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Effect of obstacle positions for turbulent forced convection heat transfer and fluid flow over a double forward facing step

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ABSTRACT

A numerical study has been performed to analyze turbulent fluid flow behaviour along with forced convective heat transfer for a rectangular channel having double forward facing step with cylindrical obstacles placed near the steps. The flow equations as well as standard $k-\varepsilon$ model used for turbulence is solved by a commercial code FLUENT. The positions of the obstacles are varied in vertical direction. The effect of different position ratios of the obstacles and Reynolds number, on the heat transfer and hydrodynamic behaviour of the flow, has been investigated. Results reveal that, when both the obstacles are positioned vertically with same position ratio, the rate of heat transfer increases as obstacle position ratio increases. Optimum vertical positions of the obstacles has also been individually obtained from the results to get the maximum heat transfer co-efficient.

1. Introduction

Forward facing step along with backward facing step flow has been considered as one of the most fundamental area of research for turbulent forced convective heat transfer in recent years. These type of flows have a wide range of engineering applications such as cooling of electronic devices, nuclear reactors, gas turbine blades, chemical process equipment, combustion chambers, high performance heat exchangers and many other energy system equipment. The phenomenon of mixing of high and low energy fluid for flow separation and reattachment by introducing steps i.e. sudden compression or expansion in geometry towards a flow has been utilized in a beneficial manner to increase the heat transfer performance. For the same flow conditions, the forward facing step (FFS) flow is more complex in nature than the backward facing step (BFS) flow for having more separating zones. Also an improved heat transfer occurs in forward facing step flow.

In the previous few decades, a number of researches, both experimentally and numerically, have been carried out to acquire a better knowledge for the separating and reattaching flow application problems. At the beginning, the prime movement of the researchers was concentrated to understand the flow behaviour i.e. the flow separation and reattachment for the backward facing step flow problems. The study of Armaly et al. [1] was focused on the relationship between the Reynolds number and the reattachment length by an experimental method as well as by a numerical method. The results of their study conveyed that the reattachment length increases with the increase in Reynolds number. Chiang and Sheu [2] numerically performed a steady three dimensional flow analysis for the Reynolds number varying from 100 to 1000 by using the flow conditions of Armaly et al. [1]. From their study, it was outcome that the flow profile for the three dimensional study become similar to the flow pattern for two dimensional analysis only when the channel width is increased up to 100 times to the upstream step height for Reynolds number of 800. Lan et al. [3] used the FLUENT solver for analyzing the three dimensional turbulent forced convection flow having backward facing step for a rectangular duct at high Reynolds number values. Kumar and Dhiman [4] performed a numerical investigation to experience the effect of cylindrical obstacles installed in backward facing step laminar flow for varying Reynolds number from 1 to 200 where they found that the enhancement in the peak Nusselt number is up to 155% for using the obstacles comparing to the unobstructed case.

On the other hand, analysis of the forward facing step flow both experimentally and numerically has been performed by a very few researchers. Abu-Mulaweh et al. [6,7] had explicitly experimented the flow behaviour and heat transfer co-efficient for a forward facing step forced convection flow by using Laser-Doppler velocimeter and cold-wire anemometer to measure velocity and temperature distribution respectively. They found that the buoyancy effect is negligible for horizontal configuration of FFS where as it is significant in vertical configuration. They also found that the local heat transfer coefficient increases with the increase in inlet flow velocity. Later Abu-Mulaweh [8] concentrated on the effect of the step height for forward-facing step flow experimentally where the results revealed that the reattachment length and the heat transfer rate increase with the increase in step height. Barbosa-Saldaña and Anand [9] developed a

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Nomenclature

d_0	diameter of obstacles (m)
h	convection co-efficient
H	duct height at inlet (m)
H_1	gap between first step and top wall (m)
H_2	gap between second step wall and top wall (m)
K	turbulent kinetic energy (m^2s^{-2})
K	thermal conductivity ($Wm^{-1}K^{-1}$)
L	total bottom length (m)
Nu_{avg}	average Nusselt number
Nu_{avg_i}	Nu_{avg} difference with unobstructed model
Nu_x	local Nusselt number ($Nu = hH/K$)
$\overline{p}$	mean pressure (Pa)
Pr	Prandtl number
PR	position ratio
Re	Reynolds number
s	step height (m)
T_h	bottom wall temperature (K)
T_{in}	inlet fluid temperature (K)
u_{in}	inlet fluid velocity (ms^{-1})
$\overline{u}$, $\overline{v}$	mean axial and normal velocity (ms^{-1})

