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Heat transfer enhancement of micro-scale backward-facing step channel by using turbulators

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A B S T R A C T

Laminar forced convection heat transfer and fluid flow of micro-scale backward-facing step (MBFS) with different types of longitudinal vortex generators (VGs) is numerical analyzed. The governing equations are discretized by finite volume method. Four basic types of VG which are rectangular and triangular wings and winglets pairs are attached to an unheated upper wall behind the stepped wall in order to enhance the thermal performance of MBFS. Three inclination angles of VGs are considered namely; 30°, 45°, and 60° with a wide range of water flow rate. The thermal and hydraulic performance of MBFS with VG is evaluated by *JF* factor in order not to show the enhancement in the heat transfer only, but the increase in the pressure drop as well. The results showed that the use of VG in MBFS increases the heat transfer and pressure drop simultaneously. The best heat transfer enhancement with a little increase in the pressure drop is observed in the case of rectangular wing VG at an attack angle of 60° and Reynolds number of 180 whereas $(Nu_{VG}/Nu_{o}) = 1.221$. *JF* factor increases with Reynolds number until 180 and then a steep decrease has been monitored.

1. Introduction

The flow over a step is a phenomenon of separation of the fluid from the channel walls and subsequently reattachment due to the sudden expansion in a flow channel which occurs in many engineering applications where cooling or heating is required. The step flow has wide engineering applications such as cooling of electronic equipment, cooling of equipment of nuclear energy system, flow in valves, combustion chambers, cooling turbine blades and heat exchangers as well as in external flows such as aircraft, buildings and etc. In many applications, the flow separation is undesirable and causes an additional pressure drop. While, in other cases, the flow separation may be desired due to mixing in the heat and mass transfer in the separation and reattachment flow region which leads consequently to enhance the thermal performance of the system [1].

Several studies have been achieved to examine the separation and reattachment of the flow particularly the flow over a backward facing step. This topic has received the concern of many researchers numerically and experimentally. Chao et al. [2] and Kumar and Dhiman [3] demonstrated analytically and numerically, respectively that the interruption in the fluid caused by a cylinder positioned behind the step at different heights reduced the intersection angle between the velocity vector and the temperature gradient and consequently higher heat transfer rate obtained. They observed an enhancement in the peak Nusselt number up to 155% compared to the case without cylinder and the peak and average Nusselt number increased monotonically with *Re* number. Nie et al. [4] inferred that numerical Nusselt number at the stepped wall was improved due to use of a baffle mounted onto the upper wall of BFS. They stated that the maximum Nusselt number on the stepped wall was increased close to the sidewall. It was further moved toward the exit direction and the friction coefficient at the stepped wall decreased as the baffle position moved far away from the step.

Nie and Armaly [5] showed numerically that the Nusselt number distribution increased as the step height increased. The higher Nusselt number values, in the spanwise distribution, and friction coefficient on the stepped wall were observed at smaller reattachment length. Louda et al. [6] revealed that the inlet channel, which was at least five-step heights long, the location of the exit boundary and the outflow boundary condition affect the accuracy of the

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Nomenclature

A	area (m^2)
b	vortex thickness (m)
c_p	specific heat capacity (kJ/kg·K)
d	distance between the tips of the winglet pairs (m)
D_h	hydraulic diameter (m)
DW	Delta wing
DWP	delta-winglet pair
$e\%$	percentage error
f	friction factor, dimensionless
h	convective heat transfer coefficient ($W/m^2·K$)
H	channel height (m)
j	Colburn factor, dimensionless ($j = Nu/Re\ Pr^{(1/3)}$)
JF	performance evaluation criterion, dimensionless ($JF = (j_{VG}/j_o)/(f_{VG}/f_o)^{(1/3)}$)
k	thermal conductivity (W/m·K)
l	length of vortex generator (m)
L	length of the channel (m)
MBFS	Micro-scale backward-facing step
Nu	Nusselt number, dimensionless ($Nu = h\ D_h/k$)
P	perimeter
Pr	Prandtl number, dimensionless ($Pr = c_p\ \mu/k$)
Re	Reynolds number ($Re = u\ D_h/\nu$)
RW	rectangular wing
RWP	rectangular winglet pair
S	step height (m)
t	thickness of the vortex generator (m)
u, v, w	velocity components in x, y, z direction, respectively (m/s)
U, V, W	dimensionless fluid velocity in x, y, and z-direction, respectively
VG	vortex generator
W	channel width (m)
X, Y, Z	dimensionless Cartesian coordinates
Z	axial length of the channel flow (m)
ΔP	differential pressure (pa)

