier or regenerator and also the outlet parameters with known inlet parameters [27]. The model predicted results were proved to be in agreement with the experimental data.

Reference [28] developed an analytical model to simulate the heat and mass transfer performance of refrigerant cooled liquid desiccant absorber system. The influence of the parameters on the cooling and dehumidification performance of the system was studied using the model. Besides that, the system performance on variable load conditions was also investigated through partial load performance analysis. Reference [29] developed a mathematical model to study the heat and mass transfer processes in a cross flow liquid desiccant dehumidifier. Honeycomb paper was used as the packing material in the dehumidifier in the work presented. The heat and mass transfers in the packed-bed liquid desiccant dehumidification system was predicted by a simplified hybrid model [1]. This simple model could be used for real-time performance monitoring, control and optimization of LDDS over a wide range of operating conditions.

Besides modeling approaches in LDDS, some research work were also focused on the applications of LDDS. Reference [30] developed a Liquid Desiccant evaporative cooling air Conditioning System (LDCS) which consisted of packed-tower dehumidifier and regenerator, evaporative cooler and heater. The dehumidified air from the dehumidifier was cooled at the evaporative cooler before sending to the air conditioning space. The heat source used to heat up diluted desiccant solution from the dehumidifier could be the low-grade heat energy. Reference [31] presented an air conditioning plant based on the liquid desiccant dehumidification in a university building operating in summer and winter modes. The air conditioning plant dehumidified the process air in summer whereas it recovered heat from the exhaust air in winter. The system energy analysis showed possible energy savings both in summer and winter modes if the design was optimized.

Most of the research work done in the literature above emphasized on developing

mathematical model to increase the performance of LDDS. However, less work was focused on the ways to increase the energy efficiency of the system. The liquid desiccant regenerator which is used to regain the concentration in the desiccant solution is one of the main components in LDDS. The liquid desiccant regenerator plays a vital role in the performance of LDDS as the major energy consumption in LDDS is the heat energy supplied for the liquid desiccant regeneration process. Therefore, the research work will mainly be emphasizing on increasing the energy efficiency of LDDS by focusing on the liquid desiccant regeneration system.

In regeneration system, the high regeneration temperature causes the high energy consumption in LDDS. When higher concentration of liquid desiccant is required to be regenerated, the regeneration temperature of the desiccant solution has to be increased and this causes the energy inefficiency of the system. This will prohibit the potential use of low grade or renewable energy in the desiccant regenerator in LDDS. This problem will be the main concern in this project. Therefore, current research work done on liquid desiccant regeneration system in LDDS will be reviewed next.

2.3 Regeneration system in LDDS

The transfer of water vapor from the air stream to the desiccant solution stream in the dehumidifier leads to dilution of the liquid desiccant which decreases the ability of absorption of the liquid desiccant. Hence, the weak liquid desiccant must be transferred to the regenerator to regain its concentration for dehumidification purpose. The regeneration process of liquid desiccant plays a dominant role in affecting the performance of the LDDS. Since the diluted desiccant solution has to be heated for regeneration process, therefore the energy used for the regeneration process is very intensive. The weak desiccant solution is preheated before sending to the regenerator to create higher surface vapor pressure than the air stream flowing into the regenerator so that the water substance in the diluted desiccant solution can be removed.

Two main types of regeneration systems which are packed-type (adiabatic) and coil-type (internally-heated) regenerators were commonly discussed in the literature. The structure in packed-type regenerator is the same as the structure of packing bed dehumidifier as explained in Section 2.2. Due to the large heat and mass transfer area between air and liquid desiccant streams and its simple structure, therefore the packed-type regenerators were mostly the focus in the earlier literature. Research work has been done on investigating the performance of packed-type regeneration systems with counter-flow configuration [4, 17, 32, 33] and cross-flow configuration [5, 34]. Since the packed-type regenerator is adiabatic where no extra heat is supplied to the regenerator, therefore the desiccant solution temperature will decrease gradually. Consequently, the heat and mass transfer rates and desiccant regeneration process will also decay consequently.

On the other hand, the internally-heated regenerator according to the design of the plate-fin heat exchanger can solve the aforementioned problem. The main difference between the adiabatic-type and the coil-type is the flowing of hot water in the plates where the liquid desiccant is distributed on its surface. Hot water is used to maintain the high liquid desiccant temperature where the problem faced in the adiabatic-type regenerator can be solved. Figure 2.1 shows the structure of an internally heated regenerator. The air enters from the top of the plates and desiccant solution is distributed on the surface of the plates. The air and solution streams come into contact directly with each other and water vapor is removed from the hot diluted solution stream to the air stream due to the surface vapor pressure difference. Hot water is allowed to flow in the plates to maintain the high temperature of the liquid desiccant.

Figure 2.1: Schematic diagram of internally-heated liquid desiccant regenerator [14]

Reference [35] showed that the internally-heated regenerator could increase the regeneration rate and at the same time was able to give higher regeneration thermal efficiency compared to that of the adiabatic regenerator. Experimental study was carried out for the internally heated regenerator under various operating conditions [36]. The regeneration experimental tests showed that the internally-heated regenerator had higher regeneration efficiency than that of the adiabatic regenerator. A mathematical model validated by the experimental results was also developed to investigate the simultaneous heat and mass transfer behavior in the internally-cooled dehumidifier and internally-heated regenerator [37]. The results showed that the internally heated regenerator was able to give higher regeneration efficiency and prevent the dehumidification from happening as what happened in the adiabatic regenerator.

There was another type of desiccant solution regenerator proposed by reference [38] which was by using hot air to concentrate the diluted liquid desiccant when the requirement of the lowest inlet solution temperature could be met. The schematic of the desiccant regenerator using hot air is shown in Figure 2.2. The waste heat from the hot air such as hot air from the condensers of vapor compression cycle could be recovered to be used for this purpose. This was able to give high thermal efficiency and energy saving. Although the performance of this regenerator was not as good as the conventional regenerator using heated desiccant solution, it was able to recover the

waste heat from the hot air and save more energy. Reference [21] also investigated on effects of regeneration modes and flow patterns on the regeneration performance. It was found that the moisture removal rate was higher in the hot desiccant driven regenerator than that in the hot air driven regenerator and concluded that the hot air should be used to heat the desiccant solution before entering the regenerator.

Figure 2.2: Schematic of desiccant solution regenerator using exhausted hot air from the condenser [38]

Liquid-to-air membrane exchanger was introduced in the regeneration system in [39, 40]. The membrane energy exchangers were used as the dehumidifier and regenerator in the liquid desiccant air conditioning system. The carryover of the desiccant droplets into the air streams could be eliminated by separating the air and desiccant solution streams using the semi-permeable membranes which allowed the only transmission of water vapor but not the liquid water. However, it was found that the regeneration temperature used was around 45-60°C. The regeneration temperature was still high and this prohibited the potential application of low-grade or renewable energy as the heat source in the regeneration system.

Besides that, ultrasonic atomization technology was also utilized in the liquid desiccant regenerator in [41, 42] where the desiccant solution was atomized into tiny droplets with diameters as small as 50 μ m. The application of this technology in the

regeneration system was able to lower the regeneration temperature to around 45-64°C and reduce the energy consumption. However, the required regeneration temperature was not low enough which would limit the potential use of low-grade renewable energy in the desiccant regeneration system.

Instead of regenerating the liquid desiccant under atmospheric pressure, reference [43] introduced a new method of regenerating diluted liquid desiccant by releasing the diluted desiccant droplets into vacuum. The process was called vacuum flash evaporation. The water component at the surface of the liquid desiccant droplets was overheated at a very low-pressure condition and hence it evaporated dramatically. Vacuum pump was used to maintain the initial low pressure for the flash evaporation to occur as evaporation would cause the vacuum pressure to increase gradually. Cooling water was used to cool the moisture released. The temperature difference between the diluted liquid desiccant and cooling water was the driving force for the vacuum flash evaporation to occur. A mathematical model and an experimental chamber were developed to predict the performance of the vacuum flash evaporation using lithium chloride solution.

Furthermore, the working principle of the absorption chiller has also been referred in this work. The absorption chiller comprises of four components which are generator, condenser, evaporator and absorber. There are two fundamental principles used in the operation of the absorption system. The first principle is that water boils at lower temperature at low vacuum pressure condition. The second principle is that evaporation results in cooling. Heat is applied to separate the refrigerant out from the diluted desiccant solution in the generator. The refrigerant vapor is then condensed in the condenser. This process is similar to the desiccant solution regeneration process, therefore the operating principles of these two components and the aforementioned first principle are utilized in designing the newly proposed regeneration system.

The working range of the single-effect absorption chiller was reported in references

[44, 45]. The operating temperature for the heat source was 80-120°C whereas the operating temperature for the cooling source was around 5-10°C when using LiBr/water as the working fluid. On the other hand, when water/ammonia was used as the solution, the operating temperature for the heat source was 120-150°C and below 0°C for the cooling source. The operating temperature of the heating source was too high as the desired operating temperature range of the heat source proposed system should be less than 60-80°C so that it would be beneficial in term of regeneration temperature compared to the conventional desiccant regeneration system. Therefore, operating ranges of the relevant parameters of the proposed system have to be fitted to those of a desiccant regeneration system. Cooling capacity is the main concern of the absorption chiller, however the regeneration performance in the generator should be the main focus for the proposed system when the principle of the absorption chiller is implemented in the proposed regeneration system. Thus, the regeneration performance of the proposed system can be referred to other types of desiccant regeneration systems from the literature which will be discussed in the next section.

The concept of applying vacuum condition to regenerate the diluted liquid desiccant is exploited in designing the newly proposed Absorption-based Liquid Desiccant Regeneration (ALDR) system in this work where it will be further explained in Chapter 3. Besides that, the operating principle of the generator and condenser in the absorption chiller is also exploited in designing the proposed regeneration system. The method of evaluating the regeneration performance of the newly proposed desiccant regeneration is important here. Therefore, different approaches used in previous literature regarding the regeneration performance indices will be reviewed and discussed in the following section.

2.4 Performance investigation of regeneration systems

Since the desiccant regeneration system is focused in the research work, suitable

and reliable regeneration performance indices should be determined and evaluated. The regeneration performance of different types of regeneration systems has been researched in several literature. Moisture removal rate [5, 34, 46, 47] and concentration increase of desiccant solution [41, 48] were the most common performance indices used to determine the performance of the regeneration system. Furthermore, the desiccant solution regeneration process involved the removal of water component in the desiccant solution, therefore volume change of solution in the regenerator tank was also one of the indices used in reference [48]. The regeneration effectiveness was also commonly used to evaluate the effectiveness of the regeneration process [16, 49].

Stepwise regression was used to investigate the performance of regeneration system under various desiccant and air inlet conditions in reference [5]. The regeneration performance could be predicted by using the regression of the regenerator effectiveness. The predicted values showed good agreement with the experimental results. However, this method might not work for the performance prediction in other work as the empirical formulations obtained from the stepwise regression using the experimental data were lacking of physical principles in the foundation [34]. A simplified prediction model which was based on the experimental data from their own work and others from open literature was developed to predict the packed-bed regenerator performance [34]. The model developed could be used for performance prediction at a wider operating range.

Besides that, reference [41] introduced an Ideal Regeneration Model (IRM) to predict the performance of the developed ultrasonic atomization desiccant regenerator. This model was developed according to the energy and mass balance equations. The system regeneration performance could be predicted by combining the developed model and the concept of system perfectness. The predicted values agreed well the experimental data with the average deviations of less than 7.9%. The abovementioned references showed reliable approaches to predict the regeneration system performance; hence these methods will be adopted to develop a performance prediction model for the newly proposed ALDR system.

The abovementioned performance investigation does not consider the dynamic factor in the desiccant regeneration system. The description of dynamic behavior in each component is important to understand the changes of relevant parameters with respect to time. Therefore, the research work will also be focusing on developing a dynamic model for the desiccant regeneration system to describe the transient behavior of each component in the proposed system. Since the ALDR system is newly proposed, hence the dynamic modeling approach used in the relevant systems will be reviewed next for references in this research work.

2.5 Dynamic modeling approaches

Dynamic simulation is very vital to describe the real performance of an energy conversion system. Hence, a dynamic model to describe the transient characteristics of the newly proposed liquid desiccant regenerator is useful for the control and optimization of the regeneration system. The approaches of modeling in other relevant fields from some available literature were reviewed here as the ALDR system is just newly invented.

Accurate prediction of transient states of cycle condition such as the startup characteristics and behavior under on-off operation is required to develop a control strategy for a dynamic system. Therefore, dynamic modeling of the system is vital to gain better understanding of dynamic characteristics of system. Reference [50] developed a new dynamic simulation program based on object-oriented formulation and parallel processing architecture. The governing differential equations were solved using the Runge-Kutta-Gill method. The energy balance, total mass and solution mass balance in every component were considered to derive the governing equations. The simulation program was useful to describe the transient behavior of various type of absorption chiller. The dynamic model developed in reference [51] was based on the energy and mass balances at internal components of the LiBr/water absorption chiller. The dynamic

behavior due to the thermal and mass storage in components was considered when developing the dynamic model. The model developed was reliable to identify the long-term behavior of single-effect absorption chiller and to follow the daily operational profile. It could be applied to the commercial solar-assisted absorption chiller using LiBr/water as the working fluid.

Reference [52] presented a model to simulate dynamics of a double-effect LiBr-H₂O absorption chiller using first order nonlinear differential equations based on heat and mass transfer. A numerical method was used to solve the nonlinear equations which were coupled with the subroutines to calculate the thermodynamic properties of the working fluids. The chiller dynamics was found to be governed by the inlet temperatures of the cooling water and chilled water when the heat input was relatively constant. The feature of short computation time enables the dynamic model to serve as a virtual real-time chiller. Reference [53] presented the use of neural network for the dynamic modeling to simulate the system performance and control of the system. The main advantage of this new modeling method was that no prior knowledge of the process phenomena was needed due to the learning capability. Besides, it was a fast tool which is suitable to be applied for the real time control system. The approach was not suitable for a large system but it gave faster diagnosis than other approaches for small system. The prediction of the neural network beyond the range of learned data was also poor.

The air conditioning system can be simplified to be represented by two heat exchangers which are evaporator and condenser, compressor and expansion valve. The dynamics of the air conditioning system were mostly dominated by the two heat exchangers whereas the compressor and expansion valve were modelled with nonlinear algebraic relationship. The modeling of the two-phase flow dynamics which was similar to the ALDR system required accurate description of characteristics in phase change process in the two heat exchangers. The most common approach in control-oriented modeling of heat exchangers in refrigeration cycles was based on the moving boundary method as in references [54-57]. A detail description of phase transition in the heat

exchangers where pressure and enthalpy dynamics were characterized based on the moving boundary approach was used to model the air conditioning system.

