International Journal of Heat and Mass Transfer 68 (2014) 554–566

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

The effect of step height of microscale backward-facing step on mixed convection nanofluid flow and heat transfer characteristics

A.Sh. Kherbeet [a,*], H.A. Mohammed [b,*], K.M. Munisamy [a], B.H. Salman [a]

[a] Mechanical Engineering Department, College of Engineering, Universiti Tenaga Nasional, Jalan IKRAM-UNITEN, 43000 Kajang, Selangor, Malaysia
[b] Department of Thermofluids, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia

ARTICLE INFO

Article history:
Received 29 July 2013
Received in revised form 18 September 2013
Accepted 19 September 2013
Available online 19 October 2013

Keywords:
Mixed convection
Microscale backward-facing step
Heat transfer
Nanofluids

ABSTRACT

Simulation of laminar mixed convective flow over a 3-D horizontal microscale backward-Facing step (MBFS) is presented to explore the effect of step height on the flow and heat transfer characteristics. The momentum and energy equations were discretized by means of a finite volume method (FVM). The SIMPLE algorithm scheme was used to link the pressure and velocity fields in the entire domain. Three values of step height were considered $S = 350$ μm, $S = 450$ μm and $S = 550$ μm. EG-SiO_2 nanofluid was considered as the working fluid with 25 nm nanoparticle diameter, 0.04 volume fraction. The results revealed that the Nusselt number and skin friction coefficient increase with the increase of the step height. The Reynolds number and pressure drop were found to decrease with the increase of the step height.

1. Introduction

The separation of the flow and following reattachment which occur due to the sudden expansion in flow geometry, such as a backward-facing step (BFS), happens in many engineering applications where cooling or heating is required [1]. This phenomenon appears in many applications such as combustors, gas turbine engines, as well as in external flows such as aircraft, buildings and many other devices of heat transfer. The separation of the flow and the reattachment represent the key of determining the flow structure and significantly affect the heat transfer mechanism. An immense deal of mixing low and high fluid energy occurs in the regions of the separation and reattachment [2]. Thus, there were many studies focused on the flow separation and reattachment in the past decades, and the BFS geometry received much attention [3,4]. Flow over a BFS with heat transfer was conducted by other researchers [5,6]. The majority of the published researches deal with the isothermal flow in two dimensional geometries, and there are little studies discussed the heat transfer and the effect of the step in three dimensional flow cases. Eyad Abu-Nada [7] presented numerical study of entropy generation over a 2D backward facing step with various expansion ratios. The expansion ratios (ER = S/H) were chosen as: 1/4, 1/3, 1/2, 2/3, and 3/4. The results showed that as the Reynolds number increases, the value of total entropy generation number (Ns) increases. For lower values of Reynolds number, the value of Ns decreases as the expansion ratio (ER) increases. However, for higher values of Reynolds number, the value of Ns decreases as expansion ratio increases but at lower rates as compared to smaller Reynolds number. Nie and Armaly [8] presents a simulation of three-dimensional laminar forced flow adjacent to backward-facing step in rectangular duct to study the effects of step height on the flow and heat transfer characteristics. The results demonstrated that the primary reattachment length increases with increasing step height. The maximum reattachment length occurs at the sidewall and not at the center of duct. The effects of step height on the Nusselt number on the stepped wall presented and the results showed as the step height increases the maximum Nusselt number increases. Biswas et al. [9] studied the laminar fluid flow behavior over a three dimensional backward-facing step with various expansion ratios. The study revealed that the formation of wall jets at the side wall within the separating shear layer, formed by the spanwise of the velocity moves towards the symmetry channel plane. The flow in 3-D microscale backward-facing step was investigated by Hsieh et al. [10]. In this study, the Direct Simulation Monte Carlo method was utilized (DSMC). The comparisons of the 3-D results with those of the 2-D simplification showed that the side walls in the 3-D structure significantly affect the flow characteristics and heat transfer. Moreover, the stability of the vortex behind the step could be affected by the side walls of a 3-D backward-facing step channel. It is found that the flow separation, recirculation, and reattachment will disappear when the cross-section aspect ratio is less than 1. Bao and Lin [11] used the DSMC method to study the transition regime in the microscale

* Corresponding authors. Tel.: +60 173895660; fax: +60 7 55 66159.
E-mail addresses: akeel.fa7@gmail.com (A.Sh. Kherbeet), Hussein.dash@yahoo.com (H.A. Mohammed).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.050

Nomenclature

C_p	specific heat, J/kg K
D_h	hydraulic diameter, 2h, m
dp	Nanoparticles diameter, nm
g	gravitational acceleration, m/s^2
Gr	Grashof number, $g\beta q_w s^4/(kv^2)$
H	total channel height, m
h	convective heat transfer coefficient, W/m^2 K
h	inlet channel height, m
k	thermal conductivity, W/m K
Nu	Nusselt number, $h.D_h/k$
P	dimensionless pressure, $P = (p + \rho gx)/\rho u_\infty^2$
Pr	Prandtl number, υ_f/α_f
q	heat flux, W/m^2
Re	Reynolds number, $\rho u_\infty D_h/\mu_f$
s	step height, m
T	fluid temperature, K
T_∞	temperature at the inlet or top wall, K
T_w	temperature of the heated wall, K
u	velocity component in x-direction, m/s
u_i	local inlet velocity, m/s
u_∞	average velocity for inlet flow, m/s
U	dimensionless streamwise velocity component, u/u_∞
v	velocity component in y-direction, m/s
V	dimensionless transverse velocity component, v/u_∞
w	velocity component in z-direction, m/s
W	dimensionless spanwise velocity component, w/u_∞
X	dimensionless streamwise coordinate, x/s
Xi	upstream length, μm
Xe	Streamwise coordinate as measured from the step, μm
Xr	reattachment length, μm

