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Enhanced heat transfer in a triangular ribbed channel with longitudinal vortex generators

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ABSTRACT

Effects of combined ribs and winglet type vortex generators (WVGs) on forced convection heat transfer and friction loss behaviors for turbulent airflow through a constant heat flux channel are experimentally investigated in the present work. The cross-section of the ribs placed inside the opposite channel walls to create a reverse flow is an isosceles triangle shape. Two rib arrangements, namely, in-line and staggered arrays, are introduced. Also, two pairs of the WVGs with various attack angles (α) of 60°, 45° and 30° are mounted on the test duct entrance to create a longitudinal vortex flow through the test channel. Measurements are carried out for a rectangular duct of aspect ratio, AR = 10 and height, H = 30 mm with a single rib height, e/H = 0.13 and rib pitch, P/H = 1.33. The flow rate is in terms of Reynolds numbers based on the inlet hydraulic diameter of the channel ranging from 5000 to 22,000. The experimental results show a significant effect of the presence of the rib turbulator and the WVGs on the heat transfer rate and friction loss over the smooth wall channel. The values of Nusselt number and friction factor for utilizing both the rib and the WVGs are found to be considerably higher than those for using the rib or the WVGs alone. The larger the attack angle value leads to higher heat transfer and friction loss than the lower one. The in-line rib together with the WVGs provides higher heat transfer and friction loss than the staggered one for similar operating conditions. In common with the WVGs, the in-line rib yields the highest increase in both the Nusselt number and the friction factor but the rib with staggered array shows better thermal performance than the others.

1. Introduction

The need of high-performance thermal systems in engineering applications has stimulated interest in finding ways to increase heat transfer rate in the systems. The conventional heat exchangers can be generally improved by means of various enhancement techniques with several types of enhanced surfaces. This is because the enhanced surfaces can create one or more combinations of the following conditions favorable for the increase in heat transfer rate with an undesirable rise of friction: (1) interruption of thermal boundary layer development and increase in turbulence intensity, (2) increase in heat transfer area, and (3) generating of swirling and/or secondary flows. So far, many investigations have been focused on passive heat transfer enhancement methods and the fluid flow. Reverse/swirl flow devices form an important group of the passive augmentation technique. The reverse flow, sometimes called "re-circulation flow", device or the turbulator is widely used in heat transfer engineering applications. The convection heat transfer along the duct wall can be improved significantly by introducing the reverse/re-circulation flow to increase the effective axial Reynolds number and decrease the cross-sectional area of flow, leading to an increase in the mean velocity and temperature gradient. The reverse flow cannot only induce the higher heat flux and momentum transfer due to the large effective driving potential force but also the higher pressure drop. The strength of reverse flow and the reattached position are the main interest in many heat transfer applications such as heat exchangers, combustion chambers, gas turbine blades, and electronic devices. For decades, rib turbulators have been widely applied in high-performance thermal systems for creating the strong reverse/re-circulation flow in the systems leading to higher heat transfer rate. The rib geometry, height, pitch and arrangement are key parameters that influence significantly on heat transfer behaviors in the channel.

Several studies have been carried out to investigate the effect of these parameters of ribs on heat transfer and friction loss for two opposite roughened surfaces. Han et al. [1] studied experimentally the heat transfer in a square channel with ribs on two walls for nine different rib configurations for P/e = 10 and e/H = 0.0625. They found that the angled ribs and 'V' ribs yield higher heat transfer enhancement than the continuous ribs and the heat transfer rate and the friction factor were highest for the 60° orientation amongst

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Nomenclature

A	convection heat transfer area of channel, m^2
AR	aspect ratio of channel (W/H)
C_p	specific heat capacity of air, J/kg K
D	hydraulic diameter, m
e	rib height, m
f	friction factor
H	channel height, m
h	average heat transfer coefficient, W/m^2 K
I	current, amp
k	thermal conductivity of air, W/m K
L	length of tested channel, m
$\dot{m}$	air mass flow rate, kg/s
Nu	Nusselt number (hD/k)
P	pitch (axial length of rib cycle), m
ΔP	pressure drop, Pa
Pr	Prandtl number
Re	Reynolds number (UD/ν)
Q	heat transfer, W
T	temperature, K
t	thickness of rib, m
U	mean velocity, m/s
V	voltage, volt
$\dot{V}$	volumetric flow rate, m^3/s
W	width of channel
WVGs	winglet type vortex generators

Greek letters

α	attack angle of WVGs, degree
ρ	density of air, kg/m^3
η	thermal enhancement factor
ν	kinematics viscosity, m^2/s

