Energy and Buildings 119 (2016) 129–142

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Performance of a quasi-counter-flow air-to-air membrane energy exchanger in cold climates

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ARTICLE INFO

Article history:
Received 21 January 2016
Received in revised form 4 March 2016
Accepted 4 March 2016
Available online 9 March 2016

Keywords:
Membrane energy exchanger
Heat exchanger
Quasi-counter-flow
Heat and mass transfer
Performance

ABSTRACT

The merits of membrane energy exchanger applied for cold climates are less known and explained. In this study a novel quasi-counter-flow membrane energy exchanger (MEE) was built and tested under cold operating conditions. The quasi-counter-flow arrangement combines advantage of the ease sealing of cross-flow and high efficiency of counter-flow. The measured sensible and latent effectivenesses are in ranges of 88.5–94.5% and 73.7–83.5%, respectively. The correlations of heat transfer Colburn factor and friction factor for the MEE are fitted in terms of Reynolds number based on the experimental results. These correlations provide thermal and hydrodynamic characteristics and membrane energy exchanger design and selection in cold climates.

This study developed an analytical model to predict heat and moisture transfer in the quasi-counter-flow MEE for low operating temperatures. For the moisture transfer, resistances of dense and porous membranes are investigated. Niu and Zhang's dense membrane resistance is adjusted and adopted for low operating temperatures. The revised resistance formula of dense membrane presents theoretical optimal sorption isotherms under different operating conditions to minimize the diffusive resistance. The moisture transfer resistance of a porous membrane, which has a completely different moisture transfer mechanism with the dense membrane, is presented in this article. The comprehensive heat and moisture transfer resistance model yields consistent agreement with experimental results for the porous membrane used in this study. A preliminary parametric study was conducted to optimize the MEE design.

1. Introduction

Air-to-air heat exchangers are widely used to reduce the energy consumption in buildings in cold climates [1–4]. Heat, that otherwise would have been exhausted from the buildings, can be recovered through the use of an exchanger and be transferred to the supply fresh air. Recovering the heat can reduce the buildings energy demand and mitigate greenhouse gas emissions in cold climates [5–7]. In the heat exchanger, the warm and moist exhaust air may be cooled down below the dew point and the water vapour consequently condenses on the cold surface. The water forms ice/frost when the surface temperature of plate is the below freezing point [8–13]. The frost reduces the heat transfer rate due to an increased thermal resistance between the air streams [10,11,14]. On the other hand, the accumulation of frost narrows or even blocks off the exchanger's channels and consequently increases the air stream pressure drop. Additional fan energy then is consumed to move the air through the exchanger [2,15].

During recent years, efforts have been made to increase the temperature (sensible) effectiveness of heat exchangers to recover more energy. Counter-flow heat exchangers with 90% or higher effectiveness are commercially available [16]. However, high effectiveness may result in a higher risk of frost because such exchanger results in a lower exhaust air temperature. The disadvantage of frost in exhaust channels is particularly significant because there is a potential to recover a maximum amount of energy when the outdoor ambient air is extremely cold. To solve the frost issue inside exchangers, defrosting and frost-preventing strategies have been extensively studied. Frost control strategies mainly include preheating or bypassing the outdoor air and recirculating or reheating the exhaust air [2,12,17,18]. However, frost control strategies

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http://dx.doi.org/10.1016/j.enbuild.2016.03.010
0378-7788/

