

Effect of channel confinement on wake dynamics and forced convective heat transfer past a blunt headed cylinder



Sonal Bhadauriya^a, Harshit Kapadia^b, Amaresh Dalal^{c,*}, Sandip Sarkar^d

^a Department of Chemical Engineering, University of Petroleum and Energy Studies, Dehradun 248007, India

^b Department of Mechanical Engineering, Indian Institute of Science Bangalore, Bangalore 560012, India

^c Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781 039, India

^d Research and Development Division, Tata Steel Ltd., Jamshedpur 831007, India

A B S T R A C T

In this paper, a two-dimensional numerical simulation is carried out to understand the effect of confinement (blockage ratio β) on fluid flow and forced convective heat transfer characteristics past a blunt headed cylinder. Utilizing air as an operating fluid, flow simulations are carried out for wide ranges of blockage ratios ($\frac{1}{10} \leq \beta \leq \frac{1}{3}$) and Reynolds numbers ($60 \leq Re \leq 200$). The flow characteristics and heat transport are analysed critically for different β . The functional dependence of C_D (Drag Coefficient) and C_L (Lift Coefficient) on blockage ratio is examined. It has been found that C_D reduces with increasing Re , while the Strouhal number and the average Nusselt number show an increasing trend when the blockage ratio is increased. The average Nusselt number also increases with increasing Re .

1. Introduction

Study of flow past two-dimensional bluff bodies and the resultant phenomena on vortex shedding has been the epicentre of various numerical and experimental investigations for decades. This kind of flow is encountered in many practical situations such as flow around suspension bridges, pillars, chimneys, masts etc. Due to their growing industrial importance, various other bluff body shapes are also paid a similar attention. These structures are used in electronic cooling equipment, cooling towers, heat exchanger tubes, offshore structures, and instrumentation equipment such as measurement probes and sensors. The oscillations of structures in a flow field are caused by the celebrated phenomena of vortex shedding. Sometimes these vibrations can lead to failure and damage when it matches with the natural frequency of the body during resonance. Therefore, it is critical to understand the fundamental physics behind this fluid-structure interaction mechanism not only for efficient designing but also in exploring the fundamental physics of occurrence.

In a channel (confined flow), the flow dynamics is highly affected by the blockage ratios (β). Davis et al. [1] conducted both experimental and numerical study to investigate the effect of channel confinement on the average drag coefficient (C_D) for a rectangular cylinder at various ranges of Reynolds numbers (Re). In a similar fashion, Suzuki et al. [2] performed numerical and experimental investigation for a channel

obstructed by a square rod. They performed simulations for $37.5 \leq Re \leq 150$ and the blockage ratios in the range $0.5 \geq \beta \geq 0.05$. They observed similar behaviour between the drag coefficient and the Reynolds number as reported by Davis et al. [1]. They also demonstrated a criss-cross motion of vortex shedding where the vortex shed from the upper half gradually moves towards the bottom wall and vice versa. Sohankar et al. [3] performed numerical simulations of flow around rectangular cylinders at low Reynolds number ($Re \leq 200$) and at a fixed blockage ratio 0.05 for different angle of incidences ($0 \leq \alpha \leq 90$) and side ratios (1–4). Their study reported that the regime of the onset of vortex shedding is $50 \leq Re \leq 55$ for side ratio of one and at 0° angle of incidence. Breuer et al. [4] computed the two-dimensional laminar flow past a square cylinder ($\beta = 1/8$) for $0.5 \leq Re \leq 300$ using two methods, namely, Lattice Boltzmann Automata (LBA) and Finite Volume Method (FVM). They found a reasonably good agreement between computed results utilizing each method. Abbassi et al. [5] conducted a numerical investigation of forced convection in a channel with a triangular prism at $20 \leq Re \leq 250$ for air as an operating fluid. They found that the transition from symmetric flow to periodic flow occurs near $Re = 45$. Chakraborty et al. [6] investigated the wall effects for flow past a circular cylinder. They conducted simulations for a large range of Reynolds numbers ($0.1 \leq Re \leq 200$). They reported that for a fixed blockage ratio, both the angle of separation and length of recirculation zone increases with increasing Reynolds numbers. Sharma and Eswaran

* Corresponding author.

E-mail address: amaresh@iitg.ernet.in (A. Dalal).

Nomenclature

D	projected diameter of the cylinder
H	height of the domain
L	length of the domain
C_D	coefficient of drag (dimensionless)
C_L	coefficient of Lift (dimensionless)
$C_{L,rms}$	root mean square of the lift coefficient
F_D	drag force acting on the cylinder (N/m)
F_L	lift force acting on the cylinder (N/m)
L_r	recirculation length
σ^L_ω	vorticity flux
Re	Reynolds Number $\left(=\frac{\rho U_\infty D}{\mu}\right)$
Pr	Prandtl Number $\left(=\frac{\nu}{\gamma}\right)$
St	Strouhal Number $\left(=\frac{g\alpha(T_W - T_\infty)D^3}{\nu^2}\right)$
Gr	Grashof Number
Ri	Richardson Number $\left(=\frac{Gr}{Re^2}\right)$
Nu_L	local Nusselt Number (dimensionless)
Nu_{avg}	average Nusselt Number over the cylinder surface
u_i	dimensionless velocity in i -direction $(u_i = \frac{U_i}{U_\infty})$
U_i	dimensional velocity in i -direction
x, y	dimensionless Cartesian coordinates $(x = \frac{X}{D}, y = \frac{Y}{D})$
X, Y	dimensional Cartesian coordinates

p	dimensionless pressure
T	dimensional temperature
t	dimensionless time
U_∞	inlet velocity

