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Unsteady mixed convection heat transfer from two confined isothermal circular cylinders in tandem: Buoyancy and tube spacing effects

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ABSTRACT

In this work, two-dimensional numerical simulations are carried out to investigate the unsteady mixed convection heat transfer in a laminar cross-flow from two equal-sized isothermal in-line cylinders confined inside a vertical channel. The governing equations are solved using the vorticity-stream function formulation of the incompressible Navier–Stokes and energy equations using the control-volume method on a non-uniform orthogonal Cartesian grid. The numerical scheme is validated for the standard case of a symmetrically confined isothermal circular cylinder in a plane channel. Calculations are performed for flow conditions with Reynolds number of $Re_D = 200$, a fixed value of the Prandtl number of $Pr = 0.744$, values of the buoyancy parameter (Richardson number) in the range $-1 \leq Ri \leq 4$, and a blockage ratio of $BR = D/H = 0.3$. All possible flow regimes are considered by setting the pitch-to-diameter ratios ($\sigma = L/D$) to 2, 3 and 5. The interference effects and complex flow features are presented in the form of mean and instantaneous velocity, vorticity and temperature distributions. In addition, separation angles, time traces of velocity fluctuation, Strouhal number, characteristic times of flow oscillation, phase-space relation between the longitudinal and transverse velocity signals, wake structure, and recirculation length behind each cylinder have been determined. Local and space-averaged Nusselt numbers for the upstream and downstream cylinders have also been obtained. The results reported herein demonstrate how the flow and heat transfer characteristics are significantly modified by the wall confinement, tube spacing, and thermal effects for a wide range in the parametric space.

1. Introduction

In the last two decades, multiple experimental and numerical work aimed to study the cross-flow past two cylinders in tandem have been performed because of their numerous engineering applications in the design of heat exchangers, cooling of nuclear fuel rods, and flow and heat transfer around offshore structures and chimney stacks. However, the majority of these studies have focused on the effects of the cylinder spacing and proximity-induced interference in the flow structure and the force coefficients, as is evident in the reviews conducted in Blevins (1977); Chen (1987); Sumner (2010); Zdravkovich (1977, 1985). The spatial arrangement of two cylinders can be aligned with the direction of the main flow (in tandem), placed side-by-side, or placed in a staggered arrangement. For the case of two cylinders of identical diameters in cross-flow placed in tandem, several flow regimes and flow interference between cylinders have been identified depending on the value of the Reynolds number and the location of the downstream cylinder with respect to the upstream one (Zdravkovich, 1977; 1987). The "extended body" regime (Xu and Zhou, 2004; Zhou and Yiu, 2006) occurs if the pitch-to-diameter ratio σ is smaller than a critical value of approximately $1 < \sigma < 2$. In this regime, the Kármán vortex shedding from the upstream cylinder is suppressed and the two cylinders behave as a single bluff body, the wake is narrower and the Strouhal number is higher than a single cylinder, the vortex roll-up takes place closer to the downstream

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cylinder and the Kármán vortices are more elongated than those for a single cylinder (Igarashi, 1981; 1984; Lin et al., 2002; Meneghini et al., 2001). The “reattachment” regime occurs for intermediate pitch ratios of approximately $2 < \sigma < 5$, and two basic flow configurations have been identified depending on whether the location of the shear layer reattachment takes place at the rear (“after-body”, $\sigma = 2$–3) or leading surface (“fore-body”, $\sigma = 3$–5) of the downstream cylinder (Hetz and Telionis, 1991; Hiwada and Yanagihara, 1982; Igarashi, 1981; 1984; Lee and Basu, 1997; Lin et al., 2002; Ljungkrona et al., 1991; Ljungkrona and Sundén, 1993; Meneghini et al., 2001; Zdravkovich, 1985; 1987) . The “co-shedding” regime takes place at higher pitch ratios of approximately $\sigma > 5$. In this regime, vortex shedding from both cylinders takes place at the same frequency (Alam and Meyer, 2011; Igarashi, 1981; 1984; Ishigai et al., 1972; Meneghini et al., 2001; Xu and Zhou, 2004; Zdravkovich, 1987; Zhou and Yiu, 2006).

