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Numerical heat transfer study of turbulent tube flow through winglet-pairs

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Abstract

A numerical investigation on heat transfer behaviors in a constant heat-fluxed round tube inserted with winglet vortex generators is conducted. Air as the working medium flows through the tube for Reynolds numbers (Re) between 4000 and 20,000. The effect of using the rectangular-winglet tape (RWT) on heat transfer characteristics in the tube is numerically examined. For comparison purpose, the trapezoidal-winglet tape (TWT) and delta-winglet tape (DWT) are also offered. The RWT parameters in this work include four relative winglet-to-tube heights or blockage ratios (B_R=b/D= 0.1, 0.15, 0.2, and 0.25) while the TWT and DWT are only at B_R= 0.2. All the winglet pairs are at a single attack angle (α= 45°) and pitch ratio (p/D=P_R=4). The numerical results show that the Nusselt number (Nu) and friction factor (f) of the tube inserts are enhanced with increasing B_R values. The Nu for the inserted tube is about 1.8-2.7 times above that for the smooth tube while the f is around 4.5-11 times higher. For the studied B_R ranges, the highest thermal performance is 1.48 for the RWT with B_R= 0.1 at lower Reynolds number.

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Keywords: Heat exchanger; Heat transfer; Winglet; Thermal performance; Vortex generator.

1. Introduction

In a modern heat exchanger system, swirl/vortex-flow devices such as twisted-tapes, coiled-wires, winglets etc., are introduced by mounting them in the cooling/heating tube/ducts of the systems to produce vortex-flow inside. This method is known as the passive heat transfer augmentation technique used in an internal flow. Winglets mounted repeatedly in tubes can interrupt the boundary layers and also induce swirling flows. The presence of the winglets leads to flow separation, recirculation, and impingement and this phenomenon is considered to be the key factors in augmenting heat transfer in tubes.

For decades, a technique by using a longitudinal vortex generator (LVG) inside the cooling/heating duct has been widely offered. Fiebig et al. [1,2] examined the influence of the LVG placed inside a heat exchanger duct. They

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found that the heat transfer rate was raised around 50% while the pressure drop increase was 45%. Biswas and Mitra [3] studied experimentally the vortex structure and temperature distribution of using the LVG in a rectangular duct and reported the considerable heat transfer enhancement. The vortex-eye of streamwise vortex flow directed along the main flow and the reciprocity of different vortices was existed. In this work, a numerical study of a 3D turbulent flow in a round tube with 45° winglet pairs placed on a tape by punching is performed in order to examine the structure of main flow and thermal characteristics for Re values ranging from 4000 to 20,000.

2. Winglet-tape geometry

The winglet tapes are inserted in a round tube as shown in Fig.1. The flow in the present work is assumed to be a fully periodic flow module where the temperature and velocity fields repeat themself from one module to another. Air flows into the tube with inlet temperature, T_i=300 K and the winglet with length, l =0.4D, placed with 45° attack angle (α). The tube inner diameter (D) is 0.05 m and the axial pitch (p) of the winglet is set to p/D=4. The ratio of p/D is called pitch ratio (P_R). The investigation is focused on the effect of the blockage ratio, $b/D=B_R$ of the RWT by varying four B_R values (0.1, 0.15, 0.2 and 0.25) while the TWT and DWT are at B_R=0.2 only.

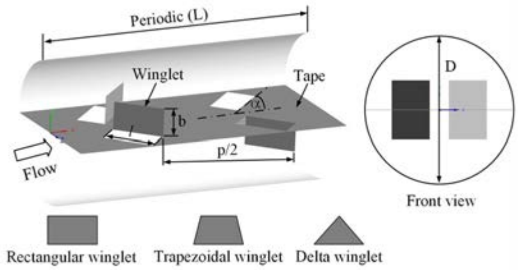


Fig. 1. Winglet pair arrangements on a tape for periodic flow.

3. Computational details

The assumptions used for the numerical model of a periodic flow module in a round tube are: steady 3D, turbulent flow and incompressible fluid; neglecting body forces and radiative heat transfer. As of the above assumptions, the flow model was governed by the Reynolds averaged Navier-Stokes (RANS) and energy equations.

