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3D numerical investigation of flow and heat transfer characteristics in smooth wavy fin-and-elliptical tube heat exchangers using new type vortex generators

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ABSTRACT

3D computational analysis was performed to investigate heat transfer and pressure drop characteristics of flow in SWFET (Smooth Wavy Fin-and-Elliptical Tube) heat exchanger with four new VGs (vortex generators), RTW (rectangular trapezoidal winglet), ARW (angle rectangular winglet), CARW (curved angle rectangular winglet) and WW (Wheeler wishbone). The numerical model was well validated with the available experimental results. Numerical results illustrate that vortex generators can bring about further heat transfer enhancement through careful adjustment of the position with respect to the elliptical tube, type and attack angle of vortex generators. The influences of the geometrical factors including attack angles of the winglets ($\alpha_{VG} = 15^\circ, 30^\circ, 45^\circ, 60^\circ$ and 75°) and width/length aspect ratio ($w/l = 0.5, 1.0$) of the Wheeler wishbones on enhancing the heat transfer performance of a smooth wavy fin heat exchanger with a three-row staggered elliptical tube bundle are investigated. A parametric study on the winglet vortex generators indicated that for the small attack angle, CARW vortex generators gives better thermohydraulic performance under the present conditions. The best thermal performance with winglet VGs in larger attack angle, was obtained at RTW VGs arrangement. For the SWFET heat exchangers, the WW VGs with $w/l = 0.5$ provide the best heat transfer performance.

1. Introduction

FTHEs (Finned tube heat exchangers) are employed in an extensive variety of commercial and engineering applications, *e.g.*, HVAC&R (heating, ventilation, air conditioning, and refrigeration) systems, cryogenics, power generation, petrochemical, aerospace, etc. The intent of heat exchangers includes heating, cooling, or heat recovery. The heat transfer coefficient on the air-side of FTHEs is generally very low due to the thermophysical property of air. Therefore, heat transfer enhancement on the air-side is essential. The heat transfer performance of FTHEs is highly dependent on the structure of fins because the dominant thermal resistance is generally on the air-side (75% or more). The goal of next generation heat exchangers, such as smooth wavy fin-and-elliptical tube heat exchanger is to increase the energy efficiency for industrial processes.

Among the enhanced fin configurations, smooth wavy fin-and-tube heat exchangers are currently widely used because the corrugated fins can provide additional surface area and enlarge the mixing length of the airflow. The SWFET heat exchanger enhances heat transfer by enlarging the air flow channel and causing better mixing of the air flow.

Many techniques are used to augment heat transfer. The most effective way to enhance the heat transfer on the air-side of a heat exchanger is to modify the fin pattern and geometry by interrupting it periodically along the streamwise direction. Another innovative technique for enhancement is the use of flow manipulators known as VGs (vortex generators), i.e., winglets which intentionally produce streamwise vortices. When a fluid is passing VGs, vortices are generated due to the friction and pressure difference on the leading and trailing edges of the winglet vortex generator.

The performance of fin-and-tube heat exchangers with vortex generators has been studied by a number of researchers. The most productive investigations amongst these have been conducted by the following scholars. Shah [1] and Kays and London [2] have carried out extensive research on the performance of compact heat exchangers. The book by Webb [3] provides a comprehensive

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overview of the research in heat transfer enhancement, including the air-side. Wavy fins are very special fin patterns that are developed to improve the heat transfer performance. The wavy surface can enlarge the flow path of the airflow and cause better air flow mixing. Therefore, higher heat transfer performance is expected compared to the other plate fin surface. The first pervasive research related to wavy fin was performed by Beecher and Fagan [4] investigating the effects of air velocity and the pattern of fin arrangement. They tested 21 wavy fin-and-tube heat exchangers. All the tested wavy fin-and-tube heat exchangers were arranged in a triple row staggered layout. Wang et al. [5–8] carried out a series of investigations for wavy fin-and-tube heat exchangers. Webb [9] used a multiple regression method to correlate the Beecher and Fagan [4] data. The Webb [9] relationship can prognosticate 88% of the wavy-fin data within ±5% and 96% of the data within ±10%. Lozza and Merlo [10] carried out an experimental investigation on the heat transfer and pressure drop performances of 15 various heat exchangers with various fin types. They reported that wavy fins are excellent in terms of heat transfer performance. Yan and Sheen [11] compared plate, wavy and louvered fin performances by using PEC (performance evaluation criteria) techniques in their experimental study.

