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STUDIES ON MCM-41 AIR-TO-AIR HEAT EXCHANGER; FABRICATION, PERFORMANCE AND MODELING

BY

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A thesis submitted in fulfilment of the requirement for the degree of Master of Science
(Materials Engineering)

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ABSTRACT

The present work describes a study on one variation of air-to-air heat exchanger using a novel hydrophilic membrane, i.e. synthesized from MCM-41 inorganic material, to transfer moisture and heat across the membrane. MCM-41 is a mesoporous molecular sieve material. The MCM-41 membrane is synthesized from sol-gel technique at room temperature and developed using deep coating technique with matrix support of polyester mesh. The synthesized MCM-41 material possessed the following properties: BJH pore size of 2.8 nm, wall thickness of 1.12 nm, BET surface area of 1102 $m^2.g^{-1}$, pore volume of 0.97 $cm^3.g^{-1}$ and permeability of $3.622x10^{-22}$ m^2. A two-chamber, concurrent (parallel) flow heat exchanger core is constructed from poly (methyl methacrylate) with the MCM-41 membrane placed in between the chambers. The channel possessed an opening size of 5 mm x 5 mm with total length of 225 mm. The air heat exchanger is intended to operate using outdoor air supply. Thus, two cooling conditions of outdoor air supply are studied; (i) dry air supply as in the case of normal bright day, and (ii) moist air supply as in the case on rainy day. The heat load in the experiment is a hot dry air flow (85 °C and 3%RH). The cooling flow is normal, ambient cooling air fixed at 26 °C and 50%RH. Under the humid or moist air cooling condition, the heat exchanger coefficient is higher i.e. 238.26 $W/m^2°C$ as compared to 186.45 $W/m^2°C$ obtained under the dry air cooling condition. The improvement in the heat exchanger coefficient is attributed to the increment of the total specific heat capacity in cool flow due to the presence of water droplets in humid cooling flow. Using the finite volume method, the heat exchanger is modeled as three volumes of fluid i.e. the heat load volume, the cooling volume and separated by the MCM-41 membrane volume. All the three volumes are defined as the same fluid but with the membrane volume subjected to porous medium type. Further, the moist cool flow volume is treated as a 3-phase flow volume i.e. air, water vapor and water droplets. The results of the CFD simulation are in very good agreement with the experimental data. The membrane air exchanger model is then further developed to simulate the form of cross-flow heat exchanger. Finally, LBM is used to model the MCM-41 membrane at mesoscale. The model could be used to estimate the permeability of the membrane separator and also to simulate the stream flow profile of fluid upon entering the hive structure of MCM-41.