The governing equations mentioned above were discretized using the QUICK numerical scheme and solved by the finite volume method [4] including the Realizable k-ε turbulence model for turbulence model closure. No slip and constant heat-flux boundary conditions were applied to tube wall but the adiabatic wall was for winglets. The fully developed periodical flow condition was set for the test section and due to symmetry, the left half-tube was employed for the computational domain as displayed in Fig. 1. Various variable solutions were assumed into converge as their values of normalized residuals were below 10^{-6} except for temperature only being less than 10^{-9}. More details on grid independence test and boundary conditions including model validation and nomenclatures are the same as in Ref. [5] and will not be repeated here for the sake of brevity.

Four key parameters introduced in the current computation include Reynolds number (Re), friction factor (f), Nusselt number (Nu) and thermal enhancement factor (η). The Re is defined as

$$\mathrm{Re} = \rho \bar{u} D / \mu \qquad (1)$$

The f is obtained from pressure drop, Δp across the periodic tube length, L as

$$f = 2D\Delta p / (L \rho \bar{u}^2) \qquad (2)$$

The area-averaged Nusselt number was calculated from integrating local Nusselt number by

$$\mathrm{Nu} = (1/A)\int \mathrm{Nu}_x \partial A \qquad (3)$$

The η defined as the ratio of Nu of an augmented tube to that of a plain tube at an equal blowing power was written as

$$\eta = (\mathrm{Nu}/\mathrm{Nu}_0)(f / f_0)^{-1/3} \qquad (4)$$

where subscript "0" denotes its value for the smooth tube.

The computational domain was resolved by using polyhedral elements. A grid independence solution was tested and found that the differences in Nu and f values for two grid systems of about 77,550 and 130,544 is less than 0.5%. Thus, the grid system of 77,550 was employed in the current work.

4. Results and discussion

4.1 Validation of smooth tube

Validation of the smooth tube results is conducted and compared with the published values as shown in Fig. 2. The current predicted data is in good agreement with the published correlation's data of Dittus-Boelter and Blasius [6] for Nu and *f*, less than 4 and 8 % deviation, respectively.

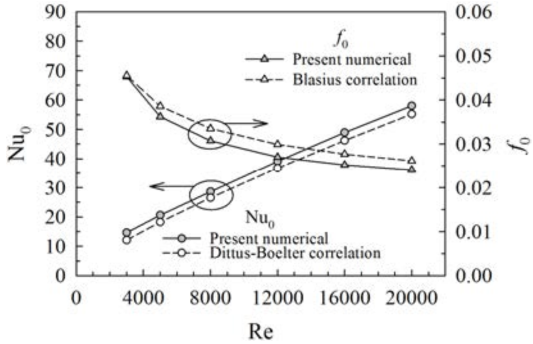
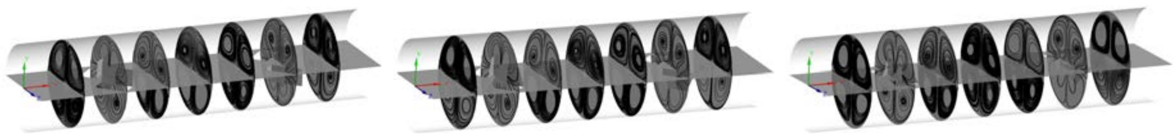


Fig. 2. Validation of Nu and *f* for smooth tube.

4.2 Flow structure

The structure of flow inside a tube inserted with winglet pairs for B_R=0.2, Re=12,000 is presented by streamlines plots on transverse planes as depicted in Fig. 3 for three types of winglets used. In the figure, it is noted that two pairs of counter vortices produced by the winglets appear on the lower and upper parts each. The secondary flows with two vortex pair are induced behind the first-winglet pair where the pair on the upper/lower part generate the common-flow down vortices to the tape surfaces. Thus, the pair near the tape edges only produce the common-flow down vortices to the tube wall that enhance considerably the heat transfer along the tape edges.