The dynamic model presented in [58, 59] was based on the internal and external energy balances and mass balances. This model also took the delay time in solution cycle into account. This approach is simpler as detailed enthalpy calculated at each state point can be avoided. The simulation results agreed well with the experimental data with dynamic deviations of 10s. The dynamic model developed was able to be used for designing a new system. It was also able to identify the transfer functions and control parameters for the system [59]. The mathematical model developed in [60] was based on the conservation of energy, mass and species. The model was able to predict the behavior of temperature, concentration and pressure when a new thermal load or to an increase in inlet temperature was submitted to the system. The model was useful in designing a new system as it was able to describe the behavior of different systems and also can do so whenever the data of system were available. The results showed that the dynamic model based on the energy and mass balances could be used to predict the dynamic change of relevant parameters in the system similar to the liquid desiccant regeneration process. Therefore, this modeling method will be applied in the study. The modeling approaches used in some relevant fields as discussed in Section 2.5 will be referred when developing the dynamic model for the newly proposed liquid desiccant regeneration system.

2.6 Summary

In a nutshell, the existing desiccant regeneration systems have high regeneration temperature which prohibits the potential use of low-grade or renewable energy as the heat source for the regeneration system in LDDS. Therefore, a novel liquid desiccant regeneration system was proposed here with the aim of increasing the energy efficiency of the system and allowing the use of renewable energy for desiccant regeneration

process.

The system design of the proposed regeneration system will be discussed in the next chapter. The concept of applying vacuum condition in the liquid desiccant regeneration system as explained in Section 2.3 will be applied in designing the new liquid desiccant regeneration system. In order to validate the feasibility of application of vacuum condition in the liquid desiccant regeneration system in reducing the regeneration temperature, the proposed regeneration system is built in the laboratory. Experimental tests will be carried out to investigate the regeneration performance of the proposed system. The operating principles of the newly proposed absorption-based liquid desiccant regenerator will also be explained in detail in Chapter 3. The next chapter will also list out the claims of the novelty of the proposed ALDR system.

Chapter 3 System Design of ALDR Systems

3.1 Introduction

The regenerator in a conventional adiabatic LDDS consists of packing beds to increase the contact area for heat and mass transfer process to occur. The mass transfer here refers to the removal of water vapor from the diluted desiccant solution to the air stream when the solution and air stream are in direct contact with each other. The problem for this conventional method of dehumidifying the process air is that high surface vapor pressure difference is required for the mass transfer process to occur. If low humidity of air is required to supply into the building or occupants' space, the concentration of the solution has to be high which requires high regeneration temperature in the regenerator. As a result, this limits the use of low grade energy or renewable energy as the heat source for the regenerator system. This shows that the regenerator of the conventional LDDS is not energy-efficient.

There are numerous ways to recover the concentration of the desiccant solution so that it can be reused in the dehumidifier. From the literature in Section 2.3, the regeneration process can be done in a solar still, packed-bed regenerator driven by solar heated air, heat driven by renewable energy, waste heat or natural gas and etc. However, these suggested liquid desiccant regenerators were only focused on the regeneration performance but not the main concern problem which is the high regeneration temperature of desiccant solution. The proposed regeneration method using ultrasonic atomization and hot air as the heat source is able to reduce the regeneration temperature, but the regeneration temperature is still not low enough and may restrict the potential use of the low-grade and renewable energy as the heat source in the regeneration system. The performance of the regeneration method using hot air is also not as good as the conventional one.

Therefore, a novel Absorption-based Liquid Desiccant Regeneration (ALDR) system operating under vacuum condition is proposed in this work. There are two main components which are generator and condenser in the ALDR system. The diluted desiccant solution is re-concentrated in the generator and water vapor released from the diluted desiccant solution is formed into water in the condenser. As per discussion in Section 2.3, flash evaporation of lithium chloride droplets in vacuum was a new method developed in reference [43] to regenerate dehumidification solution. The surrounding pressure is the main factor for the evaporation rate. Hence, the application of vacuum pressure for the evaporation process is able to increase the strength of the flash evaporation of solution droplets and reduce the droplet temperature at the start of the flash. In addition, the flash evaporation process also becomes faster. This concept is used in the proposed ALDR system in order to reduce the regeneration temperature of the desiccant solution in the regenerator of LDDS systems. The working principle of the proposed ALDR system will be discussed next.

3.2 Working principle of ALDR systems

3.2.1 The ALDR system in LDDS

Figure 3.1 shows the schematic of the inner design of the proposed ALDR system integrated with the dehumidifier. The right-hand side is the packed-bed type dehumidifier where the supply air is dehumidified, and the concentrated desiccant solution is diluted. The diluted solution as shown in dark blue lines coming out from the transfer pump 1 will flow to the weak solution tank as labeled in the diagram and is stored inside for the regeneration process later. The system at the left-hand side is the proposed ALDR system where the detail working principle inside the regenerator will be described next. The concentrated desiccant solution coming out from regenerator as indicated in yellow lines will be pumped out by transfer pump 2 through valve 3 and stored in strong solution tank for the dehumidification process.

Figure 3.1: Schematic of the Absorption-based Liquid Desiccant Regeneration (ALDR) system prototype in LDDS. Dark blue lines indicate diluted desiccant solution; yellow lines indicate concentrated desiccant solution.

For the proposed ALDR system, the mass transfer denotes the boiling process of the liquid desiccant. The water composition inside the diluted desiccant solution is removed by boiling it into the water vapor form to generate concentrated desiccant solution to use in the dehumidifier. This boiling process is a faster mass transfer process than that in the conventional LDDS. In addition, the vacuum condition is also applied in the ALDR system and hence no air stream is needed in the regeneration process. The details on how the desiccant solution is regenerated in the ALDR system are described in the next subsection.

3.2.2 Inner design of the ALDR system

The schematic of inner design of the ALDR system is shown in Figure 3.2. As related in the previous subsection, the system in Figure 3.2 is the system drawn on the left of Figure 3.1. The yellow lines in the figure indicate the concentrated desiccant solution and the green lines shows the condensed water. There are two main components which are the generator and condenser in the ALDR system where they are indicated as

red and light blue lines respectively in the figure. The container at the right of the figure is the concentrated solution storage tank. The vacuum pump is used to provide the vacuum condition in the enclosed regenerator tank with the pressure gauge measuring the system vacuum pressure.

Figure 3.2: Inner design of the proposed ALDR system

The working principle in the ALDR system is described as below:

- The ALDR system consists of a liquid desiccant cycle (yellow lines), a heating source (red lines) and a cooling source (light blue lines).
- The liquid desiccant cycle consists of two main components which are generator and condenser operating under vacuum condition.
- The heating source at the generator side provides heat to boil the diluted desiccant solution sprayed into the enclosed regenerator tank as indicated in yellow line. When the diluted desiccant solution is heated up at the generator, the water component in the desiccant solution is boiled at lower temperature at low pressure vacuum condition and hence the diluted desiccant solution is getting concentrated.
- The vacuum condition provides an advantage to this proposed ALDR system as the low-pressure condition in the regenerator tank will lower the boiling

temperature of the desiccant solution and hence the water composition in the desiccant solution can be removed through boiling process at a lower regeneration temperature. As shown in Figure 3.2, a vacuum pump is installed to realize the vacuum condition in the whole ALDR system. Besides, a pressure gauge is also placed in the tank to ensure the required low-pressure vacuum condition is maintained inside the tank.

- The desiccant solution is pumped out from the solution tank and inserted again from the top of the tank for the regeneration process to complete the desiccant solution cycle. The process is repeated until the required concentration of desiccant solution is reached and this is so called the batch operation. The concentrated desiccant solution generated as indicated in yellow line is then pumped by the transfer pump 2 to the storage tank before sending to the dehumidifier for dehumidification process.
- The pressure inside both of the generator and condenser are the same at the initial stage. When the diluted desiccant solution is boiled off by the input heat energy, the water components in the diluted desiccant solution turn into water vapor. Consequently, the pressure in the generator becomes slightly higher than that in the condenser. A pressure difference is then created between these two components. This pressure difference will then act as a driving force for the water vapor to flow into the condenser from the generator.
- Water vapor generated during the boiling process then flows to the condenser due to the pressure difference between both the generator and condenser. The water vapor releases the latent heat of condensation and water is formed in the condenser. The condensed water accumulated which is indicated as green lines in Figure 3.2 is then pumped out from the bottom of water tank in the condenser.
- A heating source supplies the heat energy to the generator to heat up the desiccant solution to produce the vapor in order to concentrate the desiccant solution. The heating source can be the low-grade energy, solar energy, the condenser in the heat pump cycle, waste heat from industry and etc.
- A cooling source absorbs the latent heat of condensation released from the vapor

formed in the generator. The cooling source can be the cooling water from cooling tower, evaporator in the heat pump cycle, chilled water from chiller, cooling sea water, chiller plant condensed water and etc.

The vacuum space is one of the main concern points in designing this ALDR system. Boiling temperature of a liquid is closely related to the surrounding pressure. This is because in order to boil a liquid, the liquid must have to absorb sufficient heat energy so that the vapor pressure can overcome the surrounding pressure. The liquid can then be converted into the vapor and boiling process can occur. At lower surrounding pressure, less heat energy is required to overcome the surrounding pressure for the water vapor to escape from the liquid surface. Therefore, the boiling temperature of the liquid is reduced, and the heat energy needed in the boiling process can be reduced. This phenomenon is used in designing this proposed ALDR system where less heating energy is needed to regenerate the diluted desiccant solution when the regenerator is operating under designed vacuum condition.

In addition, there is a concern for the conventional packed-type liquid desiccant regenerator where higher regeneration temperature is always needed to create higher surface vapor pressure difference between the air and desiccant solution streams when the liquid desiccant regenerator is required to regenerate desiccant solution with higher concentration. Higher surface vapor pressure difference between air and solution streams will create higher driving force for the water vapor to move from solution into the process air. This will prohibit the potential use of low grade-energy or renewable energy source in the desiccant regeneration system. In this proposed ALDR system, regeneration temperature is not necessarily to be increased to regenerate desiccant solution with higher concentration. The pressure in the vacuum regeneration tank can be lowered by using the vacuum pump. When the pressure is lowered, more water vapor can be escaped from the water surface at the same regeneration temperature. Hence, this proposed ALDR system is expected to be more energy efficient than the conventional packed-type liquid desiccant regenerator.

The main parts of the ALDR system can be clearly described by the block diagram in Figure 3.3 which shows the flow of liquid desiccant, water vapor and condensed water. As mentioned earlier, the system comprises of two main components which are the generator and condenser. The developed experimental platform of the ALDR system with the hot water and cooling water as the heating and cooling source at respective generator and condenser side is just the first prototype developed, other types of heating and cooling sources may be applied for the ALDR system. These two components will be focused on when developing the dynamic model of the ALDR system in Chapter 5 later.

Figure 3.3: Block diagram of the ALDR system

3.3 Experimental platform of the ALDR system

The proposed ALDR system is built and set up for the experimental purpose according to the schematic diagram shown in Figure 3.2. The heating source at generator side and cooling source at the condenser side exploited in this experimental platform is the hot water from heater and cooling water from chiller system respectively. The desiccant solution used inside the regeneration system is LiBr solution. Figure 3.4 and Figure 3.5 show the photos of the ALDR system from front and back view respectively. Several tests will be carried out to ensure the feasibility of the experimental platform built. The testing procedures and results will be discussed in Chapter 6.

Figure 3.4: Front view of the proposed ALDR system. 1-Solution flow meter; 2-Control panel; 3-Solution pump; 4-Heating source inlet; 5-Cooling source outlet

Figure 3.5: Back view of the proposed ALDR system. 6-Vacuum pump; 7-Condensed water pump; 8-Heating source outlet; 9-Cooling source inlet

As related to the schematic diagram in Figure 3.2, both the main components which are generator and condenser are labelled in Figures 3.4 and 3.5. The solution pump indicated in Figure 3.4 is the transfer pump 2 in the schematic diagram. Besides that, the exhaust pump is represented by the condensed pump in Figure 3.5. The vacuum condition is realized by the installed vacuum pump with the displacement speed of 2L/s. The regeneration process is operated by using the control panel which is marked as 2 in Figure 3.4. The arrows in red (4 and 8) show the inlet and outlet of heating source

supplied to the generator. On the other hand, 9 and 5 represents the flowing of cooling source in and out of the condenser.

The measuring devices used in the system are flowmeters, thermocouples, specific hydrometer and pressure gauge. An electromagnetic flowmeter is placed along the desiccant flow path to measure its flow rate. Besides, electromagnetic flowmeters are also placed along the hot water and cooling water circuit. The temperature sensors are placed over the desiccant solution, condensed water, hot water and cooling water circuits to measure the temperatures throughout the operation. The temperature sensors are placed at the inlet and outlet of each flow circuit to observe the change of temperature. In order to measure to the system vacuum pressure, a pressure gauge is placed in the enclosed regenerator tank. Furthermore, the density of the desiccant solution is measured at the beginning and end of the regeneration process by using the specific gravity hydrometer. By using the density measured, the mass fraction of the solution before and after the regeneration process can be calculated. The parameters and the measurement devices with their corresponding accuracies are shown in Table 3.1.

Table 3.1: Specifications of different measuring devices

Parameter	Device	Accuracy	Operational range
Desiccant solution flow rate	Electromagnetic flowmeter	$\pm 1\%$	0.2-1.2m ³ /h
Hot water flow rate	Electromagnetic flowmeter	$\pm 1\%$	0-2.0m ³ /h
Cooling water flow rate	Electromagnetic flowmeter	$\pm 1\%$	0-2.5m ³ /h
Desiccant solution temperature	PT100	0.1°C	20-40°C
Hot water temperature	PT1000	0.1°C	20-50°C
Cooling water temperature	PT1000	0.1°C	7-20°C
Desiccant solution concentration	Specific gravity hydrometer	1 kg/m ³	1300-1600kg/m ³
Vacuum pressure	Vacuum pressure gauge	1Pa	0-3000Pa

The heating source in the ALDR system can be any low grade or renewable energy source such as condenser in the heat pump cycle, solar energy, waste heat from industry and etc. On the other hand, besides the cooling water from the chiller system, the potential cooling source at the condenser side can also be the cooling sea water, chilled water, or evaporator in heat pump cycle. In this developed experimental platform, the heating and cooling sources used are hot water from heater and cooling water from the chiller. In the first prototype of experimental platform ALDR system, the aforementioned heating and cooling sources are exploited for the ease of controlling the water temperature and flow rate to investigate the system performance under various operating conditions at the initial stage of the research. The solution, hot water and cooling water flow rates can be controlled by adopting the Variable-Frequency Drive (VFD) in the water pump.

