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Numerical study of flow and heat transfer enhancement of circular tube bank fin heat exchanger with curved delta-winglet vortex generators

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A B S T R A C T

To reduce the peeling wake area and generate longitudinal vortices at the rear of circular tube employed in tube bank fin heat exchanger, a new fin pattern with curved delta-winglet vortex generators (CDWVGs) punched on fin surface was proposed. A conjugate heat transfer numerical method is employed to investigate the heat transfer performance of the staggered circular tube bank fin heat exchanger with CDWVGs. Their radial and circumferential locations, height and length are the main parameters to investigate. CDWVGs can not only guide the flow to reduce the size of the wake region, but also generate secondary flow to enhance heat transfer of the fin surface. CDWVGs can effectively enhance heat transfer under either identical pumping power or identical mass flow rate constrains. The optimal geometry parameters and position parameters of CDWVGs are found for the majority of studied *Re*. If the effect of the main working, geometry and position parameters on heat transfer is cast into the relationship between the secondary flow intensity and Nusslet number, the intensity of secondary flow mainly determines the heat transfer ability of the fin surface.

1. Introduction

Tube bank fin heat exchanger is widely used in many industrial applications such as vehicle radiators, internal cooling for diesel engine of locomotive, air conditioning systems. The energy consumption of this type of heat exchanger is very large. To reduce energy consumption further enhancing the fin side heat transfer is necessary. The effective approach to realize this goal is to modify the fin surface geometry. Several common modifications in fin surface geometries have been widely investigated, typically including the wavy fin [1], the slit fin [2], the louvered fin [3], the interrupted annular groove fin [4], the fin with winglet-type vortex generators (VGs) [5], and some combination enhanced fins [6,7]. Producing secondary flow with VGs is an effective strategy to increase the fin side heat transfer coefficients even if such secondary flow is commonly weaker than main flow. The punched VGs in flow domain not only interrupts the development of thermal boundary layer, but also generates longitudinal vortices and flow destabilization to enhance moment and mass transfer of fluid between near the wall and far away from the wall.

The early studies of the heat transfer performance and applications of VGs in compact heat exchangers were comprehensively reviewed by Fiebig [8] and Jacobi and Shah [9]. The commonly used ones are plain winglet VGs, mainly including delta-winglet [10–15] and rectangular-winglet [16]. According to the reports of Tiggelbeck et al. [17], the best performance is given by the delta winglets, closely followed by the rectangular winglets. He et al. [18] compared the heat transfer performance of two delta-winglet pairs with two layout modes of continuous and discontinuous winglets to a conventional large winglet configuration, the results showed that the arrays with discontinuous winglets have the best heat transfer enhancement. Torri et al. [19] introduced a deploying delta winglet-type VGs to realize separation delay and remove the zone of poor heat transfer from the near-wake of the tubes.

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Nomenclature

A	heat transfer surface area [m^2]
c_p	specific heat capacity [kJ/(kg K)]
C_λ	ratio of thermal conductivity $C_\lambda = \lambda_f/\lambda_a$ [−]
D_o	tube outside diameter [m]
D_c	fin collar outside diameter [m]
D_{VG}	base arc diameter of CDWVGs [m]
f	friction factor: $f = 2\Delta P/L$ [−]
H	height of CDWVGs [m]
h	heat transfer coefficient [W/(m^2 K)]
L	dimensionless length of fin [−]
l	circumferential length of CDWVGs [m]
Nu	Nusselt number: $Nu = hD_c/\lambda$ [−]
P	dimensionless pressure [−]
Pr	Prandtl number: $Pr = \eta c_p/\lambda$ [−]
Q	heat transfer rate [W]
Re	Reynolds number: $Re = \rho u_{in} D_c/\eta$ [−]
S_1	longitudinal pitch between circular tubes [m]
S_2	transversal pitch between circular tubes [m]
Se	dimensionless parameter of the intensity of secondary flow [−]
T_p	fin spacing [m]
T	temperature [K]
U_i	components of dimensionless velocity vector [−]
X_i	dimensionless coordinates axes [−]

Greeks

δ_f	fin thickness [m]
λ	thermal conductivity [W/(m K)]
η	viscosity [Pa s]
ε	relative error [−]
β	angle indicates the circumferential location of VG [°]
Θ	dimensionless temperature [−]
ΔP	dimensionless pressure drop [−]

Subscripts

f	fin surface
in	inlet
I, II	fin surface I and II
local	local value
out	outlet
ref	reference
s	span-average value
t	tube
*tube*i	the *i*th tube
w	wall

Superscripts

a	air
f	fin

Recently, other types of VGs have been proposed and widely investigated also. Lin et al. [20,21] analyzed the heat transfer and fluid flow characteristics of the heat exchanger mounted with wave-type, annular and inclined block VGs. Leu et al. [22] found the optimization of the VG's span angle and the VG's transverse location through studying the thermal-hydraulic characteristics of inlined and staggered plate fin-tube heat exchangers with block type VGs mounted behind the tubes. Bilir et al. [23] and Fan et al. [24] studied the heat transfer characteristic and pressure drop of the dimpled imprint fin-tube heat exchangers. Meanwhile, other kinds of VGs of balcony and winglet were also studied in Ref. [23]. Dupont et al. [25] experimentally studied the flow features with periodically arranged embossed-type VGs, and concluded that these smooth shaped VGs are very promising for enhanced heat exchangers. Ye et al. [26] compared the performance of curved trapezoidal winglet VGs with traditional plain VGs including rectangular-winglet, trapezoidal-winglet and delta-winglet using experimental method, and the results showed that delta winglet pair is the best in laminar and transitional flow region, while curved trapezoidal winglet pair has the best thermo-hydraulic performance in fully turbulent region. However, this type of curved trapezoidal winglet pair is hardly applied in real tube bank fin heat exchangers.

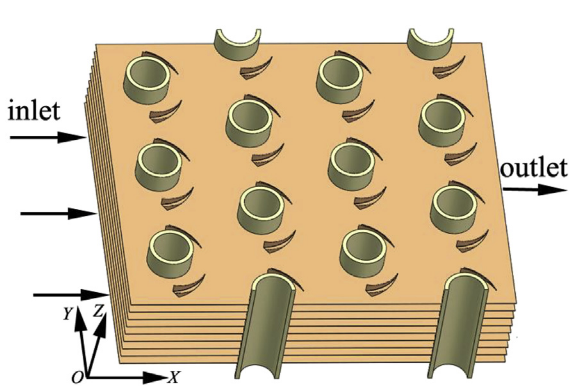

Fig. 1. Schematic view of circular bank fin heat exchanger with CDWVGs on the fins.

From above brief review it is found that in most studies VGs are used mainly to produce vortices, in few studies VGs are used not only to generate vortices, but also to guide the fluid flow. Considering the tube wake regions, one is expecting to design VGs having two roles: to guide the flow and to generate vortices. At the same time how to realize the design should be considered. For example plane VGs are easy to be punched on the fin surface, other block shape VGs do not have this convenience. Based on these considerations, a curved delta-winglet VGs (CDWVGs) punched on the fin surfaces is proposed in present paper, as shown in Fig. 1. It is expected that such fin pattern could guide fluid flow to the tube wake regions, then enhance the poor heat transfer on the fin surface contacting with the wake region, furthermore generate vortices and then enhance heat transfer on large area of the fin surface. The main focus of the present work is to investigate the roles paid by the CDWVGs using numerical method. The airside passage with four-row tubes in staggered arrangement under multi-geometry parameters is selected as the computational domain. The physical model and numerical formulation for the problem studied is firstly presented. Then the numerical analysis on the heat transfer and fluid flow characteristics is reported.

2. Physical model

The four-row circular tube bank fin heat exchanger element with CDWVGs, as shown in Fig. 1, was investigated. Usually, circular flanges are stamped out from the fin at every position of the circular tube holes to position the fins and to better join the fins to the circular tubes. At downstream zone of every circular tube hole,