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Research Paper

Numerical investigation on performance comparison of non-Newtonian fluid flow in vertical heat exchangers combined helical baffle with elliptic and circular tubes

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HIGHLIGHTS

- A novel helical baffle heat exchanger with elliptical tubes was developed and tested.
- Heat transfer performance in the elliptical tube heat exchanger was numerically studied.
- Performance comparison of elliptical tubes with circular tubes was investigated numerically.
- Elliptic tube can effectively improve the heat transfer performance.
- The correlations for Nu and f in the shell side of the elliptic tube heat exchanger were proposed.

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ABSTRACT

In the present study, heat transfer and flow resistance characteristic in the shell side of a vertical heat exchanger combined helical baffles with elliptic tubes were experimentally and numerically investigated. An aqueous solution with 3% weight fraction of carboxymethyl cellulose exhibits non-Newtonian fluid behavior selected as the working fluid whose stability is excellent found in our previous investigation, and flows in the shell side of the tested heat exchanger. A helical baffle heat exchanger with circular tubes based on the same equivalent outside diameter of the elliptic tubes was also numerically studied for the performance comparison. The numerical results showed that, the heat transfer rate per unit outside surface area and shell side Nusselt number of the elliptic tubes heat exchanger are 14.7%–16.4% and 11.4%–16.6% higher than those of the circular tubes heat exchanger, and the shell side friction factor is lower by 29.2%–36.9%. The comprehensive thermal performance factor is given to evaluate both heat transfer coefficient and pressure drop. The thermal performance factor enhances by 30–35%, which demonstrates that the elliptic tube can effectively improve the heat transfer performance of non-Newtonian fluid flowing in the helical baffle heat exchanger when compared to the circular tube. Based on experimental results, correlations for predicting the shell side Nusselt number and friction factor of the heat exchanger combined helical baffle with elliptic tubes were presented.

1. Introduction

Shell-and-tube heat exchangers are widely used for the heating or cooling of non-Newtonian fluids in various industrial sectors like oil industry, plastics industry, chemical engineering and food processing. The viscosity of non-Newtonian fluids is usually greater, involving low Reynolds number and high Prandtl number. Consequently, in the process of flow and heat transfer, the pressure drop is high while the heat transfer coefficient is considerably low [1]. The heat transfer enhancement of non-Newtonian fluids is rather important in the development of efficient shell-and-tube heat exchangers.

The non-Newtonian fluids are designed commonly to flow in the shell side of shell-and-tube heat exchangers due to the high viscosity. The shell side heat transfer coefficient can be increased by using novel baffle configurations and enhanced tubes. The baffles are of primary importance in shell-and-tube heat exchangers because they force the shell side fluid to flow across the tubes to ensure high heat transfer rates and provide support to tube bundles. A new type of heat exchanger with helical baffles was firstly reported by Lutcha and Nemcansky [2], they found that the helical baffles can eliminate the pressure losses caused by change of flow direction and maintain helical flow on the shell side, thus resulting in the improvement of heat transfer characteristics. The experimental result

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obtained by Kral et al. [3] showed that the ratio of heat transfer coefficient to pressure drop in the shell side of heat exchanger with helical baffles is obviously higher than that of heat exchanger with segmental baffles. Afterwards, many experimental and numerical investigations have been conducted by some researchers to study the effects of geometrical parameters (i.e., helix angle and baffle pitch) [4–7], baffle assembly configurations [8–11], circumferential overlap sizes [12–14], shape and quantity of helical baffles [15–20] on flow and heat transfer performance of the heat exchanger with helical baffles. Except for heat transfer performance research, different design and optimization methods of heat exchangers with helical baffles were also proposed [21–24]. But these research works mentioned above focus mainly on the horizontal heat exchangers with circular tubes, and working fluids are Newtonian fluids. In fact, the vertical heat exchangers are widely used in the industry due to the less space demand. Until now, the experimental and numerical study on flow and heat transfer characteristics of non-Newtonian fluids flowing in a vertical heat exchanger with helical baffle is not reported yet in the open literature.