Greek letters

ε	turbulent dissipation rate (m^2s^{-3})
μ	dynamic viscosity ($kgm^{-1}s^{-1}$)
μ_t	turbulent dynamic viscosity ($kgm^{-1}s^{-1}$)
ρ	density of fluid (kgm^{-3})
σ_k, σ_ε	empirical turbulence model constants
ΔP	non-dimensional pressure drop

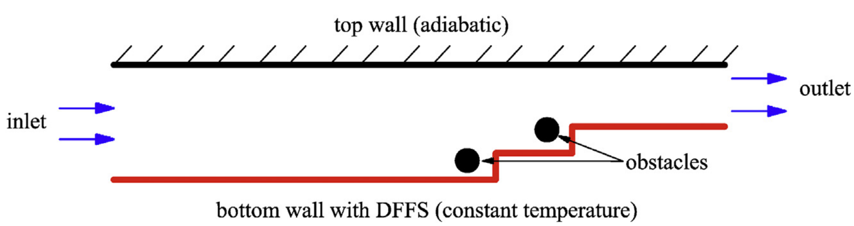

Fig. 1. Schematic diagram of physical problem.

finite volume code for a laminar three-dimensional horizontal forward-facing step flow and studied the effect of variation of Reynolds number (100, 200, 400 and 800) on the locations of the separation and reattachment line, velocity profiles at different planes and span-wise averaged Nusselt numbers. Nassab et al. [11] examined numerically the effect of step inclination angle on the heat transfer and hydrodynamic behaviour of a FFS flow.

Yilmaz and Öztop [12] performed a numerical study for the double forward facing step (DFFS) flow by using commercial code FLUENT to feel the effect of step height, step length and Reynolds number on the fluid flow and heat transfer. They proposed that the introduction of the second step is beneficial and can be used as a control device for different parameters. Later Öztop et al. [13] studied numerically the DFFS flow by installing rectangular obstacles nearby the steps and found that the rate of local heat transfer increases as well as pressure drop decreases with the increase in obstacle aspect ratio.

To the best of the authors' knowledge, the turbulent forced convection heat transfer and fluid flow for double forward facing step having cylindrical obstacles has not been yet studied. This present study shows how the installation of cylindrical obstacles before each step and also the change of their vertical positions affect the flow behaviour and accordingly the rate of heat transfer. Later an analysis has been done to find out the optimal vertical positions of the obstacles on the basis of average Nusselt number.

2. Problem statement

An incompressible, steady and two dimensional turbulent fluid flow has been considered for the double forward facing step (DFFS) channel with built-in cylindrical obstacles as schematically shown in Fig. 1.

The left side of the channel is configured as the inlet for the working fluid while the right side is the outlet. The bottom wall with two steps of the channel is maintained at a constant temperature (T_h) which is hotter than the inlet temperature of the working fluid (T_{in}). The top wall and obstacles are assumed to be well insulated.

All the dimensions of the above mentioned channel has been depicted in Fig. 2. The total length L of the channel is 1.6 m. The inlet height H is 0.1 m. The first and second steps are positioned at 1.0 m and 1.2 m respectively from the inlet. Both the steps are having a same step height ($h_{1s} = h_{2s}$) of 0.03 m. Two cylindrical obstacles are located near the two steps where both the obstacles have a same diameter (d_0) of 0.02 m and their position from the inlet are at 0.98 m and 1.18 m respectively.

In this present study, seven cases have been studied where the positions of the obstacles have been changed in y-direction with a fixed position in x-direction as shown in Table 1.

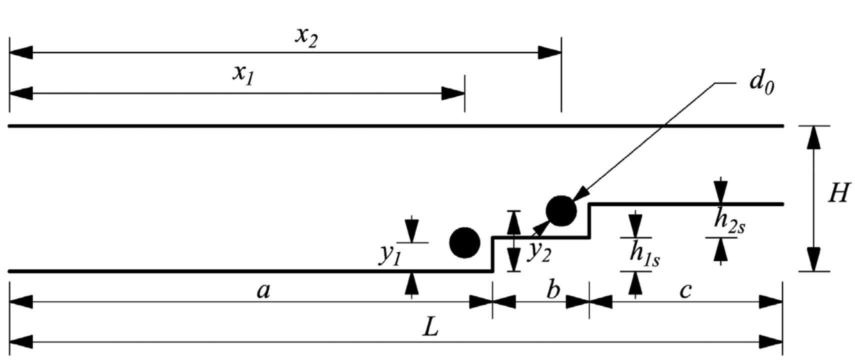

Fig. 2. Different dimensions of physical problem.