HEAT TRANSFER ENHANCEMENT WITH PRESSURE LOSS REDUCTION IN COMPACT HEAT EXCHANGERS USING VORTEX GENERATORS

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ABSTRACT

The potential of rectangular winglet vortex generators arrays used to enhance air side heat transfer performance of a finned tube heat exchanger is numerically studied. This paper proposes a novel technique that can augment heat transfer but can reduce pressure-loss in a fin-tube heat exchanger with circular tubes in a relatively low Reynolds number flow, by deploying delta winglet-type vortex generators. The position of the rectangular winglet vortex generators were particularly placed such that it is a compromise between the maximum heat transfer augmentation and the minimum pressure drop. The fundamental mechanism between the local flow structure such as separation delay, reduced form drag, which removes the zone of poor heat transfer from the near-wake of the tubes, heat transfer enhancement and the pressure drop is studied in detail by varying the angle of attack and positioning of VGs. By placing the VGs in staggered arrangement, result showed that the reduction in pressure drop is obtained for same heat transfer enhancement.

Keywords: Heat exchangers, Vortex generators (VGs), Rectangular winglet, staggered array, inline array.

INTRODUCTION

Fin-and-tube heat exchangers are widely used in various engineering fields, such as automobile, ventilation, air conditioning, and refrigeration systems. High heat exchanger performance is very important in meeting efficiency standards with low cost and environmental impact. For heat exchangers, the air side convection resistance is usually dominant due to the thermo physical property of air. Plate-fin-and-tube heat exchangers are widely used in a variety of engineering applications. Efforts have been devoted to the research and development of the enhancement of heat transfer surfaces, especially on the gas side, where a high thermal resistance exists and thus the necessity to augment the heat transfer is much larger than on the liquid side.

In general, many techniques are used to enhance the heat transfer. Among them is the periodic interruption of the growth of the thermal boundary layers close to the heat transfer surfaces. Another technique is the increase of fluid mixing, fluid vortices and turbulence intensity. Thus many efforts have been made to enhance air-side heat transfer performance and variants of fin patterns like wave, louver and slit fin have been adopted. However, with significant heat transfer enhancement, the associated penalty of pressure drop is also tremendous for those conventional heat transfer enhancement methods.

In recent years, a very promising strategy of enhancing air-side heat transfer performance is using flow manipulator, known as vortex generators. When the fluid flows through vortex generators, stream wise vortices are generated in the flow field due to flow separation on the leading edge of the vortex generators (VGs), causing bulk flow mixing, boundary-layer modification, and flow destabilization; heat transfer is enhanced due to these vortices. The longitudinal vortex generators applied in various heat exchangers have received considerable attentions for the advantage of heat transfer enhancement, accompanied by a modest pressure drop penalty.

Passive vortex generators (VGs) in form of protuberances such as delta-wings, rectangular wings, delta-winglets and rectangular winglets, not only improve the heat transfer performance, but also reveal relatively pressure drops. Due to the pressure difference between the front surface facing the flow and the back surface longitudinal stream wise vortices evolve. These vortices are carried through the main flow and induce bulk fluid mixing. Thus the heat transfer is enhanced by bringing more fresh fluid towards the heat transfer surfaces. The advantage of using VGs to improve the heat transfer was reported in a variety of experimental and numerical research works.

MODEL DESCRIPTION

Physical model: In this study, a fin-and-tube heat exchanger with longitudinal vortex generators is investigated. The schematic diagram of the heat exchanger is shown in Fig. 1. In the present study, we adopt the rectangular winglet pair as the vortex generator based on the results of previous study in the literature. A pair of rectangular winglets is symmetrically mounted on the fin surface, adjacent to heat transfer tube. The height of the winglets is

equal to 80% of the fin spacing. Fig 2 shows the dimensions of rectangular winglets and their placement with respect to the tube. The rectangular generators are placed almost on the sides of the tube.

