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Lattice Boltzmann simulations of flow and heat transfer from a permeable triangular cylinder under the influence of aiding buoyancy

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Mesoscopic numerical simulations have been carried out to learn about the flow and heat transfer characteristics of a 2-D permeable triangular cylinder, aligned at two different orientations under the influence of aiding buoyancy. Objective of this study is to investigate the effects of Darcy number and forebody shape on the hydrodynamic and thermal behaviour of the porous cylinder, under forced convection (*i.e.* $Ri = 0$) and aiding buoyancy conditions (Ri = 0.5 and 1) for a Prandtl number value of 0.71 (air). The ranges of Reynolds number (Re) and Darcy number (Da) considered in this study are $1 \leqslant Re \leqslant 40$ and $10^{-6} \leqslant Da \leqslant 10^{-2}$, respectively. Lattice Boltzmann method with two distribution functions is employed to perform the numerical experiments. Alongwith BGK collision operator, a body force term with viscous and inertial effects of the porous medium is employed at the porous zone. Detailed results are exhibited in the form of wake length, drag coefficient, streamlines, isotherm contours, heat transfer enhancement ratio and mean Nusselt number. Furthermore, a comparative investigation of drag coefficient and mean Nusselt number of permeable triangular cylinder (apex and side facing flow) with that of the square cylinder is carried out at $Da = 10^{-6}$ for different buoyancy levels. Under aiding buoyancy condition (*i.e.* $Ri > 0$), the side facing triangular cylinder experiences less drag force than the apex facing for all values of Da. A significant thermal dissipation is observed for increasing values of non-dimensional permeability (or Da) and Richardson number. Furthermore, simple expressions for mean Nusselt number, valid for the range of parameters embraced in the present study, are also provided. The appropriate selection of non-dimensional permeability under different buoyancy conditions is important while applying porous media modeling technique in diverse fields of engineering.

1. Introduction

Thermal incentives, motivated by material and energy saving deliberations, have led to efforts to look for different working fluids, utilisation of higher surface area and various configurations of elements in a system. The usage of working fluids, such as nanofluid and non-Newtonian fluid, have limitations in application inspite of their proven capability in improving heat transfer performance. The same or better augmentation in thermal behaviour of a system can be realised by choosing different fore-body and after-body shapes and orientations. For instance, considering the shape of body, convection heat dissipation of circular, diamond and triangular shaped bodies is more than that of the square-shaped [1]. Therefore, the intrinsic features, configuration of the body are considered to be important while modeling the problem in hand. Apart from modifying the shape of body, increasing its surface area aids improved fluid contact, resulting in effective transport of heat. As an illustration, pin fin arrangement is fitted on electronic chips in order to improve thermal characteristics. Such an arrangement of extended portions can be easily modeled by considering it as a porous body. Furthermore, it is evident from literature [2–4] that the configuration, porosity and permeability of porous body can be altered for the purpose of reaching higher heat performances. A working fluid with rich thermo-physical property shall additionally aid the thermal behaviour from this point. In conclusion, the knowledge of flow and heat transfer from porous bluff bodies with different cross-sections shall assist fellow scholars and engineers while using the porous media approach for seeking solution to real-time engineering problems.

Bao et al. [5] studied numerically the flow around an equilateral cylinder, at different angles (α) of flow, using a two-step Taylor-characteristic-based Galerkin method. It is seen that the triangular cylinder at $\alpha = 60^{\circ}$ (apex facing flow) experiences a lower drag force than the cylinder at $\alpha = 0^{\circ}$ (side facing flow). De and Dalal [6] analysed the flow pattern across a triangular cylinder with apex

