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Numerical investigation of forced convection heat transfer in unsteady flow past a row of square cylinders

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ABSTRACT

This paper presents the unsteady laminar forced convection heat transfer from a row of five isothermal square cylinders placed in a side-by-side arrangement at a Reynolds number of 150. The numerical simulations are performed using a finite volume code based on the PISO algorithm in a collocated grid system. Special attention is paid to investigate the effect of the spacing between the cylinders on the overall transport processes for the separation ratios (spacing to size ratio) between 0.2 and 10. No significant interaction between the wakes is observed for spacing greater than four times the diameter at this Reynolds number. However, at smaller spacing, the wakes interact in a complicated manner resulting different thermo-hydrodynamic regimes. The vortex structures and isotherm patterns obtained are systematically presented and discussed for different separation ratios. In addition, the mean and instantaneous drag and lift coefficients, mean and local Nusselt number and Strouhal number are determined and discussed for various separation ratios. A new correlation is derived for mean Nusselt number as a function of separation ratio for such flows.

1. Introduction

The forced convection heat transfer around multiple bluff bodies has wide engineering applications such as heat exchangers, space heating, cooling towers, chimneys, power generators, heat losses from high-rise buildings and other thermal applications. The most striking phenomenon during the flow past multiple bluff bodies is the generation of a complex flow structure as a consequence of the mutual interactions among the wakes behind the bodies. These wake interactions subsequently lead to the complex vortex shedding phenomena. The forced convection heat transfer and the resulting thermal field is dictated by this complex flow structure. A thorough knowledge of the vortex shedding mechanism is required for better understanding heat transfer in the wakes which is essential for the development of many engineering equipment.

Numerous attempts have been made for modeling the fluid flow and heat transfer over a single circular and/or square cylinder. Additionally, there are many reported work on flow and heat transfer over multiple circular cylinders with various arrangements. Excellent and extensive reviews of the pertinent hydrodynamic studies are available in Zdravkovich (1997, 2003) whereas the thermal aspects can be found in Morgan (1975) and Suzuki and Suzuki (1994). However, there is a real scarcity in the literature for the coupled fluid flow and heat transfer over multiple square cylinders and to the best of the authors' knowledge, there is no reported work on the forced convection heat transfer over a row of square cylinders at low Reynolds number. It needs to be emphasized at this point that the flow patterns and the wake structures for the cases of flow over row of square cylinders are considerably different from that over a row of circular cylinders because of the fact that unlike the circular cylinders the square cylinders tend to fix the separation point, causing differences in the critical regimes. Furthermore, the separation mechanisms depending on the shedding frequencies and the aerodynamic forces also differ significantly for the two geometries.

In the context of flow over a row of square cylinders, Mizushima and Takemoto (1996) performed flow visualization of the pattern downstream of a row of square cylinders. They found for a specific Reynolds number and s/d combinations, both flopping and bistable flip-flop behavior downstream of the cylinders. Kolar et al. (1997) performed measurements on a pair of square cylinders using laser Doppler velocimetry at $Re = 23100$ and $s/d = 2$. They examined the strengths of the vortices both near the gap and in the outer shear layers. It is worth mentioning that their results confirmed the dominant existence of anti-phase synchronized pattern in the flow. Valencia and Cid (2002) numerically investigated

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Nomenclature

C_D	drag coefficient
C_L	lift coefficient
$\overline{C}_D$	mean drag coefficient
d [m]	cylinder size
f [Hz]	frequency of vortex shedding
F_D [N]	drag force
F_L [N]	lift force
g [m/s^2]	acceleration due to gravity
G_r	Grashof number $= g\beta(T_W - T_\infty)d^3/v^2$
h [W/m^{2}K]	local heat transfer coefficient
k [W/mK]	thermal conductivity of fluid
L_i [m]	upstream length
L_o [m]	downstream length
L_x [m]	length of computational domain
L_y [m]	width of computational domain
Nu	local Nusselt number
$\overline{Nu}$	time average Nusselt number
n	normal direction
p	pressure
Pr	Prandtl number = v/α
Re	reynolds number $= u_\infty d/v$
Ri	richardson number $= Gr/Re^2$
s [m]	separation length
St	Strouhal number $= fd/u_\infty$
t	time
T [K]	temperature
T_f [K]	film temperature $= (T_W + T_\infty)/2$
T_W [K]	cylinder surface temperature
T_∞ [K]	free stream temperature
u	axial velocity
u_∞ [m/s]	free stream velocity
v	normal velocity
x, y	axial and normal coordinates of the system

