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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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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.

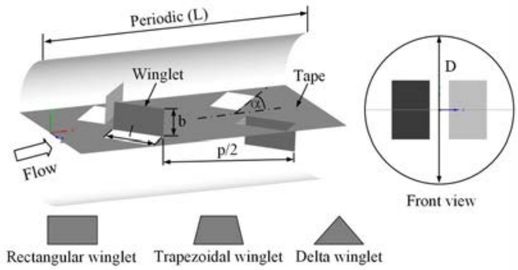

Fig. 1. Winglet pair arrangements on a tape for periodic flow.

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

$$\mathrm{Re} = \rho \bar{u} D / \mu \tag{1}$$

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

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

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

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

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

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

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.