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Buoyancy-aided/opposed convection heat transfer for unsteady turbulent flow across a square cylinder in a vertical channel

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Abstract

The Large Eddy Simulation (LES) and SIMPLE-C method coupled with preconditioned conjugate gradient methods have been employed to study the effect of aiding/opposing buoyancy on the turbulent flow field and heat transfer across a square cylinder in a vertical channel. The level of wall-confinement (blockage ratio of 10%, 30% and 50%) was changed with a constant Reynolds number (5000) under various Richardson numbers (−1 to 1). With increasing blockage ratio, the buoyancy effect is becoming weaker on the Nusselt number for the square cylinder. The turbulent heat transfer past the square cylinder can be improved by increasing the blockage ratio.

Keywords: LES; Heat transfer; Buoyancy; Blockage ratio; Vortex shedding; Square cylinder

1. Introduction

Unsteady natural convection flow past bluff bodies in vertical channels has been a subject of numerous engineering applications such as heat exchangers, natural circulation boilers, nuclear reactors, solar heating systems, dry cooling towers, and cooling of electronic equipment. The designs of the configurations require a thorough understanding of the influence of the unsteady vortex structure on the heat transfer and flow field. Most previous studies were focused on circular cylinders placed in a free-stream flow [1,2]. However, flow around the square cylinder is also an important fundamental problem of engineering interest and is investigated here.

Most of the previous heat transfer studies on channel-confined flow across a square cylinder were considered as the forced convection problem [3–5]. Rahbana and Hadi-Moghaddam [6] investigated numerically the unsteady laminar flow past a heated square cylinder mounted inside a plane channel with a blockage ratio of 1/8. Valencia [7] employed the $\kappa-\varepsilon$ turbulence model to study the heat transfer and friction in a channel with a mounted square bar of different sizes detached from the channel wall.

Although many papers have been conducted on the channel-confined flow past a square cylinder for forced convection, there are few studies on natural convection. Chang and Sa [8] numerically studied the effect of the buoyancy on the flow past a hot/cold circular cylinder, at $Re = 100$ for $-1 \leqslant Ri \leqslant 1$ and found suppression of vortex shedding at a critical Ri of 0.15. Sharma and Eswaran [9] showed the influence of channel-confinement and aiding/opposing buoyancy on the 2D laminar flow and heat transfer across a square cylinder. Ho et al. [10] investigated the aiding buoyancy in the steady flow regime with uniform inlet velocity profile for both unconfined and channel-confined upward flow across circular cylinder at $Re = 20, 40$ and $60, 0 \leqslant Ri \leqslant 4$, and blockage ratio of 50%, 25%, 16.67%, and 0%. These above cited papers investigated the laminar flow across a cylinder in a channel with various parameter Ri and blockage ratios, but there are still many other engineering problems involving the turbulent flow. Examining the effect of the buoyancy and the blockage

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Nomenclature

B	width of the square cylinder
C_K	SGS model variable in LES ($C_K = 0.094$)
C_L	lift coefficient ($F_L/\frac{1}{2}\rho v_\infty^2 B$)
C_S	Smagorinsky constant
D	hydraulic diameter of channel ($D = 2H$)
dA	surface area increment along the square cylinder
E_{SGS}	dimensionless subgrid-scale kinetic energy
f_S	frequency of the vortex shedding
f_μ	Van Driest wall damping function $\left(\left[1-\exp\left(-y_n^+/25\right)^3\right]^{1/2}\right)$
G	grid filter function
Gr	Grashof number ($g\beta(T_w^* - T_\infty^*)B^3/v^2$)
H	channel width
l	dimensionless characteristic length scale
L	channel length
L_D	distance between top surface of cylinder and exit plane
L_U	distance between inlet plane and bottom surface of cylinder
n	normal vector
Nu	Nusselt number ($\partial\theta/\partial n$)
$[Nu]$	time-mean Nusselt number ($\int Nu\,dt/\int dt$)
$\langle Nu\rangle$	surface-mean Nusselt number ($\int Nu\,dA/\int dA$)
P	dimensionless static pressure ($P_S/\rho v_\infty^2$)
P_S	static pressure
P^*	summation of $\bar{P}$ and $\frac{2}{3}E_{SGS}$
Pr	Prandtl number (v/λ)
Pr_T	turbulent Prandtl number
q	constant heat flux in Lockett's reference [26]
R	computational domain
Re	Reynolds number based on channel height ($v_\infty B/v$)
Re_D	Reynolds number based on twice channel height ($v_\infty D/v$)
Re_{eff}	effective Reynolds number
Re_{SGS}	SGS Reynolds number
Ri	Richardson number ($Ri = Gr/Re^2$)
Sr	Strouhal number ($Sr = h\cdot f_S/v_\infty$)
S_{ij}	strain rate tensor of the flow field $\left(S_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right)$
$\lvert\bar{S}\rvert$	mean strain $\left(\lvert\bar{S}\rvert = \sqrt{2\bar{S}_{ij}\bar{S}_{ij}}\right)$
S_Φ	source term for variable
T^*	temperature
T_∞^*	uniform inlet temperature
t	dimensionless time ($t^*/(B/v_\infty)$)
t^*	time
Δt	dimensionless time interval
u, v	dimensionless velocity components ($u = u^*/v_\infty$, $v = v^*/v_\infty$)
u_τ	friction velocity $\left(u_\tau \equiv \sqrt{\frac{\tau_w}{\rho}}\right)$
u^*, v^*	velocity components
v_∞	uniform inlet velocity
w	height of square rib in Lockett's reference [26]
x, y	dimensionless x^*, y^* coordinates ($x = x^*/B, y = y^*/B$)
x^*, y^*	physical coordinates
x_i	Cartesian coordinates ($i = 1$ for x-coordinate; $i = 2$ for y-coordinate)
y_w	near-wall distance
y_n^+	dimensionless distance from the wall $\left(y_n^+ \equiv \frac{y_w u_\tau}{v}\right)$

Greek symbols

$\bar{\Delta}$	grid filter width
Φ	general dependent flow variable
Φ'	subgrid-scale component of Φ
Γ_Φ	diffusion coefficient
λ	thermal diffusivity
v	laminar kinematic viscosity
ρ	density
τ_w	wall shear stress
θ	dimensionless temperature $\left((T^* - T_\infty^*)/(T_w^* - T_\infty^*)\right)$
ξ	natural coordinate in computational domain
ζ	dimensionless distance along ribbed wall in Lockett's reference [26]

Superscript

–	spatial grid filter indication

Subscripts

i, j	indication of components
w	indication of wall boundary

ratio on the turbulent flow and heat transfer past a square cylinder in a channel is a motivation to us from practical consideration. The purpose of this study is to quantify the influence of the channel-confinement of various degrees for a square cylinder on the flow field and heat transfer under various Richardson numbers.

The Reynolds-averaged simulations require a fine grid to resolve the regions of rapid variations. Given the complexity of the Reynolds-averaged simulations, a Large Eddy Simulation (LES) might actually be simpler, shorter in execution and more accurate. In the Reynolds-averaged simulations the length scales of the turbulence usually are much larger than the grid spacing. The Reynolds-averaged simulations only reveal unsteady motions of scales larger than the model's turbulence scale. Besides, the eddy viscosity is obtained from the length scale of the smallest eddy in