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Natural convection heat transfer in a square cavity with sinusoidal roughness elements

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ABSTRACT

Natural convection in a two-dimensional square cavity in the presence of roughness on vertical walls was studied numerically. A single relaxation time Bhatnagar–Gross and Krook (BGK) model of Lattice Boltzmann method (LBM) was utilized to solve coupled momentum and energy equations. Validation of computational algorithm was performed against benchmark solutions, and a good agreement was found. Numerical study was performed for a range of the Rayleigh number from 10^3 to 10^6 for a Newtonian fluid of the Prandtl number 1.0. The sinusoidal roughness elements were located on a hot, and both the hot and cold walls simultaneously with varying number of elements and the dimensionless amplitude. Hydrodynamic and thermal behavior of fluid in the presence of roughness was analyzed in form of isotherms, velocity streamlines, and the average heat transfer. Results based on this numerical study showed that the sinusoidal roughness considerably affect the hydrodynamic and thermal behavior of fluid in a square cavity. A dimensionless amplitude of sinusoidal roughness elements approximately equal to 0.025 has no significant effects on the average heat transfer. The maximum reduction in the average heat transfer was calculated to be 28% when the sinusoidal roughness elements were located on both the hot and cold walls simultaneously.

1. Introduction

Enhancement of heat transfer between constant temperature walls is desired in many heat transfer applications. Surface roughness is considered as one of the possible method to augment heat transfer [1]. Heat transfer through natural convection from vertical walls with some sort of roughness present, came across in many applications like electronic equipment, solar collectors, energy systems for buildings, safety of nuclear reactors, and thermal storage tanks for fluid etc. [2–4]. If surface roughness can cause a significant enhancement in heat transfer, it will be more appealing solution as compared to the incorporation of fins on vertical walls [5]. Natural convection in bounded and unbounded geometries is the most commonly studied aspect of heat transfer. But study of natural convection in the presence of complex geometries has not been studied at large. Moreover, the results reported by these studies are conflicting [5]. Therefore, a fundamental study is necessitated for a better understanding of the role of surface roughness during natural convection.

Buoyancy induced natural convection in a square cavity with smooth walls has been extensively studied theoretically, experimentally, and numerically for decades and detailed analysis are available in literature [3,6–9]. But studies of the natural convection heat transfer in square and rectangular enclosures in the presence of partitions, and surface roughness are limited to some shapes of partitions, and roughness elements. Bajorek and Llyod [10] experimentally studied the effects of an insulated rectangular partition located on the horizontal adiabatic wall in a square cavity. They used air and carbon dioxide as working fluid in the range of Gr from 1.7×10^5 to 3.0×10^6. They observed a decrease in the heat transfer from 12 to 21% in the presence of partitions as compared to a smooth cavity. Kaviany [11] numerically studied the influence of a cylindrical protuberance present on an adiabatic horizontal wall in the presence of isothermal vertical walls in a square cavity with air as working fluid. He used a finite difference based method for numerical study. The range of Ra number explored was up to 10^4. By varying the radius of protuberance, a decrease in the average and local heat transfer was observed.

Anderson and Bohn [12] studied the effects of square roughness elements on the heat transfer in a cubical cavity using water as a working fluid. They observed an increase in the average heat transfer up to 15% at 3.3×10^{10} with no enhancement for $Ra_L < 2.2 \times 10^{10}$. Moreover, an increase in the local heat transfer was found to be up to 40%. Shaw et al. [13] numerically studied the effects of partitions present on the adiabatic horizontal wall

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Nomenclature

A	dimensionless amplitude (h/H)
g	gravitational acceleration (m s^{-2})
H	height of cavity (m)
h	height of roughness element (m)
K	thermal conductivity (W m^{-1} k^{-1})
L	length of cavity (m)
lu	lattice unit
Nu	Nusselt number
n	number of roughness elements
Pr	Prandtl number
Ra	Rayleigh Number
ΔT	temperature difference (K)
T_c	temperature of cold wall (K)
T_h	temperature of hot wall (K)
T_{ref}	reference temperature (K)
ts	time step
U	horizontal velocity component (m s^{-1})
V	vertical velocity component (m s^{-1})
x	coordinate parallel to the wall (m)
y	coordinate normal to the wall (m)

Greek symbols

α	molecular thermal diffusivity (m^2 s^{-1})
β	coefficient of thermal expansion (K^{-1})
θ	dimensionless temperature
ν	molecular kinematic viscosity (m^2 s^{-1})
ρ	density (kg m^{-3})

with isothermal vertical walls using cubic spline method in a laminar region. They found that the increase in partition height resulted a decrease in the average heat transfer and significantly influence flow behavior inside cavity.

