NUMERICAL STUDY ON THE EFFECTS OF REGENERATION TEMPERATURE ON DEHUMIDIFICATION PERFORMANCE OF DESICCANT MATERIALS

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A thesis submitted in fulfilment of the
requirements for the award of the degree of
Master of Philosophy

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DECEMBER 2020

DEDICATION

This thesis is dedicated to beloved mother, father, sisters and brother.

ACKNOWLEDGEMENT

First and foremost, thank and praise to Allah SWT for his blessing and greatness for giving me strength and unbroken willingness that enable me to endure all the challenges faced in completing this project.

In this opportunity, I also like to express my utmost gratitude to my supervisors, Prof. Madya Dr Haslinda binti Mohamed Kamar and Dr. Nazri bin Kamsah for their relentless guidance, patience and lessons that have brought me this far, opening my mind to this whole new field in engineering. It’s always been a pleasure to learn everything I could from them. Insya’Allah the knowledge gained from them will be put into good use.

I am also indebted to Universiti Teknologi Malaysia (UTM) for providing the funding for this study, under the vote number 20H44. The financial supports are managed by the Research Management Centre (RMC), Universiti Teknologi Malaysia.

Also, I would like to thank everyone who has been involved directly or indirectly with this project from the beginning till the end especially my family who always pray for me for my good will. Not to forget my fellow postgraduate students and all my friends who always shows their support and concern while this project was in progress.

ABSTRACT

Desiccant is a material that can adsorb water vapor in the air and is widely used in the solid desiccant dehumidifier (SDD). Properties of desiccant material would affect the dehumidification performance of the SDD system. Research and development of desiccant materials have continued to gain attention by researchers. The material should have high adsorption capacity and can be easily-regenerated at a low regeneration temperature. This is as a result of the global quest to solve energy and environmental issues. Despite the development of many new desiccant materials, few studies were reported on the performance assessment of various desiccant materials in the SDD system. Such an assessment can be done through experimental work, but this requires repetitive testing, which can be expensive and time-consuming. Several researchers have used numerical simulations. However, the studies were carried out only on a two-dimensional (2D) simplified model of a single air channel for predicting the performance criteria. These models reduce the reliability of the findings because of the oversimplification from a real condition. Therefore, this study aims to determine the effects of regeneration temperature on the moisture removal capacity (MRC), dehumidification effectiveness (DE), and coefficient of performance (COP) of desiccant materials using a three-dimensional (3D) model. A 3D model of the single air channel enclosed with desiccant material was developed. The incompressible flow simulations were carried out using transient solver. The model was validated by comparing the time-variation of average moisture content and temperature of process air and regeneration air at the channel exit using experimental data obtained from the literature. It was found that the difference between the measured and predicted moisture content and temperature during adsorption process is 5.4 % and 1.0 %, respectively. For the desorption process, the difference between the measured and predicted moisture content and temperature is 3.0 % and 0.3 %, respectively. These figures show that the 3D single-channel model is well-validated and reliable for predicting the desiccant material performance. Four types of desiccant materials were considered, and six values of regeneration temperature were selected to evaluate their effects on the performance. Among all four materials, silica gel/$CaCl_2$ has the highest MRC, DE, and COP. MRC increases from 0.3 g/s at 40°C to 0.57 g/s at 90°C. DE of silica gel/$CaCl_2$ rises from about 22 % at 40°C to 43 % at 90°C. This is because at a higher regeneration temperature, more moisture can be desorbed from the desiccant material. This condition increases the ability to adsorb moisture for the next adsorption process and it leads to a higher MRC and DE. The COP values decrease from 0.9 at 40°C to 0.7 at 90°C. This is because, at a higher regeneration temperature, the regeneration heat consumption increases and lead to a lower COP. It is also observed that zeolite 13X has the lowest performance compared to other desiccant materials. The average value of MRC, DE, and COP for zeolite 13X are 0.27 g/s, 20.3 %, and 0.46, respectively. This research contributes to an economical and accurate way for determining the performance criteria of solid desiccant materials. With the established 3D model, the most suitable desiccant materials that give the highest performance can be identified accurately.

