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A comparative study on the air-side performance of wavy fin-and-tube heat exchanger with punched delta winglets in staggered and in-line arrangements

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ABSTRACT

The air-side heat transfer and fluid flow characteristics of wavy fin-and-tube heat exchanger with delta winglets are investigated numerically. The three-dimensional simulations are performed with renormalization-group (RNG) $k-\varepsilon$ model to lay the foundation for the design of the high-performance heat exchanger. The wavy fin-and-tube heat exchangers which have three-row round tubes in staggered or in-line arrangements are studied. The numerical results show that each delta winglet generates a downstream main vortex and a corner vortex. For the in-line array, the longitudinal vortices enhance the heat transfer not only on the fin surface in the tube wake region but also on the tube surface downstream of the delta winglet; for the staggered array, longitudinal vortices are disrupted at the first wavy trough downstream from the delta winglet and only develop a short distance along the main-flow direction, and the vortices mainly enhance the heat transfer of the fin surface in the tube wake region. The longitudinal vortices generated by delta winglet cause considerable augmentation of heat transfer performance for wavy fin-and-tube heat exchanger with modest pressure drop penalty. When $Re_{D_c} = 3000$, compared with the wavy fin, the j and f factors of the wavy fin with delta winglets in staggered and in-line arrays are increased by 13.1%, 7.0% and 15.4%, 10.5%, respectively.

1. Introduction

Fin-and-tube heat exchangers are widely employed in many power engineering and chemical engineering applications, especially in heating, ventilation, air-conditioning, and refrigeration (HVACR) systems. Generally, a liquid flows through the tubes and a gas flows through the channels formed by the neighboring fins. Because the thermal resistance of gas is inherently higher than that of liquid, the dominant thermal resistance of fin-and-tube heat exchanger is usually on the gas side (generally air-side), which may account for 85% or more of the total thermal resistance. The use of enhanced fin surface is the most effective way to improve the overall performance of the fin-and-tube heat exchanger to meet the demand of high efficiency and low cost. Fins employed on the gas side can increase the heat exchanger surface area and strengthen the flow disturbance. Typically, these enhanced surfaces are developed from corrugated fin to interrupted fin (such as slits, louvers, and offset-strip fin). The wavy surface can periodically change the main-flow direction and cause better flow mixing, the slit or louvered-fin can periodically interrupt the main-flow, break and renew the thermal boundary layer.

Jacobi and Shah [1] indicated that heat transfer enhancement consists of main-flow enhancement and secondary flow enhancement. Louvered and slit fins and wavy fin are examples of main-flow enhancement method. The intentional generation of vortices to enhance heat transfer is a secondary flow enhancement method. The longitudinal vortex has already been successfully applied on the fin surface of the core for heat transfer enhancement. Longitudinal vortex generators (LVGs), as a special extended surface, are usually incorporated into a heat transfer surface with an attack angle by means of embossing, stamping, or punching process. When the fluid flows over the LVGs, the pressure difference across the vortex generator causes flow separation and induces vortices downstream.

The longitudinal vortices were first used in boundary layer control by Schubauer and Spangenberg [2] in 1960. Jonhnson and Joubert [3] first reported the impact of vortex generators on the heat transfer in 1969. Later, the use of LVGs in channel flow applications has received considerable attentions. Jacobi and Shah [1] provided an excellent review of heat transfer enhancement through the use of longitudinal vortices. Gentry and Jacobi [4,5] experimentally studied the heat transfer enhancement performance of delta wing vortex generators in a flat-plate flow by

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Nomenclature

A	cross-sectional area, m^2
A_c	minimum flow cross-sectional area, m^2
A_f	fin surface area, m^2
A_0	total surface area, m^2
c_p	specific heat of the fluid, $J\,kg^{-1}\,K^{-1}$
D_c	tube outside diameter, m
D_h	$4A_cL/A_0$, hydraulic diameter, m
f	friction factor
F_p	fin pitch, m
h	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$ or height of the delta winglet, m
H	channel height, m
j	Colburn factor
k	turbulence kinetic energy, $m^2\,s^{-2}$
l	length of the delta winglet, m
L	fin length along flow direction, m
Nu	Nusselt number
p	pressure, Pa
Δp	pressure drop in flow direction, Pa
P_l	longitudinal tube pitch, m
P_t	transverse tube pitch, m
Pr	Prandtl number
q	heat flux, $W\,m^{-2}$
Q	heat transfer rate, W
Re_{D_c}	Reynolds number based on tube outside diameter
T	temperature, K
u, v, w	x, y, z velocity components, $m\,s^{-1}$
u_m	mean velocity at the minimum flow cross-sectional area, $m\,s^{-1}$
$\vec{U}$	velocity vector, $m\,s^{-1}$
x, y, z	Cartesian coordinates
X	x/H
X_L	$\sqrt{(P_t/2)^2 + P_l^2}/2$, geometric parameter, m
X_M	$P_t/2$, geometric parameter, m

