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Numerical study of heat transfer and flow behavior in a circular tube fitted with varying arrays of winglet vortex generators

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ABSTRACT

Winglet vortex generators (WVGs) mounted inside a circular tube, generate longitudinal vortices and offer increased turbulence level with a comparatively lower pressure penalty for a higher heat exchange performance. In this study, the thermal enhancement and flow structure arising from radially-arrayed winglets mounted at different attack and inclination angles, as well as different winglet lengths, are analyzed by CFD simulation. The flow and heat transfer behaviors are presented in the turbulent flow region for air flow, with Reynolds number ranging from 6000 to 27,000. Vortex generators are arranged inside the tube as a series of four rings, with each ring having 4 WVGs on the inner surface of a circular tube. The present research investigates the characteristics of WVGs which include four winglet inclination angles ($\alpha = 0^\circ$, 10°, 20° and 30°), five winglet attack angle ($\beta = 0^\circ$, 10°, 20°, 30°, and 45°), and three winglet lengths ($L = 10$ mm, 15 mm, 20 mm). The data shows that winglets in a tube result in a considerable enhancement of Nusselt number and friction factor. It is found that Nusselt number and friction factor augment with the increase of attack angle or length, yet declines with the increase of inclination angle. The maximum of Nu is 86.88, at $L = 20$ mm, $PR = 4.8$, $\alpha = 0^\circ$, and $\beta = 45^\circ$. The largest Nusselt number ratio, Nu/Nu_0, defined as a ratio of augmented Nusselt number to the Nusselt number for fully developed smooth flow is 136%, which was obtained at a lower Reynolds number ($Re = 6000$). The results also illustrated that WVGs could generate longitudinal and transverse vortices to induce both impingement flow and recirculation zone leading to higher heat transfer and comparatively lower pressure drop. Nusselt number contours reveal that the wake zone behind WVGs displays the intensity of heat transfer along the tube.

1. Introduction

Heat exchangers have a wide applications in heating, ventilation, air conditioning, and refrigeration (HVAC) system, process industries, oil and gas industries and so on. Increasing energy demands have prompted researchers to develop higher performance thermal systems. Improving the thermal performance is crucial to meet energy cost and environmental impact. Heat transfer tube play an important role for the integrated performance of heat exchangers. One of the enhanced heat transfer technologies for achieving higher performance thermal systems is to adopt passive enhancement especially in heat exchangers. Application of vortex generators (VGs) is one of the most common passive technologies to augment the thermal efficiency of heat exchangers. Vortex generators (winglets, coil wires, tapes, and ribs), can increase the inner surface area of ducts, destabilize the flow field, create secondary flow and may increase the intensity of turbulence. Recent studies [1–4] have discovered that longitudinal vortices, created by wings or winglets, could achieve better heat transfer enhancement since they persist much farther downstream. The axes of longitudinal vortices are parallel to the main flow direction while the axes of transverse vortices are perpendicular to the main flow direction. Owing to the long distance downstream from VGs, longitudinal vortices can provide higher thermal enhancement for an equivalent pressure drop. In other words, longitudinal VGs are more efficient compared with transverse VGs for reducing vortex generator number. They reduce the pressure drop and optimize the thermal performance of the heat exchanger.

One of the earliest works was done by Biswas et al. [5]. They performed both numerical and experimental studies on thermal behavior and vortex structure in the delta-winglet-fitted rectangular channel. Three kinds of vortex were obtained by simulation, and there are induced vortex, main vortex, and corner vortex. The results show that the application of delta winglet could improve the performance of heat exchanger. Noothong et al. [6] did both numerical and experimental study on square duct with diagonally-inserted discrete V-finned tapes

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(DFT). By testing different block ratios and pitch ratios, the results revealed that heat transfer and friction factor values with DFT insert increase with the increment of block ratio (BR) but the decrease of pitch ratio (PR). Promvonge [7] presented a numerical study on heat transfer characteristics in a square duct fitted with 45° V-shaped baffles on the inner wall in the laminar region. The study showed that the impingement flows created by baffles result in a greater increase of heat transfer. Later on, a modified geometry [8] was proposed with better feasibility. They diagonally mounted 30° angle-finned tapes using air as working fluid in a square duct. The results showed a good agreement with measured data and revealed the similar impingement flow, compared with the previous study, which could increase thermal transfer intensity. Yakut et al. [9] carried out an experiment to analyze heat transfer effects with double-side delta-winglets in a circular duct by varying different geometries. They pointed out that Nusselt number was influenced mainly by Reynolds number and slightly increased with the height of winglet. In another aspect, the height of winglet largely affects friction factor. Zheng et al. [10] investigated the effects of rib on flow structure and heat transfer in a circular duct. Different arrangements of ribs are analyzed and the longitudinal swirl flow induced by V shape type ribs provide a better thermal transfer efficient than that of parallel type ribs. A three-dimensional numerical model was carried out by Jedsadaratanachai et al. [11] to study the thermal behavior of 45°V-shape baffles in a circular duct. The V-shape baffles were inserted on opposite sides of the tube's inner wall, with an in-line arrangement to create longitudinal vortex. It pointed that a pair of longitudinal vortices was generated by V-shape baffles and caused an increase of heat transfer. An experimental study done by Akcayoglu [12] focused the flow structure in horizontal equilateral triangular ducts having two winglet vortex generator pairs mounted on the inner surfaces. The strength of vortices induced by the staggered and inline winglets were compared and it was found that the staggered winglets could provide a greater vorticity field than inline winglets. Chokphoemphun et al. [13] presented the influence of winglet VGs fitted in a tube heat exchanger experimentally and numerically. The winglet VGs with an attack angle of 30° show a considerably higher heat transfer and friction loss compared with the plain tube, wire coil and twisted tape. The numerical investigation illustrated the flow structure inside the tube that there are two main counter-rotating vortices flows passing through the lower and upper parts of winglets. Islam et al. [14–20] have done some experimental investigation on rectangular vortex generators in narrow and wide rectangular ducts where they detailed the mechanism of heat transfer and fluid flow behavior.