Nomenclature

BR	blockage ratio, H/D
D	cylinder diameter
f	vortex shedding frequency (Hz)
g	gravity acceleration
Gr	Grashof number based on cylinder diameter, $Gr = g\beta(T_w - T_0)D^3/\nu^2$
h	local heat transfer coefficient
H	width of computational domain (characteristic length)
k	thermal conductivity of fluid
L	pitch (centre-to-centre distance between two cylinders)
L_v	wake closure length
L_{tot}	length of computational domain
n	normal direction
Nu	local Nusselt number (see Eqs. (6) and (7))
$\overline{Nu}$	average Nusselt number (see Eq. (8))
Pe	Peclet number, $Pe = u_0D/\alpha$
Pr	Prandtl number, $Pr = \nu/\alpha$
Re	Reynolds number based on the mean inflow velocity, $Re = u_0D/\nu$
Re_D	Reynolds number based on u_D, $Re_D = u_DD/\nu$
Ri	Richardson number based on cylinder diameter, $Ri = Gr/Re^2$
S	length from the origin to the channel outlet
SD	standard deviation
St	Strouhal number based on cylinder diameter, $St = fD/u_0$
t	time
T	temperature
T_0	fluid temperature at the channel inlet
T_w	temperature at the cylinders' surface
u_0	mean fluid velocity at the channel inlet
u, v	longitudinal and transverse velocity components, respectively
u_D	average longitudinal velocity over the cylinders (see Eq. (9))
U	nondimensional longitudinal velocity component, $U = u/u_0$
V	nondimensional transverse velocity component, $V = v/u_0$
x, y	Cartesian rectangular coordinates
X	nondimensional longitudinal coordinate, $X = x/D$
Y	nondimensional transverse coordinate, $Y = y/D$

Greek symbols

α	thermal diffusivity of fluid
β	thermal volumetric expansion coefficient
γ_s	separation angle
μ	dynamic viscosity
ν	kinematic viscosity
ψ	nondimensional stream function
Ω	nondimensional vorticity
σ	nondimensional pitch-to-diameter ratio, $\sigma = L/D$
σ_v	nondimensional wake closure length, $\sigma_v = L_v/D$
θ	nondimensional temperature
τ	nondimensional time

Subscripts

0	ambient or reference
w	at the surface of the cylinders

In contrast, heat transfer from cylinder arrays in cross-flow has been studied much less extensively. Iacovides et al. (2014) performed flow simulations in large-scale in-line tube banks with confining walls using the wall-resolved large-eddy simulation (LES) and Unsteady Reynolds-Averaged Navier–Stokes (URANS) approaches to assess the effect of the confining boundaries on the flow. Chen and Wang (1989) studied the convective heat transfer and pressure drop for in-line tube and staggered tube arrays with a longitudinal and transverse pitch of two, and pointed out that at high Reynolds number, the local heat transfer tends to peak at the upstream surface of the heated tube while it becomes a minimum at the separation point. Mandhani et al. (2002) investigated numerically the forced convection heat transfer characteristics for an incompressible, steady and Newtonian fluid flow over a bundle of circular cylinders for both isothermal and constant heat flux thermal boundary conditions, and predicted the Nusselt number as a function of the Reynolds and Prandtl numbers for a range of voidages of tube banks. Gowda et al. (1998) investigated numerically the transient fluid flow and thermal response of in-line tube banks and presented the time evolution of streamlines, temperature contours, local and average Nusselt numbers, and pressure and shear-stress distribution around the cylinders. Zhang and Chen (1992) studied experimentally the effect of gap width between tube layers on the heat transfer performance of in-line tube banks. Zukauskas (1972) presented a review of experimental investigations for heat transfer from tube banks in cross flow. Mahir and Altaç (2008) numerically studied the unsteady laminar convective heat transfer from two isothermal cylinders in tandem for Reynolds numbers of 100 and 200 and several values of the pitch ratio. They found that for $\sigma > 4$, the mean Nusselt number of the upstream cylinder approaches that of a single isothermal cylinder, while the mean Nusselt number of the downstream cylinder is about 80% of the latter. Harimi and Saghafian (2012) performed numerical simulations to analyse the forced convection heat transfer from two and three isothermal circular cylinders in tandem arrangement for several spacing ratios and proposed two new correlations for the calculation of the mean Nusselt number in terms of the spacing ratio and the Reynolds and Prandtl numbers. Buyruk (2002) numerically studied the heat transfer characteristics for two isothermal tandem cylinders in cross flow of air at a Reynolds number of 400 and several pitch ratios, and obtained variations of local Nusselt number distributions and local heat transfer coefficient. Beale and Spalding (1998,1999) studied numerically the laminar fully-developed cross flow and heat transfer in tube-bank heat exchangers for in-line square, rotated square, and equilateral triangle configurations. Khan et al. (2006) developed analytical models for the heat transfer from in-line and staggered tube banks in terms of longitudinal and transverse pitches, Reynolds and Prandtl numbers (≥ 0.71). Kaptan et al. (2008) performed a numerical investigation to assess the effects of fouling on