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Design, Modelling and Experimental Evaluation of Energy Recovery Indirect Evaporative Cooling System

by Ahmed Y Taha Al-Zubaydi

Thesis submitted in fulfilment of the requirements for the degree of

Doctor of Philosophy

under the supervision of Associate Professor Dr. Guang Hong
And Dr. Lee "Mickey" Clemon

University of Technology Sydney
Faculty of Engineering and Information Technology

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I, Ahmed Y Taha Al-Zubaydi declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of philosophy, in the Mechanical engineering at the University of Technology Sydney. This thesis is wholly my own work unless otherwise reference or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis. This document has not been submitted for qualifications at any other academic institution.

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Abstract

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Heating, ventilating and air conditioning systems (HVAC) are essential for providing a comfortable and healthy indoor environment for human beings and required conditions for manufacturing and operations in industrial sectors. Maximizing energy efficiency and minimizing the environmental impact of HVAC systems has become more and more important to address the issues of sustainability and environmental protection. With the recent climate warming, the demand for air conditioning is expected to hit a new high. The dilemma of high demand while simultaneously reducing energy consumption requires a full-scale campaign to develop new technologies for HVAC systems.

Recovering wasted energy is one way to reduce the energy consumption in HVAC systems. In a modern building, the energy lost through ventilation can be more than 50% of the total thermal losses. In this study, two advanced technologies were investigated, the air-to-air heat recovery ventilation (HRV) and the indirect evaporative cooler (IEC). The energy wasted by the exhaust air was recovered by pre-cooling the supply air as the heat was transfer from the fresh air to the exhaust air in an HVAC system.

A test rig was designed, manufactured, modified and calibrated to meet the special aims of this research. It is a cost-effective and inventive test facility with the flexibility to be used for both dry (HRV) and wet (IEC) operation modes.

The experimental study of the HRV was conducted by testing two polymer heat exchangers with two different plate geometries, one with a flat plate and the other with a

dimpled surface plate. The key aims were to understand the effect of the surface geometry of the plates on the performance of the air-to-air heat exchanger. Regarding the performance of the HRV, the sensible efficiency of the heat exchanger with the dimpled surface was 50% to 60% higher than that of the heat exchanger with flat surface plate at lower air velocity and higher air initial temperatures. The highest COP of the heat exchanger with dimpled surface heat was 6.6; achieved under primary air operating temperature of 32.6 °C.

In the investigation of the IEC system, the main aim was to find the effect of water spray arrangement on the performance. Experiments were conducted with three water spray modes: (1) external spray, (2) internal spray and (3) mixed internal and external sprays. An ANSI/ASHRAE Standard 143-2015 evaluation indices with changing the primary air condition parameter (Primary air inlet temperature and velocity) were applied to evaluate the system performance with water spraying variation. The results show that the internal spraying mode performs better than the external spraying mode does in terms of the wet-bulb efficiency, cooling capacity and the COP of IEC. The mixed-mode improves the performance further but increases the water evaporation rate. The innovative internal spray system benefits the sensible heat transfer in the IEC system. The cooling load capacity increases by 12.5% with the internal spray mode and 25% with the mixed mode. The COP varies in a wide range under different water spraying modes and operating conditions with the highest of 19.12 achieved in the mixed-mode.

CFD modelling was also performed to further investigate the IEC system. An Eulerian-Lagrangian 3-D numerical model was developed which was capable of simulating a representative IEC system with realistic nozzles in the mixed-mode operation. A solid-cone spray representation in Eulerian-Lagrangian numerical models was applied in order to replicate real nozzles characteristics in the simulation. The model was verified by

experimental results. The verified model was employed to study the effects of primary air temperature, humidity ratio and velocity on the performance of the indirect evaporative heat exchanger (IEHX). Operating under variable inlet air temperature and humidity conditions, simulated results showed that the wet-bulb effectiveness for the mixed mode ranged from 68%% to 80% with a primary air supply temperature near dew-point temperature at primary air temperature lower than 28 °C and velocity less than 1.5 m/s.

