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Fluid flow and heat transfer around a confined semi-circular cylinder: Onset of vortex shedding and effects of Reynolds and Prandtl numbers

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ABSTRACT

Flow and heat transfer characteristics around a semi-circular cylinder placed in a confined channel are investigated in the unsteady regime. The two-dimensional simulations are carried out for varying values of control parameters: Reynolds number (Re) = 50–200 and Prandtl number (Pr) = 0.7, 10 and 100 at a fixed blockage ratio of 25% for Newtonian constant-property fluid. Continuity, Navier–Stokes and energy equations with appropriate boundary conditions are solved using the commercial computational fluid dynamics solver Ansys Fluent. The transition from steady to time-periodic flow occurs between Re = 69 and 70. The effect of Prandtl number on Nusselt number is pronounced; the ratio of Nusselt number values belonging to Pr = 100 and those belonging to Pr = 0.7 ranges from 6.3 to 6.5 over the Reynolds number domain investigated. Finally, the present numerical results are used to develop drag coefficient, Strouhal number and Nusselt number correlations.

1. Introduction

Analogous to a circular cylinder, confined flow and heat transfer around a semi-circular cylinder have variety of engineering applications such as cooling of electronic components and chips of various shapes, pin type heat exchange systems, thermal processing of foodstuffs, vortex flow meters, and others [1–5]. Besides, a semi-circular cylinder offers space economy in terms of the specific heat transfer area. In spite of such widespread applications, limited information is available in the open literature on the confined flow around and heat transfer from a semi-circular cylinder. We have recently systematically presented and discussed various studies on the flow and heat transfer characteristics in a channel with a built-in semi-circular cylinder [6–8]; Kumar and Dhiman [6] and Kumar et al. [7] investigated the confined forced flow and heat transfer around a semi-circular cylinder, albeit at low Reynolds numbers (Re up to 40). This motivated us to examine the confined forced convection heat transfer from a semi-circular cylinder in the unsteady regime (or at intermediate Re). On the other hand, extensive numerical/experimental literature is available on the forced flow and heat transfer around a semi-circular cylinder in the unconfined domain [9–24]. Among these studies, Kiya and Arie [9], Boisaubert et al. [10], Coutanceau et al. [11], Sophy et al. [12], Koide et al. [13], Koide et al. [14], Chandra and Chhabra [15,16], Gode et al. [17], Bhinder et al. [18] and Chatterjee et al. [19] investigated the unsteady flow around a semi-circular cylinder. Forbes and Schwartz [20] and Chandra and Chhabra [21,22] determined the effects of control parameters on a semi-circular cylinder in the steady regime (or at low Re). Tiwari and Chhabra [23] investigated the influence of flow and heat transfer parameters on flow around and heat transfer from a semi-circular cylinder for power-law fluids in the steady regime (Re = 0.01–30 and Pr = 1–100). The classical inverse variation in the value of the drag coefficient with Re is reported. In a recent study, Chatterjee and Mondal [24] studied the mixed convection heat transfer across a semi-circular cylinder in the unsteady regime for Re = 50–150 at a fixed Prandtl number (Pr = 0.71). Considerable differences in the global flow and heat transfer quantities are observed for the range of settings investigated.

Thus, as far as we know, no one has investigated the unsteady momentum and heat transfer around a confined semi-circular cylinder in a channel, in spite of its many engineering applications [1–5]. In the confined configuration, forced convection heat transfer phenomena are noticeably influenced by the wall confinement or blockage ratio (defined as the ratio of a semi-circular cylinder's diameter (D) to the channel transverse height (H), that is $\beta = D/H$) in addition to the values of Re and Pr. The present work aims to fill these gaps in the confined flow configuration for the forced flow

