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Experimental investigation on the hydrothermal performance of a double-pipe heat exchanger using helical tape insert

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ABSTRACT

This study experimentally examines the hydrothermal performance of horizontal Double Pipe Heat Exchangers (DPHEs) with and without continuous Helical Tape Insert (HTI) conducted on the outer surface of the internal pipe. Ten DPHEs of counter-flow configurations were constructed; nine of them were with HTI fabricated with different ratios of HTI height to the clearance between the two pipes (δ), and different ratios of HTI pitch to HTI diameter (). The experiments were performed with pure water in both sides with $2050 \leq Re_{an} \leq 15925$, and $Re_t \approx 26700$. Compared with plain annulus-case, the results showed that using the HTI increases both annulus average Nusselt number ($\overline{Nu}_{an}$) and Fanning friction factor (f_{an}), with average increases of 69.4–164.4% and 48.6–113.1%, respectively, when δ increases from 0.275 to 1, and with average increases of 78.1–183.2% and 67.6–99.2%, respectively, when decreases from 1 to 0.333. The hydrothermal performance index (*HTPI*) was determined to compare the performance of DPHEs with HTI to that of plain annulus case. The results demonstrated that HTI of $\delta = 0.667$ provides the highest *HTPI*, while *HTPI* increases with decreasing λ. Finally, correlations for $\overline{Nu}_{an}$, f_{an}, and *HTPI* for DPHEs with HTI in the annulus as a function of the investigated parameters were proposed.

1. Introduction

Enhancing the thermal performance of heat exchange affects directly on energy, material and cost savings. Consequently, improving the heat exchange can significantly improve the thermal efficiency in applications involving heat transfer processes as well as the economics of their design and operation [1]. DPHEs are primarily adapted to high temperature and high-pressure applications due to their small diameters. They are cheap, but the space they occupy is relatively high compared to the other types. To achieve the desired heat transfer rate in the given design and length of the heat exchanger at an economic pumping power, numerous techniques have been provided. These improvement techniques were classified as *active* and *passive* techniques [2,3].

Fins of different configurations as they are considered passive techniques were investigated to introduce the effect on the thermal performance of DPHEs. Nagarani and Mayilsamy [4] experimentally used circular and elliptical annular fins in a DPHE. They detected that heat transfer rate improved with elliptical fins than circular ones. Syed et al. [5] numerically investigated the laminar fully developed flow in the annulus-side of a DPHE employed with triangular fins. The authors found a significant enhancement in heat transfer rate and Nusselt number. For the small number of fins, fin height, ratio of radii, and half fin angle have less importance. Zhang et al. [6] experimentally studied the fluid flow characteristics in the annulus-side of a DPHE with HFs and pin fins. The results showed that for the annulus-side only with HFs at large pitch, there was a pair of vortex near the upper and lower edge of the rectangular cross-section and the weakest secondary flow occurred at the center. By installing pin fins, the three-dimensional velocity components in the helical channel were strongly affected. Kumar et al. [7] numerically studied the performance characteristics of a DPHE for three different longitudinal fin patterns, rectangular, triangular and parabolic. The results showed that fins with concave parabolic profiles owned minimum pressure drop and has reduced by 38% and 65% compared to the triangular and rectangular finned tube, respectively. Iqbal et al. [8] numerically examined the optimal pattern of a finned annulus with parabolic, triangular and trapezoidal fins. They found that no single fin shape is best in all situations and for all criteria. Hameed and Essa [9] evaluated experimentally and numerically the performance of triangular finned tube heat exchanger. The experimental results presented that the improvement of heat dissipation for the triangular finned tube is 3.25–4.5 times than that of the smooth tube, respectively.

In other studies, turbulators with different shapes were used for

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enhancing the thermal performance of DPHEs. AL-Kayiem and EL-Rahman [10] analytically studied the thermal characteristics of DPHE with a ribbed inner pipe. An enhancement of four times in the heat transfer was achieved at a penalty of increasing pressure drop of more than 18 times. Totala et al. [11] performed an experimental study on a DPHE for threaded and non-threaded of the inner pipe. The authors showed that both heat transfer rate and the pumping power were increased for the threaded pipe compared to the plain pipe. Al-Kayiem and Al-Habeeb [12] and Al-Kayiem et al. [13] experimentally investigated the hydrothermal performance enhancement of DPHE using ribs conducted on the inner surface of the annulus. They examined the effect of the pitch between the ribs in addition to the rib height. Sheikholeslami et al. [14,15] experimentally examined the influence of employing typical circular-ring and perforated circular-ring turbulators in the annulus-side of an air to water DPHE on its thermal performance. The experimental runs were performed for Reynolds number from 6000 to 12000. Compared with the circular rings, the results indicated that conducting perforated circular-rings decreased the heat transfer augmentation. Moreover, the thermal performance enhanced with increasing the number of rings but it decreased with the increase in Reynolds number and pitch ratio. Chamoli et al. [16] used Taguchi-grey analysis approach to examine the effect of geometry of perforated disk turbulaters and flow parameters on the thermal performance of a DPHE. The results indicated the feasibility of the Taguchi-grey method for predicting performance, optimization and improving the design of these heat exchangers. Sheikholeslami and Ganji [17,18] carried out numerical and experimental studies on enhancing the thermal performance of DPHEs using perforated turbulators and typical helical fin in the annulus side. The influence of turbulators geometrical parameters and flow Reynolds number; 6000–12000, were tested. The results showed that increasing turbulators perforation improves the thermal performance enhancement while increasing pitch ratio and increasing porosity of the turbulators decrease the temperature gradient. Finally, the authors proposed correlations for the friction factor, Nusselt number and thermal performance. Al-Kayiem et al. [19] tested experimentally the improvement of the heat transfer using energy promoters having rectangular cross section ribs, conducted on the inner surface of the annulus for Reynolds number from 2900 to 21000. It was found that augmentation in the heat transfer was associated with high pumping power.