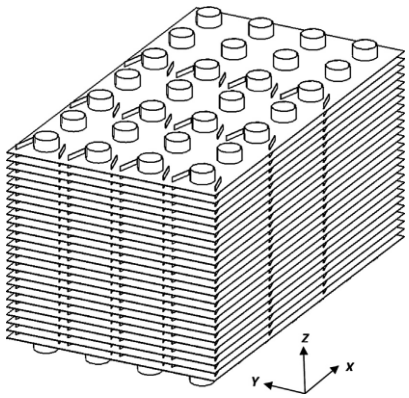

Fig. 1. Schematic diagram of core region of inline tube arrangement type, finned heat exchanger using VG

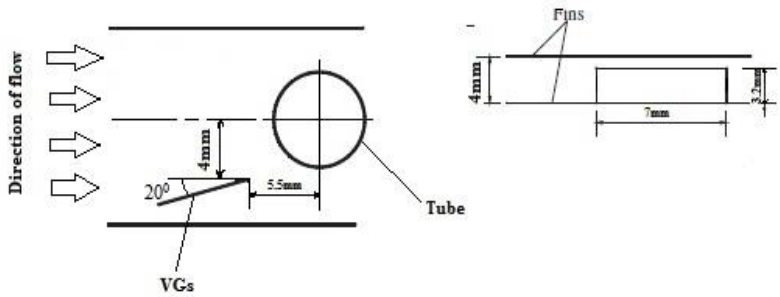

Fig.2. Vortex generator placement and its position with respective to the tube

In Fig 1. the computational domain and the coordinate system are presented, where X is the stream wise direction, Y is the span wise direction and Z direction shows the fin pitch direction. Fin spacing or the distance between the fins is set as H = 4 mm, width B = 12 mm, and length L = 40mm. The first tube of diameter D = 10 mm, is located at X = 15 mm from the inlet of the flow channel. The longitudinal tube pitch Pl = 15 mm and the transverse tube pitch Ps = 12 mm. The tube rows are arranged staggered. Each tube in the second row is placed in the centre of the adjacent tubes in the first row. The fin material is aluminum and fin thickness F_t=0.16 mm. Since the geometry of the fin-and-tube heat exchanger is symmetric, the region of space between the rows of tubes as shown in Fig.3 is selected as the computational domain. Due to the high heat transfer coefficient inside the tube and the high thermal conductivity of the tube wall, the tube temperature is set as constant. However, the temperature distribution on the fin surface is unknown and will be determined during the computational iteration process. In order to solve this problem, the computational domain should contain the whole fin surface during the numerical simulation.

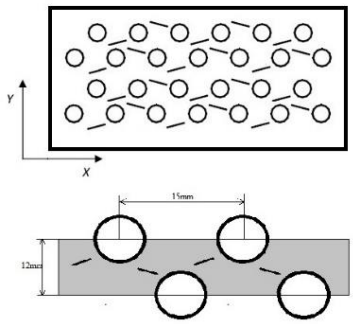

Figure.3.Co-ordinate system and the computational domain

Governing equations and boundary conditions: In this study, the fluid is considered incompressible with constant properties. The generation of longitudinal vortices is a quasi-steady phenomenon. Consequently, due to the low inlet velocity and the small fin pitch, the flow in the channel of the compact heat exchanger is assumed to be laminar and steady.

Fin thickness and heat conduction in the fins and vortex generators are taken into account. The temperature distribution for the fins can be determined by solving the conjugate heat transfer problem in the computational domain. The governing equations in Cartesian coordinates can be expressed as follows:

Continuity Equation: For steady and incompressible flow

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0$$

Momentum Equation:

$$\frac{\partial(\rho u_i u_k)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(\mu \frac{\partial u_k}{\partial x_i}\right) - \frac{\partial p}{\partial x_k}$$

Energy Equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i}\left(\frac{k}{C_p}\frac{\partial T}{\partial x_i}\right)$$

The boundary conditions for all surfaces are described as follows:

- At the inlet boundary

$U = U_{in}$ = constant, v = w = 0, $T = T_{in}$= constant

- At the top and bottom boundaries

Periodic boundary conditions are given:

At Extended region

$\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = 0$, w=0, $\frac{\partial T}{\partial z} = 0$

At fin region

u=v=w=0, $\frac{\partial T}{\partial z}$=0

- At the front and back surface of wind tunnel region (x-z plane), symmetry boundary condition are given:

$\frac{\partial u}{\partial y} = \frac{\partial v}{\partial y} = 0$, v=0, $\frac{\partial T}{\partial y} = 0$

- At the outlet, the outflow boundary condition is given

$$\frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial w}{\partial x} = \frac{\partial T}{\partial X} = 0$$

- Tube region: u = v = w = 0; $T = T_w$ = constant.

A. Numerical methods: The geometry for the three-dimensional vortex-enhanced multi-row fin-and-tube heat exchanger is complex and it can be expected that the velocity and temperature fields are complicated in the computational domain. In order to capture important scales and resolve the near-wall gradients appropriately, the grid must be generated with great care and effort. The computational meshes were generated by using ANSYS. Because of the complexity of the computational domain, it is difficult to use a single structured quadrilateral mesh in the whole flow passage. In order to improve the quality of the grid system, mapped face method and inflation is adopted to generate the mesh. Different strategies are employed for each subdomain to generate the mesh. For the blank zone, a structured mesh is employed because of its simplicity. So does it for the tube zone. The VG zone is complex and hence an unstructured tetrahedral mesh is employed. Generally, the meshes are generated much finer in the regions adjacent to tubes and winglets.

