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Effect of elliptical winglet on the air-side performance of fin-and-tube heat exchanger

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A B S T R A C T

This study numerically examines the elliptical winglets (EW) on the overall performance of fin-and-tube heat exchanger. The major geometrical parameters characterizing the EW has been investigated thoroughly, including the winglet location, attack angle and the trailing angle of the elliptical winglets with two different winglet lengths which are 1.0 mm and 1.5 mm. The numerical results indicate that the elliptical winglets with the 30° attack angle, 0 mm horizontal distance, 6 mm vertical distance and 120° trailing angle of both winglet lengths shows the highest performance. The heat transfer coefficients and pressure drops obtained by both winglet sizes are larger than that of the plain fin by about 13% and 35%, respectively. In term of the performance efficiency index, the 1.5 mm winglet length indicates about 1.8–2.9% improvement relative to plain fin geometry and the efficiency index of 1.0 mm winglet length is comparable with that of the plain fin.

1. Introduction

Fin-and-tube heat exchangers are widely used in the industries like HVAC&R (heating, ventilating, air conditioning and refrigeration) systems, petrochemical industry and chemical processing, etc. Apparently, the high efficient fin-and-tube heat exchanger is very important in supporting those industries for typically the dominant thermal resistance is on the air side [1]. In this regards, augmentation of the fin patterns is effective in reducing the corresponding resistance and the popular enhancement method is the passive method [1]. The interrupted fin surface is one of the most favored methods implemented in the fin-and-tube heat exchangers. However, the boundary renewal also brings about significant pressure drops. Hence the introduction vortex generators (VGs) is very attractive for it offers appreciable heat transfer augmentation in exchange of affordable pressure drop. The traditional VGs include the delta wing, delta winglet, rectangular wing and rectangular winglet [2].

In 1960, the investigation of the VGs in aeroplane design was initiated by Schubauer and Spangenberg [3]. For VGs investigation related to heat transfer enhancement was first studied by Johnson and Joubert [4] in 1969. They found that the local Nusselt number is increased twice by the circular tube which was attached the VGs but the average of the Nusselt number was unvaried while the pressure drag can be significantly reduced. Since then, there had been many publications in association with the VGs on the heat transfer enhancement and numbers of them were focused on the fin-and-tube heat exchangers [5–23] and some applications of VGs were also used for enhancing the heat transfer performance of the heat sink [24].

Leu et al. [5] investigated the effects of the fin and tube heat exchanger with a pair of block VGs on heat transfer and fluid flow numerically and experimentally. They examined the flow patterns via dye injection. Evidently, the presence of block VGs guided the fluid to flow into the wake zone behind the tube and the flow hits the subsequent row, thereby increasing the heat transfer at the wake region. Wu and Tao [6,7] applied synergy principle to examine the influence of the fin with delta winglet on the heat transfer and flow characteristics. They found that the delta winglet could increase the heat transfer performance and reduce the pressure drop when compared to the plain fin configuration. Lemouedda et al. [8] and Wu and Tao [9] studied the effect of VGs with and without the punched hole from the VGs and concluded that the VGs with a punched hole out performs that VGs without the punched hole. Besides the traditional VGs, the alternative VGs were also proposed, including trapezoidal winglet [16–18] and semi dimple [19,20]. All of them showed appreciable heat transfer

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Nomenclature

A_c	minimum flow area (m^2)
A_h	heat transfer area between the air and fin (m^2)
A_o	total surface area (m^2)
ATA	attack angle (degree)
c_p	specific heat at constant pressure (kJ/kg·K)
D_c	fin collar outside diameter (mm)
f	friction factor
G_c	mass flux of the air based on the minimum flow area (kg/(m^2 s))
$\bar{h}$	heat transfer coefficient (W/m^2·K)
HD	horizontal distance (mm)
j	Colburn factor
k	thermal conductivity (W/m·K)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
Pr	Prandtl number
ΔP	pressure drop (Pa)
Q	heat transfer rate (W)
Re	Reynolds number
T	temperature (K)
TA	trailing edge angle (degree)
$\bar{T}_s$	mean temperature of the fin surface (K)
u	Cartesian velocity component (m/s)
V	velocity (m/s)
VD	vertical distance (mm)
V_{max}	maximum velocity inside the heat exchanger (m/s)
WL	winglet length (mm)