خلاصة البحث

هذا البحث يصف دراسة حول تنوع مبادل حراري من نوع هواء–هواء باستخدام غشاء مائي جديد، مصنَّع من مواد غير عضوية (MCM-41)، لتقوم هذه المواد غير العضوية بنقل الرطوبة والحرارة للغشاء. المواد الغير عضوية المستخدمة عبارة عن مواد شبكية (مساميّة) متوسطة الحجم. ويتم تصنيع هذا الغشاء (MCM-41) من تقنية غِراء–هُلام (صل–جل، Sol-gel) في درجة حرارة الغرفة وتطويرها باستخدام تقنية الطلاء (الغراء) العميق بدعم مصفوفة شبكة (منخليّة) من البوليستر. يتم التحقق من التشكيل الهيكلي لمواد (MCM-41) باستخدام حيود الأشعة السينية (XRD) بالإضافة لاستخدام مُجهِر ماسح الكتروني لانبعاث المجال الضوئي (FESEM)، في حين يتم تحليل مساحة السطح وتوزيع حجم المسام بجهازBET (بروناور–ايميت–تِلر). وعلاوة على ذلك عملية تشكّل سطح الغشاء تمت ملاحظتها باستخدام مجهر القوة الذرية (AFM) ومُجهِر ماسح الكتروني (SEM). تمتلك المواد المصّنعة الخصائص التالية: حجم المسام 2.8 نانومتر، سمك الجدار 1.12 نانومتر، مساحة السطح 1102 م2\ غ، حجم المسام 0.97 سم3\ غ، ونفاذية بمقدار 3.622×10–22م2. نواة المبادل الحراري المتزامن تتألف من شفع من الحُجُرات مصنوعة من مادّة شبكة (ميتاكريليت الميثيل) مع غشاء(MCM-41) بين حجرتي المبادل. حجم فتحة القناة 5مم×5مم وطولها225مم. سيتزود المبادل الحراري الهوائي الموصوف بالهواء الطلق. بالتالي، تمّت دراسة حالتين من حالات التبريد بالهواء الطّلق: (أ) هواء جاف كما في الأيام العادية، (ب) هواء رطب كما في الأيام الماطرة. الحمل الحراري في التجربة هو هواء جاف حار دافق (85 درجة مئوية، مع رطوبة نسبية 3 بالمئة). تدفق التبريد طبيعي، وتبريد الهواء المحيط مثبّت عند 26 درجة مئوية، مع رطوبة نسبية 50 بالمئة. في ظل حالة التبريد بالهواء الرطب أو النّدي، معامل المبادل الحراري كان أعلى أي 238.26 (و\م2بدرجة مئوية)، مقارنة مع 186.45 (و\م2بدرجة مئوية) في حالة الهواء الجاف. ويعزى التحسن في معامل مبادل الحرارة إلى زيادة إجمالي السعة الحرارية النوعية في التدفق البارد بسبب وجود قطرات الماء في تدفق التبريد الرطب. باستخدام طريقة (الحجم المحدود)، تمت وضع نموذج المبادل الحراري كثلاثة كتل من السوائل ألا وهي كتلة الحمل الحراري، وكتلة التبريد مفصولين بكتلة الغشاء. الكتل الثلاثة لها نفس السائل لكن كتلة الغشاء خضعت إلى تصفية مسامية متوسطة. علاوة على ذلك، تمّ التعامل مع كتلة الدفق الرطب ككتلة دفق ثلاثي المراحل ألا وهي هواء، وبخار الماء وقطرات الماء.نتائج محاكاة حركيات الموائع الحسابية (ح.م.ح) جاءت متوافقة لحد كبير مع التجربة العملية. بعد ذلك فإنّ نموذج غشاء مبادل الهواء طوّرَ لمحاكاة نموذج تدفق المبادلات الحرارية التقاطعي (التصادمي). أخيراً تم استخدام طريقة بولتزمان للشبكات لنمذجة غشاء (MCM-41) في النطاق المتوسط. يمكن أن يستخدم النموذج لتقدير نفاذية الغشاء الفاصل وأيضاً لمحاكاة تدفق تيار الشخصي من السوائل عند دخول الهيكل النحلي لمادة (MCM-41).

APPROVAL PAGE

I certify that I have supervised and read this study and that in my opinion, it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Master of Materials Engineering.

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DECLARATION

I hereby declare that this dissertation is the result of my own investigations, except where otherwise stated. I also declare that it has not been previously or concurrently submitted as a whole for any other degrees at IIUM or other institutions.

Drajat Egowibawa

Signature …………………………………… Date ……………………

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STUDIES ON MCM-41 AS AIR-TO-AIR HEAT EXCHANGER

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LIST OF ABBREVIATIONS

AFM	Atomic Force Microscope (AFM, JEOL Co. Ltd.).
BET	Brunauer–Emmett–Teller.
BJH	Barrett-Joyner-Halenda
CFD	Computational Fluid Dynamics.
CTAB	Cetyltrimethyl ammonium bromide.
FESEM	Field Emission Scanning Electron Microscope.
IUPAC	International Union of Pure and Applied Chemistry
LBM	Lattice Boltzmann Methods.
MCM-41	Mobil Composition of Matter-41.
MCM-48	Mobil Composition of Matter-48.
PMM	Poly (methyl methacrylate).
SEM	Scanning Electron Microscope.
TEOS	Tetraethylorthosilicate.

LIST OF SYMBOLS

α	Inertial resistance coefficient.
β	Viscous resistance coefficient.
γ	Surface tension.
δ	Thickness.
ε	Porosity.
θ	Concentration.
λ	Thermal conductivity.
μ,nu	Viscosity.
ρ	Density.
τ	Relaxation parameter.
ω	Humidity.
Ω	Collision operator.
A	Surface area.
AH	Absolute humidity.
cp	Specific heat.
D	Diffusivity.
h	Heat transfer coefficient.
H	Enthalpy.
h	Convective heat transfer coefficient.
J	Flux.
k.	Convective mass heat transfer coefficient.
K,κ	Permeability.