Greek symbols

τ_{ij}	dimensionless shear stress
α	thermal expansion coefficient
β	blockage ratio (D/H)
γ	thermal diffusivity of a fluid
θ	dimensionless temperature $\left(\theta = \frac{T - T_\infty}{T_W - T_\infty}\right)$
ν	Kinematic viscosity of a fluid
μ	Dynamic viscosity of a fluid
ρ	Density of a fluid
τ	time period for a complete cycle
ω	vorticity

Subscripts

Rms	root mean square value
avg	average
w	wall
∞	free stream condition

[7] studied the effect of channel confinement on the two dimensional laminar flow and heat transfer across a square cylinder for various blockage ratio and Reynolds numbers. They reported that as β is increased, the channel wall first bestows stability to the flow until the critical value of β is reached. Thereafter it imparts instability to the flow due to increased interaction between cylinder and the walls. Sahin and Owens [8] carried out a numerical study of wall effects up to high blockage ratio on two-dimensional flow past a circular cylinder. They investigated the effect on the critical Reynolds number for $\beta > 0.7$ and its nature of instability.

Various numerical studies have focussed on confined flow past a square cylinder [9,10, and 11]. All these studies report the inverse dependence of drag coefficient on Reynolds number. Dhiman et al. [10] also reported that the blockage ratio and Reynolds number influences the size of wake region and drag greatly compared to the power law index. Patil and Tiwari [12] analysed the effect of blockage ratio on wake transition for flow past square cylinders. They found that the onset of planar vortex shedding is delayed initially with the increase in blockage ratio. Sohankar [13] performed three-dimensional large eddy simulations of flow past rectangular cylinders and their side ratio effects on the wake dynamics. Kumar and Mittal [14] studied the effect of blockage on critical parameters for flow past a circular cylinder. They found that Strouhal Number increases with the blockage ratio. Mettu et al. [15] studied the dynamics of an asymmetrically placed circular cylinder in a channel. They reported that the amplitude of oscillations in the lift coefficient (C_L) decreases as the blockage ratio increases. Singha and Sinhamahapatra [16] investigated the flow past a circular cylinder between parallel walls at low Reynolds number. They found

that no vortex shedding occurs for flow Reynolds number of about 100 if normalized gap between the cylinder and walls is less than one.

De and Dalal [17] studied the confined flow past a triangular cylinder for a range of $80 \leq Re \leq 200$ and blockage ratio $1/12 \leq \beta \leq 1/3$. They found at lower blockage ratios, flow is similar to the unconfined flow and is more prone to wake instability. Srikanth et al. [18] also performed simulations for a triangular cylinder placed in a channel. They found the critical Reynolds Number for onset of vortex shedding is nearer to 58–59. These studies [17,18] also show the inverse dependence of drag coefficient on Reynolds number. Rosales et al. [19] performed simulations for inline and offset tandem pair of rectangular cylinders. They reported that the drag coefficient and Nusselt number decreases as the heated cylinder reaches the wall and the highest value of Strouhal number is observed in the channel centred, inline configuration.

In the literature reviewed, it can easily be found that studies on forced convective flow and heat transfer past a blunt headed bluff body are scarce. Such geometry is very common now a day in electronic chips, large constructional frameworks such as pillars, columns and towers, etc. Therefore, this investigation is appealing in filling the gap in the literature. In addition, this geometry poses a complete new problem to work upon and generates a lot of academic curiosity. Our study primarily focuses on laminar unsteady flow and heat transfer past a confined blunt headed cylinder. The range of blockage ratio is considered as: $1/3 \geq \beta \geq 1/10$. The Reynolds number (based on projected length D) range is from 60 to 200, and the Prandtl number for the operating medium is 0.71 (air). Commercial CFD Solver Ansys Fluent (using no-slip condition on channel walls and parabolic velocity profile for the

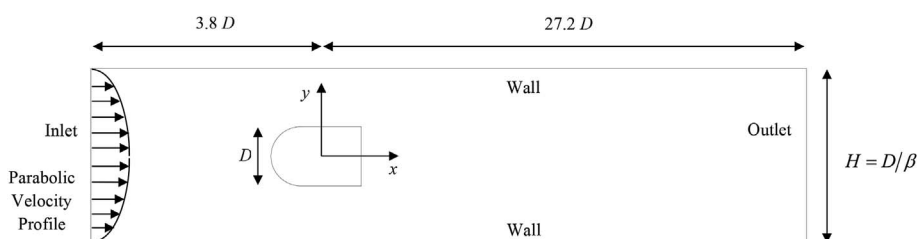


Fig. 1. Physical domain for computations.

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