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Energy transfer and energy saving potentials of air-to-air membrane energy exchanger for ventilation in cold climates

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ABSTRACT

Frosting occurring inside heat exchangers degrades the exchangers' performance and reduces energy recovery in cold climates. The moisture transport in membrane energy exchangers (MEE) provides a great potential to increase frost tolerance and decrease energy consumption by the air handling units (AHU). In addition, the moisture recovery in MEEs tends to improve the thermal comfort by adding moisture to the indoor dry air. However, applications of MEEs for cold climates are less known compared to their use in hot and humid climates as independent cooling and dehumidification. The open literatures dealing with heat and mass transfer of the MEEs for cold climates are scarce and acute. This research aims to investigate heat and moisture transfer, and energy saving potentials of MEEs compared to the sensible-only heat exchanger (HE). The applicability of transforming heat and moisture transfer analysis carried out for hot and humid conditions to cold climates is examined. The study attempts to "translate" conventional sensible-only HE correlations to the MEEs. Knowledge and data of heat exchangers are transformed to MEEs through analysing the boundary conditions of heat and mass transfer in both MEE and HE. This transformation can reduce needs of relying on computational fluid dynamics (CFD) to analyse heat and mass transfer in MEEs. As one of most important advantages of adopting MEE in cold climates, frosting reduction by the MEE is determined and compared for a specific MEE and HE in the heating season of Oslo (Norway). The energy consumption by the AHU equipped with the MEE is compared to the AHU with HE under different airflow rates. The MEE is able to significantly reduce the energy consumption by preheating and post-conditioning (reheating and humidifying) when there is frosting risk in MEE or HE for Oslo climate.

1. Introduction

Mostly given that people spend more than 90% of their time indoors [1]. A indoor environment i.e. healthy indoor air quality (IAQ) and good thermal comfort is necessary to guarantee good health, comfort and productivity [2] of occupants. In cold climates, fresh air was historically provided by infiltrations through building leakages. However, the infiltration tends to increase the risk of draught [3] and the hazard of radon exposure [4]. Newer building envelopes have become tighter and more insulated with improved building technics to migrate heat loss and leakages. Mechanical ventilation systems have become more common in these well-insulated and tight buildings [5] to fulfil the increasingly rigorous indoor environment standards and prescribed ventilation requirements [6].

Heating outdoors air to supply air states in the mechanical ventilation generally consumes a substantial amount of energy in the mechanical ventilation systems. The building sectors approximately consumes 40% of the global energy use [7]. Energy demands for heating the ventilation air can reach around 60% of annual total energy demands for buildings located in cold region [8]. The ratio can be even higher if 100% fresh air ventilation is required. The global energy demand predicted by Energy Information Administration (EIA) in building environment will grow by 34% in 2025 [9]. Energy consumed by residential buildings and non-residential buildings will approximately be 67% and 33% respectively in 2030 [9]. Consequently, providing satisfactory and healthy indoor

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Nomenclature

c_p	Pecific heat capacity of air (J/kg K)
D_h	Hydraulic diameter (m)
k_B	Boltzmann constant, 1.38×10^{-23} (J/K)
$\dot{m}$	Mass flow rate (kg/s)
P_m	Mean total pressure within the pores of membrane (Pa)
w_{max}	Maximum water uptake capacity (kg/kg)
w_{max}	Maximum water uptake of desiccant (kg/kg)
x_F	Length of supply channel (m)
y_F	Length of exhaust channel (m)
A	Total heat transfer surface area (m^2)
C	Constant from membrane sorption isotherm
C	Constant in sorption curve
d	Diameter (m)
d	Membrane channel space (m)
D	Diffusivity (m^2/s)
f	Friction factor
h	Convective heat transfer coefficient (W/m^{2}K)
H	Enthalpy (J/kg)
j	Colburn factor
J	Water vapour flux (m^3/m^{2}s or kmol/m^{2}s)
k	Convective mass transfer coefficient (m/s)
L	Length of the MEE (m)
M	Molecule weight (g/mol)
P	Permeability or pressure (Pa)
Q	Energy (MJ)
r	Resistance (m^{2}K/W or m^{2}s/kg) or pore radius (m)
R	Gas constant (J/kgK)
S	Solubility
t	Time span (h)
T	Temperature (K)
U	Total heat/mass transfer coefficient or uncertainty
w	Humidity ratio (kg/kg)
x	Thermal entrance length (m)

Acronyms

Kn	Knudsen number
Le	Lewis number
NTU	Number of transfer unit
Nu	Nusselt number
Pr	Prandtl number
RH	Relative humidity
Re	Reynolds number
Sh	Sherwood number
Sc	Schmidt number

Greek letters

δ	Thickness (m)
ε	Effectiveness/pore porosity in membrane
η	Dynamic fluid viscosity (Pa S)
θ	Moisture uptake in membrane (kg/kg)
λ	Thermal conductivity (W/mK) or mean free path (m)
σ	Molecular collision diameter (m)
α	Aspect ratio (b/a), b is the channel length, a is the channel spacing
τ	Membrane tortuosity

Superscripts

*	Dimensionless
a	Air
c	Coil
C	Conjugate
e	Exhaust/effective
f	Preheating triggering temperature
h	Heat/hydraulic
H	Constant heat flux boundary conditions
i	Inlet
K	Knudsen diffusion
l	Latent
L	Local
m	Moisture or membrane
M	Mean
max	Maximum
min	Minimum
o	Open channel/outlet
o	Outlet
O	Molecule diffusion
opt	Optimal
p	Pore
post	Post-conditioning
pre	Preheating
s	Supply or sensible
ss	Spply air state
T	Constant surface temperature boundary conditions
wv	Water vapour

environment with low energy demand is a great scientific and engineering challenge.

Heat/energy recovery systems in buildings recover sensible heat or/and latent heat from the exhaust air to the fresh air. The heat or moisture transfer from a high temperature or humidity to a low temperature or humidity between adjacent air streams which are separated by metal or plastic plates or membranes in the energy recovery process [10]. The heat/energy recovery system is a solution to meet requirements of adequate fresh air, satisfied indoor climate and energy efficiency [11]. Fehrm et al. found that around 20% of primary energy consumption and 18% of CO_2 emissions can be reduced by using heat recovery system with a field survey of 60 heat recovery units in cold climates [8].

Nevertheless, when the heat exchanger is adopted in cold climates, the ice or frost are often observed inside exchanger channels which usually degrade the exchanger performance. The warm and humid exhaust air tends to have an increasing relative humidity and starts to condensate [12–16] if the exhaust air is cooled down to the dew point. The condensation water on the plate starts to form frost if the plate surface temperature is below the freezing point. The frost layer would grow as more water vapour condensates on the below-zero surface. Typical problems caused by the frost in the exchanger are reported as follows [17,18]:

- Partial or full blockage of air flow channels of heat exchanger,
- Increase in pressure drop through the exchanger or decrease in the air flow rate,
- Decrease in the heat transfer rate between the two air streams, and
- Deflection of plates of the exchanger due to the frost build-up.

Freezing control strategies are commonly applied to reduce or avoid the consequence of frosting in practice [17–21]. The freezing control technologies can be generally classified as “frost control strategies” (such as preheating outdoor air, reheating exhaust air or reducing effectiveness, etc.) and “defrost control strategies” (such as supply fan shutoff, warm air recirculation, etc.). These strategies tend to consume extra energy to preheat or reheat the air