In addition, level gauges are placed at both the generator and condenser tank to observe the solution and condensed water level respectively. The installation of level gauge is vital to ensure the amount of desiccant solution in the tank is not too much or too less during the operation as it will cause harm to the system. For the condensed water at condenser, the condensed water will be removed after reaching a preset level. A three-way valve which is indicated as valve 3 in Figure 3.2 is installed along the desiccant solution cycle outside the regenerator tank to control the flow of solution either back to the regenerator tank or to the solution tank. The solution will be transferred to the strong solution tank when the required solution concentration is achieved, otherwise the solution will be continuously cycled back into the regenerator tank to regain the solution concentration. Wheels are set at the bottom of the regenerator to ease the movement of the regenerator. The heater, chiller and water circuits are insulated to prevent the heat lost to the environment.

After the experimental platform of the ALDR system is set up, several tests were carried out to test for its feasibility. The detailed experimental results of the proposed system for operating 3 hours of regeneration process are shown in Table A.1 in Appendix. Next, the novelty of the proposed ALDR system will be summarized to highlight the contribution of the work.

3.4 Novelty of the proposed ALDR system

The proposed ALDR system operating under vacuum condition is a novel desiccant regeneration system with the aim to reduce the regeneration temperature of desiccant solution in the system. A Singapore patent application of this proposed ALDR system has been filed which can be seen in the Author's Publication. Followings are the points of novelty claimed:

1. The ALDR system operates under vacuum condition which can reduce the

boiling temperature of the diluted desiccant solution. Therefore, low grade or renewable energy source be used in the ALDR system for higher solution concentration and hence leads to an energy-efficient desiccant regeneration system.

2. Low grade or renewable energy can also be used for energy savings by shifting away from the electrical energy. This scheme can use any heating or cooling source. For instance, condenser in the heat pump, solar energy, waste heat from industry or any other low grade renewable energy can be the heating source at the generator side. Chilled water from a chiller, cooling sea water, cooling water from cooling tower, chiller plant condensed water or evaporator in the heat pump cycle can be the cooling source for the condenser in the proposed ALDR system.
3. No air stream is needed in this proposed ALDR system as the boiling of desiccant solution is taken place in the proposed regeneration process and hence it is a faster process than that of the regenerator in conventional LDDS. Besides, no fan is required here.
4. Batch operation is the continuous effect operation of the liquid desiccant where the solution is circulated continuously in the desiccant solution loop until the required solution concentration is reached. This operation avoids unnecessary cooling and heating of the desiccant solution as in the conventional regenerator in LDDS. Therefore, the energy consumption in this proposed ALDR system is expected to be lower than that in the regenerator in conventional LDDS.
5. To regenerate higher concentration of the desiccant solution, more heating energy is required for regenerator in conventional LDDS. For this proposed ALDR system, the boiling point of the desiccant solution can be maintained by just providing lower pressure vacuum condition in the regeneration tank using the vacuum pump without increasing the heating energy. Hence, this is another point for the system to be more energy efficient than the regenerator in the conventional LDDS.
6. This scheme covers all liquid desiccants only.

In short, the difference between the conventional packed-bed liquid desiccant regenerator and the newly proposed ALDR system is summarized in Table 3.2.

Table 3.2: Difference between conventional packed-bed liquid desiccant regenerator and the proposed ALDR system

Description	Packed-bed liquid desiccant regenerator	ALDR system
Medium	Air and liquid desiccant	Liquid desiccant only
Pressure in regenerator tank	Atmospheric pressure	Vacuum pressure
Mass transfer process	Surface vapor pressure difference between the air and desiccant solution streams provides the driving force	Boiling process of desiccant solution
Way to regenerate higher concentration of desiccant solution	Increase the regeneration temperature of the desiccant solution	Reduce the vacuum pressure in the regenerator tank to reduce the boiling temperature of the desiccant solution
Fan	Fan is required	No fan is required
Regeneration rate	Lower	Higher
Energy consumption	Higher	Lower

3.5 Summary

The proposed ALDR system has been designed based on the concept of applying vacuum condition in regenerating desiccant solution. The novelty of the proposed system has been identified to highlight the advantages of the system over the

conventional packed-bed regenerator. The experimental platform of the ALDR system has been built up in the laboratory. Experiments will first be conducted to get familiar with the system operation and test the feasibility of the system.

A performance prediction model is important for accurate and reliable prediction of regeneration performance of the proposed system without having to carry out the experiment. The prediction model will be developed using the experimental results obtained together with the concept of perfectness. The performance prediction model developed will then be validated with the experimental results and used to predict the regeneration performance under varied operating conditions. These will be discussed in the next chapter.

Chapter 4 Performance Prediction Model of ALDR Systems

4.1 Introduction

From the previous chapter, the proposed ALDR system has been designed and the system experimental platform has been constructed. Experimental tests will be carried out to test for the system feasibility. Since the way of regenerating desiccant solution under vacuum condition is still a new topic to explore, an accurate and reliable regeneration performance prediction approach of the newly developed system is important here. The performance indices namely the moisture removal rate and desiccant solution mass fraction increase used for other desiccant regeneration systems in several literature [5, 34, 41, 46, 48] are referred herein.

Besides that, a performance prediction model is also developed so that the system regeneration performance can be predicted without the need of carrying out experiment. The validation of the prediction model will also be included in this chapter. Next, the prediction of regeneration performance under different operating conditions will be covered as well.

4.2 Performance indices

Two indices namely the Moisture Removal Rate (MRR) and desiccant solution Mass Fraction Increase (MFI) are employed here to evaluate the regeneration performance of the ALDR system.

4.2.1 Moisture Removal Rate (MRR)

Since the proposed system does not contain air stream and hence this index cannot be determined directly by the method shown in the previous literature [5, 34, 41]. Therefore, MRR in the newly proposed regeneration system is modified from the references and introduced as

$$MRR = \dot{m}_{sol,in} - \dot{m}_{sol,out} \quad (4-1)$$

where $\dot{m}_{sol,in}$ and $\dot{m}_{sol,out}$ are the inlet and outlet solution mass flow rate respectively.

4.2.2 Mass Fraction Increase (MFI)

The main aim of the desiccant regeneration system is to regenerate the concentration of the diluted desiccant solution. Therefore, it is important to know the difference of solution mass fraction before and after the regeneration process. The MFI has been used in several literature [41, 48] as the regeneration performance index and it can be expressed as

$$MFI = n_{out} - n_{in} \quad (4-2)$$

where n_{in} and n_{out} are the desiccant solution mass fraction before and after the regeneration process respectively.

There is no density meter installed inside the regenerator tank, therefore n_{out} is not able to be measured during the regeneration process. Therefore, the solution mass balance equation modified from [41] can be used to calculate n_{out} to obtain MFI in Equation (4-2).

$$\dot{m}_{sol,in} n_{in} = \dot{m}_{sol,out} n_{out} \quad (4-3)$$

As shown in Equations (4-1) and (4-2), a higher MRR value indicates that more water component is transferred from the desiccant solution and the regeneration efficiency is higher. On the other hand, a higher MFI value means that more concentrated

solution is regenerated and hence the regeneration performance is better. Both the regeneration performance indices introduced here will be used to evaluate the regeneration performance using the experimental and simulation results in Sections 4.3 and 4.4 respectively.

4.3 Regeneration performance prediction model

4.3.1 Development of prediction model

A prediction model is developed here for accurate regeneration performance prediction of the ALDR system. The developed model is based on the mass and energy balance equations. This method has been introduced in some desiccant dehumidifiers and regeneration system in several literature [19, 41, 61]. It has been validated that this model is of good reliability and has good agreement with the performance of various dehumidification and desiccant regeneration systems. Therefore, these mass and energy balance equations based on the new system are modified to predict the performance of the proposed ALDR system.

The performance prediction model is developed as the following. The mass and energy balance equations in the ALDR system can be modified from [41] and described as below:

$$\dot{m}_{sol,in} = \dot{m}_{sol,out} + \dot{m}_{evap} \quad (4-4)$$

$$\dot{Q}_{hw} = \dot{m}_{sol,out} h_{sol,out} + \dot{m}_{evap} h_{evap} - \dot{m}_{sol,in} h_{sol,in} \quad (4-5)$$

$$\dot{Q}_{cw} = \dot{m}_{evap} h_{evap} - \dot{m}_{cond} h_{cond} \quad (4-6)$$

where $\dot{m}_{evap}$ is the vapor generation rate, $\dot{Q}_{hw}$ is the heating power supplied to the generator, $\dot{Q}_{cw}$ is the cooling power at the condenser, $h_{sol,in}$ and $h_{sol,out}$ are the inlet and outlet of solution enthalpy respectively, h_{evap} is the enthalpy of the vapor generated, $\dot{m}_{cond}$ is the condensation rate of the vapor and h_{cond} is the latent heat of condensation.

Fully sufficient heat and mass transfer process throughout the regeneration process can be achieved when the assumed ideal conditions are fulfilled as the following: (1) the pressure in generator and condenser are the same throughout the whole regeneration process; (2) the evaporation rate at generator side and condensation rate at condenser side are the same assuming all the vapor evaporated are condensed into water, and (3) the vapor generated is saturated. The generator and condenser are designed to be side by side as shown in Figure 3.2 so that the vapor generated can flow to condenser and condense into water. Thus, the pressure in the generator and condenser can be assumed as the same throughout the regeneration process. The fully mass transfer processes which involve the evaporation and condensation processes can be achieved when all the vapor generated at the generator condenses into water in the condenser. Therefore, the evaporation rate is assumed to be same with the condensation rate at the condenser side. Hence, the pressure is assumed to maintain constant throughout the regeneration process. Besides that, the vapor generated is assumed to be saturated where there is no overheating occurred to simplify the calculation of the performance prediction model.

The ideal outlet parameters such as the outlet temperature, mass fraction and mass flow rate of the desiccant solution can be obtained by solving the mass and energy balance equations from Equations (4-3) to (4-6) with the aforementioned ideal regeneration conditions. The ideal system regeneration performance can then be obtained by using the ideal outlet parameters as the following equations [41]

$$MRR_{ideal} = \dot{m}_{sol,in} - \dot{m}_{sol,out,ideal} \quad (4-7)$$

$$MFI_{ideal} = n_{out,ideal} - n_{in} \quad (4-8)$$

where the subscript *ideal* represents ideal condition.

Since the developed experimental system cannot achieve the ideal conditions as discussed previously, the practical system's performance might be lower than the ideal one obtained from the prediction model. Therefore, the concept of perfectness, K proposed in references [41, 61] is adopted here to obtain the perfectness of the proposed

desiccant regeneration system. This concept has been validated for different LDDS and desiccant regeneration systems, and it was proved that the prediction was within maximum deviation of 20%. The parameter K is defined as the ratio of the experimental system performance to the ideal system performance obtained from the prediction model [41].

$$K_1 = \frac{MRR_{prac}}{MRR_{ideal}} \quad (4-9)$$

$$K_2 = \frac{MFI_{prac}}{MFI_{ideal}} \quad (4-10)$$

where subscript *prac* means practical.

The real performance of the ALDR system can then be predicted by combining the ideal performance calculated from the model and the perfectness K. Therefore, the predicted MRR and MFI can be obtained by [41]

$$MRR_{pred} = K_1 \times MRR_{ideal} \quad (4-11)$$

$$MFI_{pred} = K_2 \times MFI_{ideal} \quad (4-12)$$

where the subscript *pred* represents predicted condition.

As shown in Equations (4-9) and (4-10), the parameter K is defined as the ratio of actual system performance to the ideal system performance for the same operating conditions. From the definition, the parameter can be used to express how close the practical performance to the desirable one during the ideal regeneration process. The ideal performance indicates the maximum performance output of the regeneration system. A greater value of parameter K represents that the actual performance indices which are MRR and MFI are closer to their maximum potential. This may also be employed to improve the performance of the system where the parameter K can show how much the room of improvement is left.

In addition, the parameter K can be used as an indicator for evaluating the mass

transfer capability of the proposed regeneration system. The desiccant regeneration process is a heat and mass transfers process. During the desiccant regeneration process, the moisture inside the weak desiccant solution is evaporated when the solution is boiled under vacuum pressure condition. Thus, greater value of the parameter K will lead to better ability of the system to achieve full heat and mass transfers during the regeneration process. The ideal regeneration process is dynamic and depends on the variance of operating parameters of the system. With the consideration of the overall regeneration effectiveness and regeneration perfectness based on the assessment of the mass transfer capability corresponding to the system operating parameters, better understanding of the regeneration system can be obtained.

When the predicted values are compared with the experimental values, the relative error as shown in Equation (4-13) will be used as the error index to evaluate the accuracy of the model.

$$RE = \frac{|Y_{\text{exp}} - Y_{\text{pred}}|}{Y_{\text{exp}}} \times 100\% \quad (4-13)$$

where Y can be represented by MRR and MFI.

The range of the operating conditions used in the prediction model is shown in Table 4.1. The proposed system's height, length and width are 1.04m, 1.2m and 0.636m respectively. The initial solution temperature is set at 20°C with the mass fraction of 36% for all the tests. The solution flow rate is set to be around 2.2m³/h and the initial vacuum pressure is set at 1000Pa. Since the solution temperature, solution mass fraction and the vacuum pressure are related to each other, therefore, these three parameters are set as constant so that the regeneration performance can be investigated by just changing one parameter at one time. The other operating conditions such as inlet temperatures of hot water and cooling water and flow rates of hot water and cooling water are varied as in Table 4.1.

Table 4.1: Range of operating conditions of the ALDR system

Parameter	Initial value	Range
$\dot{V}_{hw}$ (m ³ /h)	1.530	1.130-1.630
$\dot{V}_{cw}$ (m ³ /h)	1.990	1.130-1.990
$T_{hw,in}$ (°C)	38.0	36.0 - 40.0
$T_{cw,in}$ (°C)	8.0	7.0 - 10.0

Figure 4.1 shows the flow chart of prediction process using the prediction model and the concept of perfectness which involves Equations (4-1) to (4-12). The flow chart summarizes the prediction process explained before. The prediction model will be first validated with the experimental results and then simulated for different operating conditions which will be explained in Section 4.4.

