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Analysis of improved novel hollow fiber heat exchanger

Xiujuan Yan [a,b,c,d], Baoan Li [a,b,c,d,*], Baoliang Liu [a,b,c,d], Jie Zhao [a,b,c,d], Yue Wang [a,b,c,d], Hao Li [e]

[a] Chemical Engineering Research Center, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, PR China
[b] State Key Laboratory of Chemical Engineering, Tianjin University, Tianjin 300072, PR China
[c] Tianjin Key Laboratory of Membrane Science and Desalination Technology, Tianjin University, Tianjin 300072, PR China
[d] Collaborative Innovation Center of Chemical Science and Engineering (Tianjin), Tianjin 300072, PR China
[e] Management and Economics Department, Tianjin University, Tianjin 300072, PR China

HIGHLIGHTS

- We reported a way to improve the heat transfer performance of the PHFHEs.
- We studied PHFHEs without net and with net experimentally as well as numerically.
- Three-dimensional models were built and the accuracy was validated.
- Shell-side heat resistance of PHFHEs with net was reduced obviously.
- The PHFHE with net has a better comprehensive performance.

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ABSTRACT

Plastic heat exchangers have been of increasing interest for lower temperature applications because of their superior resistance to chemicals and fouling characteristics. However, the quite low thermal conductivity of polymer materials limits their widespread use and acceptance. The Polymeric Hollow Fiber Heat Exchangers (PHFHEs) with extremely large surface area overcome the constraint and have attracted more and more attention. In this study, we improve the heat transfer performance of the PHFHEs by optimizing their structure. The optimized way is to place the polypropylene net between the inlet and the outlet of the shell side. The hydrodynamics and heat transfer characteristics of the PHFHEs without net and with net were studied experimentally as well as numerically. The accuracy of the numerical model is demonstrated by the comparison with the experimental results. In this model, the heat transfer coefficient and the pressure drop, together with the velocity and temperature fields are obtained and presented to help analyzing the heat transfer characteristics of the PHFHEs without net and with net. It is found that at the same flow rate, the shell-side heat transfer coefficient per unit pressure drop of the PHFHEs with net is obviously higher than that without net, indicating the PHFHEs with net have their advantages over the ones without net.

1. Introduction

Heat exchangers are used as universal equipment in many industrial departments. The most common problems of conventional metal heat exchanger are corrosion and fouling, especially in aggressive environment [1]. In addition, the use of metal heat exchangers leads to huge capital investments, large footprint, excessive weight, etc [2]. One prospective solution to these problems is to use polymeric materials. Their resistance to corrosion and fouling stimulate initial interest in the development of polymer-based heat exchangers [3]. Besides, they are less expensive and easier to shape, form, and machine than metals, and their densities are 4–5 times lower, resulting in much lower construction, transportation, and installation costs [4].

Nevertheless, the quite low thermal conductivity of polymer materials has prevented their widespread use and acceptance. To

* Corresponding author. Chemical Engineering Research Center, School of Chemical Engineering and Technology, Tianjin University, Tianjin 300072, PR China. Tel.: +86 22 2740 7854; fax: +86 22 2740 4496.
E-mail address: baoan.li@gmail.com (B. Li).

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overcome this constraint, Polymeric Hollow Fiber Heat Exchangers (PHFHEs) have been proposed by Sirkar and Zarkadas [4], Song [2]. The extremely large surface area/volume ratio of PHFHEs makes them more efficient than conventional metal heat exchanger [2,4]. Meanwhile, many researchers improve the thermal conductivity by filling polymers with graphite [5], carbon nanotubes [6–8], and other fillers [9,10]. Baoan Li and Yuchun Qin [11] developed novel graphite-modified polypropylene hollow fibers and gained satisfactory results, the overall heat transfer coefficient of water–water system achieved 1228.7 W/(m^2 K). However, we have not found any reports regarding the optimization of the structure about PHFHEs. The aim of this study is to improve the heat transfer performance of PHFHEs by optimizing their structure.

Experimental test is a common method to investigate the heat transfer performance of heat exchangers. But it is expensive and time consuming and flow visualization in the shell side is hard to deal with [12]. Simulations by means of Computational Fluid dynamics (CFD) can be helpful for studying fluid flow and heat transfer by solving mathematical equations with the help of numerical analysis [13]. Baoan Li and Jie Zhao have used CFD method to simulate the PHFHEs and analyzed their characteristics [14]. In this paper, we studied the optimized PHFHEs by using CFD code FLUENT. In the following, the experiment of PHFHEs will be presented firstly, and it is conducted to validate the simulation results. And then, the comparisons of the performance between the PHFHEs without net and with net will be presented and help analyzing the flow and heat transfer characteristics in the shell side.

