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Conjugate heat and mass transfer in a total heat exchanger with cross-corrugated triangular ducts and one-step made asymmetric membranes

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ABSTRACT

Membrane-based total heat exchanger is a device to recover both sensible heat and moisture from exhaust air stream from a building. Heat and mass transfer intensification has been undertaken by using a structure of cross-corrugated triangular ducts. To further intensify moisture transfer, recently developed membranes-one step made asymmetric membranes, are used as the exchanger materials. Conjugate heat and mass transfer under transitional flow regime in this total heat exchanger are investigated. Contrary to the traditional methods of assuming a uniform temperature (concentration) or a uniform heat flux (mass flux) boundary condition, in this study, the real boundary conditions on the exchanger surfaces are obtained by the numerical solution of the coupled equations that govern the transfer of momentum, energy and moisture in the two air streams and in the membrane materials. The naturally formed heat and mass boundary conditions are then used to calculate the local and mean Nusselt and Sherwood numbers along the exchanger ducts, in the heat and mass developing regions. The data are compared with those results under uniform temperature (concentration) and uniform heat flux (mass flux) boundary conditions, for cross-corrugated triangular ducts with typical duct apex angles of 60° and 90°.

1. Introduction

Conditioning ventilation air typically constitutes 20–40% of the thermal load for commercial buildings and can be even higher in buildings that require 100% outdoor air to meet ventilation standards. It is well known that energy recovery devices could save a large fraction of the thermal load since heat and humidity would be recovered from the exhaust stream in winter and excess heat and moisture would be transferred to the exhaust in order to cool and dehumidify the incoming air (fresh) in the summer. With energy recovery devices, the efficiency of existing HVAC systems can also be improved because otherwise fresh air needs to be dehumidified by cooling coil through condensation followed by a re-heating process, which is very energy intensive.

Membrane-based total heat exchanger has attracted much attention to fulfill this task [1–3]. The device is just like an air-to-air parallel plate sensible heat exchanger. But in place of traditional metal heat exchange plates, hydrophilic membranes, which can transfer both heat and moisture simultaneously, are used as the heat and mass transfer media. The device has many virtues like it is stationary, compact, and easy to construct. However, practical application until now is still scarce. The reason is that heat and mass transfer in the unit is slow, which limits their market penetrations.

To intensify heat and mass transfer, in this study, a novel duct structure, cross-corrugated triangular ducts, is used to augment heat and mass transfer in air side. The structure is shown in Fig. 1. It has similar geometry as chevron plates used in traditionally heat exchangers (primary surface heat exchangers). But the cross section is triangular other than sinusoidal. Literature review found that though heat transfer [4–16] and mass transfer [17–19] in chevron plate heat exchangers have been investigated by various investigators, cross corrugated triangular ducts are less fully studied.

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Nomenclature

A_{cyc}	surface area of a flow cycle (m^2)
A_{ci}	cross-sectional area at inlet (m^2)
c_p	specific heat of fluid (kJ kg^{-1} K^{-1})
d_p	membrane pore diameter (μm)
D_h	hydrodynamic diameter (m)
D_{va}	moisture diffusivity in dry air (m^2/s)
D_{vm}	effective moisture diffusivity in membrane (m^2/s)
f	friction factor
H	channel height (mm)
h	heat flux (kW/m^2)
h_{tot}	convective heat transfer coefficient (kW m^{-2} K^{-1})
k	turbulent kinetic energy (m^2/s^2)
k_{tot}	convective mass transfer coefficient (m/s)
m_v	moisture emission rate through membrane (kg m^{-2} s^{-1})
Nu	Nusselt number
P	pressure (Pa)
q	mass diffusion flux (kg m^{-2} s^{-1})
Sc	Schmidt number
Sh	Sherwood number
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
V_a	air flow rate (m^3/s)
V_{cyc}	volume of a flow cycle (m^3)
W	channel width (mm)
Y_v	humidity ratio (kg/kg)
x, y, z	coordinates (m)
Greek letters	
ρ	density (kg/m^3)
v	kinematic viscosity (m^2/s)
λ	thermal conductivity (kW m^{-1} K^{-1})
μ	dynamic viscosity (Pa s)
τ	shear stress (N/m^2)
ω	specific dissipation rate (s^{-1})
ε	turbulent dissipation rate (m^2/s^3)
δ	thickness of the membrane (m)
ψ	correction factor
θ	apex angle (°)
γ	orientation angle of neighboring layers (°)
φ	air leakage ratio
Superscripts	
t	turbulent
$'$	fluctuation
Subscripts	
a	air
c	conjugated
cyc	cyclic
e	exhaust air
f	fresh air
H	heat flux
i	inlet
J	mass flux
m	mean, membrane
o	outlet
T	temperature
v	vapor
W	wall, concentration

Of the limited number of studies with this structure, the boundary conditions are assumed either as uniform temperature or uniform heat flux boundary conditions [20–24]. That assumption may hold for common metal heat exchangers. However, for a total heat exchanger, the heat and mass transfer in the ducts are closely coupled with the membranes. A uniform temperature or a uniform heat flux boundary condition is not justified. This is a conjugate heat mass transfer problem. To address this problem, in this study, the heat and mass transfer under real boundary conditions will be considered. This is a naturally formed boundary condition resulted from the interactions between the two flows, and the membrane.

Further, besides air side augmentation, material side augmentation is also undertaken. A novel kind of membrane developed recently [25], the so called one-step made asymmetric membrane, is used as the exchanger material. The membranes are made from CA, Cellulose Acetate. With this material, the fabrication processes are much simpler and the overall cost is much lower; and more significantly, the moisture permeability of the complete membrane is about 1.5–2 times higher than those of the previously developed membranes [26].

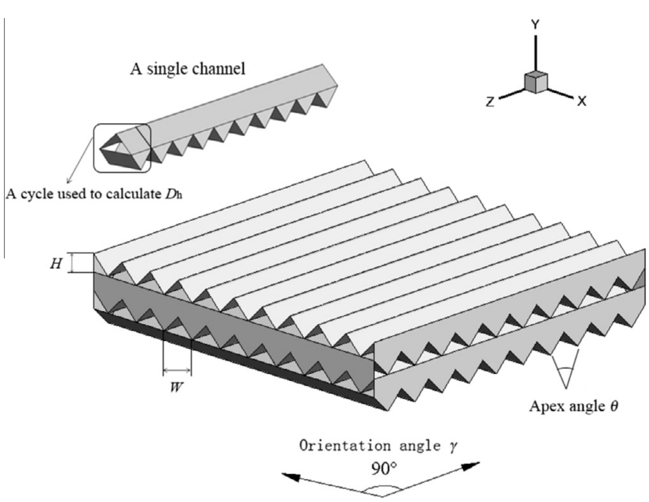

Fig. 1. Schematic of the section in the cross-corrugated exchanger.

2. Experimental works

A test rig is built to perform heat mass transfer and pressure drop experiments, as shown in Fig. 2. It comprises of variable speed blowers, wind tunnels, heaters, humidifiers, nozzles and the total heat exchanger core. Air in one side is conditioned to simulate the outdoor fresh air. The other side is to simulate the indoor stale air. The volumetric air flow rates can be adjusted to have different Reynolds numbers. The low speed wind tunnels are to ensure a continuous, steady air supply. The volumetric air flow rates are measured by a set of nozzles in the wind tunnel. Temperature and humidity sensors are inserted into the test section to measure the states of inlet and outlet air.

The leakage between the two streams mainly occurs in the joining parts the core and the supporting frames. To check the air leakage rate, air flow rates are tested in the test section by measuring area-averaged air velocities. Nine test points are uniformly