International Journal of Heat and Mass Transfer 79 (2014) 858–867

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental and numerical study of nanofluid flow and heat transfer over microscale backward-facing step

A.Sh. Kherbeet [a,*], H.A. Mohammed [b], B.H. Salman [c], Hamdi E. Ahmed [d], Omer A. Alawi [b]

[a] *Department of Mechanical Engineering, KBU International College, 47800 Petaling Jaya, Selangor, Malaysia*
[b] *Department of Thermofluids, Faculty of Mechanical Engineering, Universiti Teknologi Malaysia, 81310 UTM Skudai, Johor Bahru, Malaysia*
[c] *FABE, Limkokwing University of Creative Technology, Jalan Teknokrat 1/1, 63000 Cyberjaya, Selangor, Malaysia*
[d] *Department of Mechanical Engineering, University of Anbar, 31001 Anbar, Iraq*

ARTICLE INFO

Article history:
Received 19 April 2014
Received in revised form 26 August 2014
Accepted 27 August 2014
Available online 19 September 2014

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

ABSTRACT

Experimental and numerical studies were presented to reveal the flow and heat transfer characteristics of nanofluid laminar flow over the microscale backward-facing step (MBFS). The duct inlet and the step height were 400 μm and 600 μm respectively. All the walls considered adiabatic except the downstream wall is heated by uniform heat flux. The experiment is conducted at the Reynolds number range from 280 to 470. The distilled water is considered as a base fluid with two types of nanoparticles SiO_2 and Al_2O_3 immersed in the base fluid. The particle diameter is 30 nm and the range of nanoparticles volume fraction in the base fluid varied from 0 to 0.01. The measurement results revealed that the water–SiO_2 nanofluid has the highest Nusselt number. It is found also that the Nusselt number increase with increases volume fraction. The water–SiO_2 nanofluid with higher volume fraction has the highest Nusselt number. The friction factor of water–Al_2O_3 was higher than of water–SiO_2 mixture. The numerical results were in good agreement with the measurement results.

1. Introduction

The existence of flow separation and following reattachment which occurs due to the sudden expansion in flow geometry, such as a backward-facing step (BFS), play an important role in many engineering applications where cooling or heating is required [1]. These applications of heat transfer appear in, such as combustors, as well as in external flows such as aircraft, gas turbine engines, buildings, chemical processes and many other devices of heat transfer. The separation and the reattachment of the flow represent the key of determining the flow structure and significantly affect the heat transfer mechanism. A significant amount of mixing low and high fluid energy occurs in the reattachment region of these devices [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 discussed the isothermal flow in two dimensional geometry, and little studies discussed the heat transfer and the three dimensional flow cases. Abu-Nada [7] presented a 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. Nie and Armaly [8] present a numerical study of three-dimensional laminar forced flow adjacent to backward-facing step placed in rectangular duct. The results demonstrated that the maximum reattachment length occurs at the sidewall and not at the center of the duct and as the step height increases the maximum Nusselt number increases. Biswas et al. [9] study 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. Armaly and Nie [10] presented an experimental study of measuring the velocity in three-dimensional laminar separated airflow adjacent to a backward-facing step by using two-component laser Doppler velocimeter. Saldana and Anand [11] studied numerically the forced convective flow over a 3-D backward-facing step. The results revealed that the spanwise average Nusselt number distributions present higher values at higher Reynolds numbers. The velocity profiles revealed that for Reynolds

---

* Corresponding author. Tel.: +60 173895660; fax: +60 7 55 66159.
E-mail address: akeel.fa7@gmail.com (A.Sh. Kherbeet).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.08.074
0017-9310/© 2014 Elsevier Ltd. All rights reserved.

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, $g\beta q_w s^4/(k\nu^2)$
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, ν_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_∞
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
ν_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

number greater than 343 the flow does not reach fully developed conditions at the exit of the channel. However, for all cases considered in their study the flow never reached fully thermally flow development condition. The flow in 3-D microscale backward-facing step was investigated by Hsieh et al. [12]. In this study, the Direct Simulation Monte Carlo method (DSMC) utilized. The comparison results of the 3-D 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 [13] used the DSMC method to study the transition regime in the microscale 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 [14]. The recent researches 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 [15–18]. These solid nanoparticles can be metallic or nonmetallic such as SiO_2, Al_2O_3, TiO_2, CuO, Cu and ZnO [19]. Several researchers have investigated the enhancement of the thermal conductivity by utilizing the nanofluids, and they found that the using of nanofluids could enhance the heat transfer [20–32]. The first investigation of the thermal behavior and nanofluid flow characteristics over backward-facing step was demonstrated by Abu-Nada [33]. In this study, five types of nanoparticles were utilized which are CuO, Al_2O_3, Ag, Cu and TiO_2. He reported that the 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. [34,35] 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 the nanoparticles volume fraction. They illustrated that the nanofluids with secondary recirculation regions found to have a lower Nusselt 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. Al-Aswadi et al. [36] 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 the Reynolds number increases. Nanofluids with low dense nanoparticles such as SiO_2 have a higher velocity than those with high dense nanoparticles such as Au. Very recently Kherbeet et al. [37] 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 $25\ \text{nm} \leqslant dp \leqslant 70\ \text{nm}$. 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 fraction of the nanoparticles in the base fluid.

Heshmati et al. [38] examined numerically a forced convective heat transfer in channel over a backward facing step having a baffle on the top wall. In this study four different geometries with different expansion ratios and different type of baffles were investigated. The study clearly showed that the geometry with expansion ratio 2 and solid baffle has the highest Nusselt number compared to other geometries. Kherbeet et al. [39] investigated a numerically the laminar mixed convection flow of nanofluids over a 3-D horizontal microscale forward-facing step (MFFS) using a finite volume