Other than the optimization of baffle configurations, the enhanced tubes are widely utilized to improve the shell side heat transfer in shell-and-tube heat exchangers. Zhang et al. [25–27] have experimentally and numerically studied the shell side heat transfer enhancement of helical baffle heat exchanger with fin tubes using oil and water as the working fluids, respectively. The results showed that the shell side heat transfer coefficient was obviously higher than that of smooth tubes at the helical flow condition. But for non-Newtonian fluids, the heat transfer enhancement is rarely studied. The experimental and numerical results showed the Nusselt numbers for non-Newtonian fluids flowing inside the helical coil heat exchangers are commonly less than 37 [28,29]. Bharti et al. [30] carried out a numerical investigation to study the forced convection heat transfer to incompressible power-law fluids from a heated elliptical cylinder in the steady, laminar cross-flow regime. They found that the average heat transfer is facilitated by up to 100% in shear-thinning fluids. The functional dependence of the average Nusselt number on the Reynolds and Prandtl numbers and power-law index has been presented by empirically fitting the numerical results. Thus, combining helical baffles with elliptical tubes is supposed to enhance heat transfer and reduce pressure drop of non-Newtonian fluids in shell side of shell-and-tube heat exchanger. As far as known to us, there has been no prior study on the forced convection heat transfer of non-Newtonian fluids flowing in helical baffle heat exchanger with elliptical tubes.

In the current study, a helical baffle heat exchanger with elliptical tubes was developed and selected as a tested heat exchanger. The flow and heat transfer characteristics of a non-Newtonian fluid flowing in the shell side of the tested heat exchanger was experimentally and numerically investigated by using commercial software FLUENT. An aqueous solution of carboxymethyl cellulose (CMC) with 3.0 wt% concentration was used as the working fluid. The preparation method and thermo-physical properties and rheological characteristics measurements of CMC aqueous solution can be found in our previous paper [31]. It is found that the 3.0 wt% CMC aqueous solution is acceptable for the industrial application due to its relatively low viscosity and excellent stability. A similar helical baffle heat exchanger with circular tubes based on the same equivalent outside diameter of elliptical tubes was numerically studied for the performance comparison. The heat transfer rate, Nusselt number, friction factor and comprehensive thermal performance of the elliptical tubes heat exchanger were compared with those of the circular heat exchanger at constant Reynolds number using CFD method.

2. Experimental setup

The schematic diagram of experimental system is presented in Fig. 1. It consists of a non-Newtonian fluid loop, a cooling water loop and a data acquisition system. In the non-Newtonian fluid loop, the CMC aqueous solution as working fluid is pumped from a storage tank with a stirrer into a preheater by a gear pump and measured by an oval gear flow meter. The preheater is a shell-and-tube heat

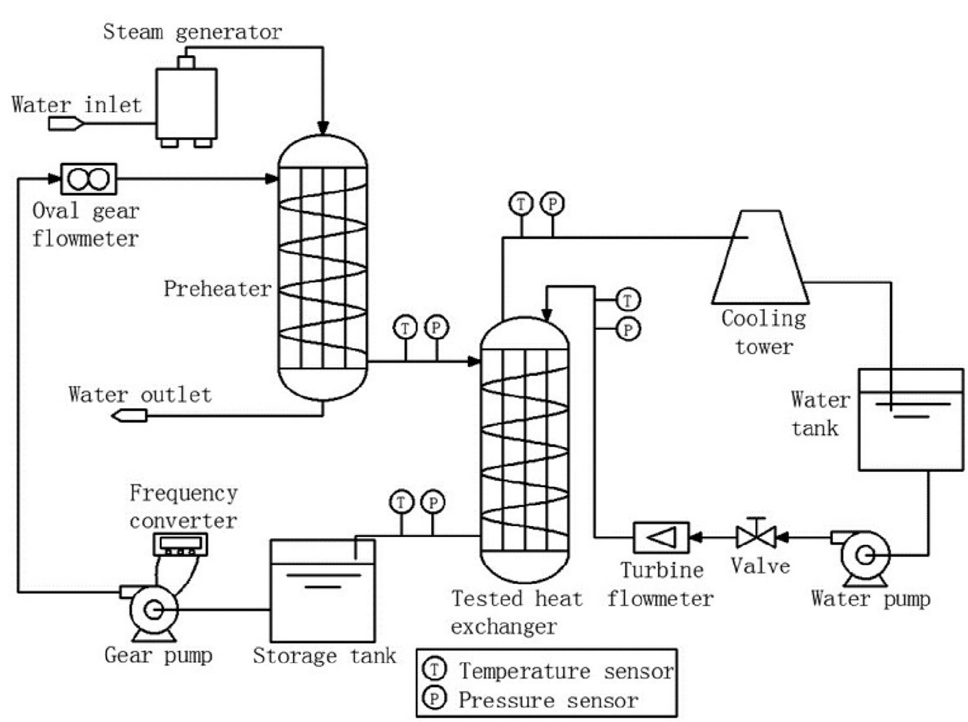

Fig. 1. Schematic diagram of the experimental setup.