International Communications in Heat and Mass Transfer 91 (2018) 48–56

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Numerical simulation on forced convection over a circular cylinder confined in a sudden expansion channel

Zhiyun Wang*, Shanshan Zu, Mo Yang

School of Energy and Power Engineering, University of Shanghai for Science and Technology, Shanghai 200093, China

ARTICLE INFO

Keywords:
Numerical simulation
Forced convection
Crossed flow over cylinder
Sudden expansion channel

ABSTRACT

Numerical simulations are presented for a 2-D, incompressible, crossed Poiseuille flow over a circular cylinder confined in a sudden expansion channel. The SIMPLE algorithm with the QUICK scheme is employed. The simulations are carried out for Reynolds number, Re, varying from 10 to 300, the expansion ratio of the channel, E_r, ranging from 1 to 4, and the position of the circular cylinder, X_c, ranging from 1 to 15. The results show that the heat transfer mechanism is a complex function of Re, E_r and X_c. Steady-state, periodical oscillating and chaotic solutions are obtained and the route of flow state from steady state to chaotic oscillation is not unique. For the fixed E_r and X_c, the time-averaged Nusselt number, $\overline{Nu_t}$, is an increasing function of Re. For the fixed Re, the heat transfer intensity depends on the flow pattern decided by both E_r and X_c.

1. Introduction

This paper is about the 2D flow and heat transfer over a cylinder symmetrically placed in a sudden expansion channel. There are lots of applications for this theoretical problem, such as space heating, heat exchangers, solar collectors, chemical reactors, energy storage systems, electronic equipment, and so on [1–10]. A literature survey indicates that numerous experimental and numerical studies have been conducted on this issue.

Careful analysis of the flow in sudden expansions were carried by Armaly [2], Biswas [3] and Kondoh et al. [4], and they reported that the flow showed strong 2-D behavior, on the plane of symmetry. In detailed study on the flow over a backward-facing step at high Re, Erturk [5] examined the effect of the inlet channel and the outflow boundary condition on the numerical solution. The result showed that, for the backward-facing step flow, an inlet channel that was at least five step heights long is required for accuracy when the expansion ratio is 2. Terhaar et al. [6] have experimentally investigated the unsteady heat transfer downstream over a backward-facing step at $Re = 300$. They showed that Nu increased up to a certain Strouhal number and then degraded as the pulsation frequency increased.

Heat transfer and fluid flow characteristics over a forward facing step in a channel with the insertion of obstacles have received attention in the literatures. Ghasemi et al. [7] studied thermo-hydrodynamic flow around a circular cylinder inserted within a backward-facing step by Thermal Finite-volume Lattice Boltzmann Method. Kumar and Dhiman [8] numerically studied the heat transfer augmentation in a backward facing step with the insertion of an adiabatic circular cylinder. They obtained the peak Nu enhancement up to 155% using a cylinder as compared to no-cylinder case. Suzuki [9] did experiments on the backward-facing step flow with insertion of a cylinder into near the top corner of the step and stated that if the cylinder was mounted at the proper position, it was effective for altering the averaged and fluctuating velocity fields in the downstream region of step.

The effects of a closely placed solid wall were given lots of attentions. Price [10], Bearman [11], Cheraghi [12] and Zovatto et al. [13] reported the flow around a circular cylinder with varying distances between the cylinder and the channel walls. Generally speaking, these studies have shown that the presence of a wall modifies the forces acting on the cylinder and the vortex shedding frequency as it approaches to the wall. Dou et al. [14] numerically studied the two-dimensional flows around a cylinder between two parallel walls at $Re = 40$ and 100. It was found that the two eddies attached at the rear of the cylinder did not contribute to the formation of Karman Vortex street. Camarri et al. [15] investigated the three-dimensional stability of the wake behind a symmetrically confined circular cylinder for a different blockage ratio. Chen et al. [16] investigated a cylinder symmetrically placed between parallel planes with a focus on the nature and occurrence of the bifurcation from steady symmetric flow to the periodic shedding regime. In the steady flow, the symmetry-breaking bifurcation was found to be of Hopf type. Sahin and Owens [17] developed a finite volume velocity only formulation to study the effects of wall proximity on the flow field around a circular cylinder. Four distinct classes of flow were identified in different regions of the parametric

* Corresponding author.
E-mail address: wangzhiyun@usst.edu.cn (Z. Wang).

https://doi.org/10.1016/j.icheatmasstransfer.2017.11.005

space. Kanaris et al. [18] found a transition which was dominated by mode A and mode B three dimensional instabilities, from a 2-D to a 3-D shedding flow regime between $Re = 180$ and $Re = 210$.

Although there have been numerous soundings on the flow over a circular cylinder and the flow in a sudden expansion channel, the more practical flow system combining the both has hitherto attracted little attention. Moreover, symmetrical or steady model were used in most literatures for predicting the flow or optimizing the performance of heat transfer in heat exchangers. While the asymmetry and unsteady of the flow and heat transfer must be considered due to their nonlinear inherence for more accurate forecast.

In this article, we present a transient numerical simulation of holonomic model of the incompressible viscous flow over a circular cylinder confined symmetrically in a sudden expansion channel. In addition to great number of engineering applications of this flow system, time-dependent phenomenon of the problem including periodical oscillation or chaotic features is another attractive theoretical aspect of the present study. The emphasis is on the effects of *Re*, the expansion ratio of channel, and the position of cylinder on the flow and heat transfer, as well as their bifurcation and transient characteristics.

