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Lattice Boltzmann analysis of natural convection in a partially heated open ended enclosure for different fluids

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ABSTRACT

This work presents the lattice Boltzmann simulation of natural convection in an open ended square cavity subjected to partial heating. The size of heater is half of characteristic length and placed at middle location of one vertical wall. Numerical simulations are performed for three different fluids of industrial, scientific as well as domestic field, *viz*., air ($Pr = 0.71$), dichloro-difluoro-methane ($Pr = 4.5$) and water ($Pr = 7$). The influence of the partial heater on heat and hydrodynamic characteristics of an open ended cavity have been elucidated. It is observed that isotherms become more confined toward the partially heated portion of wall with the increase in Prandtl number. The heat transfer rate shows linear increase with the Prandtl number, *i.e*., enclosure containing water shows higher heat transfer rate followed by R-12 refrigerant and air. The numerical results are summarized by the empirical correlation relating Nusselt number with Rayleigh and Prandtl numbers.

1. Introduction

The study of thermally driven flow and heat transfer in open ended enclosures is an important topic owing to its wide range of applications in industrial as well as domestic activities such as solar heat collectors, convection phenomenon from extended surfaces of heat exchanger, solar collectors having insulated strips [1,2], microelectronic devices [3], domestic refrigerators and oven [4].

A large amount of literature related to natural convection in enclosures is now available. For instance, a comprehensive review of natural convection in enclosures is given by Ostrach [5]. Du et al. [6] numerically investigated the mixed convection heat transfer in vertical channel with protruding discrete heaters installed on one side and open to ambient at top and bottom walls. They used SIMPLER scheme for solution of field equations for range of flow governing parameters, such as, Rayleigh number ($0 \le Ra \le 10^7$), Reynolds number ($0 \le Re \le 200$) and aspect ratio ($1 \le AR \le 6$). The results of their study indicated that heat transfer through the right wall increases with decreasing *Re* and increasing *Ra*. Subsequently, Polat and Bilgen [7] studied natural convection heat transfer characteristics in an inclined open shallow cavity. The open cavity is formed by a wall and horizontal fins with constant heat flux applied on the vertical wall of cavity while its other surface kept at isothermal condition. The physical parameters used in this work are, Rayleigh number ($10^6 \le Ra \le 10^{12}$), conductivity ratio (1–60), aspect ratio ($0.125 \le AR \le 1$), dimensionless end wall thickness (0.05–0.20), horizontal wall thickness (0.01–0.15) and inclination of the end wall (45–90°). They observed decrease in volume flow rate and Nusselt number with cavity aspect ratio, horizontal fin thickness and conductivity ratio. The influence of surface radiation on conjugate natural convection in partially open enclosures is conducted by Lauriat and Desrayaud [8]. They observed radiation tends to significantly decrease the temperature of the hot wall while the increase in temperature of the cold wall is less significant. Subsequently, Manca et al. [9] experimentally investigated mixed convection in an open cavity with a heated wall bounded by a horizontal unheated plate for range of Reynolds number ($100 \le Re \le 2000$) and Richardson number ($4.3 \le Ri \le 6400$). The results indicated that for lower Reynolds numbers, the forced motion penetrates inside the cavity, and a vortex structure is formed adjacent to the unheated vertical plate. Kiwan and Khodier [10] studied the natural convection heat transfer in an open ended inclined channel partially filled with porous medium. The Darcy–Brinkman–Forchheimer model along with Boussinesq approximation is used to describe field equations. They reported reduction in the average flow in the porous substrate due to air gap presence to zero. The numerical study of conjugate convection with surface radiation from an open cavity with a traversable flush mounted discrete heat source in the left wall is reported by Gururaja et al. [11]. They investigated the influence of range of physical parameters (surface emissivity, convection heat transfer coefficient, aspect ratio and thermal conductivity) on rate of heat transfer. The bottom end of the cavity is identified as the best possible position for the discrete heating

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Nomenclature

AR	aspect ratio (L/H), dimensionless
c	lattice speed (dx/dt), dimensionless
e_k	discrete particle velocity at link k, dimensionless
f	density distribution function, dimensionless
F_k	buoyancy force, kg s/m^2
f_k^{eq}	equilibrium distribution function for flow field, dimensionless
g	temperature distribution function, dimensionless
g_k^{eq}	equilibrium distribution function for thermal field, dimensionless
g_y	acceleration due to gravity, m^2/s
H	height of enclosure, m
k	lattice link direction, dimensionless
$\hat{k}$	opposite lattice link direction of k, dimensionless
L	length of enclosure, m
L_h	size of partial heater, m
Nu	local Nusselt number, dimensionless
Nu_{simu}	simulated Nusselt number, dimensionless
Nu_{pred}	predicted Nusselt number, dimensionless
Nu	average Nusselt number, dimensionless
P	pressure, dimensionless
t	lattice time, s
T	temperature, K
$\overline{T}$	reference temperature, $(T_h + T_c)/2$, K
Δt	lattice time step, s
$U_{x,y}$	velocity components, dimensionless
ν	kinematic viscosity, m^2/s
w_k	weight function for kth lattice link, dimensionless
X, Y	horizontal and vertical coordinates, dimensionless