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Nomenclature

Notations

AB & AC	front slant edges of apex facing cylinder
C_1 & C_2	binary constants
c_F	non-dimensional Forchheimer term
D	characteristic height of the cylinder, [m]
d_p	particle diameter, [m]
F_b	Boussinesq force term, [N]
$\tilde{f}_i$	particle density distribution function opposite to the direction i
F	body force due to the presence of the porous medium
F_r	resultant force acting on the cylinder, [N]
g	gravitational acceleration, [m s^{-2}]
g_i	temperature distribution function in direction i
G	body force due to gravity, [N]
K	permeability of the material, [m^2]
L_U	upstream length
N	number of lattices on the cylinder
p	dimensionless pressure, $\frac{p^*}{\rho v_0^2}$
PQ & PR	rear slant edges of side facing cylinder
Re	Reynolds number, $\frac{u_\infty D}{\nu}$
Ri	Richardson number, $\frac{g\beta\Delta\theta D}{v_0^2}$
u	non-dimensional x-component velocity, [m s^{-1}]
V	auxiliary velocity, [m s^{-1}]
x, y	horizontal & vertical coordinates
BC	rear flat edge of apex facing cylinder
C_D	coefficient of drag, $\frac{F_D}{0.5\rho v_0^2}$
c_s	speed of the sound [m s^{-1}]
Da	Darcy number, $\frac{K}{D^2}$
e_i	discrete lattice velocity in direction i, $\frac{\Delta x_i}{\Delta t}$
f_i	particle density distribution function in direction i
f_i^{eq}	equilibrium distribution function of density in direction i
F_i	total force term due to porous medium, [N]
F_y	drag force, [N]
g_i^{eq}	equilibrium distribution function of temperature in direction i
$\tilde{g}_i$	temperature distribution function opposite to the direction i
Gr	Grashof number, $\frac{g\beta\Delta\theta D^3}{\nu}$
L_D	downstream length
Ma	Mach number, $\frac{u}{c_s}$
Nu	local Nusselt number, $\frac{\partial\theta}{\partial n}$
Pr	Prandtl number, $\frac{\nu}{\alpha}$
QR	front flat edge of side facing cylinder
R_k	thermal conductivity ratio, $\frac{k_e}{k}$
T	dimensional temperature, [°C]
v	non-dimensional y-component velocity, [m s^{-1}]
w_i	weighing factor in direction i

Greek symbols

ρ	fluid density, [kg m^{-3}]
τ'	dimensionless relaxation time for temperature
Δt	time step, [s]
θ	dimensionless temperature, $\frac{T-T_\infty}{T_w-T_\infty}$
α	thermal diffusivity, [m^2 s^{-1}]
β	thermal expansion coefficient, [°C^{-1}]
Λ	viscosity ratio, $\frac{\mu_e}{\mu}$
τ	dimensionless relaxation time for density
Δx	lattice space
ν	fluid kinematic viscosity, [m^{2}s^{-1}]
ϕ	porosity
τ_t	non-dimensional time, $\frac{t v_\infty}{D}$
μ	fluid dynamic viscosity, [N s m^{-2}]

Subscripts

∞	far field value
M	mean value
w	wall
o	inlet value
i	lattice link direction
e	effective

Superscripts

$*$	dimensional form of variables

facing flow for Re = 10–250. They have reported that the critical Reynolds number at which flow shifts to unsteady regime is 38.9. Further, Tu et al. [7] analysed the flow characteristics and flow-induced forces of a stationary triangular cylinder with different incident angles (0–60°) at Re = 50–160. Their results show that the incident angle can greatly alter pressure distribution around the cylinder. For a example, the pressure stagnation point gradually moves from center of the windward surface (at $\alpha = 0°$) to apex of the cylinder (at $\alpha = 60°$) with increasing incident angles. Dhiman and Kumar [8] studied the effect of blockage ratio (cylinder to channel height ratio) on flow behaviour of non-Newtonian power-law fluids over a triangular cylinder for Reynolds number ranging between $1 \leqslant Re \leqslant 40$. They have found that the overall drag force decreases with the reduction in power-law index and/or blockage ratio. Also, it is evident from literature that the drag force experienced by triangular cylinder is lower than that of the square.

The triangular geometry is encountered in the novel heat exchangers (triangular pitch tube layout) and in pin-fin heat disposal used as sinks in electronic cooling [9] and porous heat sinks. Srikanth et al. [10] studied flow and heat transfer from a long equilateral triangle with apex facing flow for Re = 1–80 at a Pr value of 0.71 (air) for a blockage ratio of 0.25. Due to channel confinement, the critical value of Re is shifted to 58 from 38.9. This study also reveals that the triangular cylinder delivers heat transfer enhancement of 12.5% to 15% for $5 \leqslant Re \leqslant 45$ compared to square cylinder. Further, Zeitoun et al. [1] examined the heat transfer from a triangular cylinder with apex facing and side facing flow conditions for Reynolds number values up to 200 under uniform flow condition. They have formulated correlations for wake length, Strouhal number and Nusselt number for the ranges of parameters considered in their study. It has also shown that the apex facing flow has higher heat transfer rate than square and circular cylinder, and in the case of side facing flow, it is between square and circular cylinder. De and Dalal [11] have conducted a numerical study to see the effects of blockage ratio on flow and thermal dissipation traits from a solid triangular cylinder. Their results show that at a higher blockage ratio, vortex shedding suppresses for lower values of Re, due to viscous effects offered by the channel. However, the Strouhal number has shown increasing trend with blockage ratios for a constant Re. Also, they have reported that vortex shedding is the cause for change in Nusselt number on the rear face of triangular cylinder. Another unsteady flow and heat transfer case has been numerically investigated by Chatterjee and Mondal [12] for different values of Prandtl number (Pr = 0.71, 7 and 100). They have reported that the increase in Re affects the distribution of isotherms on the rear