Greek symbols

α [m^2/s]	thermal diffusivity of fluid
β [1/K]	thermal coefficient of volume expansion
θ	temperature
λ_{CD}	mean amplitude of drag coefficient signals
v [m^2/s]	kinematic viscosity of fluid
ρ [kg/m^3]	density of fluid
τ	period of vortex shedding
φ [°]	phase difference between lift coefficient signals

Subscripts

W	cylinder surface
∞	free stream

Superscript

–	dimensional quantity

the unsteady turbulent flow and heat transfer in a channel with stream-wise periodically mounted square bars arranged side-by-side to the approaching flow for a Reynolds number of 2×10^4. Mizushima and Akinaga (2003) investigated experimentally and also numerically the interactions of wakes for the flow past a row of square and circular bars. Their results showed that at $s/d = 1$, in-phase vortex shedding occurred between cylinders whereas at $s/d = 3$, anti-phase shedding was observed. Agrawal

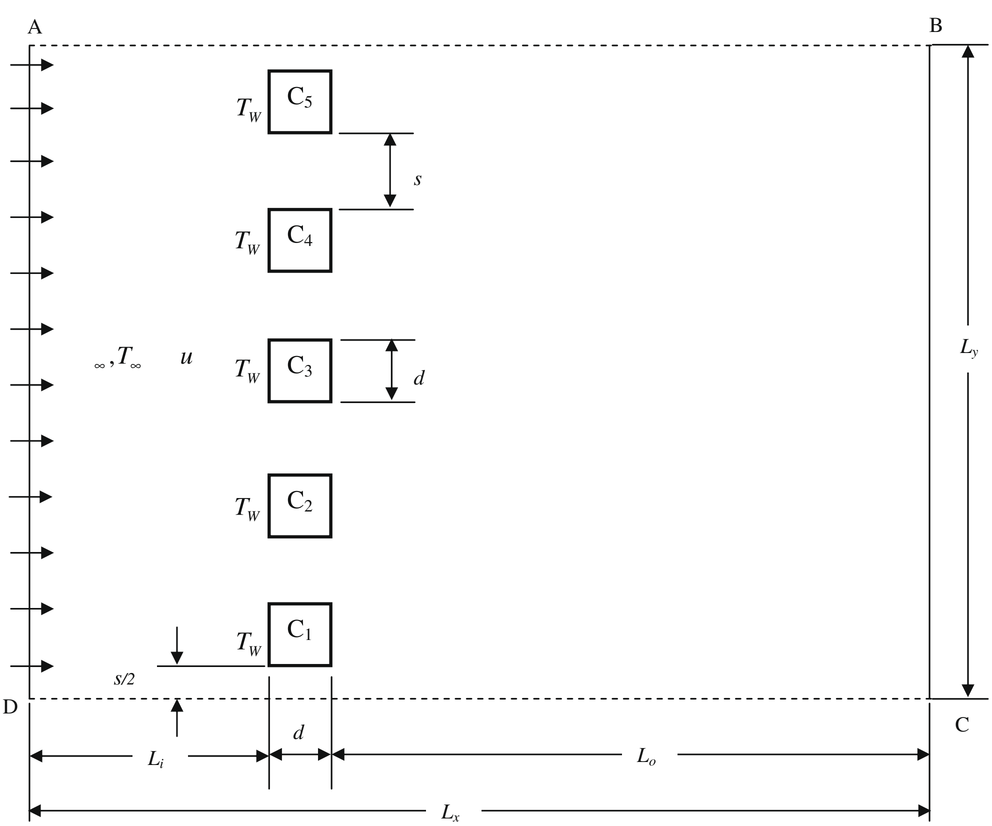

Fig. 1. Schematic diagram of the computational domain. The size of the computational domain is ($L_x = L_i + d + L_0 = 38\ d$, $L_y = 5\ (s + d)$).