ABSTRAK

Bahan pengering adalah bahan yang boleh menyerap wap air di udara dan digunakan secara meluas dalam mesin penyahlembapan udara jenis pepejal (SDD). Sifat-sifat bahan pengering memberi kesan kritikal kepada prestasi sistem SDD. Penyelidikan dan pembangunan bahan-bahan pengering terus mendapat perhatian oleh penyelidik. Bahan ini perlu mempunyai kapasiti penjerapan yang tinggi dan boleh diregenerasi dengan mudah pada suhu yang rendah. Ini adalah hasil daripada usaha global untuk menyelesaikan masalah tenaga dan persekitaran. Walaupun kejayaan yang dicapai daripada pembangunan bahan-bahan pengering, kurang kajian yang dilakukan untuk menguji prestasi pelbagai bahan-bahan pengering dalam sistem SDD. Ia boleh dilakukan dengan menggunakan kaedah eksperimen, bagaimanapun, ia memerlukan beberapa set ujian yang mahal dan memakan masa. Beberapa penyelidik telah menggunakan kaedah permodelan. Tetapi, kajian yang lepas menggunakan model saluran udara hanya dalam dua dimensi (2D) untuk meramal prestasi mesin penyahlembapan. Pendekatan ini mengurangkan kualiti data kerana simplifikasi yang berlebihan daripada model sebenar. Oleh itu, kajian ini bertujuan menentukan kesan suhu regenerasi pada kapasiti penyingkiran kelembapan (MRC), keberkesanan penyahlembapan (DE), dan pekali prestasi (COP) pelbagai jenis bahan pengering menggunakan model tiga dimensi. Model tiga dimensi (3D) saluran udara yang dikelilingi dengan bahan pengering telah dicipta dan simulasi aliran dilakukan dengan menggunakan mod penyelesaian fana. Model ini telah disahkan dengan membandingkan variasi masa untuk purata kelembapan dan suhu udara di saluran keluar dengan data eksperimen yang diperoleh dari kajian lepas. Didapati perbezaan antara nilai ukuran dan jangkaan kelembapan udara dan suhu udara semasa penjerapan masing-masing adalah 5.4 % dan 1.0 %. Semasa penyahjerapan, perbezaan antara nilai ukuran dan jangkaan kelembapan udara dan suhu udara masing-masing adalah 3.0 % dan 0.3 %. Nilai-nilai tersebut menunjukkan bahawa model saluran udara 3D disahkan dengan baik dan dipercayai mampu menganggar prestasi bahan pengering. Empat jenis bahan pengering dipertimbang dan enam nilai suhu regenerasi dipilih untuk menilai kesannya ke atas prestasi. Daripada empat jenis bahan pengering, silica gel/$CaCl_2$ mempunyai MRC, DE dan COP yang tertinggi. MRC meningkat daripada 0.3 g/s pada 40°C ke 0.57 g/s pada 90°C. DE untuk silica gel/$CaCl_2$ meningkat daripada 22 % pada 40°C ke 43 % pada 90°C. Ini kerana suhu regenerasi lebih tinggi akan meningkatkan kuantiti wap air dinyahjerap dari bahan pengering. Situasi ini meningkatkan kemampuan penjerapan wap air untuk proses seterusnya dan membawa kepada kenaikan MRC dan DE. COP menurun daripada 0.9 pada suhu 40°C ke 0.7 pada suhu 90°C. Hal ini kerana peningkatan suhu regenerasi akan meningkatkan penggunaan haba semasa regenerasi dan ini membawa kepada penurunan COP. Selain itu, zeolite 13X menunjukkan prestasi terendah berbanding bahan-bahan pengering yang lain. Purata nilai MRC, keberkesanan penyahlembapan, dan COP masing-masing adalah 0.27 g/s, 20.3 % dan 0.46. Kajian ini menyumbang kepada kaedah yang lebih menjimatkan dan tepat untuk menentukan prestasi bahan pengering. Dengan terhasilnya model 3D, bahan pengering yang sesuai dan menghasilkan prestasi tertinggi dapat dikenalpasti dengan tepat.

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LIST OF ABBREVIATIONS

CBD	-	Compressor-Based Dehumidifier
LDD	-	Liquid Desiccant Dehumidifier
SDD	-	Solid Desiccant Dehumidifier
COP	-	Coefficient of Performance
SDP	-	Specific Dehumidification Power
MRC	-	Moisture Removal Capacity
GIT	-	Grid Independence Test

LIST OF SYMBOLS

A - Cross-sectional area of air channel
C - Constant in adsorption curve
c_{pa} - Specific heat of air
c_{pd} - Specific heat of desiccant material
D_{va} - Air diffusivity
D_{vs} - Surface diffusivity
f - Desiccant content
k_a - Thermal conductivity of air
k_d - Thermal conductivity of desiccant
k_m - Effective mass transfer coefficient
q_{st} - Adsorption heat
r - Average radius of desiccant material grain
t - Time
T - Temperature
u - Velocity
w Water uptake in desiccant
x - Axial coordinate
y - Height coordinate
z - Longitudinal coordinate
ε - Porosity
ρ_a - Density of air
ω - Moisture content
a - Air
a, proinlet - Process air inlet
a, reginlet - Regeneration air inlet
d - Desiccant
eq - Equilibrium
max - Maximum
reg - Regeneration

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CHAPTER 1

INTRODUCTION

1.1 Background of Study

Temperature and moisture are two parameters that indicate the level of thermal comfort in a confined space. However, usually people only focus on temperature and rarely on the existence of moisture in the air. The amount of moisture in the air can be evaluated by its relative humidity and specific humidity. Relative humidity is defined as the ratio of the actual mass of moisture in the air at a given temperature to the maximum amount of moisture air that can be hold at that temperature (Cengel and Boles, 2004). Whereas, specific humidity or moisture content is the actual mass of water vapor in 1 kg of dry air (Cengel and Boles, 2004).