In recent years, the practical usage of vortex generators in compact heat exchangers has received more attention. It has been shown that the VGs can intentionally generate mechanisms for the heat transfer enhancement consisting of developing boundary layers, swirl and flow destabilization. Applying vortex generators on heat transfer surfaces in FTHEs is an effective method to augment heat transfer. VGs have been intensively investigated recently [12–16]. Fiebig and Chen [17] have summarized their investigation of the characteristics of heat transfer surfaces with vortex generators. According to their research, the fin heat exchanger surface may be reduced with vortex generators by more than 50% compared to a plain fin for identical heat duty and pressure loss. Jacobi and Shah [18] gave a significant review on heat transfer surface enhancement via the use of streamwise vortices. Kotcioglu et al. [19] performed a second law analysis in a cross-flow heat exchanger with a new winglet-type vortex generator. Lee et al. [20] numerically explored the heat transfer characteristics and turbulent structure in a 3D turbulent boundary layer with longitudinal vortices. Torii et al. [15] reported experimental results of heat transfer and pressure loss in a fin-and-tube heat exchanger with inline and staggered set of tubes with delta winglet vortex generators of different configurations. Pesteei et al. [21] experimentally examined the efficiency of winglet position on flow and heat transfer characteristics in fin-tube heat exchangers. Yoo [22] has developed a fin-flat tube heat exchanger with vortex generators, and demonstrated that vortex generators increase the rate of heat transfer on the fin surface almost twice. Zhou and Ye [23] experimentally investigated the performances of heat transfer enhancement by a pair of new curved trapezoidal winglet vortex generators in channel flow.

There are only very few studies of implementation of streamwise vortex generators in fin-and-elliptical tube heat exchangers in the open literature. The elliptic tube geometry has a better aerodynamic shape than the circular one; therefore, it is reasonable to expect a reduction in total drag force when comparing the former to the latter, both submitted to a cross flow free stream. According to Webb [24], the performance advantage of the elliptical tubes results from their lower pressure drop due to the smaller wake region on the fin behind the tube. In a pioneering study, Schulenberg [25] analyzed the potential of application of elliptical tubes in industrial heat exchangers. Prabhakar et al. [26] performed three-dimensional numerical simulations to investigate the heat transfer in air-cooled condenser units with elliptical tubes and delta or rectangular winglets, and concluded that vortex generators are effective means of reducing the overall size of such units. Tiwari et al. [27] analyzed the augmented heat transfer obtained by applying different numbers of winglet vortex generators on elliptical tubes. Saboya et al. [28] used a naphthalene sublimation method to compute the average convective heat transfer coefficient for an elliptical tube heat exchanger. They reported that elliptical tubes created better overall performance than circular tubes. Chu et al. [29] employed three-dimensional numerical simulations to investigate the heat transfer characteristics and flow structure in fin-and-oval-tube heat exchangers with a winglet vortex generator.

The foregoing literature review illustrates that in general most of the research work focused on simple and traditional winglet vortex generators such as delta winglets. Moreover, most of the research works were related to fin-and-tube heat exchangers with circular tubes and plain or interrupted fins. Indeed, investigations of a smooth wavy fin-and-elliptical tube heat exchanger with untraditional and new type of vortex generators have not been performed yet.

The purpose of the present work is to introduce four new types of vortex generators – RTW (rectangular trapezoidal winglet), ARW (angle rectangular winglet), CARW (curved angle rectangular winglet) and WW (Wheeler wishbone) for application in a smooth wavy fin-and-elliptical tube heat exchanger. A numerical investigation is carried out to explore the effects of geometric shape of the vortex generators, attack angles of the winglets and width-to-length aspect ratios of the Wheeler wishbone on the heat transfer and fluid flow characteristics in the smooth wavy fin channels.

2. Model descriptions

2.1. Physical model

A schematic isometric view of the core region of a SWFET (smooth wavy fin-and-elliptical tube) heat exchanger with new vortex generators under consideration in the present investigation is depicted in Fig. 1. The geometric characteristics and coordinates of a smooth wavy fin-and-elliptical tube heat exchanger are shown in Fig. 2. It has three-rows of elliptical tubes in a staggered arrangement. In the present study, four kinds of VGs (vortex generators) are adopted, namely – 1) RTW (rectangular trapezoidal winglet), 2) ARW (angle rectangular winglet), 3) CARW (curved angle rectangular winglet) and 4) WW (Wheeler wishbone). Wishbone vortex generators were designed by Wheeler [30]. Wheeler wishbone VGs are like planar forms with an "Ogee" shape. These generators consist of two joined sidewalls with included angles from 15° to approximately 60° with their apex pointing downstream. The wishbone vortex generators oriented with apexes pointing downstream (forward configuration) shed horseshoe vortices in boundary layers [31].

The model adopted in this study consists of the elliptic tubes having a semi-major diameter $R_a = 6.560$ mm and a semi-minor diameter $R_b = 4.265$ mm. The ellipticity e is given by $e = R_b/R_a$. The longitudinal tube pitch P_l is 27.5 mm and the transverse tube pitch P_t is 31.75 mm. The fin material is aluminum and two neighboring wavy fins form a channel with wavy fin height $H = 1.5$ mm, wavy fin pitch $F_p = 4.0$ mm, wavy fin thickness $\delta = 0.2$ mm, wavy fin wavelength $\lambda_w = 13.04$ mm and primary wave curvature $R = 1.80$ mm. The basic length C_r, span C_t, sweep angle Λ and leading edge sweep angle Λ_{le} of the winglet are kept at constant values. Details of the vortex generator parameters are tabulated in Table 1. Fig. 3 shows the schematic representation of the vortex generator shapes and the nomenclature used in this new heat exchanger. The winglet vortex generators are mounted on the