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Experimental investigations of polymer hollow fibre heat exchangers for building heat recovery application

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ABSTRACT

Due to low cost, light weight and corrosion resistant features, polymer heat exchangers have been extensively studied by researchers with the aim to replace metallic heat exchangers in a wide range of applications. Although the thermal conductivity of polymer material is generally lower than the metallic counterparts, the large specific surface area provided by the polymer hollow fibre heat exchanger (PHFHE) offers the same or even better heat transfer performance with smaller volume and lighter weight compared with the metallic shell-and-tube heat exchangers. This paper presents the construction and experimental investigations of polypropylene based polymer hollow fibre heat exchangers in the form of shell-and-tube. The measured overall heat transfer coefficients of such PHFHEs are in the range of 258–1675 W/m^2K for water to water application. The effects of various parameters on the overall heat transfer coefficient including flow rates and numbers of fibres, the effectiveness of heat exchanger, the number of heat transfer unit (NTU), and the height of transfer unit (HTU) are also discussed in this paper. The results indicate that the PHFHEs could offer a conductance per unit volume of 4×10^6 W/m^3K, which is 2–8 times higher than the conventional metal heat exchangers. This superior thermal performance together with its low cost, corrosive resistant and light weight features make PHFHEs potentially very good substitutes for metallic heat recovery system for building application.

1. Introduction

In the era of rapid global economic development, the growing world energy use has triggered problems such as primary energy supply difficulties and world-wide environmental concerns (carbon emission, global warming, air pollution, etc). In developed countries, the energy consumption of buildings account for 20–40% of the total final energy consumption [1]. Heat recovery systems [2] in the form of air ventilation systems [3–5], membrane heat exchangers [6,7], metal heat exchanger [8,9] have been extensively studied by researchers with the aim to improve energy efficiency and reduce energy costs for building applications. Most of such heat recovery systems are made from metallic materials, which have the disadvantages in terms of weight and cost. In addition, specially treated metal heat exchanger is needed if the working fluids are corrosive. Moreover, the manufacturing process of metal materials consumes significant amount of primary energies, accompanied by carbon emissions. Given these considerations, it is desirable to find an alternative material for heat exchangers that can overcome these disadvantages and also acquire comparable heat exchange efficiency and be easily fabricated. This is where the use of polymer heat exchanger comes into place. With the advantages of greater fouling and corrosion resistance, greater geometric flexibility and ease of manufacturing, reduced energy of formation and fabrication, and the ability to handle liquids and gases (i.e, single and two-phase duties), polymer heat exchangers have been widely studied and applied in the field of evaporative cooling system [10,11], micro-electronic cooling devices [12,13], water desalination systems [14,15], solar water heating systems [16,17], liquid desiccant cooling systems [18,19], etc. The detailed research progresses and various applications of polymer hollow fibre heat exchanger can be found in the review paper [20]. Most importantly, polymer materials can offer substantial weight, space, and volume savings, which make them more competitive compared with heat exchangers manufactured from many metallic alloys. Moreover, the energy required to produce a unit mass of polymers is about two times lower than common metals, making them environmentally attractive [21].

One of the drawbacks of polymer materials are their relatively low thermal conductivities, typically in the range of

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Nomenclature

A	Heat transfer area (m^2)
C_p	Specific heat (J/Kg K)
CUV	Conductance per unit volume (W/m^3K)
D	Tube/shell diameter (m)
Gz	Graetz number
HTU	Height of transfer unit (m or cm)
k	Thermal conductivity (W/mK)
L	Length (m)
$\dot{m}$	Mass flow rate (kg/s)
N	Number of fibres inside the heat exchanger
NTU	Number of heat transfer unit
Nu	Nusselt number
ΔP	Pressure drop (Pa)
Pr	Prandtle number
Q	Heat transfer rate (W)
$\dot{V}$	Volumetric flow rate (m^3/s)
R	Thermal resistance (m^2/KW)
Re	Reynolds number
St	Stanton number
T	Temperature (°C)
U	Overall heat transfer coefficient (W/m^2K)
V	Volume (m^3)

Greek Letters/Subscripts

α	Surface to volume ratio (m^2/m^3)
c,i	Cold side inlet
c,o	Cold side outlet
ε	Heat exchanger effectiveness
i	Inside
λ	Packing fraction of a PHFHE equals to $N{D_0}^2/{D_S}^2$
h,i	Hot side inlet
h,o	Hot side outlet
lm	Logarithmic mean
o	Outside
ov	Overall
ρ	Density of the fluid (kg/m^3)
s	Shell side
t	Tube side
u	Linear velocity inside the tube (m/s)
μ	Dynamic viscosity of the fluid(kg/ms)
w	Wall

0.1–0.4 W/m^2K, which is about 100–200 times lower than the metal materials. In order to overcome this obstacle and increase the thermal performance of polymer heat exchanger, researchers have studied the polymer heat exchangers with various configurations: gas to air heat exchanger with triangular channels [22], shell and tube or immersion coil fluoropolymer heat exchanger [23], air to water heat exchanger with rectangular channel Plate [24], plastic falling-film evaporator [25]. But the overall heat transfer coefficients achieved were still very low, which were in the range of 341–567 W/m^2K, with the fibre outside diameter between 2.54 mm and 9.53 mm.

