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Experimental study on laminar flow over two confined isothermal cylinders in tandem during mixed convection

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ABSTRACT

An experimental investigation of laminar aiding and opposing mixed convection is carried out using particle image velocimetry (PIV) to assess the thermal effects on the wake of two isothermal cylinders of equal diameter in tandem array placed horizontally and confined inside a vertical closed-loop downward rectangular water channel. The buoyancy effect on the flow distributions are revealed for flow conditions with Reynolds number based on cylinder diameter of $Re = 100$ and 200, blockage ratio of $BR = D/H = 0.3$, aspect ratio of $AR = W/D = 5$, pitch-to-diameter ratio of $\sigma = L/D = 3$, and values of the buoyancy parameter (Richardson number) in the range $-1 \leq Ri \leq 3$. In this work, the interference effects on the complex flow features are presented in the form of mean and instantaneous contours of velocity and vorticity. In addition, separation angles, wake structure, recirculation bubble lengths, time traces of velocity fluctuation, Strouhal number and vortex shedding modes of the two-cylinder system are obtained as a function of the Richardson number. In this arrangement, the results indicate that the effects of the Reynolds number are very pronounced, and that the vortex shedding patterns exhibit a strong dependence on *Ri*. We also show the modulation effect of the channel walls on the three-dimensional flow under varying thermal buoyancy, and the results reported herein demonstrate how the flow structure, wake behavior and vortex shedding pattern are entirely different from that behind a single circular cylinder under wall confinement and thermal effects.

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1. Introduction

Vortex shedding associated with the flow past two cylinders in tandem has been extensively studied because of its remarkable complex flow configurations and wide engineering applications in the design of heat exchanger tubes, electronic packages, cooling towers, cooling systems for nuclear fuel rods, offshore structures, seabed pipelines and chimney stacks. Useful reviews on how the interference effects between the cylinders affects the flow structure, wakes, shear layers and fluctuating fluid forces can be found in Refs. [1–6], and multiple investigations have provided important insight into various features of the tandem cylinder system [7–10]. In particular, for two cylinders of equal diameter, the flow structure is sensitive to the Reynolds number and the pitch ratio ($\sigma = L/D$, ratio between the center-to-center pitch and the cylinder diameter), and three basic interference flow regimes between cylinders have been identified depending on how the wake of the upstream cylinder modifies the incoming flow condition of the downstream cylinder: (i) the "extended body" regime occurs for small pitch ratios of approximately $1 < \sigma < 2$. In this regime, the two cylinders behave as a single bluff body and the shear layers that emanate from the upstream cylinder roll-up behind the downstream cylinder and form a single wake [11–15]; (ii) 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 leading surface ("fore-body", $\sigma = 3–5$) or rear ("after-body",

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Nomenclature

AR	cylinder aspect ratio, W/D
BR	blockage ratio, D/H
D	diameter of cylinders (characteristic length)
f	vortex shedding frequency (Hertz)
g	gravity acceleration
Gr	Grashof number based on cylinder diameter, $Gr = g\beta(T_w - T_0)D^3/\nu^2$
H	channel width
k	thermal conductivity of fluid
L_{tot}	total channel length
Pr	Prandtl number, $Pr = \nu/\alpha$
Re	Reynolds number based on cylinder diameter, $Re = u_0 D/\nu$
Ri	Richardson number based on cylinder diameter, $Ri = Gr/Re^2$
L	pitch (center-to-center distance between two cylinders)
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 of the surface of the cylinders
u_0	fluid velocity at the channel inlet
u, v	longitudinal and transverse velocity components, respectively
U	nondimensional longitudinal velocity component, $U = u/u_0$
V	nondimensional transverse velocity component, $V = v/u_0$
W	cylinder span (channel depth)
x, y, z	rectangular Cartesian coordinates
X	nondimensional longitudinal coordinate, $X = x/D$
Y	nondimensional transverse coordinate, $Y = y/D$
Z	nondimensional coordinate, $Z = z/D$