Cengel and Boles (2004) stated that a human body generates waste heat and it must be rejected to the environment through perspiration as latent heat. However, the high relative humidity of indoor air may affect that process. This is because, during the perspiration process, surrounding air that has a relative humidity close to 100 % is unable to hold more water vapor. Therefore, the sweat cannot be evaporated into surrounding air and unable to absorb the latent heat from the human body. Prolong exposure to these conditions can lead to people feeling thermally uncomfortable due to an increase in body temperature which could trigger dehydration and heatstroke. This can also produce a humid environment that is conducive to the growth of bacteria (Satwikasari et al., 2018) and causes respiratory and skin problems. Therefore, it is necessary to control the humidity level in the air in order to ensure thermal comfort in a confined space.

Malaysia is a tropical country which has high daytime temperatures in the range of 29-34°C and relative humidity around 70-90 % throughout the year (Daghigh, 2014). The recommended temperature and relative humidity for the indoor environment are 23-26°C and 30-60 %, respectively, as prescribed by ASHRAE Standard-55 (Yang and Zhang, 2008). To attain these conditions, air-conditioning systems are widely used in Malaysia. The numbers of air-conditioning systems in use have increased from 13,000 units in 1970 to more than 250,000 units in 1991, with the numbers expected to rise around 1.5 million units by 2020 (Rambhad et al., 2016). However, the growing demand for air-conditioning has contributed to the massive consumption of electrical power. Other than sensible cooling, air-conditioning systems are also for humidity control. In conventional air-conditioning units, the cooling process and air dehumidification are generally driven by a cooling coil (De Antonellis et al., 2010). The high relative humidity condition in Malaysia results in a significantly high air dehumidification load. Therefore, the conventional method of moisture removal would consume a large amount of energy due to the overcooling process to achieve the desired humidity condition. To overcome the issue, modern air-conditioning systems have a separate unit to handle the latent heat load, which reduces the energy consumption.

An air-dehumidifier is integrated with the air-conditioning system to produce cool air with a desired low-humidity air, for maintaining thermal comfort in building spaces. The air-dehumidifier is also useful for industries such as textile, foods, pharmaceutical, and battery production, which are susceptible to moisture. These industries require environments with low humidity, typically within the range of 20-55% in order to maintain the quality of products and well-being of their machines (Ruiz-Garcia et al., 2009). Humid surrounding air will lead to the corrosion of metals, deteriorated characteristics of hygroscopic material, and increased harmful activity of micro-organisms in products (Moncmanová, 2007).

There are two types of dehumidifier system, namely compressor-based (CBD) and desiccant-based dehumidifiers. The compressor-based-dehumidifier (CBD) is a conventional method of removing water vapors by condensation of the vapor-compression refrigeration system (Rambhad et al., 2016). Humid air passes through a cooling coil where it is cooled below its dewpoint temperature in order to be condensed. However, the CBD system consumes large amount of electrical energy during the cooling process. The desiccant dehumidification system, has received much attention recently, as an alternative to the CBD type (Yamaguchi and Saito, 2013). In this system, the humid air is dehumidified without condensation, but instead using only sorption by the desiccant material. This can help reduce the electrical energy consumption.

Desiccant dehumidifiers can be characterized into two categories, namely liquid desiccant dehumidifier (LDD) and solid desiccant dehumidifier (SDD). The main components of an LDD system are the absorber and the regenerator. Whereas, an SDD consists of an air heater, a drive motor, and desiccant materials constructed in the form of a wheel that rotates at a low speed. The advantage of the liquid desiccant is that regeneration can be carried out at a lower temperature with high moisture removal capacity (MRC) (Misha et al., 2012). However, liquid desiccant such as lithium chloride (LiCl) are highly corrosive. These liquid droplets can be carried over by dehumidified air to the conditioned space. As the droplets become dehydrated in the air, it could form “salt fog” which can cause damage to furniture, machines and materials, and also harmful to human health. Therefore, this system has potential risks on the indoor air quality in buildings (Zhang et al., 2014). The SDD system consumes less electrical energy due to the absence of the pump and other moving parts (Wu and Wang, 2006). It has a low risk of crystallization, less corrosive and only a minor risk of damage due to high temperatures compared to the liquid desiccant system (Misha et al., 2012). The solid desiccant material is also environmental-friendly.

