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Heat transfer and pressure performance of a plain fin with radiantly arranged winglets around each tube in fin-and-tube heat transfer surface

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ABSTRACT

A radiantly arranged LVGs enhanced fin-and-tube structure is numerically investigated in this paper to enhance air side heat transfer. The arrangement of LVGs is totally different from existing publications. In the proposed structure there exist 12 winglets around each tube. The attack angles are 50, 50, 50, 50, 70 and 110°, respectively. The height ends of the winglets are further away from the tube, while the closed point ends of winglets are close to the tube wall. Heat transfer and pressure drop performance is compared with other three structures: an arc-shaped wavy fin-and-tube surface, a common-flow-down LVGs enhanced fin-and-tube surface and a plain plate fin-and-tube surface. The simulation results show that the 12 winglets form five local passages which can guide the moving fluid from the main flow to the tube wall, leading to some impinging effect or reducing the wake region behind the tube. The performance evaluation of the four structures is conducted by using the newly proposed ln (Nu_e/Nu_o) vs. ln (f_e/f_o) plot based on energy saving. It is found that the proposed radiantly arranged LVGs enhanced fin-and-tube surface is the best. The field synergy principle is adopted to analyze the four structures and it is found that the domain averaged synergy angle of the proposed radiantly arranged LVGs enhanced structure is significantly less than that of other three cases. Finally characteristics of the proposed fin-and-tube surface with five tubes are investigated at five fin pitches and compared with the wavy structure of six tubes at the same other conditions. It is found that the proposed structure of five tubes can replace the wavy structure of six tubes.

1. Introduction

Fin-and-tube heat exchangers are widely employed in industries such as heating, ventilation, air-conditioning and refrigeration (HVAC&R) systems. Their efficiency directly determines the energy consumption of heat exchangers for both manufacturing and operating processes. Air is a common used working fluid in fin-and-tube heat exchangers due to its cleanness and low cost, but the heat transfer capability of air is quite low, which leads to high thermal resistance on the air side of fin-and-tube heat exchanger. In typical applications, thermal resistance of the air side takes up over 90% of all [1], so the main approach for improvement of such heat exchangers is to enhance the air side heat transfer. Researchers have developed a lot of types of fin surfaces to enhance air-side heat transfer without introducing tremendous penalty of pressure drop and material consumption. Wavy fin and longitudinal vortex generator (LVG) are two usually employed enhancement techniques. The wavy structure periodically interrupts the growth of the thermal boundary layers on the heat transfer surfaces and induces transverse vortex in wavy trough thus increasing fluid mixing and vortices. For the LVG enhanced fin surfaces, when fluid flows over LVG set at an appropriate attack angle, longitudinal vortices are generated [2] leading to the enhancement of heat transfer. In this paper a new-type arrangement of vortex generator will be proposed to enhance heat transfer of plain-fin surface and its performance is compared with an existing wavy fin surface. Hence, in the following previous studies on wavy and longitudinal vortex generator (LVG) enhanced fin surfaces will be briefly reviewed.

In general, wavy or corrugated fins have different specific forms, including herringbone wavy fin, sinusoid or co-sinusoid wavy fin, v-shaped or triangular wavy fin, cambered corrugated fin, curved wavy fin and so on. Heat transfer and fluid flow characteristics of this fin configuration were reported in detail in literatures [3–5]. Jang and Chen [3] numerically investigated the effects of geometrical parameters especially the wavy angle on the triangular wavy fin performance, and concluded that the average Nusselt number *Nu* and friction factor *f* increase with the increase of wavy angle for equal wavy height. Savino et al. [4] identified that *f* always increases with the Reynolds number *Re*, while *Nu* increases significantly with *Re* only above a critical value of *Re* for herringbone

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Nomenclature

Latin Symbols

A	air side heat transfer area
A_c	cross-section area at the inlet
b_1,b_2,b_3	$\ln C_{\Phi,\,P}$, $\ln C_{\Phi,\,\triangle p}$ and $\ln C_{\Phi,\,u}$
c_p	specific heat
L	effective length of fin
P	pump power
Pr	Pr number
q_m	mass flow rate
T	temperature
u,v,w	fluid velocity in x, y, and z direction

Greek Symbols

α_m	modulus average intersection angle
λ	thermal conductivity of fluid
ρ	density of fluid
η	dynamic viscosity

Subscripts

e	enhanced fin
o	reference fin
w	wall

wavy fin. Furthermore, according to the study of [5], there exists an optimum fin pitch at which *Nu* is the maximum, and the increase of *Re* leads to the increase of *Nu* and the decrease of *f*. The above studies show that wavy fin will possess a satisfactory performance only at some certain circumstances like high inlet velocity and specific geometrical parameters.