2. Problem description

A schematic description of the physical problem considered in this study is shown in Fig. 1. The thermos-hydrodynamic modeling consists of a circular cylinder (of diameter d, and of position x_c) placed symmetrically in a sudden expansion channel with the dimensions. The ratio of the cylinder diameter to the distance between the channel walls d_2, defines the blockage ratio, $\beta = d/d_2$. The expansion ratio of channel E_r is defined as $E_r = d_2/d_1$. The fluid temperature at the inlet is kept at a uniform value of T_H. The channel walls are all adiabatic except that the temperature on the surfaces of the cylinder is uniformly T_L ($T_H > T_L$). Barton [19] studied the entrance effect for flow over a backward-facing step and reported that the length of the channel on the upstream of the step affects the numerical solution significantly at low *Re*. To minimize the affection of the inlet distance, the inlet is placed at a distance of $L_1 = 10$ upstream of the expansion step as suggested in [19], and a standard parabolic velocity profile is prescribed at the channel inlet. This means the flow is fully developed on the upstream of the step. The outlet boundary is set far enough from the circular cylinder that we can impose the zero diffusion flux condition for all variables. Physically, this choice implies that the conditions of the outflow plane are extrapolated from upstream flow and have negligible influence by downstream flow. This is similar to the homogeneous Neumann condition.

Computations are carried out by assuming that the fluid is a Newtonian fluid with constant properties and no viscous dissipation. The governing equations are the conservation of mass, the *X*- and *Y*-components of momentum equation and the conservation of energy equation, as given in the following dimensionless forms:

Continuity equation:

$$\frac{\partial U}{\partial X} + \frac{\partial V}{\partial Y} = 0 \tag{1}$$

X-momentum:

$$\frac{\partial U}{\partial \tau} + U\frac{\partial U}{\partial X} + V\frac{\partial U}{\partial Y} = -\frac{\partial P}{\partial X} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 U}{\partial X^2} + \frac{\partial^2 U}{\partial Y^2}\right) \tag{2}$$

Y-momentum:

$$\frac{\partial V}{\partial \tau} + U\frac{\partial V}{\partial X} + V\frac{\partial V}{\partial Y} = -\frac{\partial P}{\partial Y} + \frac{1}{\mathrm{Re}}\left(\frac{\partial^2 V}{\partial X^2} + \frac{\partial^2 V}{\partial Y^2}\right) \tag{3}$$

Energy equation:

$$\frac{\partial \Theta}{\partial \tau} + U\frac{\partial \Theta}{\partial X} + V\frac{\partial \Theta}{\partial Y} = \frac{1}{\mathrm{RePr}}\left(\frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2}\right) \tag{4}$$

In the present study, the notation of Mussa et al. [20] is used, where d is chosen as the hydraulic diameter of the circular cylinder. The dimensionless parameters used in Eqs. (1)–(4) are defined as follows:

$$X = \frac{x}{d},\ Y = \frac{y}{d},\ \tau = \frac{u_b t}{d},\ P = \frac{p}{\rho u_b^2},\ U = \frac{u}{u_b},\ V = \frac{v}{u_b},\ \Theta = \frac{T - T_L}{T_H - T_L} \tag{5}$$

The Reynolds number, *Re*, Prandtl number, *Pr*, and dimensionless distance between the cylinder and the expansion step, X_c, are defined as:

$$\mathrm{Re} = \frac{u_b d}{\nu} \tag{6}$$

$$\mathrm{Pr} = \frac{\nu}{\alpha} \tag{7}$$

$$X_c = \frac{x_c}{d} \tag{8}$$

where ρ, α, and υ are the density, thermal diffusivity and the kinematic viscosity of the fluid, respectively. u_b denotes the average velocity of the inlet flow, which corresponds to two-thirds of the maximum inlet velocity in the laminar cases. *Pr* is kept to be constant value of 0.7 and β to be 1/6 in this study.

The boundary conditions used for the present problem could be written as follows:

- At the inlet boundary: $U = \frac{3}{2}\left[1 - 4\left(\frac{Y}{D_1}\right)^2\right]$, $V = 0$, $\Theta = 1$
- On all solid channel walls: $U = 0$, $V = 0$, $\partial\Theta/\partial n = 0$, (no-slip and insulated boundary condition, with "n" representing the normal coordinate on the channel walls)
- On the surface of cylinder: $U = 0$, $V = 0$, $\Theta = 0$
- At the exit channel: $\partial U/\partial x = 0$ and $\partial V/\partial x = 0$.
- The local *Nu* at the surface of cylinder is calculated as:

$$Nu_\varphi = \frac{h_\varphi d}{\lambda} = -\left(\frac{\partial \Theta}{\partial n}\right)_{cylinders\ wall} \tag{9}$$

where, h_φ is the local surface heat transfer coefficient, n is the unit normal coordinate to the surface of the cylinder and φ is the angle of point displacement from the front stagnation point.

The area-averaged *Nu* of the cylinder is calculated by integrating the local Nu_φ along its wall as the following:

$$\overline{Nu_s} = \frac{1}{2\pi}\int_0^{2\pi} Nu_\varphi d\varphi \tag{10}$$

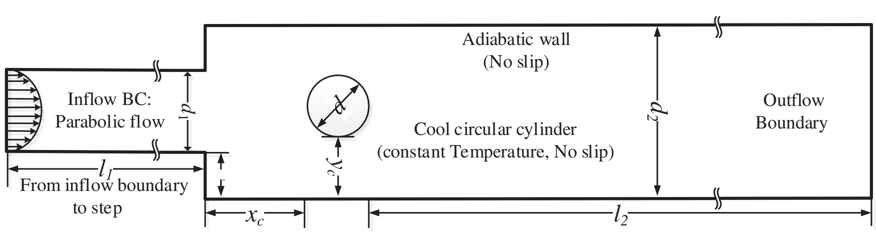

Fig. 1. Schematic diagram of the flow configuration and definition of length scales.