Greek symbols

α	thermal diffusivity of fluid
β	volumetric expansion coefficient
ρ	fluid density
ν	kinematic viscosity
ψ	nondimensional stream function
Ω	nondimensional instantaneous out of plane vorticity
σ	nondimensional pitch-to-diameter ratio, $\sigma = L/D$
σ_{v1}	nondimensional wake closure length, $\sigma_{v1} = L_{v1}/D$
σ_{v2}	nondimensional wake closure length, $\sigma_{v2} = L_{v2}/D$
τ	nondimensional time
θ_s	separation angle

Subscripts

0	ambient or reference
1,2	refers to the upstream and downstream cylinder, respectively
w	at the surface of the cylinders

$\sigma = 2$–3) of the downstream cylinder [16–20]; and (iii) the co-shedding regime takes place at higher pitch ratios of approximately $\sigma > 5$. In this regime, a vortex street forms behind each cylinder and the vortex shedding from both cylinders takes place at the same frequency [21,22]. In spite that investigations of flow past a circular cylinder placed in a plane channel show that the blockage effect has a significant influence on the flow pattern, force coefficients, length of the recirculation zone, separation angle and Strouhal number, the great majority of research has been made for unconfined cylinder arrays [23–26], and only few comprehensive flow and heat transfer studies have been conducted to assess the confinement effect [27–30].

The foregoing survey of literature reveals that although the interest in heat transfer from tandem cylinders in cross-flow has grown in the last decades, the majority of the contributions to the scientific literature consider the natural [31–45] or forced convection regime [46–56], and limited research has been conducted regarding the effect of blockage constraints under varying thermal buoyancy [57–59]. The main goal of the present study is to perform an experimental investigation using PIV to characterize the flow patterns around two stationary isothermal circular cylinders of equal diameter in tandem arrangement under assisting/opposing buoyancy conditions subjected to a steady cross-flow and wall proximity effects. Two-dimensional spatio-temporal measurements of velocity and vorticity in parallel and perpendicular planes with respect to the span of the cylinders are made in order to gain a better insight of the dynamic interaction between the boundary layers, separating shear layers and the unsteady wakes. Flow visualization images are presented to support the PIV data.

The paper is organised as follows. In Section 2, we describe the experimental setup and provide details about image acquisition, data processing and the uncertainty analysis. Results for the mean

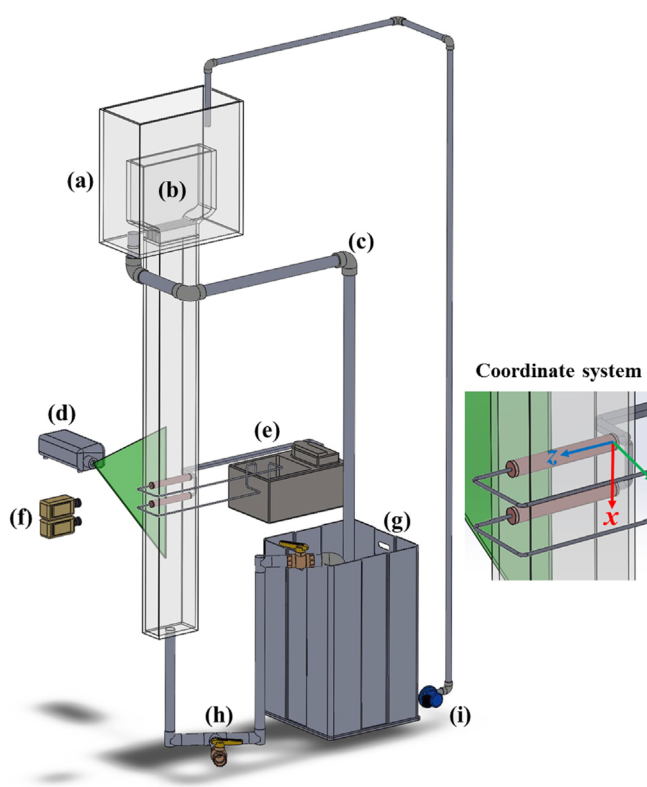

Fig. 1. Schematic diagram of the experimental setup. (a) Constant head tank. (b) Nozzle section with honeycomb and mesh structures. (c) Overflow tube. (d) Laser. (e) Constant-temperature refrigerated bath. (f) CMOS digital cameras. (g) Storage tank. (h) Adjustable valve. (i) Centrifugal pump.

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