Greek letters

α	thermal diffusivity, m^2/s
β	coefficient of thermal expansion, 1/K
δ_{th}	thickness of thermal boundary layer, $\approx \mathrm{Pr}^{(1/6)}\sqrt{\frac{\alpha H}{V}}$, m
θ	normalized temperature, $(T - T_c)/(T_h - T_c)$, dimensionless
ρ	density, kg/m^3
τ_ν	relaxation time for flow field, m^2/s
τ_g	relaxation time for thermal field, m^2/s
ξ	vorticity, m^2/s
ψ	stream function, m^2/s

Dimensionless groups

Gr	Grashof number, $(\frac{g\beta\Delta TH^3}{\nu^2})$
Pr	Prandtl number (ν/α)
Ra	Rayleigh number, $(\frac{g\beta\Delta TH^3}{\nu\alpha})$

source. Subsequently, Shi and Vafai [12] studied the mixed convection heat transfer analysis in an obstructed cavity with open end by using Brinkman–Forchheimer–extended Darcy model for range of physical parameters, such as, Grashof number ($10^2 \le Gr \le 10^9$), Reynolds number ($100 \le Re \le 10^5$), Darcy number ($10^{-6} \le Da \le 10^{-1}$) and aspect ratio ($0.25 \le \mathrm{AR} \le 2$). The increase in aspect ratio leads to increase in the thickness of the thermal boundary layer, resulting in a decrease in the heat transfer rate though the horizontal walls.

The numerical study of the natural convection in a horizontal open ended cavity with upper wall heated is reported by Andreozzi and Manca [13]. The streamline behavior showed a convective loop outside of the cavity for the $Ra = 10^3$; whereas at $Ra = 10^5$, a plume lifted off the edges of the upper plate very close to the vertical external unheated walls. Hinojosa and Gortari [14] delineated the steady-state and transient natural convection ($Ra = 10^4$–10^7) in an isothermal open cubic cavity. The field equations are solved by using finite volume method and the SIMPLEC algorithm. The results of the study indicated flow instabilities and Nusselt number oscillations for high Rayleigh numbers. Similarly, numerical investigation of natural convection in a vertical annulus closed at top and opened at bottom is delineated by Lal and Verma [15]. For a given value of % gap ratio, the flow is observed to be smooth and heat transfer does not suffer sharp variations up to a certain value of Rayleigh number. The increase of Ra beyond this value leads to occurrence of number of recirculating loops in the flow and sharp spatial fluctuations of heat transfer within the annulus. Few recent studies of natural convection in an open ended cavity are reported by [16–18]. Mahmoudi et al. [16] analyzed the MHD natural convection heat transfer nanofluids-filled open cavity with non uniform boundary condition in the presence of uniform heat generation/absorption by using lattice Boltzmann method. The study was carried out by using physical flow governing parameters, such as, Rayleigh number (10^3–10^6), Hartmann number ($Ha = 0$–60), heat generation/absorption coefficient ($q = -10, -5, 0, 5, 10$) and the solid volume fraction of nanoparticles between $\varphi = 0$ and 6%. The results of this study indicated the decrease in heat transfer rate with Hartmann number and linear variation with Rayleigh number. Similarly, lattice Boltzmann simulation of MHD natural convection heat transfer in an open enclosure filled with Cu-water nanofluids is illustrated by Hussein et al. [17]. The absolute values of stream-function decrease significantly with Hartmann number while these values increase by increasing Rayleigh numbers. More recently, Pina-Ortiz et al. [18] presented a comparison of six turbulence models and experimental temperature profiles for the turbulent natural convection in a tilted open cubic cavity. The lowest absolute average percentage difference for the experimental and numerical temperature profiles was for the $rk - \varepsilon_t$ model and the highest was for the $sk - \omega$ model.

Tables 1 and 2 represent the summary of available literature on the natural convection in open ended as well as differentially heated cavity with wall completely [19–28] and partially heated [29–35], respectively with their ranges of physical parameters. It can be concluded that from Tables 1 and 2 and aforementioned discussion that huge amount of the literature pertaining to the convection heat transfer characteristics from cavity with one wall completely heated is now available. But the study of natural convection in partially heated cavity is much less extensive. Few studies have explored the influence of partial heating on natural [29–33,35] as well as mixed convection heat transfer [34]. But the physical domain considered in their work was triangular cavity [29], differentially heated square cavity [29,31–35] and differentially heated lid driven cavity [30]. The influence of Prandtl number on natural convective heat transfer in an open ended cavity has been explored by [20,22,26,29]. The physical domain used by Khanafer and Vafai [20] is partially open enclosure (enclosure with partial opening), whereas Varol et al. [22] used square differentially cavity with partition. Kefayati et al. [26] have explored the natural convection in an open ended cavity for three Prandtl numbers, but the vertical wall of cavity is completely heated. Recently, Gangawane et al. [28] studied the influence of wide range of Prandtl number ($0.71 \le Pr \le 100$) and Rayleigh number ($10^4 \le Ra \le 10^6$) on heat transfer characteristics of differentially heated square cavity by using lattice Boltzmann method.

Therefore, from aforementioned discussion and Tables 1 and 2, it can be safely concluded that, there is scant literature available on study of the convective heat transfer characteristics in an open ended enclosures by lattice Boltzmann method (LBM) as well as convectional CFD methods. But most of the studies, to the best of our knowledge have considered uniformly heated wall containing single fluid or nano-fluids. No study is available for exploring natural convection heat transfer in a partially heated open ended cavity. The gaps available in the literature have inspired us to conduct this study. Therefore, the present work aims to explore the heat and fluid flow characteristics due to natural convection in an open ended enclosure with one