Nomenclature

Parameter	Definition
D_h	Hydrodynamic diameter of an air channel (m)
$\dot{Q}$	Volumetric flow rate (m^3/s)
c_p	Specific heat capacity of air (J/kg K)
$\dot{m}$	Mass flow rate of dry air (kg/s)
w	Humidity ratio (kg/kg)
w_{max}	Maximum water uptake capacity (kg/kg)
ΔH_{vap}	Heat of vapourization (J/kg)
h	Convective heat transfer coefficient (W/m^2 K)
A	Total heat transfer surface area (m^2)
B	Bias error
C	Constant from membrane sorption isotherm
D	Diffusivity (m2/s)
H	Enthalpy (J/kg)
H^*	Operating condition factor
J	Water vapour flux (m^3/m^2s)
L	Length of the MEE (m)
D_p	Diffusivity of porous membrane (m2s)
P	Precision error or pressure (Pa)
R	Gas constant (J/kg K)
S	Sample standard deviation
t	Constant
T	Temperature (K)
U	Total heat/mass transfer coefficient or uncertainty
V	Volume (m^3)
X	Variable
a	Constant
b	Constant
f	Friction factor
j	Colburn factor
k	Moisture transfer coefficient from the membrane
k	Convective mass transfer coefficient (m/s)
r	Thermal resistance (m^2K/W) or moisture resistance (m^2s/kg)
v	Bulk velocity (m/s)
w	Moisture content (kg/kg)

Acronyms

Le	Lewis number
NTU	Number of Transfer Unit
Nu	Nusselt number
RH	Relative humidity
Re	Reynolds number
Sh	Sherwood number

Greek letters

λ	Thermal conductivity (W/mK)
ϕ	Relative humidity
η	Efficiency
δ	Thickness (m)
ε	Effectiveness/pore porosity in membrane
ρ	Density (kg/m^3)
θ	Moisture uptake in membrane (kg/kg)

Subscripts

h	Heat/hydraulic
a	Air
c	Coil
cou	Counter-flow
cro	Cross-flow
d	Dense membrane
e	Exhaust
f	Frosting limits
fan	Fan
i	Inlet
l	Latent
m	Moisture or membrane
max	Maximum
min	minimum
o	Outlet
p	Plate/porous membrane
r	Room
ref	Reference
s	Supply or sensible
sat	Saturation
v	Vapour
w	Water

usually consume extra energy to preheat or reheat the air. Bypassing the outdoor air or intermittent operation to defrost tends to disturb the indoor thermal comfort and decreases the effectiveness of the heat exchanger. Moreover, the complicated control increases cost and reduces the reliability of the heat recovery system.

A membrane energy exchangers (MEE) is one type of energy exchanger which can simultaneously transfer heat (sensible energy) and moisture (latent energy). A semi-permeable membrane enables heat and moisture to be transferred from exhaust to fresh air in cold climates. Although sensible heat recovery dominates over latent heat recovery in general for cold climates, the existence of latent recovery can mitigate frost formation which in turn benefits a high sensible recovery. The moisture transfer lowers the dew point of the exhaust air which results in condensation and frost forming at lower outdoor air temperatures compared to sensible-only heat exchanger [11]. Recent reviews of heat/energy exchangers for cold climates concluded that MEE has a promising frost-resistant potential [1,2] to reduce or avoid frosting compared to conventional sensibly-only heat exchangers. The potential was also observed experimentally for a cross-flow MEE in the lab [11] and in an occupied house [19]. Garber-Slaght et al. tested eight commercial MEEs in-situ installed in Fairbanks and Alaska for cold climates. The eight models were operable when the average outdoor air temperature ranged from 1.4 °C down to −16.7 °C [20]. Transfer of moisture to the supply air can contribute (mostly in winter of cold climates) to proper humidity levels having positive effects on health, comfort and materials [21].

Liu developed a theoretical model of critical sensible and latent effectiveness to maintain frost free pure-counter-flow MEE [22]. The study indicates that latent effectiveness of 80% can eliminate frost at nearly every typical operating conditions when the sensible effectiveness is below 80%. The theoretical model implied that a higher sensible effectiveness could cause a higher frosting risk in MEE. In this study, the effectiveness-NTU method was applied as a powerful and straightforward approach to determine outlet conditions for given exchanger and inlet conditions. Sensible effectiveness, latent effectiveness and pressure drops are widely adopted as the three most important performance indicators in design, selection and operation of exchangers. The research and practical applications of MEEs in open literatures mainly focus on hot climates which generally covers heat and mass transfer, performance parametric analysis, energy savings and integration with HVAC systems.

Membranes are typically categorized as dense and porous types according to pore structure. The dense membrane commonly has pore size on the order of 0.1 nm and the porous membrane is on