Dedication

First to the memory of my father, Yassin Al-Zubaydi

To my mother Natheera Abdul-Baki, my wife Sarab Mansoor, my daughters Basma and Tanya and all my family

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List of Publications

- Al-Zubaydi, A.Y.T., G. Hong, and W.J. Dartnall. 2016, CFD Modelling and Analysis of Different Designs Plate Heat Exchangers. In 10th Australasian Heat & Mass Transfer Conference. Brisbane, QLD.
- Al-Zubaydi, A.Y.T. and G. Hong, 2018.Experimental investigation of counter flow heat exchangers for energy recovery ventilation in cooling mode, International Journal of Refrigeration. 93: p. 132-143.
- Al-Zubaydi, A.Y.T. and G. Hong, 2019.Experimental study of a novel water-spraying configuration in indirect evaporative cooling, Applied Thermal Engineering. 151: p. 283-293.

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Abbreviation

3-D	Three Dimensional Geometry
AHRI	Air-Conditioning, Heating and Refrigeration Institute
AHU	Air-Handling Unit
ANSI	American National Standards Institute
ASHRAE	The American Society of Heating, Refrigerating and Air-Conditioning Engineers
BOM	Bureau of Metrology
CAD	Computer Aided Design
CFD	Computational Fluid Dynamic
CSIRO	Commonwealth Industrial and Scientific Research Organisation
DEC	Direct Evaporative Cooling
DIEC	Direct-Indirect Evaporative cooler
DNS	Direct Numerical Simulation
DOEE	Department of Environmental and Energy - Australia
DPM	Discrete Phase Modelling
HFC	hydrofluorocarbons
HMX	Heat and Mass Exchange
HRV	Heat Recovery Ventilation
HVAC	Heating, Ventilation and Air-Conditioning)

HX	Heat Exchanger
IEA	International Energy Agency
IEC	Indirect Evaporative Cooling
IEHX	Indirect Evaporative Heat Exchanger
LDPE	Low-Density Polyethylene
LMTD	Logarithmic mean temperature difference
M-Cycle	Maisotsenko Cycle
NGER	National Greenhouse and Energy Reporting
NTU	Number of Transfer Units method
PETG	Polyethylene Terephthalate Glycol
PHE	Plates Heat Exchanger
PVC	Polyvinyl Chloride
RANS	Reynolds-Averaged Navier-Stokes
R-IEC	Regenerative Indirect Evaporative Cooling
ε-NTU	Effectiveness-Number of Transfer Units

Nomenclature

A : Area, m^2

b : Gap between two plates, mm

c_{pa} : Specific heat of air, J/kg. °C

COP : Coefficient of performance

$eff._s$: Sensible efficiency, %

h : Enthalpy of air, J/kg

H : Height of Plate, mm

L : Length of Plate, mm

l_{fg} : Latent heat of vaporization of water, J/kg

$\dot{m}$: Mass flow rate, kg/s

N : Number of plates

p : Precision

P : Power, W

$\dot{Q}$: Heat Transfer Rate, W

RH : Relative Humidity, %

S_φ : The source term for the continuous phase

$S_{p\varphi}$: The additional source due to the interaction between air and water droplets

t : Temperature, °C

u(x) : The absolute uncertainty of directly measured variable, %

v : Air velocity, m/s

$\dot{V}$: Volumetric flow rate, m^3/s

V_w : Water evaporation rate, kg/hr

X : Total Width, mm

y : The indirectly measured variable

Z The differential pressure across the orifice plate, mmH_2O

Greek Letters

β : The sum of bias error

δ : The total uncertainty error, %

ε : Effectiveness

ϕ : Flow variable

Γ_{φ} : The diffusion coefficient

ρ : Air density, kg/m^3

t : Temperature depression, °C

ω : Relative humidity/moisture content of air, g/kg

Δx : The instrument accuracy

ΔP : Pressure variation, Pa

Δy : The absolute uncertainty, %

Δz : Plate thickness, mm

Subscripts

1 : Inlet

2 : Outlet

p : Primary air

s : Secondary air

DB : Dry-Bulb

WB : Wet-Bulb