$\dot{m}$	Mass flow.
P,p	Pressure.
q	Heat transfer rate.
Q	Heat.
R	Universal gas constant.
r	Radius.
RH	Relative humidity.
SH	Specific humidity.
T	Temperature.
t	Time.
U	Heat transfer coefficient.
V	Volume.

CHAPTER ONE

INTRODUCTION

1.1 OVERVIEW

Humidity is commonly associated with indoor comfort since air humidity influences the release of heat from human body. For example, humid air in hot weather prevents cooling evaporation of sweat, while not enough humidity in hot air evaporates the moisture from human mucous membranes, skin and hair (Cooper, 2002). Apart from comfort, humidity control is one of the important aspects in thermal management for a variety of applications. Among others, humid air, combine with dust, can cause short circuit to electronic equipments, and too dry-air evaporates moisture from material, in which over period of time damages the surface coating.

Humid air is considered as a binary gas mixture of dry air and water vapor. The amount of water vapor in the air is known as humidity. Humidity can be described as one of the three ways i.e. absolute humidity (AH), relative humidity (RH) and specific humidity (SH). Absolute humidity is the weight of water vapor per unit volume of air steam mixture. Relative humidity is the ratio of actual vapor pressure to saturated vapor pressure of the same temperature. 100% RH means that the air is totally saturated with water vapor and cannot hold any more. Specific humidity is the mass ratio of water vapor to dry air. The study of humid air is known as hygrometry or psychrometry and the device used to measure humidity is called a psychrometer or hygrometer.

Two important processes in humidity are evaporation and condensation, which are both related to latent heat. Latent heat is absorbed during evaporation and released during condensation. As such, managing humidity is one of the key parameters in designing heat exchanger. The consideration is ranging from the effect of condensation in heat exchanger system to study of membrane-based enthalpy exchanger (Jung, 2002; Niu and Zhang, 2001).

A heat exchanger is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact, with usually no external heat and work interactions. Typical applications of heat exchanger involve heating or cooling of a fluid stream and evaporation or condensation of single or multiple component fluid streams. Objective of heat exchanger may be to recover or reject heat, or sterilize, pasteurize, fractionate, distill, concentrate, crystallize, or control a process fluid.

An air-to-air heat exchanger is a heat exchanger in which the energy transfer occurs between airstreams i.e. the heat exchanger is positioned between the supply and exhaust air streams of an air-controlling unit. One of the applications of air-to-air heat exchanger is in electronic enclosure. The introduction of electronics into the outdoor enclosure unit has imposed major challenges on its design since the enclosure unit must now provide an environment in which the system can survive. The main constraints shall be managing the temperature and humidity as they are reported as the contributing factors of electronics failure (BCC Research, 2011). The internal heat generation due to the solar loading can be substantial depending upon the size of the enclosure and its orientation towards the sun. While humidity is good for heat transfer because water particles absorb heat faster than air, water particles mixed with dust will trap heat and eventually causing overheating of the electronic components.

Besides, water particles mixed with dust is a potential cause of short circuit between the electronic components.

In 1992, researchers of Mobil Research and Development Corporation published the synthesis of a group of mesoporous materials known as M41S. This class of material consists of MCM-48 that possesses a three-dimensional, cubic-ordered tortuous pore structure, MCM-41, which has a one-dimensional, hexagonally-ordered pore structure, and MCM-50, which is characterized by its unstable lamellar structure. The acronym MCM stands for *Mobil Composition of Matter*.

The characteristic of hexagonally ordered MCM-41 pore structure material is uniform nano-channels with large surface area and pore volume density (i.e. about 1000 m^2/g and 1 cm^3/g respectively) (Kresge, et al, 1992). These properties are of considerable interest in the development of membrane materials for air exchangers as shall be elaborated in the succeeding sections.

1.2 PROBLEM STATEMENT

Air exchanger transfers thermal energy of the indoor air to incoming fresh air, hence allowing the moisture and pollutants to be vented out but retaining the heat. While the ventilation cycles dilute or remove the indoor pollutants and moisture, the remaining issue is how to retain the heated or cooled air. The present work describes a study on one variation of air-to-air heat exchanger using a novel hydrophilic membrane, i.e. synthesized from MCM-41 inorganic material, to transfer moisture and heat across the membrane.

