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Unsteady laminar mixed convection heat transfer from a horizontal isothermal cylinder in contra-flow: Buoyancy and wall proximity effects on the flow response and wake structure

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ABSTRACT

Particle image velocimetry (PIV) measurements are carried out in an experimental investigation of laminar opposing mixed convection to assess the thermal effects on the wake of an isothermal circular cylinder 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 $Re = 170$, blockage ratio, $D/H = 0.287$, aspect ratio, $L/D = 6.97$ and values of the buoyancy parameter (Richardson number) in the range $-1 \leqslant Ri \leqslant 5$. In this work, flow distributions are presented in the form of mean and instantaneous contours of velocity and vorticity. To elucidate the effects of the lateral wall proximity effect and cylinder aspect ratio, separation angle, wake structure behind the cylinder, recirculation bubble length, time traces of velocity fluctuation, Strouhal number and vortex shedding modes are obtained as a function of the Richardson number. The results reported herein demonstrate how the flow structure and vortex shedding pattern are significantly modified by the wall confinement and thermal effects. In addition, our measurements show that for assisted buoyancy ($Ri = -1$), the breakdown of the Kármán vortex street takes place and vortex shedding is completely suppressed.

1. Introduction

Vortex shedding associated with the flow past a bluff body represents a classical problem in fluid mechanics because of its rich flow physics. In particular, a vast amount of literature exists for the flow past a circular cylinder over a wide range of Reynolds numbers, as is evident in the extensive reviews provided by Berger and Wille [1], Oertel [2], Coutanceau [3], Williamson [4], Norberg [5] and Zdavkovich [6,7]. In contrast, although the problem of mixed convection heat transfer from a circular cylinder has received considerable attention in recent years because of its numerous engineering applications, reference results in mixed convection heat transfer past a circular cylinder are relatively sparse. Badr [8–10] studied numerically the laminar combined convection heat transfer of air from an isothermal horizontal circular cylinder for the two cases of parallel and contra flow regimes for $1 < Re < 40$ and Gr/Re^2 up to 5. Oosthuizen and Madan [11] investigated experimentally the effect of flow direction on combined convective heat transfer from cylinders to air and presented variations of measured Nusselt number with Reynolds number in the range $100 \leqslant Re \leqslant 300$. Jain and Lohar [12] pointed out that an increase in the shedding frequency takes place with increasing cylinder temperature. Soares et al. [13] performed numerical simulations to study the effect of buoyancy on a two-dimensional, steady, incompressible cross-flow over a heated circular cylinder for constant temperature and constant heat flux boundary conditions and pointed out that the buoyancy effects were more pronounced for the case of isothermal boundary condition. Ribeiro et al. [14] performed an experimental and numerical investigation on the laminar steady flow around a confined cylinder placed in a rectangular duct with a 50% blockage ratio duct and presented results for flow patterns, streamwise velocity profiles along the cylinder centerline, contours of normalized pressure and recirculation bubble length for aspect ratios of $AR = 2$, 8 and 16. Kanaris et al. [15] presented two- and three-dimensional direct numerical simulations of the flow around a circular cylinder placed symmetrically in a plane channel for a Reynolds number range of 10–390 and blockage ratio of 0.2 to investigate the confinement effect due to the channel's stationary walls on the force coefficients, the associated Strouhal numbers and generated flow regimes. Their results suggest that up to $Re = 180$, the flow remains two-dimensional, while for higher values, $Re \geqslant 210$, the flow develops three-dimensional effects.

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Nomenclature

AR	cylinder aspect ratio, L/D
BR	blockage ratio, H/D
D	cylinder diameter (characteristic length)
f	vortex shedding frequency (Hz)
g	gravity acceleration
Gr	Grashof number based on cylinder diameter, $Gr = g\beta(T_w - T_0)D^3/\nu^2$
k	thermal conductivity
L	cylinder span
L_v	wake closure length
Pr	Prandtl number, $Pr = \nu/\alpha$
Re	Reynolds number based on cylinder diameter, $Re = u_0D/\nu$
Ri	Richardson number based on cylinder diameter, $Ri = Gr/Re^2$
SD	standard deviation
St	Strouhal number based on cylinder diameter, $St = fD/u_0$
T_0	fluid temperature at the channel inlet
T_w	temperature of the surface of the cylinder
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, $V = v/u_0$
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

β	volumetric expansion coefficient
ρ	fluid density
ν	kinematic viscosity
Ω	nondimensional instantaneous out of plane vorticity
θ_s	separation angle