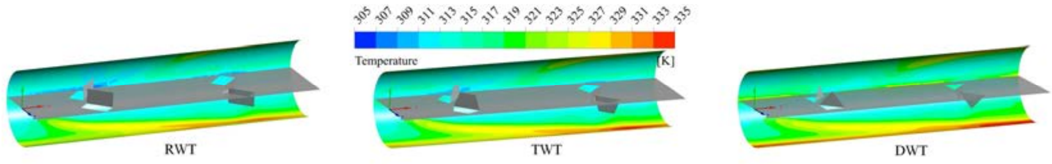
(a) (b) (c)

Fig 3. Streamlines on transverse planes for (a) rectangular winglet, (b) trapezoidal winglet and (c) delta winglet at Re=12,000.

4.3 Heat transfer, pressure drop and performance behaviors

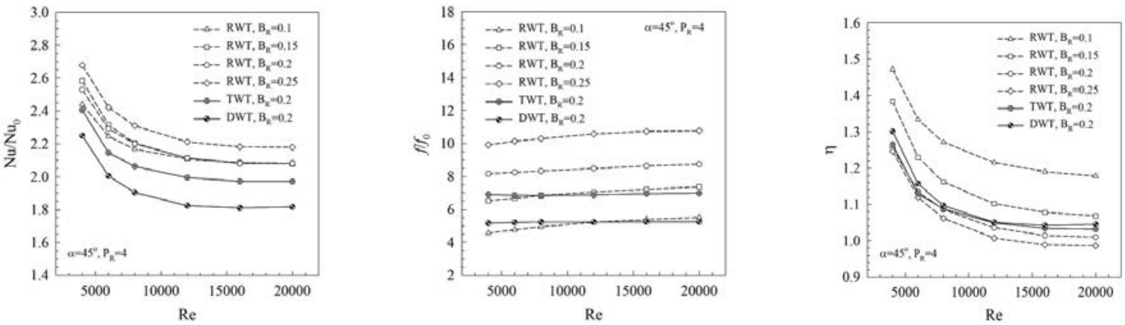
Surface temperature contours for using the RWT, TWT and DWT with B_R=0.2, α=45° at Re=12,000 are presented in Fig. 4(a), (b) and (c), respectively. It is found that large areas of lower temperature are seen over the tube wall. The lowest one is at the impingement area on the wall along the tape edges. This points that the winglet inserts give a significant effect on temperature fields due to the appearance of swirl flows inducing the core flow region having lower temperature into the higher temperature regime at the near-wall.

The variation of Nu/Nu_0 defined as a ratio of augmented Nu to Nu of smooth tube with Re is exhibited in Fig. 5(a) where the Nu/Nu_0 shows the downtrend with the rise of Re. In this work, the heat transfer for the winglet insert extends gains at about 1.8-2.7 times above the smooth tube. The trend of Nu/Nu_0 is found to increase with the increment in B_R. Also, the relationship of f/f_0 with Re is proposed in Fig. 5(b) where the f/f_0 shows the tendency to slightly increase with rising Re. The application of winglets yields greater f/f_0 around 4.5-11 depending on Re and B_R values. Fig. 5(c) showing the thermal enhancement factor (η) against Re reveals that η values mostly are higher than unity and thus, this is the merit of using the winglets over the smooth tube alone. The η shows the downtrend with increasing Re but the uptrend with reducing B_R. The maximum η is about 1.48 for using the RWT at B_R = 0.1.



(a) (b) (c)

Fig. 4. Temperature contours on tube wall for (a) RWT, (b) TWT and (c) DWT.



(a) (b) (c)

Fig. 5. Relationship of (a) Nu/Nu_0, (b) f/f_0 and (c) η with Re.

5. Conclusion

Turbulent periodic-flow model of a round tube with 45° winglet-pair inserts at various B_R for Re from 4000 to 20,000 has been simulated numerically. The use of winglet pairs can induce two main swirl flows inside the tube module leading to stronger flow mixing than the smooth tube. The Nu and friction factor for the tube insert are, respectively, augmented around 1.8-2.7 and 4.5-11 times above those of the smooth tube. The highest η of about 1.48 is obtained for the RWT at $B_R = 0.1$ and Re = 4000.

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