International Communications in Heat and Mass Transfer 78 (2016) 145–154

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Mixed convection nanofluid flow over microscale forward-facing step — Effect of inclination and step heights☆

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ARTICLE INFO

Available online 21 September 2016

Keywords:
Mixed convection
Microscale forward-facing step
Heat transfer enhancement
Nanofluids
Nanoparticle
Base fluid

ABSTRACT

A numerical study of nanofluid flow and heat transfer of laminar mixed convection flow over a three-dimensional, horizontal microscale forward-facing step (MFFS) is reported. The effects of different step heights and the duct inclination angle on the heat transfer and fluid flow are discussed in this study. The straight and downstream walls were heated to a constant temperature and uniform heat flux respectively. The numerical results were carried out for step heights of 350 μm, 450 μm, 550 μm and 650 μm. Different inclination angles were considered to determine their effects on the flow and heat transfer. Ethylene glycol-SiO_2 nanofluid is considered with a 25 nm particle diameter and 4% volume fraction. The results reveal that the Nusselt increases as the step heights increase. Additionally, no significant effect of the duct inclination angle is found on the heat transfer rate and the fluid flow.

1. Introduction

The separation and reattachment flow region in the microscale forward-facing step (MFFS) plays an important role in the heat transfer performance. The flow separation and the subsequent reattachment are carried out by sudden compression in the geometry of the flow such as the forward-facing step (FFS). The local heat transfer has a large variation within the separation flow region and remarkable augmentation in heat transfer yields in the reattachment region. Thus, it is essential to understand the basic mechanism of heat transfer in thermal engineering applications in such flows, where cooling or heating is required. These applications could be required in energy system equipment, cooling systems for electronic equipment, combustion chambers, cooling passages for turbine blades, high performance heat exchangers and chemical processes. Remarkable mixing of high and low energy fluid takes place in the reattachment region within these devices, and subsequently significant effects occur to their heat transfer performance. In the backward-facing step (BFS), owing to it having the simplest design, a large number of studies have been conducted in relation to this geometry. Conversely, only a few studies have discussed the flow over the FFS. This may be because the flow separation takes place at the edge of the step in the case of BFS geometry, causing a recirculation region behind the step position. However, when the flow passes over the FFS geometry one or more recirculation regions will be developed. The number of recirculation regions depends on the thickness of the momentum boundary layer at the step and the value of the flow velocity [1]. The existence of more than one recirculation region makes the FFS geometry more complicated compared to the BFS, with a very limited available data about the flow over a FFS.

The effect of the step height (SH) on the flow over the BFS geometry in natural, mixed, and forced convection heat transfer has been examined extensively by former investigators such as Abu-Nada [2] and Nie and Armaly [3] and others. However, the effect of SH on the flow over a FFS has been discussed in just one study presented by Abu-Mulaweh [4] to the best knowledge of the authors. In this study, the measurements of heat transfer and fluid flow of turbulent mixed convection boundary-layer air flow over an isothermal two-dimensional, vertical FFS is presented. The experimental investigation was carried out in an existing low turbulence, open circuit tunnel that was oriented vertically. Three values of SHs were utilized to study their effects on the hydrothermal performance, which were 0 mm, 11 mm and 22 mm. The flat plate and both step geometries were supported in the test section of the tunnel and spanned its entire width of 85.1 cm. The upstream and downstream lengths were

☆ Communicated by W.J. Minkowycz.
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http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.08.016

Nomenclature

C_p	specific heat, J/kg.K
D_h	hydraulic diameter, 2 h, 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, $W/m^2 \cdot K$
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, v_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	channel width, μm
X	dimensionless streamwise coordinate, x/s
x,y,z	streamwise, transverse and spanwise coordinates, μm
Xi	upstream length, μm
Xe	streamwise coordinate as measured from the step, μm
Xr	reattachment length, μm
Y	dimensionless spanwise coordinate, y/s
Z	dimensionless transverse coordinate, z/s