Mittal [16] performed three-dimensional numerical simulations for the unsteady flow past a confined cylinder of aspect ratio 16 and $Re = 100$, 300 and 1000. His computations confirm that for a cylinder of small aspect ratio with no slip walls, the wake transition regime that determines the mode of vortex shedding (parallel or oblique) is either extended and/or delayed. Wu et al. [17] studied numerically and experimentally the separation angle of the flow around a circular cylinder in the range $7 < Re < 200$ and different blockage ratios. Their results reveal that the blockage effect has much more significant influence on the separation angle in the steady recirculation regime than that in the laminar vortex-shedding regime. Biswas and Sarkar [18] carried out a numerical investigation to study the combined effects of forced and natural convection on the vortex shedding process behind a heated cylinder in a cross-flow at low Reynolds numbers under varying thermal buoyancy and computed eddy length, separation angle, local Nusselt number distributions and isotherms. Their predicted results confirm that the steady wake downstream of the cylinder becomes unsteady periodic in the presence of superimposed thermal buoyancy. Chang and Sa [19] studied numerically the behavior of the shedding frequency, the drag coefficient, and the convective heat transfer due to the buoyant effect from a heated/cooled cylinder in the mixed, natural and forced convection regimes in an upward free stream ($Re = 100$). Their results demonstrate that shedding frequency is heavily dependent on the Grashof number and they distinguished two different flow patterns: periodic flow for $Gr < 1500$ and steady flow with attached twin vortices for $Gr > 1500$. Varma et al. [20] performed numerical simulations of unsteady mixed convection laminar flow past a circular cylinder to assess the influence of small aspect ratio and end effects on the wake instability due to buoyancy effects for $Re = 130$ and $0 < Ri < 1$. Hu and Koochesfahani [21] conducted experiments using molecular tagging velocimetry and thermometry (MTV&T) to reveal the thermal effects on the wake flow pattern and wake vortex shedding process behind a circular cylinder operating in the contra-flow mixed convection regime at $Re = 135$ and for a Richardson number range of 0.0–1.04. They found that for relatively small Richardson numbers ($Ri < 0.31$), the wake closure length is slightly shorter than that of an unheated cylinder. However, with increasing Richardson number ($Ri > 0.31$), the wake closure lengths were found to increase rapidly. In addition, a similar trend was observed with the drag coefficient, and the average Nusselt number was found to decrease almost linearly with increasing Richardson number.

Although the majority of studies in mixed convection flow are aimed towards assessing the thermal effects on the wake of the flow past a circular cylinder for buoyancy opposing flow, several studies regarding the suppression of vortex shedding behind a cylinder during buoyancy assisted mixed convection flow are available. Merkin [22] studied the combined convection boundary layer on a horizontal circular cylinder in a stream flowing vertically upwards for both opposing and assisting buoyancy. He found that heating the cylinder can delay or completely suppress separation, while cooling the cylinder brings the separation point nearer to

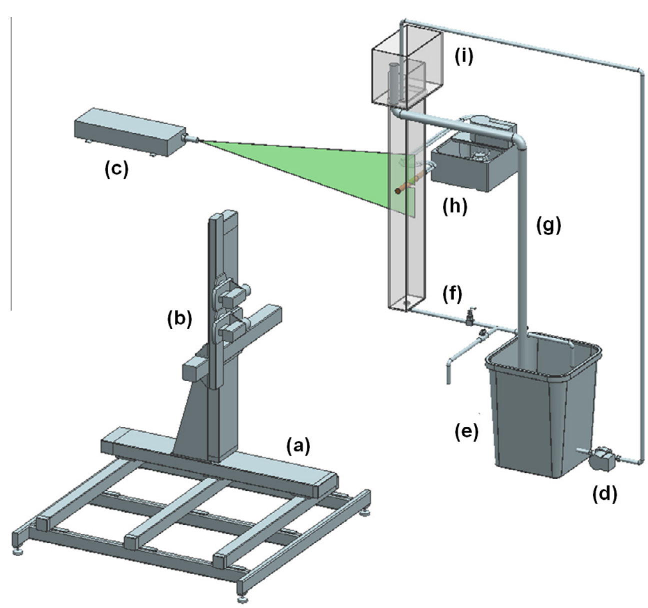

Fig. 1. Schematic diagram of the experimental setup. (a) 3D traverse system. (b) CCD cameras. (c) Laser. (d) Centrifugal pump. (e) Storage tank. (f) Adjustable valve. (g) Overflow tube. (h) Constant temperature bath. (i) Constant head tank.