Greek letters

μ	viscosity (kg/m·s)
ρ	density (kg/m^3)
σ	contraction ratio of the cross-sectional area

Subscripts

a	air
c	collar
in	inlet
m	average value
o	overall
out	outlet

performance than those of the plain fin. Lotfi et al. [21] investigated the heat transfer performances of the fin-and-tube heat exchanger with rectangular trapezoidal winglet, angle rectangular winglet, curved angle rectangular winglet and Wheeler wishbone. The best VGs in term of j/f ratio is the curved angle rectangular with the curved edge on the upper edge of the winglet, meaning a superior heat transfer performance of the curved edge on the top of the winglet Sarangi and Mishra [22] examined the location of winglet on the thermal performance of fin-and-tube heat exchanger. They reported that placing the winglet near the tube center alongside the flow direction producing the greatest heat transfer performance. However, the attack angle of winglet casts the major impact on the thermal performance. Song et al. [23] studied the effect of the size of the curved delta winglet and tube pitch on heat transfer characteristic of a heat exchanger. They found that placing a small curved delta winglet near the tube shows superior heat transfer performance at a low Reynolds number but a large curved delta winglet revealed a better heat transfer performance at a larger Reynolds number.

In view of the foregoing discussions, the curved shape winglet was shown to be effective in enhancing the heat transfer performance. In this study, a novel elliptical winglets (EW) is proposed and it will be shown later to have a more superior performance than aforementioned designs. Yet the design is further optimized through detailed numerical examination and relevant geometric influences are also reported in this study.

2. Mathematical analysis

2.1. Computational models

The computational model of this investigation includes a reference fin-and-tube heat exchanger having plain fin from Wang et al. [20]. For the proposed EW geometry, details are given in Fig. 1 where a pair of VGs was punched on the fin as shown in Fig. 1 (a). The basic geometric dimensions of the EW are described as follows. The horizontal distance (HD) and vertical distance (VD) are measured from the center of the tube to the center of the ellipse in each direction as presented in Fig. 1(b). The attack angle (ATA) is the angle between flow direction and the base alignment of the ellipse as demonstrated in Fig. 1(c). The angle between the flow direction and the elliptical alignment in a clockwise direction is regarded as the positive, and the angle in a counter clockwise direction is considered negative. The winglet length (WL) is the length of the winglet base. The trailing angle (TA) is the angle between two straight edges of the winglet. The winglet span (WS) is the high of the winglet which is measured from the fin base to the top of the winglet. All the parameters details are presented in Table 1. Notice that half of the fin is used in the computational model as illustrated in Fig. 2(a). The computational model consists of the air and fin domains. The air domain is divided to be 3 zones, including entrance zone, fin zone, and exit zone. The length of entrance zone, fin zone, and exit zone 31 mm, 21 mm, and 161 mm, respectively. The front and bottom view are also presented in Fig. 2(b). The computational meshes are generated by the unstructured non-uniform grid system. The meshes are mainly created in tetrahedral, prismatic and pyramid elements. The meshes around the winglet are shown in Fig. 3.

2.2. Governing equations and parameter definition

The relatively operational velocity for typical fin-and-tube heat exchanger suggests incompressible fluid and the thermal properties of the air are assumed constant. The governing equations of continuity equation, momentum equation and energy equation are listed in the following:

Continuity equation:

$$\rho\left(\frac{\partial u_i}{\partial x_i}\right) = 0, \quad (i = 1, 2, 3) \tag{1}$$

Momentum equation:

$$\rho\frac{\partial(u_i u_k)}{\partial x_i} = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left(\mu\frac{\partial u_j}{\partial x_i}\right), \quad (i,j = 1, 2, 3 \text{ and } i \neq j) \tag{2}$$

Energy equation:

$$\rho c_p\frac{\partial(u_i T)}{\partial x_i} = k\frac{\partial}{\partial x_i}\left(\frac{\partial T}{\partial x_i}\right), \quad (i = 1, 2, 3) \tag{3}$$

Notice ρ is the fluid density; μ is the fluid viscosity; c_p is the fluid specific heat and k is the fluid thermal conductivity. For modeling the foregoing equations subject to fin-and-tube heat exchangers, both laminar and turbulent flow had been used in pre-