Figure 4.1: Flow chart of predicting the regeneration performance with performance prediction model [41]

4.3.2 Validation of the prediction model

The predicted MRR and MFI are compared with the experimental results for validation purpose as shown in Figure 4.2 and Figure 4.3 respectively. From Figure 4.2,

it could be noticed that 94.12% of the points was within $\pm 10\%$ deviation and the average deviation was around 3.37%. It could also be noticed from Figure 4.3 that 94.12% of the points was within $\pm 10\%$ deviation for MFI and the average deviation was about 2.66%. In addition, most of the points lied within $\pm 5\%$ error and all the experimental and predicted performance indices were within $\pm 15\%$ error. Therefore, it could be said that the predicted regeneration performance agreed well with the experimental results and the proposed model with the perfectness concept can be employed to predict the performance of the ALDR system.

Figure 4.2: Comparison between experimental MRR and predicted MRR from prediction model. Solid line: 10% error; dashed line: 5% error

Figure 4.3: Comparison between experimental MFI and predicted MFI from prediction model. Solid line: 10% error; dashed line: 5% error

4.4 Performance prediction under various operating conditions

The regeneration performance of the ALDR system is then investigated using the performance prediction model developed in previous section under different operating conditions. The predicted performance is then compared and validated using the experimental results obtained.

In the proposed ALDR system, the regeneration performance can be affected by heating and cooling sources applied to the system. Therefore, the hot water and cooling water temperatures and flow rates are varied to investigate the corresponding regeneration performance as shown in Table 4.1. The solution temperature, concentration and vacuum pressure are closely related to each other. Therefore, these parameters are not varied for the performance investigation. Only one parameter is varied at one time while the other parameters remain unchanged. The regeneration performance is analyzed in terms of MRR and MFI as discussed in previous section.

4.4.1 Hot water temperature

The effect of hot water temperature on the regeneration performance of the ALDR system is shown in Figure 4.4. From Figure 4.4 (a), it could be observed that the trend of the experimental MRR was consistent with that of the predicted MRR values with average deviation of 4.26%. The experimental MRR showed the increment from 1.66g/s to 2.07g/s when the heating source temperature increased from 36°C to 40°C which showed significant increase of regeneration performance with the change of parameter. This could be explained by that the higher the hot water temperature, the higher is the amount energy provided from the heating source to the desiccant solution during the boiling process. Therefore, more water component inside the desiccant solution could be removed from the solution and hence the moisture removal rate was increased. Consequently, the desiccant solution could be regenerated with higher concentration. As

a result, the MFI value was increased from 0.073% to 0.091% when the hot water temperature was increased from 36°C to 40°C. From Figure 4.4 (b), the predicted MFI value agreed well with the experimental value with the average deviation of 2.59%. The red dotted line shown in the figure shows the best fit line for the experimental values and each experimental value is marked with the error bar.

(a)

(b)

Figure 4.4: Effect of hot water temperature on (a) MRR and (b) MFI of the ALDR system.

4.4.2 Hot water flow rate

Figure 4.5 shows the effect of the hot water flow rate on the regeneration performance of the ALDR system. It could be observed that both the regeneration performance indices increased with the hot water flow rate. Both of the model predicted trends were consistent with those of the experimental results with an average deviation of 1.73% and 0.69% for MRR and MFI respectively. The experimental MRR increased from 1.82g/s to 2.04g/s when the flow rate of hot water was increased from 1.13 m³/h to 1.63m³/h. This could be related to the amount of heat energy provided to the desiccant solution at the generator side. The higher the flow rate of the hot water, the higher is the amount of heat energy provided to the solution. Hence, more water vapor could gain enough of energy to escape from the solution surface and consequently the rate of moisture removal was increased too. The solution became more concentrated and the desiccant mass fraction increase was enhanced as well. This led to the increase of MFI from 0.081% to 0.088% when the flow rate increased from 1.13 m³/h to 1.63m³/h. Due to the limitation of varying the range of hot water flow rate, the increase of MRR and MFI was less significant if compared to that of the variable hot water temperature in Subsection 4.6.1.

(a)

(b)

Figure 4.5: Effect of hot water flow rate on (a) MRR and (b) MFI of the ALDR system

4.4.3 Cooling water temperature

The effect of cooling source to regeneration performance was also discussed here. Figure 4.6 (a) and (b) show the change of the MRR and MFI with the variation of cooling water temperature respectively. From the figure, it could be observed that the MRR decreased from 2.10g/s to 1.63g/s when the cooling water temperature was increased from 7°C to 10°C. The MFI obtained from experiment also decreased from 0.090% to 0.073% with the cooling water temperature. This was because less cooling energy was provided to the condenser when the temperature of cooling water was increased and hence fewer vapors would be condensed in the condenser. Therefore, the vacuum pressure in the enclosed regenerator would be higher and fewer vapors at the generator side could be vaporized. As a result, this led to lower moisture removal rate at the generator side when higher temperature of cooling water at condenser side was provided. Therefore, the increase of desiccant mass fraction also reduced consequently. The predicted MRR and MFI trends agreed well with the experimental results with average deviation of 5.90% and 5.30%.

Figure 4.6: Effect of cooling water temperature on (a) MRR and (b) MFI of the ALDR system

4.4.4 Cooling water flow rate

Last but not least, the regeneration performance of the ALDR system was also investigated with different cooling water flow rates at the condenser side. From Figure 4.7, it could be observed that both the performance indices namely MRR and MFI increased with the cooling water flow rate where the model prediction values were consistent with the experimental values with the average deviation of 1.35% and 2.06% respectively. The MRR increased from 1.85g/s to 1.94g/s with the cooling water flow rate as shown in Figure 4.7. This could be explained by more heat energy being absorbed

by the cooling water when the flow rate of cooling water was increased. More vapor could condense and hence lower vacuum pressure condition could be provided for the desiccant boiling process at the generator side. When the vacuum pressure was reduced, more water vapor could be evaporated from the weak desiccant solution. More moisture in the desiccant solution could be removed and the desiccant solution could be regenerated with higher concentration. The MFI was observed to be increasing 0.081% to 0.084% when the cooling water increased from 1.13m³/h to 1.99m³/h. The change in the regeneration performance was not obvious as there was limitation in regulating the water flow rate. The setting of lower flow rate of water will cause harm to the water pump.

(a)

(b)

Figure 4.7: Effect of cooling water flow rate on (a) MRR and (b) MFI of the ALDR system

From the results obtained, it could be noticed that the effect of hot water temperature on system regeneration performance was more obvious than that of hot water flow rate. This was because the range of hot water flow rate to be regulated was limited and hence the effect of the flow rate on the system performance was less significant. This was also applied to the effect of parameters of cooling water at the condenser side where the cooling water temperature had more significant effect on the regeneration performance than the cooling water flow rate. Hence, these two parameters can be taken as the regulating parameters to modulate or obtain better regeneration performance of the ALDR system.

4.5 Summary

In short, a simple and accurate performance prediction model has been developed to predict the regeneration performance of the proposed system. The model developed was based on the energy and mass balance equations and the concept of perfectness. The feasibility of these concepts has been validated with the experimental results where the average deviation was less than 5.90%. The system regeneration performance was also investigated under different operating conditions. It was observed that the temperatures of both heating and cooling sources had more significant effects towards the regeneration performance than respective flow rates.

The model developed in this chapter was based on the steady state of the system, the dynamic behavior inside the system was not considered. During the experimental tests, the vacuum pressure inside the enclosed regenerator tank was found to have increased dramatically at the beginning of the regeneration process and reduced during the end of the regeneration process. This was probably due to the imbalance of regeneration rate and condensation rate at respective generator and condenser. Due to the change of vacuum pressure throughout the regeneration process, the regeneration performance is affected.

The system performance investigation model discussed in this chapter did not consider the dynamic behavior in the system. The time-dependent description, prediction and control of real process in real time can become possible with the dynamic simulation of the system. In order to describe this phenomenon, the description of dynamic behavior of each main component in the system is vital here. Therefore, a dynamic model for the proposed ALDR system will be developed in the following chapter. The dynamic model of the ALDR system will first be developed and the developed model will then be validated with the experimental results. Next, the dynamic performance of the proposed system will be investigated when a step change of temperature is inserted.

Chapter 5 Dynamic Modeling of ALDR Systems

5.1 Introduction

As mentioned in Section 4.5, the phenomenon of vacuum pressure change during the regeneration process in the ALDR system has to be studied as it affects the performance of the proposed system. The mathematical model described in Chapter 4 considered the ideal condition where vacuum pressure remained the same during the regeneration process. Therefore, in order to perform the real-time description, prediction and control of the proposed ALDR system in the future, a model that is able to describe the transient performance of the system is required.

The study of dynamic performance of the regeneration system is important as the desiccant regeneration system often operates outside the vicinity of the users. The description of dynamic behavior in each component in the system allows us to understand the changes of relevant parameters with respect to time when it is submitted to a step change input. The high thermal mass consisting of heat exchangers, the desiccant solution and the heat transfer fluid often makes the system operates under off-design conditions. The process of boiling and condensation of water component in desiccant solution in vacuum state also play an important role in dynamics of the desiccant regeneration system. Therefore, the dynamic solution is an essential tool for the prediction of the system performance. The elaboration of the control system can also be done based on the dynamic model developed.

The dynamic of heat and mass transfer in other relevant fields [51, 58-60, 62, 63] can be referred in this work. Firstly, the dynamic of the system can be described in two main components which are the generator and condenser. The governing equations based on the energy and mass balance equations in each main component are first developed. The heat transfer equations in the heat exchanger at both the generator and condenser

sides are also developed to describe the heat transfer process during the desiccant regeneration process.

5.2 Governing equations

The governing equations of the ALDR system are first developed based on the heat and mass transfer equations in each main component in the system. As discussed in Section 3.2, there are two main components which are generator and condenser in the ALDR system as in Figure 3.2. Thus, the governing equations will be developed based on the boiling and condensation process at generator and condenser respectively.

5.2.1 Generator model

Figure 5.1: Schematic representation of the ALDR system

The boiling process in the generator can be described by the schematic diagram in Figure 5.1. The desiccant solution is sprayed on the heat exchanger carrying the hot water. The weak desiccant solution is evaporated when water component absorbs sufficient energy to escape from the solution. The vapor generated will then flow to the condenser.

From the mass balance equation, the change in solution mass in the generator relies on vapor generation rate, $\dot{m}_{evap}$ [62].

$$\frac{dM_{sol}}{dt} = -\dot{m}_{evap} \quad (5-1)$$

Besides, the mass balance of LiBr solution depends on the mass flows of the weak $\dot{m}_{sol,in}$ and strong $\dot{m}_{sol,out}$ LiBr solutions in the generator [60]. This can be explained by

$$\frac{d(M_{sol} X_{sol})}{dt} = \dot{m}_{sol,in} X_{sol,in} - \dot{m}_{sol,out} X_{sol} \quad (5-2)$$

where X_{sol} is the mass fraction of the desiccant solution.

The system pressure can be obtained by referring to the ideal gas law as in Equation (5-3). The volume of vapor V_v can be obtained by the difference between the total volume of vessel and volume of the solution [51].

$$\frac{dP}{dt} = \frac{(dM_v/dt)RT_v}{V_v} \quad (5-3)$$

where M_v is the mass of vapor, R is the gas constant and T_v is the temperature of vapor.

Figure 5.2 shows the schematic diagram of enthalpy balance of generator in the ALDR system which will be referred when developing the energy balance equations for the generator.

Figure 5.2: Enthalpy balance diagram of generator in the ALDR system [58]

The temperature change of all the components is a complex three-dimensional heat transfer problem, therefore a simplified approach to modelling from reference [58] is used here. The total thermal mass is divided into internal and external part to account for the different rates of heat transfer. The internal and external energy balances can be expressed by taking the internal and external thermal storage into account. The external parts follow the algebraic mean external temperature $\bar{T}_w$ ($\bar{T}_{hw}$ or $\bar{T}_{cw}$) whereas the internal parts follow the algebraic mean internal temperature $\bar{T}_x$ ($\bar{T}_{gen}$ or $\bar{T}_{con}$). T_x is the virtual temperature between the internal and external temperatures. Besides that, the heat transfer coefficients and heat transfer areas also account for internal and external parts accordingly. The relevant temperatures can be obtained as in Equations (5-4) to (5-7) [58]

$$\bar{T}_{hw} = \frac{T_{hw,in} + T_{hw,out}}{2} \quad (5-4)$$

$$\bar{T}_{cw} = \frac{T_{cw,in} + T_{cw,out}}{2} \quad (5-5)$$

$$T_{gen} = \left(\bar{T}_{gen} + \frac{T_{hw,in} + T_{hw,out}}{2} \right) / 2 \quad (5-6)$$

$$T_{con} = \left(\bar{T}_{con} + \frac{T_{cw,in} + T_{cw,out}}{2} \right) / 2 \quad (5-7)$$

From the simplified approach, the external components for generator can be assumed as consisting of 50% of the mass of heat exchanger tube bundles and the hot water whereas the internal components comprise of another 50% of the mass of heat exchanger tube bundles and the LiBr solution in the generator. This assumption is reasonable as the heat exchanger tubes have flow both internally and externally by solution and hot water respectively. Similar assumption is applied for the condenser side. The internal parts include the 50% of the mass of heat exchanger tube bundles and the water vapor generated whereas the external parts comprise of 50% of the mass of heat exchanger tube bundles and the cooling water which act as the cooling source [58].

The energy balance of the desiccant solution in the generator can be given as Equations (5-8) and (5-9). For the internal enthalpy balance, the heat supplied by the heat exchanger is partly used to heat and boil the desiccant solution and partly is used to heat the internal parts of heat exchanger [58].

$$\left(Mc_p\right)_{\text{int,gen}} \frac{d\bar{T}_{\text{gen}}}{dt} = (UA)_{\text{int,gen}} \left(T_{\text{gen}} - \bar{T}_{\text{gen}}\right) - \dot{m}_{\text{evap}} \left(r + l + c_{p,\text{sol}} \left(\bar{T}_{\text{gen}} - T_{\text{sol,in}}\right)\right) \quad (5-8)$$

where M is the mass, U is the heat transfer equation, A is the heat transfer area, r is the latent heat of vaporization, l is the heat absorption of solution, $c_{p,\text{sol}}$ is the specific heat of solution and $T_{\text{sol,in}}$ is the inlet temperature of the solution.

