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Mixed convective nanofluid flow in a channel having backward-facing step with a baffle

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ABSTRACT

Two-dimensional laminar and turbulent mixed convection flows using nanofluids over backward facing step in a heated rectangular duct having a baffle mounted on its wall are numerically simulated. The continuity, momentum and energy equations are solved using Finite Volume Method (FVM) and the SIMPLE algorithm scheme is applied to examine the effects of the baffle on flow and heat transfer characteristics. The bottom wall of the duct is being heated with a constant heat flux, while other walls are being thermally insulated. In this study, several parameters such as different types of the nanoparticles (Al_2O_3, CuO, SiO_2 and ZnO), different volume fractions in the range of 1% to 4%, and different nanoparticle diameters in the range of 25 to 80 nm were used. The Reynolds number of laminar flow was in the range of $100 \leq Re \leq 400$, while for turbulent flow it was in the range of $7500 \leq Re \leq 15{,}000$. The effects of baffle distances in the range of $\infty \leq D \leq 4$, baffle widths in the range of $0.01 \leq w_b \leq 0.04$, and baffle heights in the range of $0.005 \leq h_b \leq 0.015$ were studied. Baffle locations at the top wall and at bottom wall of the duct, and the number of baffles from 1 to 3 were also examined. The numerical results indicate that the nanofluid with SiO_2 has the highest Nusselt number compared with other nanofluid types. The Nusselt number increases as the volume fraction of the nanoparticles and the Reynolds number increase, while it decreases as the nanoparticle diameter increases. The effects of baffle distance heights, and baffle locations on fluid flow and heat transfer characteristics are significant, while the effects of baffle widths and baffle numbers are slightly insignificant.

1. Introduction

Convection flow and heat transfers in the channels with abrupt expansion in flow geometry are widely encountered in engineering applications and thermal systems, such as cooling passages of turbine blades, diffusers, combustors, and heat exchangers. In the flow reattachment region a great deal of mixing of high and low energy fluids occurs, thus significantly impacting the flow and heat transfer performances of these devices. In particular, momentum and thermal transports in the reattaching flow region and inside the reverse flow regions vary greatly. For example, the minimum wall shear stress and the maximum heat transfer rate occur in the neighborhood of reattaching flow region, while the minimum heat transfer rate occurs at the corner where the sudden change in flow geometry starts [1].

One of the ways to enhance heat transfer in the separated regions is to employ nanofluids. Nanofluids are fluids that contain suspended nanoparticles such as metals and oxides. These nanoscale particles keep suspended in the base fluid. Thus, it does not cause an increase in pressure drop in the flow field. Past studies showed that nanofluids exhibit enhanced thermal properties, such as higher thermal conductivity and convective heat transfer coefficients compared to the base fluid; see, for example, Daungthongsuk and Wongwises [2], Mujumdar [3], and Mohammed et al. [4,5].

Experimental and numerical studies on separated-reattached laminar and turbulent mixed convection flows have been extensively conducted during the past decades (see, for example, [6–13] and the references cited therein). This geometry is simple, yet the flow and the heat transfer through it contain most of the features encountered in more complex geometries. In addition, several other studies [14–16] examined laminar and turbulent mixed convection characteristics over backward facing step flows. Unsteady Navier–Stokes and energy equations are solved numerically together with the continuity equation using the finite difference method. A fifth-order upwind scheme and a fourth-order central deference scheme are adopted for the convection and diffusion terms of the governing equations, respectively. Properties of the working fluid (air) are assumed to be constant, and the Boussinesq approximation is used to evaluate the buoyancy term. SIMPLE algorithm is used for the computation of pressure correction in the iteration procedure.

The heat flux in thermal devices has become more and vast due to the increasing requirements of compactness for the relative systems. It should be important to seek ways to effectively augment the heat transfer characteristics of backward-facing step flow in the channels. Among important studies Tsay et al. [17] examined the influence of baffle

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Nomenclature

A	area, m^2
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$, σ_k, σ_ε	model constants
C_f	skin friction coefficient $= 2\tau_w/\rho u_o{}^2$
C_p	specific heat, kJ/kg K
D	normalized distance of the baffle $= d/H$
d	distance of the baffle from the sudden expansion, m
d_p	diameter of nanofluid particles, nm
ER	expansion ratio $= H/(H - S)$
FVM	Finite Volume Method
g	gravitational acceleration, m/s^2
Gr	Grashof number $= g\beta q_w H^4/k\nu^2$
H	duct height down-stream of the step, m
h	duct height up-stream of the step, m
h_b	baffle height, m
K	thermal conductivity, W/m K
k	turbulent energy
Nu	Nusselt number $= q_w S/k(T_w - T_o)$
Nu_p	Nusselt number for the heating section of the bottom plate
Nu_s	Nusselt number for the heating facing-step
P	pressure, Pa
Pr	Prandtl number $= \mu C_p/k$
q_w	wall heat flux, W/m^2
Re	Reynolds number $= 2\rho u_o h/\mu$
Ri	Richardson number $= Gr/Re^2$
S	step height, m
T	temperature, K
T_o	inlet temperature, K
T_w	wall temperature, K
u	velocity component in the x-direction, m/s
u_o	inlet velocity, m/s
w_b	baffle width, m
x_u	location where the stream-wise velocity is zero
x_w	location where the span-wise velocity is zero
y	transverse coordinate direction
v	velocity component in the y-direction, m/s

