Applied Thermal Engineering 59 (2013) 134–141

Contents lists available at SciVerse ScienceDirect

Applied Thermal Engineering

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

Numerical simulation of novel polypropylene hollow fiber heat exchanger and analysis of its characteristics

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HIGHLIGHTS

- Novel polypropylene tube-and-shell hollow fiber heat exchanger was fabricated and studied.
- Fluent was used to investigate novel polypropylene tube-and-shell hollow fiber heat exchanger.
- A three-dimensional model was built and the accuracy was validated.
- Shell-side heat resistance of hollow fiber heat exchanger is the dominant resistance.
- The optimized packing fraction of hollow fibers in heat exchanger is 13–19%.

ARTICLE INFO

Article history:
Received 16 January 2013
Accepted 15 May 2013
Available online 22 May 2013

Keywords:
Hollow fiber
Heat exchanger
FLUENT
Heat transfer characteristics
Packing fraction

ABSTRACT

Hollow fiber heat exchangers for lower temperature applications have attracted more and more attention because of their resistances to scaling and corrosion, and substantial space, cost and energy savings. It is important to study flow and heat transfer characteristics to develop the new type and promote wide application of hollow fiber heat exchangers. In this study, a three-dimensional model of tube-and-shell hollow fiber heat exchanger (there were no baffles on the shell-side) was proposed using Computational Fluid Dynamics (CFD) software tool FLUENT. The study of the hollow fiber heat exchanger used water–water system. Firstly, the impacts of velocities in tube-side and shell-side on total heat transfer coefficient were simulated. The calculated contributions of tube, shell and fiber wall heat resistances to the total resistance are 20%, 50% and 30%, respectively. Secondly, the velocity distribution in the hollow fiber heat exchanger was given, the thermal resistance of each side and the flow and heat transfer characteristics of the heat exchanger were discussed. Thirdly, the influence of packing fraction of hollow fibers to overall heat transfer coefficient was simulated. The result showed that there was an optimal value of packing fraction, which is 13–19%. The proposed method provides a significant reference for further study of hollow fiber heat exchangers.

1. Introduction

Heat exchangers play a significant role in the operation of many industrial systems. Conventional metal heat exchangers have some non-negligible shortcomings such as large footprint, excessive weight, huge capital investments, corrosion and fouling especially in a caustic environment, etc [1]. It has been recognized over 50 years ago that polymeric materials offered numerous advantages over metals. Their resistances to fouling and corrosion, substantial weight, space and cost savings, and ease of molding, manufacturing and maintenance [2–4] stimulated initial interest in the development of polymer-based heat exchangers. In recent years, polymer-based heat exchangers have been successfully applied in many industrial fields including air conditioning [5], seawater and brackish water desalination [6,7], material separation and purification [8], and heat recovery [9], etc.

Nevertheless, plastic heat exchangers are characterized by an inferior thermal performance. Polymeric Hollow Fiber Heat Exchangers (PHFHEs) have been proposed [10,11] as a new type of heat exchangers that can overcome this constraint. The quite large surface area/volume ratio plays an important role in improving the heat transfer coefficient. Zarkadas and Sirkar reported polymeric hollow fiber heat exchangers [4,11]. Polypropylene (PP), polyethereth-erketone (PEEK) and asymmetric polyethersulfone (PES) hollow fibers

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http://dx.doi.org/10.1016/j.applthermaleng.2013.05.025

have been used to manufacture heat exchangers [1,4,11]. The overall heat transfer coefficients for the water–water, ethanol–water, and stream–water systems reached 647–1314, 414–642, and 2000 W/(m^2 K), respectively. Baoan Li et al. [12] developed a novel graphite-modified polypropylene hollow fiber as the heat transfer medium, gained satisfied results, the overall heat transfer coefficient of water–water system achieved 1228.7 W/(m^2 K).