On the other hand, the external enthalpy balance indicates the heat which is given off by the hot water crosses the heat exchanger and heats up the parts, $M_{\text{ext,gen}}$ [58]. It can be represented by

$$\left(Mc_p\right)_{\text{ext,gen}} \frac{d\bar{T}_{\text{hw}}}{dt} = \dot{m}_{\text{hw}} c_{p,\text{hw}} \left(T_{\text{hw,in}} - T_{\text{hw,out}}\right) - (UA)_{\text{ext,gen}} \left(\bar{T}_{\text{hw}} - T_{\text{gen}}\right) \quad (5-9)$$

where $\dot{m}_{\text{hw}}$ is the mass flow rate of hot water and $c_{p,\text{hw}}$ is the specific heat capacity of hot water.

5.2.2 Condenser model

Figure 5.3: Schematic representation of the condenser in the ALDR system

Another component in the ALDR system to be focused on is the condenser as in Figure 3.2. Figure 5.3 shows the condensation process occurred in the condenser in the

ALDR system. The vapor generated from generator flows in to the condenser. The vapor releases the latent heat of condensation and condenses into water by the heat exchanger carrying the cooling source.

The mass balances for the vapor M_v and condensed water $M_{con,w}$ which depends on the condensation rate, $\dot{m}_{cond}$ [62] are shown in Equation (5-10) and Equation (5-11) respectively.

$$\frac{dM_v}{dt} = \dot{m}_{evap} - \dot{m}_{cond} \quad (5-10)$$

$$\frac{dM_{con,w}}{dt} = \dot{m}_{cond} \quad (5-11)$$

Figure 5.4: Enthalpy balance diagram of condenser in the ALDR system [58]

The enthalpy balance diagram for the condenser is shown in Figure 5.4 which will be referred when developing the corresponding energy balance equations. As per discussion in Subsection 5.2.1, the internal and external enthalpy balances are also considered for the condenser model. For the internal part, the heat given off by the water vapor is used partly to heat the cooling water and the other part of it is used to heat the internal parts of the heat exchanger [58].

$$\left(Mc_p \right)_{int,con} \frac{d\bar{T}_{con}}{dt} = (UA)_{int,con} \left(T_{con} - \bar{T}_{con} \right) - \dot{m}_{evap} \left(r + c_{p,v} \left(\bar{T}_{gen} - \bar{T}_{con} \right) \right) \quad (5-12)$$

where $c_{p,v}$ is the specific heat capacity of vapor.

For the external heat transfer, the heat taken by the cooling water partly crosses the heat exchanger and others heat the external parts [58].

$$\left(Mc_p\right)_{ext,con} \frac{d\bar{T}_{cw}}{dt} = \dot{m}_{cw} c_{p,cw} \left(T_{cw,out} - T_{cw,in}\right) - (UA)_{ext,con} \left(\bar{T}_{cw} - T_{con}\right) \quad (5-13)$$

where $\dot{m}_{cw}$ is the mass flow rate of cooling water, $c_{p,cw}$ is the specific heat capacity of cooling water and $T_{cw,in}$ and $T_{cw,out}$ are the inlet and outlet cooling water temperatures respectively.

5.2.3 Heat exchanger model

The heat exchangers exist in both the generator and condenser. The heat exchanger consists of a bundle of cylindrical tubes. In generator, the heat is exchanged between the hot water and the desiccant solution entering the enclosed vessel. On the other hand, the heat is exchanged between the cooling water and the vapor in condenser. In order to describe the heat transferred by the hot water to the desiccant solution inside the generator, a heat exchanger model is required. This also applies to the heat exchanger at the condenser side where the heat is transferred from the vapor to the cooling water in the heat exchanger.

The heat energy equation for the heat exchanger can be described as [60]

$$\dot{Q}_{hex} = UA \left(\bar{T}_w - \bar{T}_x\right) \quad (5-14)$$

where U is the overall heat transfer coefficient, A is the heat transfer area of the heat exchanger, $\bar{T}_w$ is the arithmetic average temperature of hot water or cooling water, and $\bar{T}_x$ is the arithmetic average temperature of generator or condenser.

The overall heat transfer coefficient U is based on the internal α_{int} and external α_{ext} heat transfer coefficient, the thermal conductivity of tube wall k_{tube} , the heat transfer area A and the fouling factor F . This can be determined by Equation (5-15) [60]. The thermal conductivity resistance of the tube wall is neglected in this study since

it is much smaller than other resistances.

$$U = \frac{1}{\frac{1}{\alpha_{int}} + F_{int} + \frac{1}{2k_{tube}} \cdot A_{in} \cdot \ln\left(\frac{A_{ext}}{A_{int}}\right) + F_{ext} \cdot \frac{A_{int}}{A_{ext}} + \frac{1}{\alpha_{ext}} \cdot \frac{A_{int}}{A_{ext}}} \quad (5-15)$$

The heat transfer between the heat exchanger surface and fluid inside depends on the external heat transfer coefficient, α_{ext} . It can be obtained by determining the Nusselt number which describes the turbulent flow in circular tubes. Equations (5-16) and (5-17) are used to determine the internal heat transfer coefficients for heat exchanger at generator and condenser respectively [63].

$$Nu_D = 0.0243 Re_D^{0.8} Pr^{0.4} \quad (5-16)$$

$$Nu_D = 0.0265 Re_D^{0.8} Pr^{0.3} \quad (5-17)$$

where Re_D and Pr are evaluated at the average temperature between the inlet and outlet water inside the heat exchanger. These correlations are suitable to be used for $Re_D \geq 10000$ and $0.6 \leq Pr \leq 160$ [63].

On the other hand, the heat transfer between the heat exchanger surface and fluid outside the heat exchanger depends on the internal heat transfer coefficient, α_{int} . The fluids outside the heat exchangers refer to the desiccant solution in the generator and water vapor in the condenser. At the generator side, the boiling heat transfer coefficient α_{boil} is considered and can be given by [62]

$$\alpha_{boil} = 0.62 \left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v) [h_{fg} + 0.4 c_{p,v} (T_s - T_{sat})]}{\mu_v D (T_s - T_{sat})} \right]^{1/4} \quad (5-18)$$

where D is the diameter of the heat exchanger tube. The vapor properties are evaluated at the film temperature, $T_f = (T_{sat} + T_s)/2$ and the liquid properties and h_{fg} are evaluated at saturation temperature, T_{sat} at the specified pressure.

At the condenser side, the condensation heat transfer coefficient α_{cond} can be

obtained based on the film condensation on the surfaces of horizontal tubes as in the Equation (5-19) [62].

$$\alpha_{cond} = 0.729 \left[\frac{g \rho_l (\rho_l - \rho_v) h_{fg}^* k_l^3}{\mu_l (T_{sat} - T_s) N D} \right]^{1/4} \quad (5-19)$$

where N is the number of the horizontal heat exchanger tube. The vapor and liquid properties are also evaluated accordingly as mentioned previously. h_{fg}^* is the modified latent heat of vaporization which can be evaluated as [62]

$$h_{fg}^* = h_{fg} + 0.68 c_{p,l} (T_{sat} - T_s) \quad (5-20)$$

where T_s is the surface temperature and $c_{p,l}$ is the specific heat capacity of liquid.

5.2.4 Thermodynamic properties

The thermodynamic properties used in the dynamic model are referred from the literature as per for LiBr solution [64], for pure water [65, 66] and for vapor [66, 67]. The thermodynamic properties of LiBr solution are calculated based on the system pressure, temperature and concentration of solution. On the other hand, the thermodynamic properties of water in hot water and cooling water circuits are based on the temperature.

5.2.5 Numerical procedures

Figure 5.5 shows the basic flow chart which outlines how the dynamic model for the ALDR system is developed. The program developed in MATLAB platform starts by introducing the initial conditions of the system. The input data for the inlet hot water and cooling water temperatures is then read. The thermodynamic properties as in Subsection 5.2.4 are calculated together with T_v and T_{sat} . The internal α_{int} and external heat transfer coefficient α_{ext} are also calculated for the heat exchanger in generator and condenser using the Equation (5-16) to Equation (5-19). Then, the heat flow is also

determined from Equations (5-14) and (5-15). The temperature profiles in the ALDR system are also determined based on the definition of internal and external heat balance as shown from Equations (5-4) to (5-7). The parameters related to the mass balances are also evaluated next. After that, Equations (5-1) - (5-3) and (5-8) - (5-13) were being solved by using Runge-Kutta method. The values of the 9 parameters (M_{sol} , X_{sol} , $\bar{T}_{gen}$, $\bar{T}_{hw}$, M_v , $M_{con,w}$, $\bar{T}_{con}$, $\bar{T}_{cw}$, P) are determined and stored for plot with the next initialization values are then updated. The iteration is continued until the final simulation time is met.

Figure 5.5: Basic flow chart of the dynamic model of the ALDR system

5.3 Validation of the model

The inputs of the models are the characteristics of the regeneration system and measured $T_{hw,in}$, $T_{cw,in}$, $\dot{m}_{hw}$ and $\dot{m}_{cw}$ from experiment. The simulation is based on the initial conditions and parameters shown in Table 5.1. The outputs of the model are M_{sol} , X_{sol} , $\bar{T}_{gen}$, $\bar{T}_{hw}$, M_v , $M_{con,w}$, $\bar{T}_{con}$, $\bar{T}_{cw}$ and P .

Table 5.1: Initial conditions and parameters used in the simulation model

Data	Value	Data	Value
$T_{hw,in}$ (°C)	37.5	$X_{sol,in}$ (%)	38.0
$T_{hw,out}$ (°C)	33.0	$\dot{m}_{sol}$ (kg/s)	0.82
$T_{cw,in}$ (°C)	6.5	$\dot{m}_{hw}$ (kg/s)	0.45
$T_{cw,out}$ (°C)	13.0	$\dot{m}_{cw}$ (kg/s)	0.56
T_{gen} (°C)	20.0	P (Pa)	1100
T_{con} (°C)	10.0	M_{sol} (kg)	135
A_{gen} (m ²)	1.60	$M_{con,w}$ (kg)	0.1
A_{con} (m ²)	1.60	D_{gen} (m)	0.0254
R_v (Jkg ⁻¹ K ⁻¹)	455	D_{con} (m)	0.0254

The developed dynamic model can be validated by comparing the outlet temperatures of hot water and cooling water obtained from the model and those measured from the experiment. The data such as the inlet and outlet solution temperatures and concentration are not able to be acquired from the system because no sensors are installed by the manufacturer in the regenerator. Since the hot water and cooling water temperatures are also the outputs of the simulation model, thus the comparison data are taken from the external water circuits. This kind of validation method has been employed in several literature [51, 58-60, 68].

The measured and simulated outlet temperatures of the hot water in the heat exchanger at generator side are shown in Figure 5.6(a). From the figure, it could be

noticed that hot water temperature underwent a sudden loss of energy power. This is because the heater installed in the experimental platform was undersized and this led to an obvious drop in energy at the beginning of operation. The maximum absolute error between the measured and simulated hot water temperatures was around 4.08°C while the mean absolute error was 0.49°C . The maximum error occurred during the transient phase which was the starting phase of the system. It could be observed that the simulated results varied following the pattern of the measured values from the experiment during the transient phase when the regeneration system started to operate. The simulated temperature then reached a steady state around 7000s. Even though the steady-state value was slightly different from the measured temperature, the steady-state accuracy was not the focus in this paper. Therefore, the small deviation of the simulated temperature from the experimental value during the steady state would not be discussed here.

(a)

(b)

Figure 5.6: Comparison between simulated and experimental outlet temperatures of (a) hot water (b) cooling water circuit in the ALDR system

Next, the measured and simulated outlet temperatures of the cooling water in the heat exchanger at condenser side are also compared in Figure 5.6(b). From the graph shown, it could be noticed that the changing pattern of both the simulated and experimental data also agreed well with each other. The maximum absolute error between the simulated and measured cooling water temperatures was around 2.10°C which appeared during the starting phase of the system. The mean absolute error between the simulated and experimental cooling water temperatures was around 0.51°C . The dynamic behavior in both components is the main focus in the study. From these two graphs, it could be noticed that the fluctuation of the simulated and measured output temperatures of hot water and cooling water in respective generator and condenser agreed well with each other. Therefore, it can be concluded that the model is able to predict the system accurately for a period of time.

(a)

(b)

Figure 5.7: Comparison between simulated and experimental thermal power for (a) generator and (b) condenser in the ALDR system. Solid line: 15% error; dashed line: 10% error

The model was again validated by comparing the experimental and simulated thermal power of the generator and condenser. From Figure 5.7, it could be noticed that the percentage errors between the simulated and experimental thermal power for both generator and condenser were within $\pm 15\%$. It could be noticed that 90% of the total data points were within $\pm 10\%$ error for the generator whereas for condenser, 85.56% of the total points were within $\pm 10\%$ error. Due to the fluctuation at the beginning of the simulation, some points were within $\pm 15\%$ error. It can be concluded that the model is able to predict the dynamic performance of the ALDR system accurately.

From these validation results, it can be noticed that the dynamic response of the simulated output temperatures is within acceptable agreement. Therefore, it can be concluded that this model is able to predict the dynamic performance of the regeneration system when there is a small variation of inlet temperature of the external water circuits. This verified model is then used to predict the system performance during a dynamic state when a step change in the inlet temperature of hot water is inserted at which it will be discussed in the following section. The system dynamic performance is then analyzed using the model.

5.4 Dynamic performance of the ALDR system

The dynamic performance of the ALDR system is analyzed with the temperature profile in the generator and condenser. The internal mean temperatures in the generator and condenser are plotted with time in Figure 5.8. The internal mean temperature in generator kept in the range 28-35°C. Since the operating pressure was between 1000Pa and 2000Pa, therefore the solution boiling temperature was around 20-35°C with corresponding solution concentration. Therefore, it could be said that the simulation results agreed well with the theory. At the condenser side, the mean temperature inside showed around 10-16°C from the simulation results which also agreed with the theory where the saturation temperature of water at operating pressure was around 7-17°C. Besides that, the trends of the internal mean temperatures of the generator and condenser were also consistent with those of the hot water and cooling water inlet temperatures respectively as in Figure 5.6. This showed the accurate prediction of the internal temperatures in both of the components.

