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Turbulent flow and heat transfer enhancement in a heat exchanger tube fitted with novel discrete inclined grooves

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In the present work, we propose a novel enhanced tube with discrete inclined grooves, aiming to enhance heat transfer with minimum consumption of pump power by generating longitudinal swirl flows with multiple vortices in the proposed grooved tube. A numerical study has been conducted to investigate the turbulent flow structures and the effects of geometric parameters on the thermal performance. According to the results, longitudinal swirl flows with multiple vortices are generated in the grooved tube, and the number of induced vortices is proportional to the number of circumferential grooves. The heat transfer and friction factor are enhanced by a factor of approximately 1.23–2.17 and 1.02 to 3.75 over the smooth tube, respectively. To further understand the physical mechanism of the enhanced grooved tube and to assess the effects of geometric parameters, entropy generation analyses have also been performed. The results show that the entropy generation number ratios decrease with increasing the number of circumferential grooves and with the reduced groove pitch ratio, and a number of circumferential grooves of 12 and a groove pitch ratio of 3 are recommended for the proposed grooved tube. In addition, comparisons with previous work show that the proposed grooved tube provides considerably higher overall thermal performance than the transversally grooved tube, internally helical grooved tube and continuous corrugated tube, but lower thermal performance than the discrete corrugated tube at lower Reynolds numbers, indicating that the proposed grooved tube is very promising for heat transfer enhancement in practical applications.

1. Introduction

Heat exchangers, which ensure heat transfer from one medium to another, have wide applications ranging from petroleum, chemical, power generation industries and domestic uses. Enhancement in a heat exchanger's overall performance contributes to reducing the size of heat exchangers and make material and energy savings related to the heat exchange processes [1]. In practical applications, it is usually necessary to develop efficient enhanced heat transfer tubes to improve the efficiency of a heat exchanger, due to the fact that a heat exchanger's overall performance is determined by the heat transfer in the tubes which are the basic heat transfer units for a heat exchanger. Tube inserts like twisted tapes and coiled wires or artificial roughness elements such as ribs, grooves and corrugations on the surface are commonly used heat transfer enhancement techniques for tubes. Among these techniques available, artificial grooved tubes show better overall thermal performance and are widely used in modern heat exchangers, because they are very effective in heat transfer augmentation [2].

Bilen et al. [2] experimentally investigated the effects of groove geometry on heat transfer for internally grooved tube. Three geometric groove shapes (circular, trapezoidal, and rectangle) were adopted to perform the tests. The heat transfer enhancement was obtained up to 63% for circular groove, 58% for trapezoidal groove and 47% for rectangle groove, compared to the smooth tube. Aroonrat et al. [3] studied the heat transfer and flow characteristics of water flowing through horizontal internally grooved tubes, including one straight grooved tube and four helical grooved tubes with different pitches. The results showed that the thermal enhancement factor obtained from helical grooved tubes is about 1.4–2.2 for a pitch of 0.5 inch; 1.1 to 1.3 for pitches of 8, 10, and 12 inches, respectively; and 0.8 to 0.9 for a straight grooved tube. Bharadwaj et al. [4] determined pressure drop and heat transfer characteristics of flow of water in a 75-start spirally grooved tube

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with twisted tape insert experimentally. Laminar to fully turbulent ranges of Reynolds numbers were considered in the experiments. It was found that heat transfer enhancement due to spiral grooves was further augmented by inserting twisted tapes compared to smooth tube.

Experimental measurements and analyses about transition and turbulent convective heat transfer performances of molten salt in the spirally grooved tube were conducted by Lu et al. [5]. According to the experimental results, the groove height increment remarkably enhanced heat transfer in the spirally grooved tube. Later, Lu et al. [6] experimentally investigated the convective heat transfer of high temperature molten salt in transversely grooved tube using electric power through the testing tube, and developed experimental correlation for molten salt flow in transversely grooved by considering the groove height.

There are further studies concerning the thermal-hydraulic performance for condensation and evaporation in the grooved tubes. Goto et al. [7] measured heat transfer coefficient and pressure drop for condensation and evaporation of R410A and HCFC22 inside conventional spiral groove tubes and herring-born groove tubes. The results showed that the local heat transfer coefficients of the herring-bone grooved tubes were about twice as large as those of spiral one for condensation, and were slightly larger than those of spiral one for the evaporation. Zhang et al. [8,9] carried out experimental studies on heat transfer characteristics for evaporation of R417A flowing inside horizontal smooth and internally grooved tubes. Recently, Zhang et al. [10] investigated heat transfer enhancement and pressure drop performance for R417A flow boiling in smooth and internally grooved tubes experimentally. The results indicated that both enhancement factor and penalty factor increased with increasing mass flux, while enhancement parameters showed different situations in different internally grooved tubes.

Grooves have also been applied in other channels besides circular tubes. A numerical investigation of turbulent forced convection in a two-dimensional channel with periodic transverse grooves on the lower channel wall was conducted by Eiamsa-ard and Promvonge [11]. Latser, they [12] experimentally examined the turbulent forced convection heat transfer and friction characteristics in a rectangular duct with rib-grooved turbulators. Bi et al. [13] examined the local heat transfer characteristics in the mini-channels with enhanced dimples, cylindrical grooves and low fins by using the field synergy principle. Liu et al. [14] proposed novel groove geometries, which were conventional cylindrical grooves with rounded transitions to the adjacent flat surfaces and with modifications to their bases, and numerically analyzed the turbulent flow characteristics and heat transfer performances in square channels with different cylindrical-shaped grooves. According to the numerical results, the rounded transition of the grooves had a large advantage over conventional cylindrical grooved surfaces in both enhancing heat transfer and reducing pressure loss penalty. Tang et al. [15] numerically investigated the effects of groove configurations and various geometric parameters on heat transfer enhancement in a narrow channel with discrete grooved structures. The results of parameters study showed that the case of P-type grooves with $p_h = 1.2, f_h = 2.6, e_h = 1, \alpha = 30°$ provided the best overall thermal performance factor at $Re = 4016$.

According to the above literature survey, grooves can be used to improve thermal performance for single-phase flow or two-phase flow in circular tubes or other channels. However, utilizations of the grooves usually result in a considerable increase in the pressure drop for the heat transfer enhancement. To provide guidelines for achieving energy savings by improving the balance between heat transfer enhancement and pressure drop, our group has carried out several heat transfer optimization studies [16–20]. The theoretical results obtained show that longitudinal swirl flow with multiple vortices is a flow pattern that can lead to high overall thermal performance of circular tubes.

In Ref. [21], Meng proposed a double discrete inclined ribbed tube (DDIR-tube) for heat transfer enhancement. The results show that longitudinal swirl flows with multiple vortices can be generated with the unique arrangement of the ribs. In the present work, we propose a novel enhanced tube with discrete inclined grooves. The arrangement and size of grooves are similar to those of ribs as shown Ref. [21]. The objective of this work is aiming to enhance heat transfer with minimum consumption of pump power by generating longitudinal swirl flows with multiple vortices in the proposed grooved tube. A numerical study of turbulent flow and heat transfer in the grooved tube is conducted to document the possibilities. Turbulent flow and heat transfer details, and effects of geometric parameters on the flow and heat transfer are presented and analyzed. To understand the physical mechanism of the enhanced grooved tube and to assess the effects of geometric parameters on the heat transfer performance, entropy generation analyses have also been performed to further reveal the essence of heat transfer enhancement.

2. Model description

The schematic diagram of the circular tube with discrete grooves characterized by a discrete and inclined distribution investigated in the present numerical work is shown in Fig. 1. The tube consisted of three sections with a total length of 0.4 m (l). The test section had a length of 0.2 m (L_2), an inner diameter (D_1) of 0.017 m and an outer diameter (D_2) of 0.019 m. To guarantee a nearly fully developed flow situation and to eliminate downstream disturbance effects; two extended smooth tubes with lengths of $10D_1$ (L_1) and $10D_1$ (L_3) were connected upstream and downstream of the test section, respectively.

In the test section, discrete inclined grooves were uniformly arranged on the inner wall surface of the tube as shown in Fig. 2. The fixed geometric parameters for the grooves were groove length (L = 0.006 m), groove width (W = 0.002 m), groove depth ($H = 0.0005$ m) and groove inclination angle ($\alpha = 30°$). Five values of the number of circumferential grooves (N = 4, 6, 8, 10, 12); and five values of the groove pitch ratio, defined as the ratio of the groove pitch to the groove width ($P^* = P/W = 3, 4, 5, 6, 7$) were used to examine the influence of geometric parameters on heat transfer and flow performance in the grooved tube.

3. Numerical simulations

3.1. Selection of turbulence model

The selection of an appropriate turbulence model is crucial to the accuracy of numerical results. The commonly used turbulence models in engineering applications, including the *realizable* k-ε Model, the *standard* k-ω Model and the *SST* k-ω Model were used to investigate the steady-state, three-dimensional turbulent flow and heat transfer characteristics of the DDIR-tube as documented in Ref. [21]. The results obtained using these turbulent models were compared with the experimental data, as shown in Fig. 3. It is evident that the average Nusselt number calculated by the *SST* k-ω Model is most similar to the experimental data of the model tested than that using other turbulence models. Quantitatively, the maximum deviations for the average Nusselt number between the experimental and numerical data for the *realizable* k-ε Model, the *standard* k-ω Model and the *SST* k-ω Model are 9.4%, 8.4% and 6%, respectively, indicating that the *SST* k-ω Model is more reliable than other models. Therefore, the *SST* k-ω Model was employed for