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

E. Salcedo[a], J.C. Cajas[b], C. Treviño[c,d], L. Martínez-Suástegui[e,*]

[a] Departamento de Termofluidos, Facultad de Ingeniería, UNAM, México, Ciudad de México 04510, Mexico
[b] Barcelona Supercomputing Center (BCS-CNS), Edificio NEXUS I, Campus Nord UPC, Gran Capitán 2-4, Barcelona 08034, Spain
[c] UMDI, Facultad de Ciencias, Universidad Nacional Autónoma de México, Sisal, Yucatán, Mexico
[d] Chemical Kinetics Laboratory, Institute of Chemistry, Eötvös Lorand University, ELTE, Budapest, Hungary (sabbatical leave)
[e] ESIME Azcapotzalco, Instituto Politécnico Nacional, Avenida de las Granjas No. 682, Colonia Santa Catarina, Delegación Azcapotzalco, México, Ciudad de México 02250, Mexico

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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 $\sigma$ 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

* Corresponding author. Tel.: +52 55 57296000x64505; fax: +52 5557296000x64493.
*E-mail address:* lamartinezs@ipn.mx (L. Martínez-Suástegui).

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