Figure 5.8: Internal mean temperatures of generator and condenser in the ALDR system

The evaporation rate and condensation rate at respective generator and condenser sides are shown in Figure 5.9. At the beginning of the regeneration process, the solution was diluted and the low boiling temperature caused the boiling of solution to occur easily. Therefore, the evaporation rate was higher than the condensation rate at the beginning of process. The evaporation rate would then become the same with the condensation rate in the condenser when the evaporation rate was slowly reduced. During the last hour, the solution became more concentrated causing the evaporation rate to be lower than the condensation rate.

Figure 5.9: Rate of evaporation and condensation in the ALDR system.

The results show that the dynamic model is able to describe the dynamic performance of the proposed ALDR system. This is especially important to show the

change of evaporation rate and condensation rate happened in the system. As discussed previously in Section 4.5, the drastic change of vacuum pressure during the regeneration process is due to the imbalance of the rate of evaporation and condensation in generator and condenser respectively. Therefore, a dynamic model which is able to describe this phenomenon is important to be exploited to design a control strategy to control the system vacuum pressure in the future.

5.5 Consistency examination - a step change in the inlet temperature of hot water

The consistency examination of the mathematical model developed can be used to verify the transient performance of the ALDR system when a step change of input temperature is given after the system has reached a steady state. An input step change of inlet hot water temperature from 38°C to 43°C is applied and other operating conditions such as the cooling water inlet temperature as well as the water mass flow rates in external water circuits are remained constant. The duration of the simulation is 1500s and the temperature step is set at 500s after the simulation is started to ensure the initial values has enough time to be equal to the steady-state values. This analysis is useful to investigate the effects of step variation in hot water temperature to the relevant parameters.

The required simulated output parameters are output temperatures of hot water and cooling water, solution concentration and mass, mass of vapor and condensed water and temperatures in both the generator and condenser. The temperature step was followed by the increase of average hot water temperature which is the heat source to the generator as shown in Figure 5.10(b). Consequently, it could be noticed in Figure 5.10(a) that the average temperature in the generator was also increased from 32°C and reached steady state around 36°C. The hot water is the heating source at the generator providing the heat energy to heat and boil the desiccant solution. Therefore, all the temperatures inside the generator increased following the temperature ramp of external

hot water circuits, as shown in Figure 5.10. The temperatures inside the generator include the temperature of hot water and average temperature inside the generator.

Due to the increase of solution temperature in the generator for a step change in hot water temperature, more moisture in the desiccant solution was evaporated during the boiling process occurred in generator. Therefore, the evaporation rate of solution was also increased as shown in Figure 5.11(a). Since more water component was transferred from the liquid desiccant, the gradient of solution concentration change was also increased accordingly as shown in Figure 5.11(b). This information is useful to control the system to achieve certain evaporation rate or required concentration of solution to be regenerated for the ALDR system. The evaporation rate is closely related to the regeneration rate of the ALDR system where higher evaporation rate will give better regeneration performance of the regenerator.

The increase of hot water temperature also led to the increase of solution temperature at the generator. The water component in the solution was supplied with greater heating energy and hence more water vapor was able to gain enough energy to escape from the surface of the solution. As a result, more water vapors were generated at higher solution temperature as shown in Figure 5.12(a). The increase of evaporation rate of the desiccant solution increased the mass flow of vapor flowing to the condenser accordingly. Therefore, more water vapor would be condensed into water. The rate of condensation in condenser which was indicated by the slope of the graph was also increased consequently as shown in Figure 5.12(b).

The solution temperature was increased with the increase of the hot water which acted as the heating source at the generator. Therefore, the water vapor was also generated with higher temperature. Due to the increase of average temperature of vapor inside the generator, the average temperature in the condenser was also increased. Consequently, the temperature of the condensed water formed in the condenser was also increased for a larger amount of vapor generated with higher vapor temperature from

the generator. These situations were proved in Figure 5.13 (a) and (b).

(a)

(b)

Figure 5.10: Temperature profiles in generator in the ALDR system after a step change in hot water temperature

(a)

(b)

Figure 5.11: (a) Mass of solution (b) concentration of solution in generator of the ALDR system after a step change in hot water temperature

(a)

(b)

Figure 5.12: (a) Mass of vapor generated (b) mass of condensed water in condenser of the ALDR system after a step change in hot water temperature

Figure 5.13: Temperature profiles in condenser of the ALDR system after a step change in hot water temperature

From the results obtained, the dynamic behavior of the proposed desiccant regeneration system was showed by applying an increase in the inlet temperature to the system model. This showed that the model could be used to describe the dynamic performance of the proposed liquid desiccant regeneration system operating under vacuum condition. Therefore, this model will be able to be used to design a control strategy to control the vacuum pressure in the future. The developed dynamic model can also be adapted to other regeneration system operating under vacuum condition as long as all the system design data are available.

5.6 Summary

In short, a dynamic model for the proposed ALDR system has been developed. The dynamic model developed was based on the simplified approach where the concept of the internal and external heat and mass transfer equations was considered when developing the system governing equations. The dynamic performance of the proposed liquid desiccant regeneration system under vacuum condition has then been investigated. The simulation model was validated with the experimental data obtained from the system experiment platform built in the laboratory. The experimental and simulated output temperatures were in good agreement where the maximum absolute error

between the measured and simulated water temperatures was less than 4.08°C while the mean absolute error was less than 0.49°C. In addition, the model was also validated by comparing the simulation thermal power with the experimental thermal power for both generator and condenser with the errors within $\pm 15\%$. Therefore, it could be said that the model developed was accurate enough to predict what happen in the regeneration system when the system was operating.

In order to verify the transient performance of the ALDR system, a step change in temperature was inserted to the system model. The results showed that the model was able to describe the dynamic performance of the proposed desiccant regeneration system operating under vacuum condition. Therefore, this model is very useful to identify the control parameters of the regeneration system without the need of performing experiments. As per discussion in Section 4.5, the drastic change of vacuum pressure during the beginning and the end of the regeneration process affects the regeneration performance of the ALDR system. The model developed in this chapter is able to describe the aforementioned situation. Thus, this model will be able to be used to control the system vacuum pressure in the future. The model can also be useful to design a new ALDR system as it may be adapted to explain the behavior of different liquid desiccant regeneration systems under vacuum condition as long as the system design data are available.

Chapter 6 Experimental Investigation of the ALDR system

6.1 Introduction

The concept of applying vacuum condition in the liquid desiccant regeneration system as explained in Section 2.3 has to be proved for its feasibility. The regeneration temperature is especially important to act as the compared parameter between the proposed regeneration system and the conventional packed-bed regenerator. The possible regeneration temperature with the corresponding concentration of LiBr solution and surrounding vacuum pressure is shown in Figure 6.1.

Figure 6.1: Range of possible regeneration temperature under operating vacuum pressure with different desiccant solution concentrations

From Figure 6.1, it can be noticed that if the vacuum pressure lies between 1400Pa and 2000Pa, the regeneration temperature for LiBr solution will be around 20-35°C to regenerate the solution from concentration of 35% to 45%. The expected regeneration

temperature is much lower than that of the packed-bed regenerator which is normally more than 60°C. Therefore, several experimental tests will be carried out in order to validate this in this chapter.

The proposed ALDR system has been designed and the system experimental platform has been built up as shown in Figure 3.4 and Figure 3.5. In order to validate the feasibility of the application of the vacuum condition in regenerating desiccant solution, several tests will be carried out. Experimental tests will be carried out to investigate the system performance. In order to highlight the contribution of the proposed ALDR system, the power consumption and regeneration temperature of the proposed system will be compared with that of the conventional packed-bed regenerator from the literature to highlight the contribution of developing this novel desiccant regeneration system. The design of the operating conditions and experimental procedures will be discussed first.

6.2 Description of the system conditions

6.2.1 Operating conditions

Prior to the start of the experiment, the operating conditions shown in Table 6.1 are realized. The working ranges of the solution temperature, solution concentration and vacuum pressure depend on the type of the solution which is LiBr solution in this work. The range of LiBr solution concentration to be used for the dehumidification process lies between 35% and 45% of mass concentration. From Figure 6.1, the regeneration temperature of LiBr solution will be around 20-35°C to regenerate the solution when the vacuum pressure lies between 1400Pa and 2000Pa. Therefore, the initial solution temperature is set at 20°C with the mass fraction of 36% for all the tests. The solution flow rate is set around 2.2m³/h and the initial vacuum pressure is set at 1000Pa. The solution temperature, solution mass fraction and the vacuum pressure are set as constant as explained in Subsection 4.3.1. The other operating conditions such as inlet

temperatures of hot water and cooling water and flow rates of hot water and cooling water are varied as in Table 4.1.

Table 6.1: Initial operating conditions of the ALDR system

P	$\dot{V}_{sol}$	$\dot{V}_{hw}$	$T_{hw,in}$	$\dot{V}_{cw}$	$T_{cw,in}$	$n_{sol,in}$
(Pa)	(m ³ /h)	(m ³ /h)	(°C)	(m ³ /h)	(°C)	(%)
1000	2.20	1.63	38.0	1.99	10.0	36.31

6.2.2 Experimental procedures

Based on the operating conditions in Table 6.1, the procedure designed and adopted is given below:

1. Before starting the experiment, the weak LiBr solution is prepared with the mass fraction of 36% and then stored in the solution tank at the bottom of the regenerator tank.
2. The volume of desiccant solution in the regenerator must be constant so that the regeneration performance would not be altered.
3. The vacuum pressure is adjusted to the desired pressure by using the vacuum pump.
4. The hot water and cooling water temperatures are adjusted to the required temperature values while the flow rates are adjusted by varying the frequency of the water pump.
5. The initial solution flow rate is also adjusted by using the variable frequency device.
6. After switching on the solution pump, the solution is pumped and sprayed on the heat exchanger at generator side to undergo the boiling process.
7. The solution is pumped continuously to complete the solution cycle and the regeneration process is stopped after 3 hours.
8. The outlet conditions are recorded and the procedures were repeated for varied operating conditions.

The results of the sensors listed in Table 3.1 are obtained by the data acquisition system. In order to evaluate the regeneration performance of the ALDR system using the experimental results obtained, performance indices to indicate the regeneration performance have to be determined here. The performance indices commonly discussed in the regeneration system available in the literature are referred herein.

6.3 Performance indices

To determine the regeneration performance of the ALDR system, two experimental performance indices namely moisture removal rate and regeneration efficiency are introduced here.

6.3.1 Moisture Removal Rate (MRR)

Even though MRR has been discussed in Chapter 4, an alternative formulation to determine the index using experimental results is discussed here. The experimental MRR discussed here represents the average amount of water vapor removed from the concentrated liquid desiccant per second. This indicator has been introduced in several literature [5, 34, 41, 69]. Since there is no air stream involved in the ALDR system, the way of determining MRR reported in the literature is therefore modified here. MRR calculated from the experimental results can be obtained from the total amount of water removed from the desiccant solution during the 3 hour regeneration process. The total amount of water removed from the solution can be obtained by getting the difference of solution volume before and after the regeneration process as

$$MRR_{exp} = \frac{\Delta M_{water}}{t} \quad (6-1)$$

where subscript *exp* indicates experiment, ΔM_{water} is the total mass of water removed in the desiccant solution, and *t* is the total time of operation.

6.3.2 Thermal efficiency

Regenerating thermal efficiency, η_{th} is another performance index used to indicate the energy consumption efficiency in the ALDR system which can be expressed as [70, 71]

$$\eta_{th} = \frac{\dot{m}_{evap} h_{fg}}{\dot{m}_{hw} c_{p,hw} (T_{hw,in} - T_{hw,out})} \quad (6-2)$$

where $\dot{m}_{evap}$ is the evaporation rate of the solution, h_{fg} is the latent heat of vaporization, $\dot{m}_{hw}$ is the mass flow rate of water, $c_{p,hw}$ is the specific heat capacity of the hot water, $T_{hw,in}$ and $T_{hw,out}$ are the inlet and outlet hot water temperatures respectively.

For these two indices, a higher MRR value indicates that more moisture is removed from the desiccant solution. On the other hand, the higher the regenerating thermal efficiency of the system, the more effective is the system in regenerating the desiccant solution. These two performance indices will be employed to discuss the experimental regeneration performance in the next section.

6.4 Experimental results and analysis

6.4.1 Experimental regeneration performance analysis

Several tests are first carried out on the experimental platform of the ALDR system developed in Section 3.3 to test for the feasibility of the proposed ALDR system designed in Chapter 3. Experimental procedures described in Subsection 6.2.2 are followed. Figure 6.2 to Figure 6.4 show the results on the temperature profiles in the regeneration system and system vacuum pressure based on the operating conditions in Table 6.1.

Figure 6.2 shows the temperature profiles in the system for the 3-hour regeneration

process. It could be noticed that there was a drastic change of inlet and outlet hot water temperatures during the start of the regeneration process. This was due to the problem that the heater employed in the system was undersized and hence it led to obvious drop of energy at the beginning of the operation. A higher heating capacity of the heater will be changed in the future for better system performance. The hot water inlet temperature maintained at the set temperature of 38°C and the cooling water inlet temperature was maintained at 10°C. The hot water outlet temperature maintained at 32°C whereas the cooling water outlet temperature obtained was around 15°C.

Figure 6.2: Inlet and outlet temperatures of hot water and cooling water in the ALDR system for 3 hours of operation

The range of the solution temperature in the ALDR system is shown in Figure 6.3. From the figure, it could be noticed that the solution temperature increased from 20°C to around 31°C throughout the regeneration process. Since the regeneration process was a batch operation where the desiccant solution was kept cycling and entering into the regenerator until the regeneration process was stopped, therefore the regeneration temperature would increase with time. Besides that, the range of the regeneration temperature obtained agreed with the theoretical temperature range in Figure 6.1 when the vacuum pressure operated within 1000-2000Pa to regenerate the desiccant solution from 36.31% to 48.66% mass fraction in this case. The temperature of the condensed water at the condenser was also found to be 14-16°C. This was theoretically true as the saturation temperature of water was at around 14-15°C for surrounding pressure of

around 1600Pa as in Figure 6.4.

Figure 6.3: Temperatures of solution (red) and condensed water (blue) in the ALDR system for 3 hours of operation

The range of operating vacuum pressure in the enclosed regenerator tank was shown in Figure 6.4. It could be observed that the vacuum pressure increased dramatically from 1000Pa to around 1600Pa at the beginning of the process. This was because the evaporation rate of the solution was facilitated when the solution started to circulate in the system. Besides that, the evaporation rate of the diluted solution was higher than the condensation rate at the condenser side at the beginning of the regeneration process. This consequently led to the drastic increase of the pressure during the beginning of the operation. In addition, it was also observed that the vacuum pressure reduced with time at the end of the regeneration process. This was due to that the solution was getting concentrated and the condensation rate of the vapor became higher than the solution evaporation rate inside the generator. As a result, fewer vapors stayed inside the enclosed regenerator tank and hence the vacuum pressure was reduced.

