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Comparison of winglet-type vortex generators periodically deployed in a plate-fin heat exchanger – A synergy based analysis

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ABSTRACT

The objective of the present investigation is to assess the performance of a plate-fin heat exchanger with an emphasis on acquiring fundamental understanding of the relation between local flow behavior and heat transfer augmentation mechanism. Numerical simulations are performed in a rectangular channel containing built-in longitudinal vortex generators on the bottom wall arranged periodically both in the streamwise and spanwise directions. Two types of vortex generators, namely, rectangular winglet pair (RWP) and delta-winglet pair (DWP) with two different flow arrangements, common-flow-up (CFU) and common-flow-down (CFD) have been explored to assess the influence of shape and flow arrangements on heat transfer enhancement. The basic mechanisms of flow structure and heat transfer characteristics have been examined with the help of secondary velocity vectors, streamlines, and temperature contours. Additionally, the mechanism of the local heat transfer augmentation has been explained using a novel concept called the field synergy principle. The performance of the vortex generators has been compared based on integral quantities such as Nusselt number, pressure loss, performance evaluation factor and domain averaged synergy angle. The computations reveal enhanced mixing of fluid between the wall layer and the core due to strong secondary flows produced by vortex generators. The performance analysis indicates that the RWP is more effective in terms of heat transfer enhancement as compared to DWP. The field synergy analysis has shown that the sites with higher Nusselt number are associated with smaller synergy angle or better coordination between the velocity vector and the temperature gradient.

1. Introduction

The light-weight and highly efficient heat exchangers require some special enhancement technique for heat transfer improvement. In practice, the gas-side surfaces of a heat exchanger are required to be specially designed to offset the poor heat transfer coefficient on the gas-side. One of the heat transfer enhancement techniques is introduction of longitudinal vortices in the flow field by using specially designed surfaces. This is a deliberate modification of heat transfer surfaces, where longitudinal vortex generators (LVGs), such as wings or winglets in the form of rectangular or delta shapes are mounted on the heat transfer surfaces. The introduction of LVGs increases the heat transfer area, and also provides an additional heat transfer mechanism in the form of swirling the flow. The heat transfer benefit due to swirling motion exceeds the benefit obtained due to increase in heat transfer area (see Fig. 1).

The literature survey reveals the existence of a considerable amount of research on the topic of heat transfer enhancement using longitudinal vortex generators. A comprehensive coverage of the different aspects of heat transfer surfaces with vortex generators has been systematically presented by Jacobi et al. [1] and by Fiebig [2] in their review articles. Another recent review article of Biswas et al. [3] has focused on the present state-of-the-art of augmentation techniques for heat exchanger surfaces using longitudinal vortex generators. The authors [3] have systematically addressed the different forms of protrusions, types of flow configurations and flow conditions, and strategies related to optimized heat transfer enhancement with minimal flow losses. The pioneering experimental investigation of Tiggelbeck et al. [4,5] revealed the enhancement in heat transfer of heat exchanger surfaces due to longitudinal vortices generated by wings or winglet pairs in the form of delta or rectangular shape. Subsequently, they studied the flow structure and heat transfer in a channel with single and double rows of vortex generators in aligned and staggered arrangements. The results showed that the Nusselt number at the second row was dependent on the distances between the rows and became highest for a distance of 7–10 channel heights. Moreover,

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Nomenclature

H	channel height
L_p	longitudinal pitch
B_p	lateral pitch
h	height of winglet
l	chord length of winglet
p	pressure
t	dimensional time
U_{av}	average streamwise velocity
Re	Reynolds number, $(U_{av}H/\nu)$
Pr	Prandtl number
T	dimensional temperature
T_0	reference temperature
Nu	Nusselt number
C_f	friction coefficient
f	apparent friction factor
u, v, w	streamwise, wall-normal and spanwise components of velocity
x, y, z	streamwise, wall-normal and spanwise coordinates
RWP	rectangular winglet pair
DWP	delta winglet pair
CFD	common-flow-down
CFU	common-flow-up

Greek symbols

ν	kinematic viscosity of the fluid
α	local intersection angle or synergy angle
ρ	density
τ	nondimensional time, (tU_{av}/H)
θ	nondimensional temperature, (T/T_0)
β	angle of attack of winglet

Subscripts

w	wall
b	bulk value
av	average value
m	mean value
o	reference value

the experimental results pointed out that pressure loss and heat transfer enhancement is highly sensitive to the angle of attack of the vortex generators. One notable experimental work was pursued by Gentry et al. [6] which observed similar trends of improvement in heat transfer performance of a plate-fin heat exchanger using delta wing vortex generators.

Biswas and Chattopadhyay [7], numerically examined the flow structure in laminar a channel flow with built-in wing type vortex generators and obtained 34% increase in the spanwise averaged Nusselt number even at the exit. Biswas et al. [8] analyzed flow structure and heat transfer in a fin-tube heat exchanger with built-in delta winglet pairs. A punched-out delta winglet pair with an aspect ratio of 2 was located behind each tube at an angle of attack of 45°. At a Reynolds number of 500, a local heat transfer enhancement of more than 240% was reported at a location about 12 times the channel height downstream of the inlet. Furthermore, Biswas et al. [9] performed a comparison of the numerical investigation with its experimental counterpart to study the flow structure and heat transfer effects of longitudinal vortices behind a delta winglet attached in a fully developed laminar channel flow. Sohankar et al. [10] numerically investigated the effect of rectangular vortex generators on heat transfer enhancement with an emphasis on the flow structure in a plate-fin heat exchanger. Their observations pointed out the effects of the angle of attack and Reynolds number on heat transfer enhancement. Recently, a comprehensive numerical investigation on improvement of heat transfer performance of a plate-fin heat exchanger was conducted by Wu et al. [11], employing both delta and rectangular winglet pairs as vortex generators. The mechanism of heat transfer augmentation was examined. Additionally, an extensive parametric study was carried out to quantify the effect of shape and type of the vortex generator, angle of attack and height of the winglet on heat transfer and pressure loss for a wide range of Reynolds numbers. Apart from these, recent articles such as those by Tian et al. [12] and Promvonge et al. [13] have also clearly examined the effectiveness of longitudinal vortex generators in heat transfer enhancement.

In practical applications, the ratio of gas-side channel length to channel height is at least 30 for compact heat exchangers. This large ratio requires several rows of vortex generators for sufficient heat transfer enhancement. Such a configuration shows periodically repeating flow conditions at some downstream rows of vortex generators. This situation is referred to as periodically fully developed flow [14].

Both, numerical and experimental studies in a channel with periodically arranged rectangular winglets in the laminar regime were discussed by Fiebig [2]. The experimental study noticed self-sustained oscillatory flow at a Reynolds number of 150 based on channel height for the winglet with an angle of attack of $\beta = 45°$. The critical Reynolds number is an order of magnitude below the critical Re of plane channel flow. The results also pointed out that the critical Reynolds number increased with decrease in both the winglet height and the angle of attack. In ref [2], the numerical investigation focused on steady and self-sustained oscillatory flow situations in a periodic module or element using both the symmetric and periodic boundary conditions in the spanwise direction. They found a global heat transfer enhancement of 50% over plane channel value at $Re = 175$ and angle of attack of $\beta = 45°$ for steady flow. In another similar work of Fiebig et al. [15], eight different winglet configurations obtained from the combination of inline or staggered, symmetric or parallel and winglets on one or both walls were compared for flows in a periodic channel with built-in rectangular winglets. On the other hand, Lau et al. [16] carried out an experimental study for transition to a turbulent regime for the same geometric configurations.

Available literature reports limited research articles related to periodical array of longitudinal vortex generators, and mainly considers rectangular winglets as vortex generators. In order to have optimal heat exchanger configuration, one has to examine various parameters in terms of shape of the winglets, flow configurations, the effects of domain size, the ratio of height of vortex generators to channel height, the gap between the winglets, etc. Therefore, the present authors feel that work involving different types of vortex generators with different types of flow arrangements may add valuable input towards efficient compact heat exchanger design.

The aim of the present study is to carry out a numerical investigation on the performance of plate-fin heat exchangers with rows of winglets as vortex generators. In particular, a comparative study has been undertaken for two types of vortex generators, rectangular winglet pair (RWP) and delta winglet pair (DWP) with two types of flow configurations, common-flow-down (CFD) and common-flow-up (CFU). The periodic nature in the flow field allows for consideration of only one periodic element of the channel as the computational domain. Therefore, we compute periodically fully