The Navier Stokes and energy equations with the boundary condition equations are solved by using a computational fluid dynamics code (Fluent). The convective terms in governing equations for momentum and energy are discretized with the second-order upwind scheme. The coupling between velocity and pressure is performed with SIMPLE algorithm. The convergence criterion for the velocities is that the maximum mass residual of the cells divided by the maximum residual of the first 5 iterations is less than 1.0×10^{-5}, and the convergence criterion for the energy is that the maximum temperature residual of the cells divided by the maximum residual of the first 5 iterations is less than 1.0×10^{6}.

RESULTS AND DISCUSSION

Influence of the angle of attack: In order to study the influence of angle of attack of VGs on the heat transfer characteristics and the flow structure for fin-and-tube heat exchangers, a comparative study for fin-and-tube heat exchangers with VGs of different attack angle is performed. The VGs are symmetrically mounted adjacent to the tubes. The angle of attack α is set as 0, 10^0, 20^0, 30^0 to the flow direction. The Reynolds number based on the hydraulic diameter is 500. Fig. 4 shows the configurations for fin-and tube heat exchangers with VGs of different attack angle.

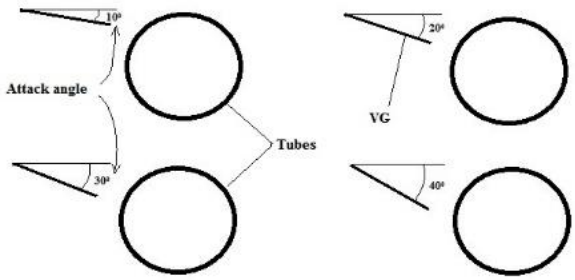

Figure.4.Arrangement of fin and tube heat exchanger with different attack angle

As the flow approaches the VGs in the flow passage, the longitudinal vortices are generated due to the pressure difference between the upstream side and the downstream side of the VGs. The strong swirling flow in the vicinity of the axis parallel to the main flow direction can disrupt the growth of boundary layer on the fin surface, drag fluid from the wake region of tube to the mainstream, and enhance the mixing of fluid from the periphery and the core region of the flow (Ya- Ling, 2013). All these effects of the strong swirling flow ultimately bring about enhancement of heat transfer in the flow passage. Moreover, the particular placement and orientation of the VGs can yield additional enhancement. In our present study, the VGs are arranged in "flow-down" orientation. In this congested passage, the fluid is accelerated. As a consequence, the boundary layer separation is suppressed and the tube wake region is narrowed. Furthermore, the fluid accelerated in the constricted passage will impinge directly on the downstream tube resulting in a local heat transfer enhancement. The combination effect of separation delay, narrowing of tube wake and impingement can significantly augment the heat transfer in the flow channel (Ya-Ling, 2013).

It is clear from the figure 6 that the streamlines are stretched and bended toward the wake region behind the first tube. These converged streamlines are formed because of the formation of longitudinal vortices behind the VGs. The longitudinal vortices bring more fluid into this wake region. Then the wake region is compressed and the size of this region is reduced.

It is observed that, as the angle of attack is increased, the streamlines are bended more closely to the center of wake region in the rear of the first tube and the size of the wake region reduces with the increasing attack angle. This phenomenon can be explained by the vortex strength of the longitudinal vortices. With the increase of the angle of attack, the vortex strength is becoming larger. The larger vortex strength will bring higher-momentum fluid into wake region. Then the accelerated flows compress the fluid in the wake region and delay the flow separation on the tube and result in a reduced wake size (Anirudh, 2012).

However, we can conclude that case where the angle of attack is 10^0 holds the best overall heat transfer performance. The heat transfer enhancement for case with 10^0 angle of attack is only about 26% for the Reynolds number considered. It doesn't get a lot of advantages compared to the conventional heat transfer techniques like slit or louver fins (Jiong Li, 2011). But for the angle of attack 20^0, the heat transfer coefficient was increased about 54% under the same Reynolds number range. Compared with the case where angle of attack is 0^0, the heat transfer augmentation is considerable and the overall heat transfer performance is better for the 20^0 case, therefore we choose the angle of attack 20^0 case as the basis for our further research.