Subscripts

a	augmented
b	bulk
0	smooth channel
conv	convection
i	inlet
o	out
pp	pumping power
s	channel surface

the angled ribs. For heating either only one of the ribbed walls or both of them, or all four channel walls, Han et al. [2] also reported that the former two conditions resulted in an increase in the heat transfer with respect to the latter one. Han and Zhang [3] studied the heat transfer augmentation in a square channel with various broken ribs of $e/H = 0.0625$ and $P/e = 10$ on two channel walls. They found that 60° broken 'V' ribs provide higher heat transfer at about 4.5 times the smooth channel and perform better than the continuous ribs. By using a real time Laser Holographic Interferometry to measure the local as well as average heat transfer coefficient, Liou and Hwang [4,5] investigated experimentally the performance of square, triangular and semi-circular ribs and found that the square ribs give the best heat transfer performance among them. This is contrary to the experimental result of Ahn [6] indicated that the triangular rib performs better than the square one. Taslim et al. [7] examined the heat transfer behaviors in a ribbed square channel with three e/H ratios ($e/H = 0.083$, 0.125 and 0.167) and a fixed $P/e = 10$ using a liquid crystal technique. They reported that the average Nusselt number was increased with the rise in e/H ratio and the best e/H ratio was found to lie between 0.083 and 0.125.

The effect of rib arrangements placed at 60° with $e/H = 0.09$ and the rib pitch ratio of 1.0 on heat transfer in a channel with uniformly heating the four walls was experimentally investigated by Mochizuki et al. [8]. The measured data showed an asymmetry of the Nusselt number distribution caused by the secondary flows as already found by previous authors. Murata and Mochizuki [9] studied numerically the heat transfer distribution in a square channel with ribs placed at 60°, $e/H = 0.1$ and $P/e = 10$ using a large eddy simulation method and reported that the flow reattachment at the midpoint between ribs caused a significant increase in the local heat transfer. Chandra et al. [10] carried out measurements on heat transfer and pressure loss in a square channel with continuous ribs of $e/H = 0.0625$ and $P/e = 8$ on one, two, three and four walls. They found that the heat transfer increasing with the rise in the number of ribbed walls was decreased with increasing Reynolds number while the friction factor increased with both cases.

Tanda [11] examined the effect of transverse, angled ribs, discrete, angled discrete ribs, V-shaped, V-shaped broken and parallel broken ribs on heat transfer and friction and reported that 90° transverse ribs provided the lowest thermal performance while the 60° parallel broken ribs or 60° V-shaped broken ribs yielded a higher heat transfer augmentation than the 45° parallel broken ribs or 45° V-shaped broken ribs. Parallel angled discrete ribs were seen to be superior to parallel angled full ribs and its 60° discrete ribs performed the highest heat transfer. Promvonge and Thianpong [12] experimentally studied the thermal performance of wedge ribs pointing upstream and downstream, triangular and rectangular ribs with $e/H = 0.3$ and $P/e = 6.67$ mounted on the two opposite walls of a channel with AR = 15. They found that the in-line wedge rib pointing downstream performed the highest heat transfer but the best thermal performance is the staggered triangular rib. Thianpong et al. [13] again investigated the thermal behaviors of isosceles triangular ribs attached on the two opposite channel walls with AR = 10 and suggested the optimum thermal performance of the staggered ribs could be at about $e/H = 0.1$ and $P/H = 1.0$. Extensive literature reviews over hundred references on various rib turbulators were reported by Varun et al. [14] and Han et al. [15].

In general, the swirl/vortex flow generator is used in augmentative heat transfer in several engineering applications to enhance the rate of the heat and mass transfer equipment such as heat exchanger, vortex combustor, drying process, etc. The methods of generation of decaying swirl/vortex flow can be classified into three categories. The first is the tangential flow injection to induce a swirling fluid motion along the tube [16–19]. The second is the guide vanes swirl generator [20,21] classified into two types: the radial guide vane and the axial guide vane. The third is the winglet classified as delta, triangular and rectangular winglet types [22–29]. These winglets are designed to create longitudinal vortices that help to increase turbulence levels resulting in improved heat transfer performance, albeit with a minimal pressure loss penalty. The vortices generated are a result of the high pressure difference across the winglet leading to the introduction or exploitation of secondary flows, rather than the manipulation or alteration of the main flow. Heat transfer enhancement by winglet type vortex generators mounted at the leading edge of a flat plate was found to be about 50–60% improvement in average heat transfer over the surface of the plate [23,28]. To date, most winglets have been widely used to improve the thermal performance of fin and tube heat exchangers due to its merit of very low pres-