Additionally, other researchers investigated the effect of inserts with different shapes on the heat transfer and pressure drop characteristics in DPHEs. Gunes et al. [20] experimentally tested the thermal performance of a tube with equilateral triangle cross-sectioned coiled wire inserts. The experiments revealed that the highest overall enhancement efficiency of 36.5% was achieved. Pardhi and Baredar [21] experimentally investigated the performance improvement of a DPHE by using two different twisted tapes. They concluded that was that the heat transfer coefficient increased by 61–78% as compared to the conventional heat exchanger. Pachegaonkar et al. [22] experimentally investigated the performance of a DPHE with annular twisted tape insert. Their results demonstrated that both heat transfer coefficient and pressure drop in the pipe with twisted tape were higher than those in the plain pipe. Gaikwad and Mali [23] conducted experiments to investigate the effect of twisted wire brush inserts in the inner pipe of the DPHE. The obtained results showed that the Nusselt number and the pressure drop for the tube with twisted wire brush inserts varied from 1.55 to 2.35 times in comparison to those of the plain tube. While the pressure drop for twisted wire brush inserts was 4–5% higher than that obtained for the plain case. Chen et al. [24] studied experimentally the performances of helically baffled heat exchangers for oil-water heat transfer. The test results showed that both the shell-side heat transfer coefficient and pressure drop increased but the comprehensive index $h/\Delta P$ decreased with the increase of the mass flow rate and with the increase of the helical baffle pitch. Kumar et al. [25] experimentally tested the influence of circular perforated ring insert on the heat transfer and flow resistance characteristics of the heat exchanger. The experiments were performed in an iso-fluxed test section for Reynolds number range of 6500–23000. It was observed that there is a sharp increase in both heat transfer and friction loss, with a maximum thermal performance index of 1.47. Maakoul et al. [26] numerically simulated the thermal characteristics in a helically baffled DPHE. The simulations indicated that heat transfer performance and annulus flow resistance increased compared to the simple heat exchanger, and they increase with the increase of baffle spacing and Reynolds number.

From the aforementioned literature survey, it is clear that there are numerous shapes of fins, turbulators, and inserts that were used as passive heat transfer enhancement techniques. It was shown that the main problem in using conventional inserts is the sharp increase in flow pressure drop. In addition, there is no experimental study performed to investigate the effect of the geometrical parameters of the HTI conducted in the annulus-side on the performance of DPHEs. The HTI was selected in the present study as it was expected that it might enhance the hydrothermal performance of the DPHEs. Therefore, the present work is devoted to experimentally investigate the characteristics of the forced convective heat transfer and pressure drop in the annulus-side of horizontal DPHEs with inserting a continuous helical tape with different height and pitch ratios. This is to extend DPHEs designers with Nusselt number, friction factor and hydrothermal performance index correlations for a wide range of HTI geometrical parameters and annulus-side operating conditions.

2. Experimental apparatus

The experimental facility employed in the present investigation comprises hot and cold loops in addition to the flow, temperature and pressure difference measuring instruments, which were described in the previous work [27]. Here, the test section is a horizontal DPHEs with HTI conducted in the annulus side. Fig. 1 is a schematic diagram of the experimental setup, while Fig. 2 displays photographs of the used HTIs. In the present apparatus, two variable area flow meters (1.7–18 l/min) were employed to measure the flow rates of the hot and cold water in both sides of the DPHE. The two flow meters have been calibrated by determining the time required to fill a vessel with 20-L capacity. Four K-type thermocouples (wires of 0.1 mm diameter) were directly inserted into the flow streams, at approximately 50 mm from the heat exchanger ports, to measure the inlet and outlet temperatures of the annulus and internal pipe fluids. The thermocouples were linked through a switching box to a digital thermometer indicator with a resolution of ± 0.1°C to display the measured temperatures. All thermocouples were calibrated in the laboratory against a mercury-in-glass thermometer, which could be accurately read to ±0.5°C. A digital differential pressure transducer was used for measuring the pressure drop of water between the annulus inlet and outlet. The transducer has a working range of 0–206.8 kPa and accuracy of ± 2% of full scale. Two 1.5 hp power rating centrifugal pumps were used to circulate the heating and cooling water. Flexible nylon and Polyvinyl Chloride (PVC) tubing were used for all connections.

The HTIs were formed from 0.6 mm thick soft copper sheet and a laser was used during cutting and drilling processes. The sheet was cut to form many disks, which were drilled in their centers (elliptic hollow). The hollow disk was cut again from one side. The new two ends of the disk were pulled with a specified pitch to form one turn of the HTI. To achieve a continuous HTI on the outer surface of the internal pipe, many turns were prepared and welded end to end using copper welding. Finally, the HTI were conducted on the internal tube using copper welding. Fig. 3 illustrates the geometry of the DPHE with its HTI.

To explain the effects of the HTI pitch and height, the following dimensionless parameters; height ratio (δ) and pitch ratio (λ) are used. They are defined as follows: