Numerical heat transfer investigation in a heat exchanger tube with hexagonal conical-ring inserts

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Abstract

The hexagonal conical rings (HCR) modified from the typical conical ring (CR) are used as a turbulence promoter for producing the vortex flows to enhance the heat transfer rate in a heat exchanger tube. To reduce the pressure loss, the V-shaped HCR (V-HCR) obtained by cutting both symmetric plane of the cone-tip of HCR at 30°, 45° and 60° is offered in the present work. The tube fitted with V-HCR elements having a fixed inlet and outlet diameter is numerically investigated. The computation is carried out for Reynolds number in a range of 3000 to 20,000 in a uniform heat-fluxed test tube. The numerical results show that the V-HCR insert leads to much higher heat transfer than the typical CR/HCR insert or the smooth tube alone and also provides lower friction factor. The 30° V-shaped HCR gives the highest heat transfer and thermal performance due to the lowest friction loss, indicating the promising device of the V-HCR.

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1. Introduction

Heat transfer augmentation methods in a heat exchanger/solar hot water heater systems are of interest because such a system is the main part in chemical process plants that directly involves the energy consumption. Several heat exchangers are applied in many industries such as chemical-product plants, air conditioners, refrigerators, car radiators, etc. In general, the passive technique is more popular than the active one for enhancing the heat transfer coefficient of the system, it includes the employ of rough surfaces, coiled-wire, vortex-flow devices, helical strips, twisted tapes, conical ring, V-shaped ribs and inclined rings [1–6]. For decades, experimental investigations have been made on conical rings but there has been very few on numerical work. Also, the use of V-HCRs mounted repeatedly in a heat exchanger tube has never been come across in the literature. Therefore, a numerical investigation for three dimensional turbulent flows through the V-HCRs mounted in the tube is conducted to examine the flow structure and thermal behaviors for turbulent region.

2. Physical Model

2.1 Hexagonal conical ring geometry and arrangement

The typical conical ring (CR) and V-shaped hexagonal conical ring (V-HCR) were inserted periodically in a circular tube as shown in Fig. 1. The flow in the present work is expected to be a fully periodical flow where the velocity field repeats itself from one module/cell to another. Thus, a single module of the HCR was set as a periodic flow model and due to symmetry, only a quarter of the flow model was selected as a computational domain as shown in Fig. 1. The concept of periodically fully developed flow in duct was first offered by Patankar et al. [7]. In the figure, the air entered the tube with CR/HCR insert at inlet temperature, $T_i$. The attack angle or V-tip half-angle ($\alpha$) of the V-HCR was set to $\alpha=30^\circ$, $45^\circ$ and $60^\circ$; $D$ was the tube diameter set to 0.05 m. The HCR length was equal to $D$ where its inlet and outlet diameter ratios were fixed to $D_{RI} = d_i/D = 0.6$ and $D_{RO} = d_o/D = 0.99$. The axial pitch, $P$ was axial distance between the HCR module and set to $P=L=2D$ in which $P/D$ is defined as the pitch ratio, $P/R=2$. To examine an influence of the HCR inserts, three values of the attack angle, $\alpha$ were given to $30^\circ$, $45^\circ$ and $60^\circ$, apart from $90^\circ$ (HCR with no V-cut). Also, the CR insert with similar dimensions was made for comparison purpose.

![Fig. 1. Arrangements of HCR, CR and V-HCR and computational domain.](image)

2.2 Boundary conditions

Periodic boundaries were applied for the inlet and outlet of flow domain and then a constant mass airflow rate at 300 K obtained from the preset Reynolds number was input due to fully periodical flow. Air was used as the test fluid and its physical properties were assumed to remain constant at the mean bulk temperature (300K). For all wall surfaces, impermeable boundary and no-slip conditions were utilized. A uniform heat-flux of 600 W/m$^2$ was applied on the tube wall whereas the surfaces of HCR/V-HCR were set to be adiabatic wall.

3. Mathematical formulation

The following assumptions: 3D steady turbulent and incompressible flow with neglecting body forces, viscous dissipation and radiation were applied to the current periodic flow model that was governed by the continuity, the momentum and the energy equations. The Reynolds-averaged Navier-Stokes equations created the Reynolds stress terms that were modelled by using the Realizable $k–\epsilon$ turbulence model for closure of the variables. The QUICK scheme was applied to all the discretized governing equations and then, the finite volume method [8] was used to solve the discretized equations. The numerical solutions were converged when the residual values were below $10^{-6}$ except that the energy equation was under $10^{-9}$. 
Reynolds number (Re), friction factor (f), Nusselt number (Nu) and thermal enhancement factor (TEF) are parameters of interest. The Reynolds number was defined as

\[ \text{Re} = \frac{\rho \bar{u} D}{\mu} \]  

The friction factor, \( f \), was evaluated from pressure drop, \( \Delta p \) across the periodic flow length, \( L \) as

\[ f = 2 \frac{\Delta p}{(L \rho \bar{u}^2)} \]  

The average Nusselt number was obtained by integrating local Nusselt number over the surface area, \( A \) as

\[ \text{Nu} = \frac{(1/A) \int \text{Nu} \, dA}{\text{Nu}_0} \]  

The TEF defined as the ratio of Nu of inserted tube to Nu of plain tube at similar blowing power was written as

\[ \text{TEF} = \left( \frac{\text{Nu}}{\text{Nu}_0} \right) \left( \frac{f}{f_0} \right)^{-1/3} \]  

where subscript “0” denotes its value for the smooth tube.

The computational domain was resolved by polyhedral elements. A grid independence solution was tested by using the Nu solutions for three different grids, 172,452, 292,465 and 485,378, and the Nu difference of the last two grids was less than 0.2%. Therefore, the grid of 292,465 was adopted in the current work.

4. Results and discussion

4.1 Validation of numerical results

Validation of numerical Nu and \( f \) for the reversed CR insert is made with measurements as depicted in Fig. 2a and b, respectively. In the figure, good agreement between numerical and measured data [6] is within 6% each.

4.2 Flow structure

The streamlines in transverse planes and temperature contours for a flow model fitted with CR, HCR and 30°V-HCR for \( D_{Ri} = 0.6, D_{Ro} = 0.99 \) at Re=12,000 can be shown in Fig. 3a, b and c, respectively. In Fig. 3c, the 30° V-HCR can produce two main counter-rotating vortices that assist to induce impinging jets over certain regions of the tube wall while both the HCR and CR cannot. This means that only the V-HCR can be viewed as “a vortex-flow device”. As presented also in Fig. 3c, the low temperature for the V-HCR can be seen in some regions. The lowest temperature is at the flow impingement area on the surface where the outlet HCRs attached. The high temperature (red area) is seen in a larger area, especially at the CR inlet area but it shows smaller one for the HCR and V-HCR.

4.3 Heat transfer, pressure loss and thermal performance

The variation of Nu/Nu\(_0\) with Re for the V-HCR is shown in Fig. 4a, including the CR and HCR for comparison. In the figure, the Nu/Nu\(_0\) for all cases shows the decreasing trend with increasing Re and \( \alpha \). The highest Nu/Nu\(_0\) is up to 3.7 times for the 30° V-HCR and about 2.75 for the CR. It is observed that the HCR/V-HCR provides higher heat transfer than the CR. Fig. 4b depicts the distribution of \( ff_0 \) with Re. It is noted that the \( ff_0 \) increases steeply with increasing Re for the CR while increases slightly for the HCR/V-HCR. The use of HCR/V-HCR instead of CR can reduce the \( ff_0 \) around 6–17 times, especially for the 30° V-HCR. The \( ff_0 \) value is about 11–56 for the V-HCR and 188–345 times for the CR. This indicates the merit of HCR/V-HCR over the CR in extremely reducing pressure loss, apart from enhancing heat transfer. Fig. 4c displays the sensitivity of the HCR/V-HCR to TEF. It is seen that TEF decreases rapidly with increasing Re and then reduce gradually for Re > 10,000. Also, TEF shows the downturn with the increment of \( \alpha \) and is about 0.7–1.65 and 0.3–0.5 for the V-HCR and CR, respectively. The highest TEF is around 1.65 for 30° V-HCR at lower Re. This means that the smaller the \( \alpha \), the greater the Nu is. The lowest TEF is for the CR and thus, the use of CR without modification as mentioned above should be avoided.
5. Conclusions

A numerical investigation on thermal behaviors of fully turbulent periodical tube-flow through the HCR/V-HCR has been conducted. The V-HCR yields higher heat transfer enhancement in a uniform heat-fluxed tube. The heat transfer augmentation is found to be about 2.1–2.3 and 2.3–3.7 times for the typical CR and the HCR/V-HCR with $\alpha$ from 30° to 90° while the friction factor is enlarged in a range of 188–345 and 11–56 times above the smooth tube, respectively. The application of the V-HCR can reduce the friction loss around 6–17 times below the CR. The maximum TEF is about 1.65 for 30° V-HCR, indicating much higher thermal performance over the CR.

References