2. Experiment

2.1. Heat exchanger module

Module 1 (M1) is an ordinary PHFHE. Module 2 (M2) is improved with polypropylene (PP) net. The net was placed between the inlet and outlet of shell side, and it is shown in Fig. 1. They were all fabricated by PP hollow fibers with graphite whose geometrical characteristics are shown in Table 1. M1 was made by packing the hollow fibers in the Polypropylene Random Copolymer (PPR) shell. However, each layer of the hollow fibers of M2 was firstly separated by PP net, and then packed them in the PPR shell. After that, the two ends of the hollow fiber surfaces were attached to the shell end caps with epoxy resin glue. After the glue solidified, the excess fibers were cut off. Finally the injection molding headers were fixed to the shell with stainless steel bolts and nuts.

2.2. Experimental apparatus and procedure

The experimental setup is schematically shown in Fig. 2. The setup included two independent loops: a cool water loop and a hot water loop. The cool water flowed through the shell-side of the heat exchanger by a diaphragm pump. The hot water flowed through the

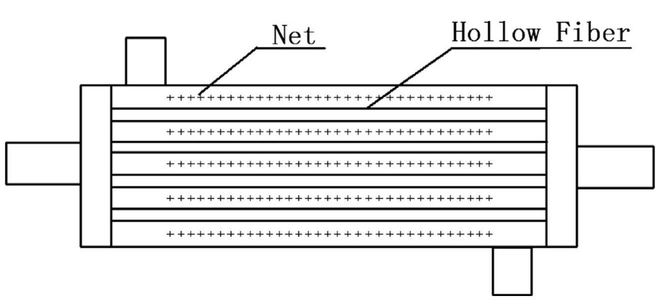

Fig. 1. Positions of the net and the hollow fibers.

Table 1
Geometrical characteristics of tube-and-shell hollow fiber heat exchanger.

Module	N	d_o (μm)	b (μm)	L (cm)	D_s (cm)	α (m^2/m^3)
Heat exchanger	120	1500	200	22.0	3.5	587.76

N, d_o, b and L is the effective number, the outside diameter, the wall thickness and the effective length of the hollow fibers, respectively. D_s is the inside diameter of the shell, α is the surface area to volume ratio based on total volume.

tube-side of the heat exchanger by a diaphragm pump and was kept at a constant temperature by using a thermostatic bath. The flow form was countercurrent. In order to prevent the heat loss of the facility, heat insulation materials were used to cover on the outer surface of the heat exchanger.

The inlet and outlet fluid temperature was measured by thermocouples (PT 100) and shown on the temperature monitoring device with an accuracy of ±0.1 °C. Measurements of the flow rates of the liquid system were carried out using flow meters with a relative uncertainty of ±1.5%. The pressure difference between inlet and outlet of the shell-side was measured by U-tube mercury manometer.

The experiment was carried out under steady-state. The different flow rates of the shell-side ranging from 5.4 to 22.5 L/min were repeated several times, while the flow rate of the tube-side was maintained at 3.4 L/min. The inlet temperatures of hot water and cool water were kept at 82 °C and 18 °C, respectively. In each experiment run, the data was recorded after achieving a steady state. Usually, it took 1.5 h to reach the steady state which was judged by the constant readings of the flow rates, pressure and temperature.

3. Numerical simulation

All the simulations were performed with FLUENT 6.3 and the preprocessor GAMBIT 2.3 [15].

Different from metal heat exchangers, the heat transfer resistance of polymeric material cannot be ignored and must be an integral part of the analysis. In this research, we built a fluid-solid coupled heat transfer system including tube-side, hollow fiber wall and shell-side. The following suppositions to the mode were made:

(1) Physical properties of fluid such as density, viscosity, specific heat and so on in duct were constant.
(2) Fluid was incompressible, isotropic and continuous.
(3) Fluid was Newton fluid.
(4) Gravitation was not taken into consideration.

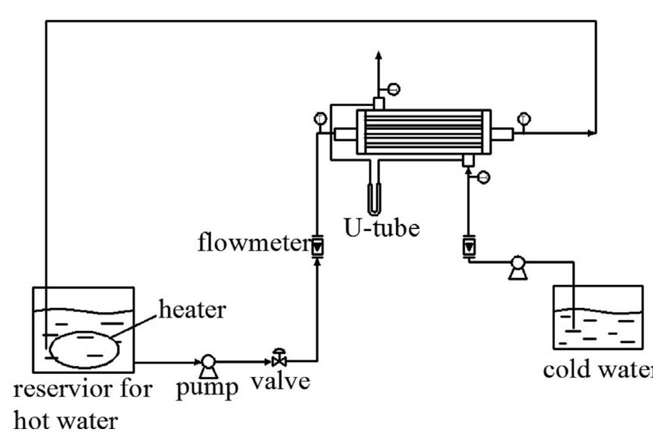

Fig. 2. Experimental setup for measurements of the hollow fiber heat exchanger.