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

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ABSTRACT

Experimental and numerical investigations are presented to illustrate the nanofluid flow and heat transfer characteristics over microscale forward-facing step (MFFS). The duct inlet and the step height were 400 μm and 600 μm respectively. All the walls are considered adiabatic except the downstream wall was exposed to a uniform heat flux boundary condition. The distilled water was utilized as a base fluid with two types of nanoparticles Al_2O_3 and SiO_2 suspended in the base fluid. The nanoparticle volume fraction range was from 0 to 0.01 with an average nanoparticle diameter of 30 nm. The experiments were conducted at a Reynolds number range from 280 to 480. The experimental and numerical results revealed that the water–SiO_2 nanofluid has the highest Nusselt number, and the Nusselt number increases with the increase of volume fraction. The average friction factor of water–Al_2O_3 was less than of water–SiO_2 mixture and pure water. The experimental results showed 30.6% enhancement in the average Nusselt number using water–SiO_2 nanofluid at 1% volume fraction. The numerical results were in a good agreement with the experimental results.

1. Introduction

The separation in the fluid flow can be generated from a sudden change in flow geometry. The forward facing step (FFS) plays an important role in the design of many engineering applications where heating or cooling is required. These applications are required in cooling systems for electronic equipment, combustion chambers, cooling passages for turbine blades, energy system equipment and high performance heat exchangers. The flow separation and the fluid impact in the reattachment region significantly affect the heat transfer in these devices because of the mixing of high and low fluid energy. When the flow passes over the forward-facing step design, there are one or more recirculation regions being developed adjacent to the step. This condition depends on the Reynolds number magnitude and the thickness of the momentum boundary layer at the step [1]. Due to this fact, the FFS geometry is more complicated to investigate than the backward-facing step (BFS), in which only one separation region is developed behind the step.

Abu-Mulaweh et al. [2,3] presented study of laminar mixed convection over 2D forward facing step to examine the buoyancy-assisting property in the horizontal and vertical directions, respectively. In both studies, the wall downstream of the step and the step were heated and maintained at a uniform temperature, while the upstream wall was kept adiabatic. It was found that the step height and inlet velocity significantly affect the size of the recirculation regions and the local heat transfer rate downstream of the step. Moreover, the buoyancy force arising from the heating of the downstream wall has negligible effects on these parameters because the buoyancy force has no streamwise component. However, both the recirculation region and the heat transfer rate from the downstream wall increase with increasing the Reynolds number. In the case of laminar mixed convection flow over a vertical forward-facing step [4], the results showed that the opposing buoyancy force significantly affects the Nusselt number and the recirculation flow region downstream of the step. It was found that the recirculation region downstream of the step decreases with the increase of the downstream wall heating.

Stuer et al. [5] presented study on the separation ahead of a forward-facing step at laminar flow conditions by using the hydrogen bubble technique for visualization and particle tracking velocimetry (PTV) for evaluating the 3-D velocity field in an Eulerian representation in the vicinity of the step. The results have demonstrated that the fluid inside the

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Nomenclature

C_p	specific heat, J/kg K
D_h	hydraulic diameter, 2 h, m
dp	nanoparticle 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, 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_∞
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	nanoparticle 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

separation bubble is transported parallel to the step and released in streaks over the step. The transverse movement of the streaks becomes faster with increasing Reynolds number. The results show that there is no effect of the side-walls on the unsteady behavior. However, the separation bubble travels parallel to the step and another bigger one moves into the observation area. The results indicated that the new vortex generated on the step is much larger than the transported vortex. Barbosa-saldana and Anand [6] presented a numerical study using finite volume method in order to simulate the laminar flow over 3D horizontal FFS. The results revealed that the flow is separated and reattached in two different regions, one is upstream and adjacent to the step and the second is downstream and adjacent to the step. Furthermore, both of these recirculation zones increase in their size as the Reynolds number increases.

One of the utilized techniques to enhance the heat transfer rate is using nanofluids. Nanofluids are fluids in which nanometer-sized particles are suspended in conventional heat transfer base fluids [7]. Most of the recent studies have shown that solid nanoparticles with high thermal conductivity enhance the convective heat transfer coefficient and the effective thermal conductivity of the base fluid when suspended in the base fluid [8–11]. These nanoparticles can be metallic or nonmetallic, such as Al_2O_3, SiO_2, Cu, CuO, ZnO and TiO_2 [12]. Many researchers have presented investigations of the nanofluid roles on heat transfer enhancement and their effects on the fluid flow characteristics [13–25].

The first investigation of the thermal behavior and nanofluid flow characteristics over backward-facing step was demonstrated by Abu-Nada [26]. He reported that the Nusselt number can be enhanced by increasing the nanoparticle volume fraction. Mohammed et al. [27,28] studied the effect of nanofluids on mixed convective heat transfer over a vertical and horizontal backward-facing step. They illustrated that the diamond nanofluid has the highest Nusselt number in the primary recirculation region, whereas the SiO_2 nanofluid has the highest Nusselt number downstream of the primary recirculation region. Al-aswadi et al. [29] 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 dense nanoparticles such as SiO_2 have a higher velocity than those with high dense nanoparticles such as Au. Kherbeet et al. [30] 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 ≤ dp ≤ 70 nm. Four types of nanoparticles were utilized (Al_2O_3, CuO, SiO_2 and ZnO), with a volume fraction in the range of 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 have the highest Nusselt number among other nanoparticles. In addition, the results show that the Nusselt number increases with the increment of nanoparticle volume fraction.

Very recently Kherbeet et al. [31] investigated numerically the laminar mixed convection flow of nanofluids over a 3D horizontal microscale forward-facing step (MFFS) using a finite volume method. Various nanoparticle materials, such as SiO_2, Al_2O_3, CuO, and ZnO, were dispersed in ethylene glycol as a base fluid with volume fractions in the range of 0 and 0.04. The duct has a step height of 650 μm. The results revealed that the SiO_2 nanofluid had the highest Nusselt number, which increased with decreasing nanoparticle material density, increasing volume fraction and decreasing nanoparticles diameter. Kherbeet et al. [32] presented numerical study of mixed convective flow over 3D horizontal microscale backward-facing step (MBFS). In this study EG-SiO_2 nanofluid was considered 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.

Thus far, the effect of nanofluid on forced convective heat transfer over a 3D microscale forward-facing step has not been investigated experimentally, which has motivated the present study. The present study deals with laminar forced convective flow over a 3D microscale forward-facing step (MFFS) placed in a horizontal duct utilizing nanofluid. In this study, different types of nanofluids and volume fractions were used. The results, such as friction factor and Nusselt number were reported to illustrate the effect of nanofluids on these parameters.