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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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