Greek symbols

μ	dynamic viscosity (kg/m s)
α	attack angle of vortex generator (degree)
θ	dimensionless temperature, dimensionless
ρ	density (kg/m^3)

Subscripts

c	cross-section
e	after the step
HW	heated wall
i	before the step
in	inlet
m	mean
o	initial
out	outlet
sw	spanwise
v	distance from the step wall to the leading tip of the vortex

CFD results. They highlighted that the size of the recirculating regions grew almost linearly with the flow rate.

Kanna et al. [7] demonstrated numerically that the thickness of the thermal boundary layer was reduced when Prandtl number (Pr) was increased and the temperature of the solid wall was reduced.

Lin et al. [8], Abu-Mulaweh et al. [9–12], Abu-Nada et al. [13–16], Nie and Armaly [17] and Tylli et al. [18] investigated numerically and experimentally the separation and reattachment of the flow particularly the flow over a backward facing step. Although it was a very simple geometry, the flow over a backward facing step demonstrated the most important flow structures concerning with the separation and reattached flow [19]. It should be noticed that a few studies have been focused on the heat transfer and fluid flow characteristics over micro-scale backward-facing step such as the investigation of Hsieh et al. [20] and Xue et al. [21,22]. Mohammed et al. [23] reviewed many previous investigations in this research area and they concluded that the Nusselt number increased as the parameter such as step height, fluid velocity, Prandtl number and aspect ratio increased, and vice versa for the expansion ratio. Nevertheless, they did not cover the enhancement of heat transfer in BFS using obstacles, protrusions or any turbulators. Al-aswadi et al. [24] studied numerically the plain macro-scale BFS while Kherbeet et al. [25–29] studied experimentally and numerically the forced and mixed laminar convection heat transfer and nanofluid flow characteristics over a backward-facing step (MBFS) and forward-facing step (MFFS) at micro-scale. They revealed that the heat removal with nanofluids was outperformed the conventional fluids and the thermal enhancing was dependent on the volume fraction, nanoparticle diameters, and nanofluid type. This enhancement was accompanied by a slight increase in the frictional losses. They monitored the higher Nusselt number and greater friction factor through the utilizing of MFFS in comparison with MBFS. Higher step wall showed higher heat transfer rate and there was no effect for the channel inclination angle on the hydrothermal structure. In general, Kherbeet et al. [30] carried out a survey on the hydrothermal performance of backward-facing step and forward-facing step at micro-scale focusing on the effect of geometric parameters, the channel inclination angle, and the flow regime. From their overview, there is no investigation on using the longitudinal vortex generators as that considered in this study in channels such MBFS.

One of many different methods used to enhance the heat transfer rate in the thermal systems is by using a longitudinal vortex generator (VG). Vortex generators are small protrusions used to generate secondary flow or vortices by swirling the flow. Because of the pressure difference between the forward and backward of vortex generators, the flow along the side edges separates and generates longitudinal vortices. Rectangular wing (RW), delta wing (DW), rectangular winglet pair (RWP) and delta winglet pair (DWP) are the main types of the vortex generators first considered for heat transfer augmentation by Johnson and Joubert, 1969 [31].

Many researchers investigated the effect of the basic types of vortex generators in a macro-scale plain macro-scale rectangular channel (without stepped wall) since a few decades ago. Zhu et al. [32] and Tiggelbeck et al. [33] revealed that the VGs could enhance the heat transfer significantly with low increase in the pressure drop. Biswas et al. [34,35] inferred that the use of winglets pairs was effective enhancement technique. Greater than 34% enhancement in Nusselt number was obtained. Hiravennavar et al. [36] reported that the heat transfer augmented around 33% was registered when single winglet was implemented and more than 67% when a winglet pair was used. Wang et al. [37] revealed that the heat transfer enhancement by using RWP attached on upper and bottom walls of a narrow rectangular channel was better than those on one side. Min et al. [38,39] reported that the chamfered RWP has good heat transfer and low increase in the friction factors. Generally, they highlighted that the heat transfer rate