Greek symbols

φ	nanoparticles concentration
α_f	thermal diffusion of fluid, N s/m^2
β	thermal expansion coefficient, 1/K
θ	dimensionless temperature
ρ_f	density of fluid, kg/m^3
ρ_s	density of solid, kg/m^3
v_f	kinematic viscosity of fluid, m^2/s
μ	dynamic viscosity, N s/m^2

Subscripts

o	outlet
eff	effective
f	fluid
s	solid
nf	nanofluid
w	wall
∞	inlet condition

backward-facing step. They found that at Knudsen number = 0.136, the streamwise velocity is always positive which indicated that there is no reversed flow existing after the step. The adverse pressure gradient behind the step was too small to stagnate the flow. Furthermore, the mass flow rate increases with the increase of pressure ratio and the relation is not linear as in traditional flow. However, it was found that the gradient increases with the pressure ratio.

One of the techniques utilized to improve the heat transfer rate is by utilizing nanofluids. Nanofluids are conventional fluids in which particles of nanometer-size are suspended [12]. The recent research showed that the solid nanoparticle which has high thermal conductivity when it suspended in the conventional fluids could intensify the effective thermal conductivity and convective heat transfer coefficient of these fluids [13–16]. These solid nanoparticles can be metallic or nonmetallic such as SiO_2, Al_2O_3, TiO_2, CuO, Cu and ZnO [17].

Several researchers have investigated the enhancement of the thermal conductivity by utilizing the nanofluids, for instance Kim [18], Murshed et al. [19], Timofeeva et al. [20], Khanafer et al. [21], Yu and Choi [22] Xue and Xu [23], Xu et al. [24], Li et al. [25], Xie et al. [26], Minsta et al. [27], Taher and Adam [28], Salman et al. [29] and Mohammed et al. [30] . The first investigation of the thermal behavior and nanofluid flow characteristics over backward-facing step was demonstrated by Abu-Nada [31]. In this study, five types of nanoparticles were utilized which are CuO, Al_2O_3, Ag, Cu and TiO_2. He reported that Nusselt number can be enhanced by increasing the nanoparticles volume fraction. However, the high value of the Nusselt number inside the recirculation zone is independent of Reynolds number value, while it strongly depends on the thermophysical properties of the nanoparticles. Mohammed et al. [32,33] studied the effect of nanofluids on mixed convective heat transfer over a vertical and horizontal backward-facing step. In this investigation, eight types of nanoparticles were utilized with 5% of nanoparticles volume fraction. They illustrated that the nanofluids with secondary recirculation regions found to have a lower Nusselt number. However, the nanofluids without secondary recirculation region have a higher value of Nusselt number and it increases with the decrement value of Prandtl number. Furthermore, the diamond nanofluid has the highest Nusselt number in the primary recirculation region, while downstream the primary recirculation region the SiO_2 nanofluid has the highest value. Al-aswadi et al. [34] investigated numerically the laminar forced convection flow over a BFS in a duct using different nanofluids. They reported that the recirculation size and reattachment length increase as Reynolds number increases. Nanofluids with low density nanoparticles such as SiO_2 have a higher velocity than those with high density nanoparticles such as Au. Recently Kherbeet et al. [35] presented a numerical investigation of the nanofluid effect of laminar flow on a mixed convection heat transfer over 2D microscale backward-facing step. The nanoparticle size was in the range of 25 nm $\leqslant$ dp $\leqslant$ 70 nm. The expansion ration was of 2. Four types of nanoparticles were utilized which are Al_2O_3, CuO, SiO_2 and ZnO, with a volume fraction of the range 1–4%. The results revealed that there is no recirculation region observed behind the step for all the mentioned nanofluids. The fluids with SiO_2 nanoparticles showed to have the highest Nusselt number. In addition, the results showed Nusselt number increases with the increment of the volume faction of the nanoparticles in the base fluid.

Mohammed et al. [36] presented a numerical simulations of two dimensional laminar combined convection flows using nanofluids over forward facing step with a blockage are analyzed. In this study, different types of nanofluids (Al_2O_3, SiO_2, CuO and ZnO), different nanoparticles diameters in the range of 25 nm-80 nm and different volume fractions in the range of 1–4%, were used. The effects of different shapes of blockage (Circular, Square and Triangular) were investigated. The results show that the circular blockage produced the highest Nusselt number followed by square blockage and triangular blockage. The results also indicated that SiO_2 nanofluid has the highest Nusselt number. However, the Nusselt number decreases as the nanoparticles diameter increases and increased as the volume fraction and Reynolds number increase. Heshmati et al. [37] examined numerically a forced convective heat transfer in channel over