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Nomenclature

C	heat capacity of fluid (J kg^{-1} K^{-1})
C_D	total drag coefficient ($=F_D/(1/2\rho U_\infty^2 D)$)
C_L	total lift coefficient ($=F_L/(1/2\rho U_\infty^2 D)$)
CV	control volume
D	diameter of the semi-circular cylinder (m)
f	vortex shedding frequency (s^{-1})
F_D	drag force per unit length of the semi-circular cylinder (N m^{-1})
F_L	lift force per unit length of the semi-circular cylinder (N m^{-1})
h	local heat transfer coefficient (W m^{-2} K^{-1})
$\bar{h}$	average heat transfer coefficient (W m^{-2} K^{-1})
H	height of the computational domain (m)
k	thermal conductivity of fluid (W m^{-1} K^{-1})
L	length of the computational domain (m)
$\mathrm{Nu_L}$	local Nusselt number ($=hD/k$)
Nu	average Nusselt number ($=\bar{h}D/k$)
p	dimensionless pressure ($=p^*/(\rho U_\infty^2)$)
Pr	Prandtl number ($=\mu C/k$)
Re	Reynolds number ($=DU_\infty\rho/\mu$)
St	Strouhal number ($=fD/U_\infty$)
t	dimensionless time ($=t^*/(D/U_\infty)$)
Δt	dimensionless time-step
T	absolute temperature (K)
T_p	dimensionless time period of one periodic cycle
T_∞	fluid temperature at the inlet (K)
T_w	surface temperature of the semi-circular cylinder (K)
$\mathbf{U}$	dimensionless velocity vector ($=\mathbf{U}^*/U_\infty$)
U_∞	average velocity at the inlet (m s^{-1})
U_x, U_y	x and y components of dimensionless velocity
x, y	dimensionless streamwise and transverse coordinates ($=x^*/D$, y^*/D)
X_d	downstream distance (m)
X_u	upstream distance (m)
Greek symbols	
β	blockage ratio ($=D/H$)
δ	size of the CV clustered around a semi-circular cylinder (m)
θ	dimensionless temperature ($=(T-T_\infty)/(T_w-T_\infty)$)
μ	dynamic viscosity of fluid (Pa s)
ρ	fluid density (kg m^{-3})
Superscript	
$*$	dimensional value

around and heat transfer from a semi-circular cylinder in the unsteady regime. The effect of various values of control parameters (Re and Pr) on the engineering output parameters (such as drag coefficient, Nusselt and Strouhal numbers) and temporal variation in the values of drag and lift coefficients and Nusselt number are discussed. Instantaneous flow and thermal patterns around a semi-circular cylinder are also presented. Lastly, simple expressions of drag coefficient, Strouhal number and Nusselt number are determined.

2. Problem formulation

Confined laminar flow of constant property incompressible Newtonian fluids in a channel with a built-in heated semi-circular cylinder is shown schematically in Fig. 1. The long semi-circular cylinder is exposed to a fully developed velocity field with average velocity U_∞ and uniform temperature T_∞ at the inlet. The semi-circular cylinder is located symmetrically on the centerline of the channel at an upstream distance of X_u from the inlet and at a downstream distance of X_d from the outlet measured from the flat side of the cylinder. The total length of the computational domain is L ($=X_u + X_d$) in the axial direction and the height of the computational domain is H in the lateral direction. The blockage ratio $\beta = D/H$ (where D is the diameter of the semi-circular cylinder) is fixed at 0.25.

The dimensionless forms of the continuity, Navier–Stokes and energy equations are represented by Eqs. (1)–(3), respectively.

$$\nabla \cdot \mathbf{U} \tag{1}$$

$$\frac{D\mathbf{U}}{Dt} = -\nabla p + \frac{1}{\mathrm{Re}}\nabla^2\mathbf{U} \tag{2}$$

$$\frac{D\theta}{Dt} = \frac{1}{\mathrm{RePr}}\nabla^2\theta \tag{3}$$

In Eq. (2) the free convection term is neglected because it is much smaller for our case than the forced convection. The importance of free convection relative to forced convection is characterized by the buoyancy parameter, the Richardson number

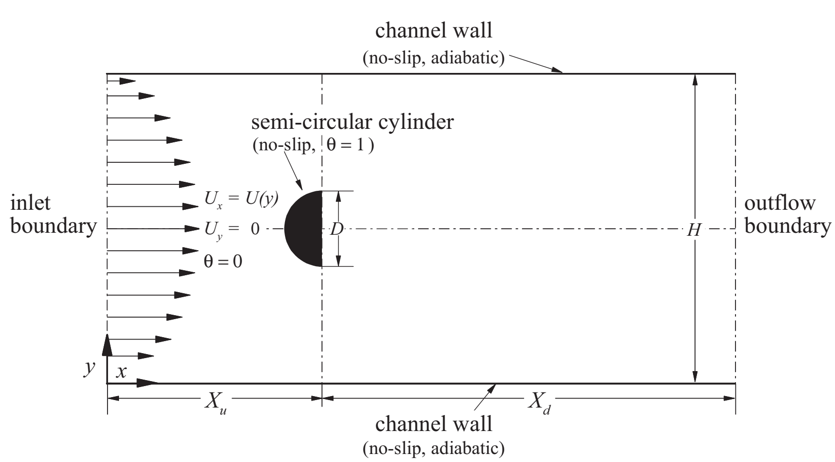

Fig. 1. Schematic diagram.