Figure 6.4: Vacuum pressure in the ALDR system for 3 hours operation

Some experimental results with different operating conditions are listed in Table 6.2. As mentioned in Subsection 4.3.1, since the solution temperature, solution mass fraction and the vacuum pressure are related to each other, therefore, these three parameters are set as constant so that the regeneration performance can be investigated by just changing one parameter at one time. The regeneration performance indices namely MRR and η_{th} are calculated based on Equations (6-1) and (6-2).

The experimental testing sets in Table 6.2 are selected based on the possible operating conditions of the ALDR system. Each test is performed for 3 hours. Each test is done with one changing parameter while other parameters remain the same to observe the regeneration performance at different operating conditions. The experimental MRR, regenerating thermal efficiency and outlet concentration of the solution are the indices to be discussed. Detailed experimental results including the inlet and outlet parameters of solution, heating and cooling medias as well as the device vacuum pressure are shown in Table A.1 in Appendix.

Table 6.2: Experimental results of the ALDR system

No.	1	2	3	4	5
P (Pa)	1100	1100	1100	1100	1100
$\dot{V}_{sol,in}$ (m ³ /h)	2.21	2.24	2.21	2.24	2.25
$\dot{V}_{hw}$ (m ³ /h)	1.53	1.53	1.53	1.53	1.63
$T_{hw,in}$ (°C)	38.0	40.0	38.0	38.0	38.0
$\dot{V}_{cw}$ (m ³ /h)	1.99	1.99	1.99	1.13	1.99
$T_{cw,in}$ (°C)	8.0	8.0	10.0	8.0	8.0
$n_{sol,in}$ (%)	36.46	36.62	36.62	36.77	36.31
$n_{sol,out}$ (%)	47.93	49.08	45.55	47.57	48.66
MRR_{exp} (g/s)	1.948	2.073	1.634	1.853	2.042
η_{th}	0.7551	0.7453	0.6898	0.7379	0.7317

Test 1 was the experimental test with the standard design operating conditions. The results obtained from Test 2 to Test 5 were compared with Test 1 to observe the change of the regeneration performance with the changing parameters. For Test 2, the hot water inlet temperature was increased from 38°C to 40°C. More energy could be absorbed by the solution and hence more water vapor could be evaporated. Therefore, this resulted in higher final solution concentration. It could be noticed that the MRR was increased due to increase of evaporation rate of the solution. The thermal efficiency was around 0.75 which was almost the same with Test 1 as the higher regeneration rate compensated the higher heating energy provided in Test 2.

The inlet temperature of the cooling water was increased from 8°C to 10°C in Test 3. The increase in cooling water temperature led to the lower condensation rate of the vapor in the condenser. This resulted in higher pressure in the regenerator tank and consequently reduced the MRR. The generated solution concentration also reduced due to the lower evaporation rate of solution. The reduction of MRR also resulted in lower regeneration effectiveness compared to Test 1.

Lower cooling water flow rate was used in Test 4. It could be observed that the calculated MRR was reduced. This was due to the cooling power supplied to the condenser was reduced. Fewer vapors were condensed and this led to higher pressure maintained in the enclosed regenerator tank. Therefore, the evaporation rate of the solution and the final solution concentration would be reduced. Hence, the system regeneration performance was also decreased causing the regeneration thermal efficiency to be lower than that in Test 1.

For Test 5, it could be noticed that the increase of hot water flow rate would increase the evaporation rate of the desiccant solution in the generator. This was due to the increase of heat energy supplied to the generator. The higher solution evaporation rate consequently generated higher solution concentration compared to Test 1. As a result, the MRR was also increased in this case with regeneration thermal efficiency about 0.73.

Besides the performance indices mentioned earlier, the operating range of the regeneration temperature is also one of the main concerns of developing the ALDR system. This is because the proposed system is aimed at solving the problem of high regeneration temperature in current liquid desiccant regenerator.

6.4.2 Regeneration temperature range

The regeneration temperature is taken as the compared parameter in this subsection. In the ALDR system, the temperature of desiccant solution does not remain constant as the desiccant solution is kept cycled until the required concentration is reached which is called the batch operation. That is why the regeneration temperature of the proposed system will keep increasing during the regeneration process but not exceeding the inlet temperature of the heating source. Since the desiccant solution is heated by the heat exchanger carrying the heating source, therefore the regeneration temperature is mostly influenced by the parameters of the hot water. Thus, the range of the operating

regeneration temperature in the ALDR system is investigated under different hot water inlet temperatures and flow rates.

Figure 6.5: Regeneration temperature range of the ALDR system under different hot water inlet temperatures

First, Figure 6.5 shows the range of regeneration temperature of the proposed system with different hot water inlet temperatures. It could be observed that the regeneration temperature ranged from temperature around 20°C to a maximum temperature around 34.5°C for hot water inlet temperature. The regeneration temperature depends on the amount of heat supplied from the source. Thus, it could be observed from the figure that lower hot water inlet temperature resulted in lower maximum regeneration temperature that the system could reach. In addition, noticed that the black line in the figure was from Test 2 in Table 6.2 and the pressure ranged from 1000Pa to 1600Pa for this case, the regeneration temperature range agreed well with the theoretical possible temperature in Figure 6.1 in regenerating solution with mass fraction of 49%.

Figure 6.6: Regeneration temperature range of the ALDR system under different hot water flow rate

The influence of hot water flow rate on the range of regeneration temperature of the system was also investigated. From Figure 6.6, it could be observed that the regeneration temperature did not show obvious change with the hot water flow rates. The regeneration temperature showed little increment with an increase of the hot water flow rate. This was due to the greater heat energy supplied to the solution for higher hot water flow rate. From these two figures, the range of regeneration temperature showed between 20°C and 35°C which was much lower than that of the conventional desiccant regenerators reported in literature.

6.5 Comparison with packed-bed desiccant regeneration system

In order to highlight the advantages of the proposed ALDR system, the proposed system is compared with the other desiccant regeneration system in LDDS available in literature. Since the ALDR system is a newly proposed desiccant regeneration system, it is compared with the conventional packed-type regenerator using same desiccant solution. Table 6.3 shows the type, structure of regenerators, liquid desiccant used and inlet parameters of desiccant solution during the experiments for the present work and [5]. Regeneration temperature is also taken as the compared parameters since the

proposed ALDR system is aimed to solve the high regeneration temperature problem in current desiccant regeneration systems. The regeneration temperature of the solution depends on the type of desiccant solution, surrounding pressure and solution concentration. Different desiccant solution may yield different range of regeneration temperature at specific pressure. Furthermore, higher solution concentration will also lead to higher regeneration temperature. Since vacuum pressure in the proposed system is the variable influencing the regeneration temperature, therefore present study is compared with the other regeneration system using same working fluid and solution concentration range to ensure fair comparison.

Table 6.3: Parameters comparison of the ALDR system with other desiccant regeneration system in literature

Reference	[5]	Present study
Type	Packed-bed type	ALDR system
Packing	Random	NA
Desiccant	LiBr	LiBr
P (Pa)	1×10^5	1000-2000
$\dot{m}_{sol,in}$ (kg /s)	0.36-0.63	0.63-0.83
n_{in} (%)	38-54	36-41
$T_{sol,in}$ (°C)	49-63	20-35

From Table 6.3, it can be observed that the proposed ALDR system does not contain any packing in the regenerator. The heat and mass transfer process in the packed-bed type regenerator is through the direct contact between the air and solution streams, therefore packing is often needed to increase the heat and mass transfer area. The moisture in the air stream is transferred into desiccant solution stream by the driving force due to the surface vapor pressure difference between the air and solution streams. On the other hand, the water component in the desiccant solution is removed through the boiling process by spraying the desiccant solution onto the tube bundles carrying heating source in the ALDR system. For the same inlet solution concentration used in

both regeneration systems, the proposed ALDR system is able to regain the concentration of the solution with lower regeneration temperature. In the present study, the regeneration temperature is reduced from 49-63°C to 20-35°C to regenerate the desiccant solution with initial solution mass fraction of about 36%.

The desiccant regeneration temperature for the ALDR system using LiBr solution as the working fluid is around 20-35°C at operating vacuum pressure as shown in Figure 6.4. This is much lower than that of the conventional packed-bed desiccant regeneration system which is normally more than 60°C. The reduction of the regeneration temperature allows the potential use of the renewable or low-grade energy source as the heat source for the regeneration system in LDDS and hence it is more energy efficient. For instance, the regeneration temperature of the proposed system can be useful and suited for the condenser in the heat pump or low-grade waste heat from industry to act as the heat source at the generator tank. This lower regeneration temperature is able to correspond to the working temperature of the low-grade energy sources. This solves the aforementioned problem which is the high regeneration temperature problem in the current available desiccant regeneration systems in LDDS. In order to prove the energy saving potential of the ALDR system, the energy consumption of both desiccant regeneration systems will be discussed in the next section.

6.6 Energy saving potential of the ALDR system

The power consumption of the proposed ALDR system is compared with that of the conventional packed-bed regenerator from [5] for regenerating unit mass flow of desiccant solution. The total power consumption, E_{total} in the ALDR system can be obtained by [41]

$$E_{total} = E_{gen} + E_{con} + E_{vacuum} + E_{pump} \quad (6-3)$$

where E_{gen} indicates the power consumption for heating the desiccant solution at generator side, E_{con} is the power consumption for condensing the vapor at condenser

side, E_{vacuum} is the power consumption of the vacuum pump in the ALDR system and E_{pump} refers to the power consumption of the pump of the solution.

The power consumption of the heat exchangers can be obtained as [41, 46]

$$E_{gen} = \dot{m}_{hw} c_{p,hw} (T_{hw,out} - T_{hw,in}) / \eta_{gen} \quad (6-4)$$

$$E_{con} = \dot{m}_{cw} c_{p,cw} (T_{cw,in} - T_{cw,out}) / COP \quad (6-5)$$

where $\dot{m}_{hw}$ and $\dot{m}_{cw}$ are the mass flow rate of hot water and cooling water respectively, $c_{p,hw}$ and $c_{p,cw}$ are the specific heat capacity of hot water and cooling water respectively, $T_{hw,in}$ and $T_{hw,out}$ are the inlet and outlet hot water temperatures respectively, $T_{cw,in}$ and $T_{cw,out}$ are the inlet and outlet cooling water temperatures respectively, η_{gen} is the efficiency of the heat exchanger at generator and COP is the overall performance coefficient of the chiller system.

The efficiency of the heat exchanger of generator is assumed as 80% and the COP of the chiller system is assumed to be 2.5 as a constant. The power consumption of the pump can be neglected as the power consumption of both systems is compared with the same mass flow rate of the desiccant solution. The power consumption of the vacuum pump in the ALDR system provided by the manufacturer is 370W for the displacement speed of 2L/s.

From reference [5], the system is an adiabatic packed-type regeneration system which consists of an air handling system, a liquid desiccant system and a water system. The air handling system which is used to create the desired air flow conditions consists of a cooling coil, a heater, a humidifier and a fan. The liquid desiccant system includes the concentrated solution tank, the diluted solution tank, solution pump, solution valve and heat exchanger. Thirdly, the water system involves a heater, water valve and heat exchanger. Both the liquid desiccant system and water system handle the solution before being inserted into the regenerator. Therefore, the total power consumption by the system to regenerate solution can be obtained by summing the power consumed by the

heat exchanger, fan and pump. To ensure fair comparison, the power consumption of the proposed system and the conventional system from the reference are compared for regenerating unit mass flow of solution.

Figure 6.7: Comparison of power consumption between packed-bed regenerator from reference [5] and the ALDR system when regenerating unit mass flow of desiccant solution

Figure 6.7 and Table 6.4 show the comparison of power consumption in the packed-bed regeneration system from [5] and the ALDR system for regenerating unit mass flow of desiccant solution with respect to the regeneration rate. It could be observed that the proposed ALDR system consumed less energy to regenerate the desiccant solution. This was due to the regeneration temperature of the ALDR system was much lower than that of the conventional packed-bed regenerator. The regeneration temperature of the proposed ALDR system was 20-35°C as shown in Subsection 6.4.2 whereas the regeneration temperature was 49-63°C for the regeneration system in [5]. The regeneration temperature of the proposed system depends on the vacuum pressure in the enclosed regenerator tank. When the surrounding pressure is lower, the boiling temperature of the solution which is the regeneration temperature will also be lower. Hence, the energy required for the water vapor to escape from the desiccant solution is

also lower.

From the results, the power consumption of the heating system obtained was around 9-12kW by using Equation (6-4) considering the efficiency of the heat exchanger, sensible and latent heat transfers. On the other hand, the condenser also required around 5-7.5kW to condense the vapor generated which can be calculated using Equation (6-5) considering the COP of the chiller. Summing the power consumption at these two components and vacuum pump resulted in the total power consumption for the system to be around 15-20kW. Since this was compared with the packed-bed regeneration system from the literature, the power consumptions for the both systems were compared for regenerating unit mass flow of solution to ensure fair comparison. Therefore, the total power consumption for regenerating unit mass of solution was around 20-30kW with the operational range of solution mass flow at around 0.63-0.83kg/s in the proposed ALDR system.

As compared to the packed-bed desiccant regenerator from the reference, the results showed that the proposed ALDR system had a significant energy saving potential as high as 40.66% in regenerating the desiccant solution by operating the liquid desiccant regeneration system under vacuum condition. The power consumption for regenerating unit mass flow of solution in both systems can be fitted as in Equations (6-6) and (6-7) respectively:

$$\bar{E}_{packed-bed} = -0.1187 \times \overline{MRR}^2 + 8.0686 \times \overline{MRR} + 18.555, R^2 = 0.99 \quad (6-6)$$

$$\bar{E}_{ALDR} = -2.216 \times \overline{MRR}^2 + 23.732 \times \overline{MRR} - 19.707, R^2 = 0.99 \quad (6-7)$$

where $\bar{E}$ and $\overline{MRR}$ are the power consumption in kW and MRR in g/s for regenerating unit mass flow of solution respectively and the subscript *packed – bed* and *ALDR* represent the packed-bed regenerator from [5] and the proposed ALDR system respectively.