Greek symbols

α	thermal diffusivity of the fluid, m^2/s
β	volumetric coefficient of thermal expansion, 1/K
ε	turbulent dissipation rate, m^2/s^2
μ	dynamic viscosity, N m/s
μ_k	turbulent viscosity
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ_w	wall shear stress
φ	nanoparticle volume fraction (%)

Subscripts

bf	base fluid
C	value of cold temperature
f	fluid
nf	nanofluid
p	particles
s	solid
W	wall

vertically mounted onto the channel wall on the convective behaviors of backward-facing step flow. Comparing the results of cases with and without baffle, the maximum augmentation on the average Nusselt number is about 190% for the heating step and 150% for the heating section of the bottom plate. Berner et al. [18,19] obtained experimental result of mean velocity and turbulent distributions in flow around 12 segmented baffles. After about two baffles, the profiles of vertical mean velocity and fluctuations along the horizontal center plan become periodic. Experimental investigation of the turbulent flow and heat transfer characteristics inside the periodic cell formed between segmented baffles staggered in a rectangular duct was studied by Habib et al. [20] Numerical prediction of the flow and heat transfers in the channel with staggered fins was investigated by Webb and Ramadhyani [21], Kelkar and Patankar [22], and Habib et al. [23].

Very few numbers of research works were conducted numerically and experimentally by Dutta and Dutta [24], and Yang and Hwang [25] to capture more detail of the fluid flow pattern and heat transfer phenomena in the channel with perforated baffle. Three-dimensional laminar convection flow adjacent to backward-facing step in a heated rectangular duct with a baffle mounted on the upper wall was numerically simulated by Nie et al. [1].

There are rather limited articles that have been reported in the literature on the convective heat transfer in nanofluids; see, for example, Daungthongsuk and Wongwises [2], Wang and Mujumdar [3] and Mohammed [4,5]. It should be noted, however, that the vast majority of the studies of a backward-facing step that are reported in the open literature involved “regular” fluids (i.e., not nanofluids). Very few studies that involve nanofluids in backward-facing step geometry have been reported in the past. The first numerical study to investigate the flow and heat transfers over a backward-facing step using nanofluids is by Abu-Nada [26]. The Reynolds number and nanoparticle volume fraction used were in the range of $200 \leq Re \leq 600$ and $0 \leq \varphi \leq 0.2$, respectively, for five types of the nanoparticles which are Cu, Ag, Al_2O_3, CuO, and TiO_2. He reported that the high Nusselt number inside the recirculation zone mainly depended on the thermophysical properties of the nanoparticles and it is independent of Reynolds number. Numerical analysis of the forced and mixed convection (buoyancy-assisting flow condition) over a vertical and horizontal backward facing step in a duct using different nanofluids has been conducted by Mohammed et al. [4,5]. The effects of Reynolds number ($75 \leq Re \leq 225$), temperature difference ($0 \leq \Delta T \leq 30$ °C), and nanofluid type (such as Au, Ag, Al_2O_3, Cu, CuO, diamond, SiO_2, and TiO_2) were investigated on the fluid flow and heat transfer characteristics. It is found that a recirculation region developed straight behind the backward-facing step which appeared between the edge of the step and few millimeters before the corner which connects the step and the downstream wall. In the few millimeter zones between the recirculation region and the downstream wall, a U-turn flow was developed opposite to the recirculation flow which is mixed with the unrecirculated flow and travels along the channel. Two maximum and one minimum peaks in Nusselt number were observed along the heated downstream wall. It is inferred that Au nanofluid has the highest maximum peak of Nusselt number, while diamond nanofluid has the highest minimum peak in the recirculation region. Nanofluids with a higher Prandtl number have a higher maximum peak of Nusselt numbers after the separation and recirculation flow vanished.

The literature search indicates that the case of mixed laminar and turbulent convective flows over a horizontal backward-facing step having a baffle utilizing nanofluids has not been investigated yet and motivated the present study. Thus, the main objective of this study is to examine the heat transfer enhancement of 2D laminar and turbulent mixed convective flows adjacent to backward facing step with baffle installation onto the channel wall using different types of nanofluids.

2. Numerical model

2.1. Physical model

Two-dimensional laminar and turbulent mixed convection flows over backward facing step in a heated rectangular duct having a baffle