MCM-41 is a mesoporous molecular sieve material that has potential to be applied to membrane based air-to-air heat exchangers. Current membrane air-to-air heat exchanger is based on polymeric or other mesh structure materials i.e. screen and paper. In outdoor environment application, where the weather vary from sunny to rainy, the choice of these materials allows water droplets to get into the inside of the heat exchanger. Adding MCM-41 material to the support structure membrane is the interesting aspect because of MCM-41 uniform nano channels structure, with hydrophilic characteristic, permits heat and moisture to be transferred across the membrane surface causing a decrease in temperature and humidity. The use of MCM-41 material also intended to address the application of air-to-air membrane in outdoor environment, in the aspect to prevent water droplet transportation.

1.3 RESEARCH OBJECTIVES

The objectives of this research project can be summarized as mentioned:

1. To synthesize and characterize the hexagonally ordered, mesoporous MCM-41 membrane on a supporting matrix for use in air-to-air heat exchanger.
2. To characterize the performance of the MCM-41 air-to-air heat exchanger utilizing MCM-41 membrane in dry (3 % RH) and moist cooling conditions (98 % RH).
3. To simulate the temperature profiles of MCM-41 air-to-air heat exchanger using Computational Fluid Dynamics (CFD) simulation for both parallel flow and cross flow configurations.
4. To develop MCM-41 hexagonal pore model for the mass transport phenomena in membrane air-to-air heat exchanger using Lattice Boltzmann Method (LBM).

1.4 RESEARCH METHODOLOGY

The present research could be briefly described through the following steps:

1. MCM-41 membrane preparation.

   MCM-41 is prepared from a parent solution consisting cetyltrimethyl ammonium bromide (CTAB), tetraethylorthosilicate (TEOS), hydrochloric acid (HCl), distilled water (H_2O) and ethanol (C_2H_5OH). Polyester is selected as the matrix of the membrane. MCM-41 material is coated on the polyester substrate using the dip-coating method. The dip coating method is chosen to obtain a thin MCM-41 coating on the substrate.

2. Membrane analysis and characterization.

   The structural formation of MCM-41 material is verified using X-ray diffraction (Cu Kα radiation, Lab X6000, Shimadzu). Its surface morphology micrograph is observed with Scanning Electron Microscope (JED-2100, JEOL Co. Ltd.) while the surface roughness of the membrane is observed using Atomic Force Microscope (AFM, JEOL Co. Ltd.). The BET surface area, pore volume and pore size distribution are obtained from the physisorption measurement conducted at 44 K (Autosorb-1, Quanta-chrome).

3. Heat exchanger design.

   The air-to-air heat exchanger design consists of two chambers separated by a single layer MCM-41 membrane. Thermocouple and flow meter are installed in both sides of chambers at several positions. A hot stream is passed through the bottom chamber while a cool air flow is passed through top chamber.

4. Heat exchanger evaluation and simulation.

Based on the performance of the MCM-41 membrane air-to-air heat exchanger obtained, its efficacy is then elucidated based on Computational Fluid Dynamics modeling using finite volume and also Lattice Boltzmann methods.

1.5 SCOPE OF RESEARCH

This work investigates the efficacy of an air-to-air membrane heat exchanger using a novel membrane material i.e. MCM-41 mesoporous silicates, to transfer both moisture and heat across the parallel flow streams through the membrane matrix. MCM-41 material structure consists of hexagonally ordered nano channels, uniformly around 2 nm in pore size. The air-to-air MCM-41 membrane heat exchanger is designed as a parallel flow type with narrow chamber's height. Force convection occurs at the length of the membrane that separated the chambers. The steady state energy balance and model are investigated based on this flow arrangement. Three dimensional model of heat exchanger with parallel flow is built for Computational Fluid Dynamic analysis using finite volume and Lattice Boltzmann methods.

1.6 THESIS ORGANIZATION

This thesis consists of five chapters. Chapter one provides an overview of the research. The literature review is presented in Chapter Two; with the main aspects include MCM-41 membrane, air-to-air heat exchangers, and Computational Fluid Dynamics and Lattice Boltzmann Method of modeling. Chapter Three presents the details of experimental procedures and characterization techniques which include the MCM-41 material preparation and characterizations, and air exchanger design, characterizations and simulation. The experimental and modeling results are discussed in Chapter Four. Chapter Five concludes the thesis and presents several recommendations for future research.