Table 6.4: Energy saving of the ALDR system compared to packed-bed regeneration system from reference [5] when regenerating unit mass flow of solution

MRR (g/s)	Power consumption (kW)		Energy saving (%)
	ALDR system	Reference [5]	
2.145	20.96	35.32	40.66
2.371	24.44	37.02	33.98
2.449	24.71	37.60	34.28
2.486	25.68	37.88	32.19
2.738	28.69	39.76	27.84

6.7 Summary

In summary, several experiments have been conducted to test for the feasibility of the proposed ALDR system. From the results obtained, it was proved that the application of vacuum condition in regenerating the desiccant solution was able to reduce the regeneration temperature of a desiccant regeneration system in LDDS. The regeneration temperature was found to be ranged between 20°C and 35°C when operating in vacuum pressure between 1000Pa and 2000Pa to regenerate solution from 36% mass fraction which agreed well with the possible regeneration temperature discussed in Figure 6.1.

In addition, the energy saving potential of the proposed ALDR system in regenerating the desiccant solution was shown by comparing to the conventional packed-bed regenerator from literature and this brought out the contribution of this research work. Results showed that the ALDR system was able to show its energy saving potential as high as 40.66% for regenerating unit mass flow of desiccant solution compared to the packed-bed desiccant regenerator. Furthermore, the reduction of regeneration temperature in desiccant regeneration system allows more potential use of low-grade or renewable energy source in the regenerator.

Chapter 7 Conclusion and Future Work

7.1 Conclusion and summary

A novel liquid desiccant regeneration system operating under vacuum condition namely ALDR system has been proposed in this work as an alternative to replace the conventional packed-bed regenerator in LDDS. The proposed liquid desiccant regeneration system was aimed at reducing the regeneration temperature of the desiccant solution in the regeneration system so as to reduce the energy consumption of the LDDS. Besides that, more low-grade or renewable energy source can be used as the heating source in the desiccant regeneration system. The design of the proposed system operating under vacuum condition has been described in detail. A Singapore patent application has been submitted and filed for this novel ALDR system.

An accurate and reliable performance prediction model has been developed to predict the regeneration performance of the proposed ALDR system. The prediction model was developed based on the energy and mass balance equations and the concept of perfectness. Two main performance indices namely MRR and MFI were introduced to indicate the regeneration performance of the newly proposed system. The developed performance prediction model was then validated with the experimental results. It was found that the prediction values were in good agreement with the experimental values where the 94.12% of the points was within $\pm 10\%$ error with the average deviation of less than 3.37%. The performance of the proposed system was also investigated under different operating conditions. From the results, the temperatures of both heating and cooling sources had more significant effects towards the regeneration performance than respective flow rates. These two parameters can be taken as the regulating parameters to obtain better regeneration performance of the ALDR system. The relevant parameters can also be used when designing the control strategies of the proposed system.

A dynamic model for the ALDR system has also been developed. The dynamic model was based on the simplified approach where the internal and external energy and mass balance equations were considered. The simulation model was validated with the experimental data obtained from the system experimental platform developed in the laboratory. The experimental and simulated output temperatures agreed well with each other where the mean absolute errors between the simulated and experimental temperatures were less than 0.51°C . Besides that, the deviation between the simulated and experimental thermal power for both the generator and condenser was within $\pm 15\%$ error. Therefore, it could be said that the model developed was accurate enough to predict what happen in the system during the regeneration process. The dynamic behavior of the regeneration system was also showed by applying an increase in the inlet temperature to the system model. The simulated dynamic behavior of the proposed system after the step change in temperature was consistent with what would be expected with thermodynamics. The results showed that it could be used to describe the dynamic performance of the proposed liquid desiccant regeneration system operating under vacuum condition. The dynamic model developed in this chapter is able to describe the vacuum pressure phenomenon in the system which will be useful to be employed to design a vacuum pressure controller in the ALDR system. The model is can also be adapted to explain the behavior of different liquid desiccant regeneration systems operating under vacuum condition if the system design data are available.

A series of experimental tests has been carried out to test for the feasibility of application of vacuum pressure condition in regenerating the desiccant solution. It has been proved that the regeneration temperature has been reduced to $20\text{-}35^{\circ}\text{C}$ at vacuum pressure around $1000\text{-}2000\text{Pa}$ in order to regenerate the LiBr solution from 36% solution concentration. The parameters and operating conditions of the proposed ALDR system were also compared with those of the conventional packed-bed regenerator from literature. In addition, the power consumption of the ALDR system was also compared with the packed-bed regenerator from the literature and it was found that the power consumption of the proposed system was reduced by 40.66% where the energy saving

potential of the proposed ALDR system was validated. The reduction of the regeneration temperature and power consumption in the proposed system highlighted the contribution of this work.

7.2 Future work

From the work done so far, several future directions are suggested as continuation work on this topic.

A) Modification of the experimental platform of the ALDR system

The first prototype of the ALDR system platform has been developed. Several difficulties and problems were encountered when operating the experimental platform of the proposed ALDR system. Therefore, some modifications of the system are recommended as follows:

1. The capacity of the heater which acts as the heating source in the ALDR system are not large enough to maintain the temperature of hot water throughout the regeneration process. Therefore, a heater with higher capacity should be installed to obtain more accurate experimental results. The current installed heater has the capacity of 8 kW, a heater with 10 kW heating capacity is suggested to increase the performance of the system.
2. The vacuum pump in the system should be replaced by a pump with higher displacement speed which can reduce the time of setting the initial vacuum pressure before an experimental test is carried out. For experimental purpose, it takes long time to set the initial vacuum pressure of the system which is around 1000Pa. Therefore, a vacuum pump with higher displacement speed (DM15) is suggested for the effectiveness in carrying out the experimental tests.
3. For the next prototype of the ALDR system, more sensors should be installed inside the enclosed regenerator tank to have a clearer view of the change of some relevant parameters. As per discussion in Chapter 5, since temperature sensors and density meter are not installed inside the regenerator tank, the change of important

parameters cannot be observed. For instance, a concentration sensor or density meter should be installed inside the regenerator tank or along the solution path to observe the change of the solution concentration with time.

- B) Investigation of the system performance and energy savings of regeneration process when integrated with the dehumidifier in LDDS

In LDDS, the desiccant solution absorbs the moisture in the process air and becomes diluted. The diluted desiccant solution then flows to the desiccant regeneration system to regenerate the solution concentration. The ALDR system should be integrated with the dehumidifier in LDDS as in Figure 3.1 to ensure the feasibility of the integration and investigate the overall performance in LDDS.

Several attentions should be paid when integrating the ALDR system with the dehumidifier. The solution concentration range in the regeneration process must be compatible to that in the dehumidifier. Therefore, an effective solution concentration controller is needed for the ALDR system. Besides that, the temperature difference between the solution leaving the dehumidifier and entering the regenerator and also the temperature difference between solution leaving the regenerator and entering the dehumidifier should be focused as well. Additional heater and cooler may be required for this purpose. The overall energy consumption for the integrated system should be investigated to validate its energy saving potential.

The moisture removed from the dehumidification system must be equal to the moisture removed from the diluted desiccant solution in the regeneration system considering the handling process of the whole LDDS. In short, the dehumidification load should be equal to the regeneration load as shown in Equations (7-1) and (7-2)[41].

$$MRR_{deh} = \dot{m}_{air,in,deh} \times (d_{air,in,deh} - d_{air,out,deh}) \quad (7-1)$$

$$MRR_{deh} = MRR_{reg} \quad (7-2)$$

where subscripts *deh* and *reg* represent dehumidification and regeneration systems

respectively, and d is the humidity ratio of the air stream in dehumidifier.

C) Application of low-grade or renewable energy sources in the ALDR system

Since this is the first prototype of the proposed system, the heating and cooling sources installed in the first prototype system are the electric heater and chiller system respectively as per discussion in Chapter 3. The two sources are employed at the beginning stage of the system development as the parameters such as the temperature and flow rate of water can be easily regulated to investigate the regeneration performance of the system. Different heating or cooling sources such as the waste heat or renewable energy sources can be installed to investigate the regeneration performance and energy saving potential of the proposed system.

The heating source at the generator side of the system can be the condenser in the heat pump cycle, solar energy, waste heat from industry or any other low grade renewable energy source. On the other hand, chilled water from a chiller, cooling sea water, cooling water from cooling tower, chiller plant condensed water or evaporator in the heat pump cycle can be the cooling source for the condenser in the proposed ALDR system. In order to realize it, the working conditions discussed in Chapters 4 and 6 can be referred. The working conditions of the energy sources must be compatible with those in the ALDR system.

D) Design of controller of the ALDR system

The drastic change of vacuum pressure as discussed in Section 4.5 was able to be described by the dynamic model developed in Chapter 5. Based on the dynamic model developed, a vacuum pressure controller can be designed for the ALDR system to increase its regeneration performance and system energy efficiency.

Since this topic is still under-explored, different control strategies for vacuum pressure should be proposed first. The control strategies in absorption chiller and air conditioning system can be taken as references here [2, 14, 72]. The control performance

in the ALDR system is then investigated when different control methods are adopted. The effectiveness of each control strategy is then evaluated and compared under different operating conditions. The model-based multivariable control design method presented in references [54, 73] can be exploited for the ALDR system. A model-based controller can be developed to control the vacuum pressure in the ALDR system by using the appropriate control strategy.

E) Economic analysis of the ALDR system

By using the calculated energy saving potential of the proposed ALDR system in Section 6.6, the payback years of the proposed system could be obtained in order to further investigate the feasibility of the ALDR system. The initial cost of the proposed system employed in this study was about S\$30000. The current cost of electricity in Singapore is S\$0.2030/kWh. By considering the energy saving potential at standard operating conditions shown in Table 4.1, the estimated annual energy saving costs could be obtained. The payback period was found to be around 6 years and 10 months which shows that the extra costs could be refunded in a short period. The payback period was thus reasonable and practical for installing the proposed ALDR system in LDDS in regenerating the desiccant solution.

A thorough and detail economic analysis of the proposed system can be carried out in the future to further investigate the feasibility of the proposed system in the real applications and compared with the conventional regeneration systems. Several parameters such as the initial cost, operating cost, life cycle cost and payback period can be calculated to investigate the system feasibility from the economic point of view. The initial cost is the cost required for the purchase and installment of the system. The operating cost is the cost to operate the system. Meanwhile, the life cycle cost is the summation of the initial cost and operating cost. The payback period is the time required for the energy savings of a more energy efficient technology to cover the additional initial cost of the system.

Author's publications

1. Patent application filing of the proposed ALDR system

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Filing Date : 15 July 2016

Ref : PAT/071/15/16/SG

Title : Regenerator For A Dehumidification System, Dehumidification
System And Method Of Regenerating Liquid Desiccant

Inventors : 1) **CAI** Wenjian; 2) **WANG** Xinli; 3) **YON** Hao Ren

2. Yon Hao Ren, Cai Wenjian, Shen Suping, Dynamic Study of Liquid Desiccant Regeneration System Operating in Vacuum Condition, The 13th IEEE International Conference on Control and Automation (IEEE ICCA 2017), 3-6th July 2017, in Ohrid, Macedonia
3. Yon Hao Ren, Cai Wenjian, Wang Youyi, Shen Suping, Performance investigation on a novel liquid desiccant regeneration system operating in vacuum condition, Applied Energy, 2018, 211: 249-258
4. Yon Hao Ren, Cai Wenjian, Wang Youyi, Wang Xinli, Shen Suping, Dynamic model for a novel liquid desiccant regeneration system operating in vacuum condition, Energy and Buildings, 2018, 167: 69-78

Appendix

Table A.1: Detailed experimental results of the proposed ALDR system

No.	P (Pa)	$T_{sol,in}$ (°C)	$T_{hw,in}$ (°C)	$T_{cw,in}$ (°C)	$\dot{V}_{sol,in}$ (m ³ /h)	$\dot{V}_{hw}$ (m ³ /h)	$\dot{V}_{cw}$ (m ³ /h)	$n_{sol,in}$ (%)	$n_{sol,out}$ (%)	$T_{sol,out}$ (°C)	$T_{hw,out}$ (°C)	$T_{cw,out}$ (°C)	ΔV_{water} (m ³)
1	1100	22.7	38.0	8.0	2.209	1.13	1.99	36.46	47.07	31.9	30.4	15.0	0.01968
2	1100	22.2	38.0	8.0	2.210	1.28	1.99	36.54	47.75	33.1	31.1	15.0	0.02036
3	1100	23.1	38.0	8.0	2.214	1.53	1.99	36.46	47.93	34.9	31.5	14.7	0.02104
4	1100	22.4	38.0	8.0	2.245	1.63	1.99	36.31	48.66	35.4	31.1	15.5	0.02205
5	1100	22.8	36.0	8.0	2.210	1.63	1.99	36.31	46.13	32.5	31.7	14.4	0.01798
6	1100	23.4	37.0	8.0	2.223	1.63	1.99	36.46	47.26	32.5	31.7	14.9	0.01968
7	1100	21.5	38.0	8.0	2.234	1.63	1.99	36.77	47.81	34.1	32.5	14.7	0.02036
8	1100	21.9	39.0	8.0	2.243	1.63	1.99	36.31	47.93	34.3	33.2	15.1	0.02104
9	1100	22.1	40.0	8.0	2.237	1.63	1.99	36.62	49.08	36.2	32.7	14.9	0.02239
10	1100	21.7	38.0	8.0	2.235	1.63	1.13	36.70	47.57	34.3	32.2	15.5	0.02002
11	1100	22.7	38.0	8.0	2.230	1.63	1.31	36.46	47.50	34.5	32.0	15.8	0.02019
12	1100	21.1	38.0	8.0	2.230	1.63	1.65	36.39	47.57	34.5	31.5	15.2	0.02036
13	1100	21.9	38.0	8.0	2.244	1.63	1.99	36.46	48.06	34.4	31.2	15.2	0.02104
14	1100	21.8	38.0	7.0	2.251	1.63	1.99	36.39	48.36	34.4	31.3	13.8	0.02273
15	1100	23.1	38.0	8.0	2.245	1.63	1.99	36.46	47.93	34.9	32.5	14.7	0.02171
16	1100	22.4	38.0	9.0	2.230	1.63	1.99	36.62	47.13	35.1	32.3	16.0	0.02070
17	1100	21.5	38.0	10.0	2.212	1.63	1.99	36.62	45.55	34.8	32.7	15.6	0.01764

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