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

274.3 cm and 81.3 cm respectively. Both the upstream and the downstream walls and the step itself were heated to a constant and uniform temperature. The front edge of the upstream plate was chamfered to ensure a proper development of the boundary layer flow. The results clearly indicated that the introduction of the FFS significantly affects the flow characteristics in the recirculation region. The largest magnitude of maximum mean transverse velocity increases with the SH increase. The magnitude of the negative transverse velocity component in the flow region near the heated downstream wall decreases as the streamwise distance increases downstream from the step. The results showed that the effect of the FFS somewhat diminishes as the streamwise distance increases downstream from the step. The values of turbulent intensities fluctuations at a streamwise location increase to its maximum value with the increases of distance from the heated wall, then decrease as the distance from the heated wall continues to increase, reaching to its minimum value at the edge of the boundary-layer. The results showed that, the local Nusselt number starts with its minimum value at the step edge and increases to its maximum value at the reattachment region. The magnitude of the local Nusselt number decreases as the distance continues to increase in the streamwise direction. The measured local Nusselt number downstream of the FFS increases with the increasing SH.

One technique of heat transfer enhancement is by utilizing nanofluids. These are fluids in which nanometer-size particles are suspended in conventional heat transfer base fluids [5]. Past studies have shown that nanofluids exhibit enhanced thermal properties, such as higher thermal conductivity and convective heat transfer coefficients compared to the base fluid [6–9]. The nanoparticles are either metallic or nonmetallic materials such as Al_2O_3, SiO_2, Cu, CuO, ZnO and TiO_2 [10]. Several researchers have investigated the effect of nanofluids on the thermal conductivity enhancement [11–29].

The first investigation of the thermal behavior and nanofluid flow characteristics over the BFS was presented by Abu-Nada [30]. He reported that by increasing the nanoparticles volume fraction the Nusselt number can be enhanced. Mohammed et al. [31,32] studied the effect of nanofluids on mixed convective heat transfer over a vertical and horizontal BFS. Their results showed that the SiO_2 nanofluid has the highest primary recirculation region and the diamond nanofluid has the highest Nusselt number in the primary recirculation region. More recently Kherbeet et al. [33] presented a numerical investigation of the nanofluid effect of laminar flow on a mixed convection heat transfer over a two-dimensional microscale backward facing step (MBFS). It was revealed that the fluids with SiO_2 nanoparticles were shown to have the highest Nusselt number. Moreover, increases in the nanoparticles' volume fraction increased the Nusselt number. As a continuous work, Kherbeet et al. [34] investigated the effect of SH of MBSF on the heat transfer and nanofluid flow characteristics. They outlined that the Nusselt number and skin friction coefficient increased with increasing the SH, while Reynolds number and pressure drop decreased. In addition, Kherbeet et al., [35] examined different types of nanofluids with different volume fractions and particles diameters in the MBFS. They displayed that silica oxide nanofluid provided the highest heat transfer rate, which increased with increasing nanoparticles concentrations and decreasing nanoparticles diameter. Besides, the static pressure and the wall shear stress increased with increasing particle concentration and decreasing particles diameter. In addition, they did not observed any effect for the nanoparticle volume factions, materials and diameters on the skin friction coefficient.

From the above literature review, it is clearly shown that the effect of SH on mixed convection heat transfer and nanofluid flow over a three-dimensional MFFS has not received any attention yet which motivated the present study. Moreover, there is no existing work discussing the effect of the inclination of MFFS on a mixed convection nanofluid flow. Therefore, the present study focuses on laminar mixed convection nanofluid flow over a 3-D MFFS having several values of SHs with different inclination angles with the horizon. The results of interest, including velocity distribution and skin friction coefficient, wall shear stress, pressure drop and Nusselt number are depicted to illustrate the effect of SH and the inclination angle on these parameters.

2. Channel flow system and implementing equations

2.1. Physical model and assumption

The schematic diagram of the adopted geometry and the flow configuration used in this study is shown in Fig. 1. Four values of SH were chosen to study the effect of the step, these being 350 μm, 450 μm,