Greek symbols

α	circumferential angle, °
β	attack angle of the delta winglet, °
δ_f	fin thickness, m
μ	dynamic viscosity, $kg\,m^{-1}\,s^{-1}$
ρ	density, $kg\,m^{-3}$
λ	thermal conductivity, $W\,m^{-1}\,K^{-1}$
ε	turbulent energy dissipation rate, $m^2\,s^{-3}$
Γ	circulation of cross-section, $m^2\,s^{-1}$
θ	wavy angle of fin, °
Θ	dimensionless temperature
η_f	fin efficiency
η_0	surface efficiency

Subscripts

a	air
f	fin
in	inlet
m	mean
out	outlet
w	tube wall
x	local

a naphthalene sublimation technique. The results indicated that the average heat and mass transfer could be enhanced by 50–60% at low Reynolds number over the unenhanced performance. Biswas et al. [6] carried out numerical and experimental studies on flow structure and heat transfer performance of longitudinal vortices behind a delta winglet placed in a fully developed laminar channel flow. In recent years, LVGs are widely applied in various heat exchangers to increase the heat transfer coefficient with only small increase in pressure drop penalty, which have been studied by many researchers. Wang et al. [7] utilized a dye-injection technique to visualize the flow structure for enlarged plain fin-and-tube heat exchanger with annular and delta winglet vortex generators. They found that for the same winglet height, the delta winglet showed more intensive vertical motion and flow unsteadiness than annular winglet, however, the corresponding pressure drop of the delta winglet was lower than that of annular winglet. Chen et al. [8,9] explored the heat transfer enhancement and pressure drop increase of finned oval-tube heat exchanger with punched delta-winglet pairs in staggered and in-line arrangements. Tiwari et al. [10] made a numerical study on laminar flow and heat transfer in a channel with built-in oval-tube and delta winglets, the different attack angles and the axial locations of the winglets were considered. The results indicated that vortex generators in conjunction with the oval-tubes could definitely enhance the improvement of fin-tube heat exchangers. O'Brien et al. [11] presented an experimental study on forced convection heat transfer in a narrow rectangular duct fitted with an oval-tube and one or two delta-winglet pairs. Mean heat transfer results indicated that the oval-tube geometry with single winglet pair yielded significant heat transfer enhancement, the average heat transfer performance was about 38% higher than the oval-tube without winglet, and the corresponding increase in friction factor was limited to less than 10%. Then O'Brien et al. [12] made an experimental study in a narrow duct fitted with a circular tube and/or a delta-winglet pair. The results of overall mean fin surface Nusselt number indicated a significant heat transfer enhancement with the winglets and circular tube. At the lowest Reynolds number, the enhancement was nearly a factor of 2. At the higher Reynolds number, the enhancement was close to 50%. Leu et al. [13] carried out numerical and experimental analyses to study the effects of different attack angles ($\beta = 30°$, $45°$ and $60°$) on enhanced heat transfer in a three-row plain fin-and-tube heat exchanger with rectangular winglets, they reported that the case of $\beta = 45°$ provided the best heat transfer enhancement. Pesteei et al. [14] experimentally studied the effect of winglet location on heat transfer enhancement and pressure drop in plain fin-and-tube heat transfer. Biswas et al. [15] presented a numerical investigation of the flow structure and heat transfer enhancement in a channel with a built-in circular tube and a pair of delta winglets. The results showed that the longitudinal vortices generated by the winglets placed in the wake region behind the tube enhanced the local heat transfer by 240%. Torii et al. [16] proposed a novel delta winglet configuration, called common-flow-up. The proposed configuration was shown to be effective in delaying boundary layer separation from the tube, reducing form drag, and removing the zone of poor heat transfer from the near-wake of the tube. Heat transfer enhancement and pressure drop caused by delta winglets were compared between common-flow-up and common-flow-down configurations by Kwak et al. [17]. Allison et al. [18] presented an experimental analysis of the effects of delta winglets on the performance of a fin-and-flat tube radiator, the winglets were arranged in common-flow-up configuration and placed directly upstream of the tube.