The relatively low overall heat transfer coefficients can be improved and reach values comparable to metal heat exchangers, when the heat exchanger is made from polymer micro-hollow fibre with fibre wall thickness below 100 μm [25]. Several researches have been focused on the heat transfer mechanism of polymer micro-hollow fibre heat exchangers (PHFHE), with inside and outside diameter (ID and OD) less than 0.1 mm. Bourouni et al. [26] presented experimental data on a falling film evaporator and condenser made of 2.5 cm diameter circular PP tubes (wall thickness of 5 mm) used in an 'aero-evapo-condensation process' for desalination. The results showed that for the same thermal performance, such polymer heat exchanger was 2–3 times cheaper than its metal counterpart. Zarkadas and Sirkar [27] reported polymeric hollow fibre heat exchangers (PHFHE) for low temperature (up to 150–200 °C) applications. The overall heat transfer coefficients for the water-water, ethanol–water, and steam-water systems reached 647–1314, 414–642, and 2000 W/(m^2K), respectively. An olefin/paraffin distillation system using hollow fibre structured packings (HFSP) was proposed by Yang et al. [28]. This group of researchers recently scaled up the experiment and long-term operational testing results were obtained and reported (Yang et al. [29]). The results demonstrated that after long-term exposure to light hydrocarbon environments (≤70 °C), the mechanical properties of the PP polymer did not degrade significantly. Astrouski I. et al. [30] studied the fouling effect of polymeric heat exchanger made from PP (inner and out fibre diameter of 0.461 mm and 0.523 mm respectively) for the purpose of cooling TiO_2 suspension. The experimental test results showed a very high overall heat transfer coefficient, with up to 2100 W/m^2K for clean conditions and 1750 W/m^2K for dirty conditions at the flow velocity of 0.05 m/s. Zhao et al. [31] presented a numerical analysis of a novel PP hollow fibre heat exchanger for low temperature applications using FLUENT. The heat transfer coefficient of PP fibres was predicted to be achieved at 1109 W/m^2K with inside and outside fibre diameters of 0.6 mm and 1 mm respectively.

The lack of extensive experience and testing data for polymer hollow fibre plastic heat exchanger and the unwillingness of industry partners to depart from well established metal heat exchanger remain to be big barriers for the wide applications of this technology. With the aim to experimentally investigate the effects of various working flow rates and number of fibres on the overall heat transfer coefficients, and to validate the theoretical simulation model developed by the authors, three different modules of polymer hollow fibre heat exchanger (fibre ID of 450 μm and OD of 550 μm) were fabricated and tested in the laboratory testing conditions. The effects of various parameters on the overall heat transfer coefficient including flow rates, numbers of fibres, the effectiveness of heat exchanger, the number of heat transfer unit (NTU), and the height of transfer unit (HTU) are discussed in this paper. The experimental obtained overall heat transfer coefficient and overall conductance per unit volume for PHFHE are compared with these of metal heat exchangers. The experimental uncertainties occurred associated with the measurement of flow rates and working fluid temperatures, etc. are also analysed.

2. Theory

Assuming there is no heat loss to the surrounding, the overall heat transfer rate Q, between the shell side and tube side fluids, is defined by the flow rates of the hot and cold fluids flow rates and their inlet and outlet temperatures, as shown in the following equation:

$$Q = \dot{m}_t c_{p,t}\left(\mathrm{T}_{\mathrm{c,o}} - \mathrm{T}_{\mathrm{c,i}}\right) = \dot{m}_s c_s\left(\mathrm{T}_{\mathrm{h,i}} - \mathrm{T}_{\mathrm{h,o}}\right) \tag{1}$$

where subscript *t* denotes tube side and *s* denotes shell side.

The overall heat transfer coefficient U, can be given by:

$$\mathrm{U} = \mathrm{Q}/\left(\mathrm{A}\Delta T_{lm}\right) \tag{2}$$

where Q is an average heat transfer rate value between two fluids;

A is the heat transfer area (for hollow fibre heat exchanger, A is the total inside surface area of the hollow fibres);