Numerical investigation of heat transfer augmentation through geometrical optimization of vortex generators

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Abstract: In this paper a two-dimensional numerical simulation of a steady incompressible and turbulent model has been carried out to study the effects of vortex generators in a compact heat exchanger in a curvilinear coordinate system. The mesh which is applied in this study is boundary fitted and has been smoothed by a Laplace operator. Experimental data of a former study has been applied to validate the numerical results. The effects of geometrical variation are studied by adjusting vortex generators’ inclination and relative cross location. The major issue of this study is the optimal trade-off by selecting an optimal geometric, considering the opposite influences of geometrical variation on Nusselt number and pressure drop.

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1. Introduction

Plate-finned-tube heat exchangers are one of the most used compact heat exchangers in automobiles, air-conditioners, and chemical industries. For typical applications, the fin-side resistance generally comprises over 90% of the total thermal resistance. Therefore, enhanced surfaces are often employed to selectively improve the fin-side heat transfer performance of the plate-fin and tube heat exchangers. One frequently used method for heat transfer enhancement employs surfaces that are interrupted periodically along the streamwise direction. Typically, these surfaces are in the form of wavy, louver, slit or offset strip fins.

Fin and tube heat exchangers have wide applications in contemporary industrial fields and applied thermal engineering. Industries such as automotive, oil and gas refinery, petrochemical manufacturing, food processing and electrical coolant utilize this type of thermal system as an essential element. Since energy saving has become a high priority principle in research and industrial activities, a lot of experimental and numerical studies have been conducted in this field with different methods and optimizing parameters. The majority of leading studies...
were related to basic reorganization of the flow field and heat transfer of heat exchanger elements such as Buyruk et al. [1] which used computational fluid dynamics (CFD) and an experimental set up to study a cross flow around a tube at low Reynolds number. Wang et al. [2, 3] conducted an experimental study on pressure drop and heat transfer characteristics in fin and tube heat exchangers. The two-dimensional fluid flow and heat transfer in a circular tube heat exchanger with two elliptic vortex generators was studied by Mohseni et al. [4]. Jang and Chen [5] investigated heat transfer and fluid flow in fin and tube heat exchanger using a numerical method. Afterwards other parameters, such as fin pitch and tube array, were investigated more precisely. The effect of fin pitch and the number of tube rows on heat performance was studied by Somchai and Yutasak [6] and followed by others such as Manglik et al. [7] who analyzed the effects of fin density on a low Reynolds number forced convection in three-dimensional wavy plate fin compact channels. Besides, there are some studies through which the effect of tube shape or location on the performance of heat exchangers have been investigated [8–13]. Yonghan Kim [14] studied the effect of a large fin pitch on heat transfer characteristics in heat exchangers both numerically and experimentally. One of the leading studies in the concept of using a vortex generator to enhance heat transfer in a heat exchanger was performed by Jin-Sheng et al. [15]. They applied a thermovision method and used the experimental data to verify with numerical results of a turbulence model in the plate-fin and tube heat exchangers with inclined block shape vortex generators mounted behind the cylinders. They worked mostly on the flow and temperature field validation and the effect of vortex generator inclination on heat transfer characteristics. Considering the fluctuating nature of the turbulent flow, both the experimental and numerical investigations lead to slightly different results especially when the optimization interval is small. Wu et al. [16] developed a numerical model using finite volume approach, based on the combined radiative and conductive heat transfer through the highly porous materials with thin interlayers. The effects of interlayer parameters on the total resistance of the constrictions were evaluated with a view of optimal thermal insulation ability. Chen et al. [17] investigated the irreversibility of heat conduction in porous media, its relation to effective thermal conductivities, and the optimization of thermal conduction process based on the concept of entropy dissipation. The irreversibility of heat conduction in porous media, its relation to effective thermal conductivities, and the optimization of the thermal conduction process were investigated in their work based on the concept of entropy dissipation. They showed that the effective thermal conductivity not only influences the heat transfer ability, but also causes the irreversibility of heat conduction in porous media, which is a dissipation coefficient for heat transfer. Meanwhile, decreasing the structural particle size will increase the contact points, i.e. more heat bridges, decreasing the temperature gradient approximating the contact points, and hence significantly increasing the effective thermal coefficient of porous media.

The most effective design factors which are related to geometry are inclination and relative location of the vortex generators. In this study, the effect of relative distance of two adjacent vortex generators and their inclination on heat transfer and pressure drop was investigated. Relative distance is defined as the ratio of edge to edge distance of two adjacent vortex generators, to center to center cross distance of two adjacent cylinders. A boundary fitted mesh which has been smoothed using a Laplace operator, has been applied to a steady, incompressible and turbulent solver. Since it is intended to study a swirl flow, a $K - \varepsilon$ $RNG$ model was used. Different longitudinal distances and span angles have been studied to evaluate their effects on both the pressure drop and average Nusselt number with their criteria, considering both parameters for geometry optimization, being used. Finally, the pressure drop coefficient which would be defined and formulated is selected as the criterion of the pressure drop and pumping energy, which it would be studied along the symmetric boundaries.

2. Model description and numerical analysis

Fig. 1 presents the physical model and relevant geometrical dimensions in both the present numerical study and the experimental one conducted by Leu et al. [15] studies for the plate-fin and tube heat exchanger with a pair of block shape vortex generators. Three different span angles $\alpha (30^{\circ}, 45^{\circ}$, and $60^{\circ})$ relative to the main flow direction, were investigated in this study. The fluid is considered incompressible with constant properties and the flow is assumed to be turbulent, steady and with no viscous dissipation. The dimensionless time averaged equations for continuity, momentum (Reynolds-averaged Navier–Stokes equations) and energy may be expressed in tensor form as follows:

$$\frac{\partial U_j}{\partial X_j} = 0, \quad (1)$$

$$\frac{\partial}{\partial X_j}(U_j U_j) = -\frac{1}{\rho} \frac{\partial P}{\partial X_j} + \frac{\mu}{\rho} \nabla^2 U_j - \frac{\partial}{\partial X_j}[\tau_{ij}], \quad (2)$$