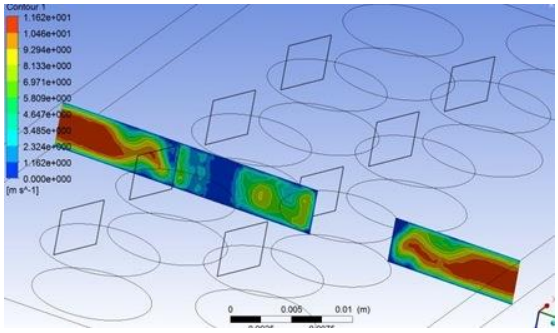

Figure.5. Diagram showing the streamline of flow on a plane at the downstream of the vortex generator

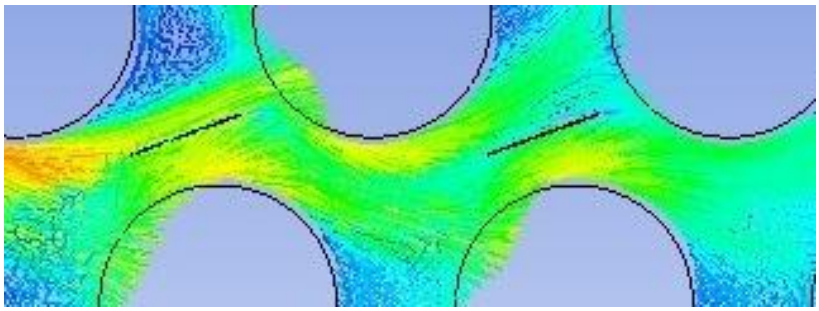

Figure.6.Velocity vector diagram of the flow in the computational domain corresponding to Reynolds number 500, for staggered arrangement of tube.

Influence of Arrangement of VGs: Joardar and Jacobi found that the vortex generators can significantly improve the heat transfer performance at a modest pressure loss. By changing the arrangement of vortex generators array from inline array to staggered array, the performance of heat transfer almost remains in the same level but the

pressure loss is reduced by 6%. It implies that the optimization of vortex generators arrangement can result in a better pressure distribution and a reduced pressure loss without reducing the heat transfer enhancement.

In order to investigate the influence of different arrangement of rectangular winglets on the performance of finned tube heat exchangers, a comparative investigation for fined tube heat exchanger with inline VGs array and staggered VGs array was performed. The angle of attack is set as 20^0. The Reynolds number is set as 500. The number of rows considered is 4. Due to the asymmetry of staggered-VG array, its grid system is also asymmetric.

The performance of heat exchanger with staggered tube arrangement with VG array is compared with the heat exchanger with inline tube arrangement with VG array. For the inline-VGs array, the velocity distribution is symmetrical due to the symmetry of the flow passage. The vortex generators pairs are placed on same sides of the tubes. Thus, the tube wake in the rear of the tube is narrowed due to the longitudinal vortices and the impingement of high-momentum fluid. For the staggered-VGs array, the placement of vortex generators is only on one side. Vortex generators are placed in the neighbour of the first, third, fifth and second, fourth and sixth tubes in alternate pattern as shown in figure 4.

Every vortex generator will independently modify the tube wake region. The vortex generators in the staggered array can modify six tube wake regions. However, only three tube wake regions are highly influenced by the VGs in the inline array.

For the Reynolds number 500, the heat transfer coefficient for the staggered array is increased by 0.8% in comparison with that of the inline array of tubes. In fact, the difference of heat transfer coefficient is very small for the two cases and it only presents the changing trend of different configurations.

CONCLUSION

In this study, three-dimensional numerical simulations are employed to investigate the heat transfer characteristics and flow structure in full-scale fin-and-tube heat exchangers with VGs.

It is proved that the rectangular winglet Vortex generators are one promising heat transfer enhancement technique. The generated vortices can enhance the thermal mixing of the fluid, delay the boundary layer separation, and reduce the size of tube wake. The longitudinal vortices generated by VGs rearrange the temperature distribution and the flow field, and as a consequence significantly enhance the heat transfer performance of the fin-and-tube heat exchanger.

Compared with the baseline case, the heat transfer coefficient of the fin-and-tube heat exchanger is improved by 23%, 48% and 78% for angle of attack 10^0,20^0 and 30^0 respectively. The corresponding pressure drop is also increased.

The staggered tube array with VGs in the fin-and-tube heat exchangers can augment the heat transfer better than that of the inline tube array with VGs. In addition, compared with the inline array, the staggered array can further reduce the pressure loss due to the asymmetric arrangement of the vortex generators.

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