Two of the most critical components in the SDD system are the desiccant wheel and solid desiccant material itself. The solid desiccant material is corrugated in numerous channels inside the rotary wheel. Cheng et al. (2016) carried out a study on the influence of desiccant material properties on dehumidification effectiveness. It was found that the thermal conductivity, specific heat, porosity, tortuosity, and thickness of desiccant materials affect the SDD performances. Jia et al. (2007) compared the silica gel and composite desiccant on the coefficient of performance (COP) and MRC. It was found that the composite desiccant wheel adsorbed more water vapor than the silica gel. Zhang et al. (2014) investigated the effects of ten types of desiccant materials on COP, specific dehumidification power (SDP), and dehumidification effectiveness.

The performance of the desiccant wheel is also affected by several design and operating parameters, including the wheel geometry, rotation wheel speed, inlet process air properties, inlet regeneration temperature, and inlet airflow velocity (Yamaguchi and Saito, 2013; Cheng et al. 2016). Jia et al. (2007) conducted a similar study through an experimental method. Other researchers have used a numerical method (Misha et al., 2012; Yamaguchi and Saito, 2013). This approach is less complicated, cheaper, consumes less time and labor. Cheng et al. (2016) established a three-dimensional single-channel model to represent the desiccant material. It was concluded that the three-dimensional model is reliable and gave accurate predictions with real situation compared to the two-dimensional model. Many researchers have used a single-channel model to describe the airflow through the desiccant wheel. To reduce the computational costs, it is reasonable to use a single channel to represent the multiple channels in the desiccant wheel (Yadav et al., 2014).

1.2 Problem Statement

Research and development of desiccant materials have continued to gain attention by researchers. The desiccant materials should have a high adsorption capacity and can be easily-regenerated at low regeneration temperature when applied in a dehumidifier. Some of the developed materials have been analyzed in the solid desiccant dehumidifier (SDD) system to evaluate its performance. The analyses have involved conducting experiments on the SDD system with extensive parametric analysis. However, a series of tests are needed, which make this approach become expensive and time-consuming. To ensure efficiency in carrying out the parametric analysis, numerical modeling can be adopted where it promotes both energy- and cost-savings. To this date, there are insufficient studies in three-dimensional modeling. Many researchers' studies have only developed simplified models of the desiccant material in two-dimensional. This reduces the accuracy of the simplified models of the SDD. This study aims to determine the effects of regeneration temperature on the moisture removal capacity (MRC), dehumidification effectiveness and coefficient of performance (COP) for various types of desiccant materials; using three-dimensional numerical modeling approach. A mathematical model of mass and energy conservations in an air channel was presented. A three-dimensional model of the single air channel enclosed with desiccant material was developed. The flow simulations were carried out under a transient-state condition. The model was validated by comparing the time-variation of average moisture content and temperature of process air at channel exit with the experimental data obtained from the literature. Four types of desiccant materials were considered. The effects of various regeneration temperatures on moisture removal capacity, dehumidification effectiveness, and thermal effectiveness were examined. This research contributes to an economical way for determining the performance criteria of solid desiccant materials. With the established method, the most suitable desiccant materials that give the lowest possible humidity of process air at any given regeneration air temperature can easily be identified.

1.3 Research Objectives

The objectives of this research are:

(a) To develop and validate a three-dimensional model of a single channel of solid desiccant air dehumidifier.

(b) To examine the effects of regeneration temperature on the moisture removal capacity, dehumidification effectiveness and coefficient of performance for various desiccant materials.

1.4 Research Scopes

The scopes of the research are:

(a) Type of dehumidifier used in this study is rotary-type solid desiccant air dehumidifier.

(b) Four types of desiccant materials to be considered are:

a. Silica gel B

b. Composite of silica gel and calcium chloride, $CaCl_2$ (silica gel/$CaCl_2$)

c. Zeolite 13X

d. Composite of zeolite 13X and calcium chloride, $CaCl_2$ (zeolite 13X/$CaCl_2$)

(c) A three-dimensional single-channel model is developed using commercial multi-physics software.

(d) The analysis is carried out in transient condition.

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1. Norazam, A.S., Kamar, H.M., Kamsah, N., Alhamid, M. (2019). Performance Analysis of a Solid Desiccant Wheel Material. *International Journal of Technology*. *10*(6), 1120-1130. https://doi.org/10.14716/ijtech.v10i6.3590. (Indexed by SCOPUS)

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1. Norazam, A.S., Kamar, H.M., Kamsah, N. and Alhamid, M.I., (2019). Simulation of adsorption process in a rotary solid desiccant wheel. *The 10th International Meeting of Advances in Thermofluids.* 16- 17 November. Bali, Indonesia; AIP Publishing LLC, 020012. (Indexed by SCOPUS)