The requirements for economic design, optimization of operating conditions and enhancement of heat transfer performance create the need for quantitative information about hollow fiber heat exchangers. With the rapidly improved CFD technology, which can both save experimental cost and time, offers a numerical means to study the detailed flow and heat exchange process that takes place inside heat exchangers [13,14]. The use of CFD offers a very detailed solution containing local values of all relevant variables that are difficult to measure, such as inner pressure, velocities, temperature, viscosity, shear stress and so on. In the related studies, publications and literatures concerning of applying CFD software tool FLUENT to the hollow fiber heat exchanger are rarely found. The aim of this study is to try to establish an appropriate three-dimensional simulation model, use CFD method to analyze the flow and heat transfer characteristics of hollow fiber heat exchanger. Experimental studies were also conducted to validate the simulation results. The hollow fiber heat exchanger design was tube-and-shell countercurrent flow; there were no baffles on the shell-side, no cross-countercurrent flow. The heat transfer medium was water–water.

2. Experimental details

2.1. Heat exchanger module

PP solid hollow fibers of 0.2 mm wall thickness were used for the fabrication of heat transfer module whose geometrical characteristics are shown in Table 1. Fibers were firstly packed in the Polypropylene Random Copolymer (PPR) shell, and then the two ends of the hollow fiber surfaces were attached to the shell end caps with epoxy resin glue and no baffles were used. 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. A module photograph is shown in Fig. 1.

2.2. Leakage testing

Before the experiment was carried out, the heat exchanger was tested for leakage. Specific operations were as follows: While connected to the entrance of the shell-side of module with tap water, the exit was sealed. When water pressure was slowly raised up to 0.2 MPa, maintained that steady-state for half an hour. The appearance of water seepage in the tube-side indicated that the module was leaking; otherwise, there was no leakage.

2.3. Experimental apparatus and procedure

The experimental setup used for heat transfer measurements is shown in Fig. 2. Heat insulation materials were used to prevent the heat transfer between the shell and the ambient air of the whole system. Tap water was used as coolant and flowed through the tube-side of heat exchanger. Hot water kept at a constant temperature by means of a thermostatic and circulated through the shell-side of heat exchanger module by a diaphragm pump. The flow form was countercurrent. In this study, another process that hot water circulated through the tube-side and the coolant flowed through the shell-side was also employed. The inlet and outlet temperature was measured by thermal resistances (PT 100) and shown on the temperature monitoring device with an accuracy of ± 0.1 °C. The flow rates of the liquid system were obtained from flow meters with a relative uncertainty of $\pm 1.5\%$. The inlet and outlet pressure of the tube-side was measured by U-tube mercury manometer.

The experimental process was as followings. The flow rates magnitude of the system were 1–10 LPM on the shell-side and 1–10 LPM on the tube-side. Inlet temperature of hot water and coolant was kept at 85 °C and 24 °C, respectively. For each tube-side flow rate, five different shell-side flow rates were employed and vice versa. In each run, when the readings of the flow rates, pressure and temperature reached constant values, it was assumed that steady-state was achieved. The steady values of measuring instruments were recorded and used to calculate overall heat transfer coefficient.

Table 1
Geometrical characteristics of PP-based 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	244	1000	200	22.0	3.5	796.73

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.

Fig. 1. Photograph of the PP heat exchanger module.

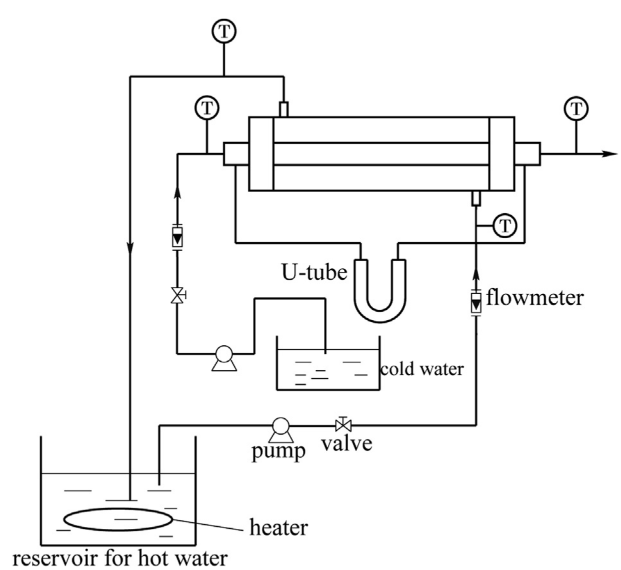

Fig. 2. Experimental setup for measurements of the PP-based hollow fiber heat exchanger.