Longitudinal vortex generator is the fourth generation of enhanced measures [6]. In earlier studies, Jacobi and Shah [7] and Fiebig [8] gave thorough reviews of the development of LVG. Many kinds of generators in different shapes have been developed during the past two decays, such as wedge type, plough type, rectangular wing, delta winglet and so on. Among these types of LVGs triangular wing, rectangular wing, delta winglet and rectangular winglet are the most widely used ones [7]. Most of the typically used LVGs are summarized in [9]. Fiebig and his coworkers [10–12] made a great contribution to the development and application of LVG. They found that delta winglet has the best performance. So in this paper delta winglet generators are adopted, but the orientation and arrangement are different from all previous studies.

Except the shape discussed above, the arrangement of LVGs is also an important factor influencing the comprehensive characteristics of enhanced surfaces. Chen et al. [13,14] employed punched winglet longitudinal vortex generators in staggered and inline arrangements to enhance heat transfer of oval tube heat exchanger, and found that winglets in staggered arrangement can bring larger heat transfer enhancement than in in-line arrangement. Torii et al. [15] referred to a pair of delta winglets as common-flow-up (in this winglets orientation flows between two adjacent winglets accelerate) and found it effective in reducing form drag and enhancing heat transfer of the wake region. Allison and Dally [16] also investigated common-flow-up winglets and found that the heat transfer of the winglet surface is 87% of a standard louver fin surface while the pressure drop is only 53%. Kwak et al. [17] and Biswas et al. [18] studied the common-flow-down configuration (in this winglets orientation flows between two adjacent winglets decelerate) and found it more effective for higher *Re* than for lower *Re*. He et al. [19] proposed a vortex generator array of "V" configuration inspired by the locomotion formation of bird and fish. The array is composed of two delta-winglet pairs placed at the attack angle of 10 degree or 30 degree. It is found that VG array with 30° is more efficient than two conventional single-pair designs at low *Re* representative of many HVAC&R applications. Fan et al. [20] combined LVGs with slotted protruding parallel strips and tried different variations of arrangement, finally substituted two tube-rows of the combined structure for an air-side wavy surface with three tube-rows.

Researchers also conducted lots of studies on the effects of geometric parameters of LVGs. Wu and Tao [21] investigated geometric shape, size and the location of LVGs in a channel, and found that the overall *Nu* of the channel is higher with larger space between the LVG pair and larger area of LVG, and decreases with the LVG's location away from the inlet of the channel. Lemouedda et al. [22] utilized a CFD analysis, response surface methodology and genetic algorithms to investigate the optimal attack angle of delta-winglet LVGs. They concluded that common-flow-up configuration shows better performance for the staggered arrangement, while common-flow-down is better for inline arrangement. Zeng et al. [23] studied and optimized the parameters of vortex-generator by the Taguchi method. They revealed that fin pitch has the greatest effect on the comprehensive performance, and then does the transverse tube pitch, attack angle, length of vortex generator, longitudinal tube pitch, and height of vortex generator. The friction factor and Nusselt number of heat transfer surface are almost independent of fin thickness and fin material.

As far as the basic mechanism of enhancing heat transfer by LVG is concerned, it is often attributed to the disturbing of the thermal boundary layer, swirling and flow destabilization caused by LVG [2,7,8]. Wu and Tao [24,25] made comprehensive studies on this issue and their results definitely show that the fundamental reason that LVG can enhance heat transfer is the improvement of synergy between velocity and fluid temperature gradient.

For more information of the recent developments and applications of LVG the review paper of [26] is recommended.

The winglets adopted in the enhanced surfaces in open literatures are mostly placed in the line along the main flow direction, for either staggered or parallel arrangement. Considering that the flow passing a tube bank periodically changes its local direction: sometime towards the tube wall sometime leaving the tube wall, if we arrange individual winglet orientation to accommodate the local fluid flow direction, we may get some profits in enhancing heat transfer. The major goals of this paper is to find a more efficient structure to replace a wavy fin-and-tube surface already used in air-coolers widely adopted in air-conditioning equipment for clean air space in China. The present authors propose a new type of winglet orientation arrangement with 12 winglets being radiantly arranged around each tube. Considering that 'common-flow-down' structure of longitudinal vortex generator is one of the earliest and most representative LVG arrangements in literatures and the plain fin once was undoubtedly the most widely used fin in heat exchanger for its simple structure, we choose these four kinds of structure to make a comparison study in this paper. Numerical simulation is conducted and the results are compared with 3 referenced configurations (a corrugated fin in use, a conventional single-pair LVGs