Very recently, Naik et al. [21] have done numerical investigation on heat transfer characteristics of curved rectangular winglet vortex generators (RWVGs) in a channel flow. They investigated the effect of curvature in concave and convex RWVG on flow and heat transfer and compared with that of plane RWVG. Maximum heat transfer enhancement of 22% was achieved for concave shape RWVG having arc angle equal to 75°. More disruption in boundary layer growth and fluid mixing was observed for concave RWVG than that of other two shapes which leads to higher overall thermal performance for concave RWVG. Tian et al. [22] numerically studied the heat transfer enhancement by the rectangular and delta winglet VG pairs in a flat plate channel. They compared the heat transfer enhancement between them and concluded that delta winglet VG pair performs better on an overall than that of rectangular pair.

Wu et al. [23] experimentally studied the effect of delta winglet attack angle on heat transfer performance of a flat plate. They varied the attack angle from 30 to 60° in 15- degree increments and mainly focused the role of attack angle on heat transfer and flow vortices. Bottom surface of the flat plate was uniformly heated by a condensing steam of 100 °C and a thermal camera was used to assess the thermal performance. With the help of thermal imaging technique they noticed that the peak Nusselt number (Nu) increases with the attack angles and this enhancement was attributed due to the larger share of transverse vortex at the higher attack angles. The maximum heat transfer enhancement achieved by higher attack angle dropped sharply near the wake. It remained significant, but found largely insensitive to attack angle, with a gradual decay at farther downstream. They also observed that the turbulence fluctuation substantially enhanced the heat transfer rate near the center of the vortex. With the increase of attack angle, the heat transfer enhancement caused by turbulence was escalated.

Lei et al. [24] have numerically studied the thermal hydraulic behavior of a circular tube inserting the delta winglet vortex generators in the center of the tube. They studied in details the effects of attack angles (for 15 deg, 30 deg, 45 deg and 60 deg) and pitch (P = 1D, P = 2D, P = 3D and P = 4D) on heat transfer and fluid flow. Their key findings was that the delta winglet vortex generators creates swirling flow which enhance the fluid mixing and ultimately causes heat transfer augmentation with moderate pressure penalty. They also found the Nusselt number increase with the increase of attack angle and decreasing pitch of vortex generators.

Apart from the literature mentioned above, the common practice [25–30] of applying vortex generator in the circular tube is adopting coiled wires, strips, twisted tapes. However, previous studies have rarely focused on the heat transfer and flow behavior for arrays of delta winglets in a circular tube. Current authors previously numerically investigated [31], the effects of attack angles and blockage ratios for radially inserted one row of VGs only inside a smooth tube. The present work is conducted with arrays of radially inserted delta winglets for four repeated rows inside of the circular duct. Here the authors have further studied the effect of inclination angles, effect of length for four rows of WVGs on heat transfer and flow. This novelty of vortex generator's arrangement along the inside wall of the circular tube is aiming to explore the thermal performance and flow characteristics when WVGs are arranged in series. The implementation of delta winglets with different attack angle, inclination angle with arrays is expected to create longitudinal vortices hence enhancing the thermal performance.

2. Flow configuration and mathematical approach

2.1. Winglet geometry

The test section is a circular duct with four rows of delta WVGs placed in series on the inner wall, as depicted in Fig. 1. The full length (l) of current test section is 1 m and the hydraulic diameter (D) is 52 mm. The air enters the test section at an inlet temperature T_{in} and flows over the delta winglets where the height of winglets (H) is 5 mm. Thus, the blockage ratio is defined as H/D = 0.1. The distance between the leading edge of the winglets and the inlet of the test section equals 50 mm. The pitch, P, the distance between two rows of winglets, is set to P = 250 mm in which P/D is defined as the pitch ratio, PR = 4.8.

To investigate an interaction effect of winglets, the inclination angle, α is varied in a range of $\alpha = 0°–30°$ with three winglet lengths L = 10, 15, and 20 mm and the attack angle β varies from 0° to 45°at L = 10 mm in the current computation.

2.2. Mathematical approach

The numerical model for fluid flow and heat transfer in the circular tube was based on the following assumptions:

- Steady, three-dimensional air flow and heat transfer.
- The flow is fully turbulent and incompressible.
- Constant air properties.
- Constant heat flux.
- Body forces, thermal radiation, and viscous dissipation are ignored.

Based on the above assumptions, the governing equations are Navier-Stokes equations with two-equation eddy-viscosity Shear Stress Transport (SST k-omega) model [31,32]. The preliminary investigation