Shakerin et al. [14] studied the role of rectangular roughness elements in a square cavity experimentally using dye flow visualization technique and numerically using finite difference method. They introduced a single and double rectangular roughness elements by varying spacing between them in a square cavity on isothermal vertical walls and adiabatic horizontal walls. An increase of up to 12% in the average heat transfer was observed as compared to a smooth cavity for a single roughness element. For double roughness elements, the increase was up to 16%. They concluded that addition in the surface area due to the roughness on isothermal wall was balanced by the obstruction caused in velocity, as increase in the average Nu was much smaller as compared to increase in the surface area due to the presence of the roughness. They did not report formation of eddies in the wakes of the roughness elements. Moreover, they found that single roughness element was a poor fin and spacing between elements may significantly affect the average heat transfer.

Acharya and Jetli [15] numerically studied the role of partition in a laminar and turbulent region in a square cavity by varying position and height of partition. They concluded that the height of partition significantly influence the heat transfer as compared to position of partition. Ruhul Amin [16] used a finite element based computational code NACHOS to study natural convection in a square cavity with rectangular roughness elements. He considered a fluid of Pr number 10 and variable amplitude and spacing between the roughness elements. He observed that the presence of roughness on bottom isothermal wall causes a delay in the onset of convection in enclosure. Also, he concluded that the average heat transfer increased at low Ra number of 2×10^3 while it decreased at Ra number 3×10^4. A maximum decrease was found to be 61% at Ra number 3×10^4. Yucel and Ozdem [17] numerically investigated the role of adiabatic and fully conducting multiple partitions on horizontal walls with air as working fluid. They used finite difference method based computational code by varying boundary conditions of horizontal walls as adiabatic and conducting while keeping vertical walls as isothermal throughout the study. They observed that average Nu decreased in both cases either insulated or conducting horizontal walls or partitions and also due to increase in the height of partitions.

Shi and Khodadadi [18] performed a numerical study to observe the role of a thin fin on an isothermal vertical wall in a square enclosure in a laminar flow region of a fluid of Pr number 0.7. They used finite difference method based approach and concluded that average Nu always degraded in the presence of thin fin with variation of position and length. Hasan et al. [19] studied effects of wavy top horizontal wall in a cavity of different aspect ratio (H/L) from 0.5 to 2.0. They utilized finite element based approach with air as a working fluid. They varied the frequency of corrugation. Vertical walls were kept isothermal with bottom horizontal wall as adiabatic and wavy wall at uniform heat flux. They observed that for small aspect ratio, average Nu decreased up to Ra number < 10^4, when the Ra was increase past 10^4, Nu increased. Moreover, they concluded that an increase in corrugation of top wall enhances convective heat transfer.

Besides traditional numerical schemes illustrated above based on finite volume, finite difference, and finite element method, Lattice Boltzmann method has obtained a significant success in solving Navier–Stokes and energy equations in computational fluid dynamics [20,21]. Lattice Boltzmann method (LBM) was originated from lattice gas automata. In the last two decades, LBM extensively used in the study of complex fluid flow systems for single and multi-phases [22,23]. Mohamad and Kuzmin [24] studied natural convection in a square cavity by using a simple LBM to analyze different force incorporation schemes. Dixit and Babu [20] utilized non-uniform mesh to observe thermal and fluid flow behavior using BGK model of LBM in a square cavity up to 10^{10} for a fluid of Pr number 1.0. Yang et al. [23] modified BGK model of LBM to enhance its numerical stability. They studied natural convection in a square cavity up to Ra number 10^{12} by introducing a correction parameter with air as a working fluid.

Most of the experimental and numerical studies discussed above, investigated the natural convection in a square cavity with rectangular or square roughness elements, partitions or fins on isothermal or adiabatic walls. However, reports on buoyancy induced natural convection in a square cavity with sinusoidal roughness elements on isothermal vertical walls in a laminar region of fluid flow are rare. Based on the literature survey, for natural convection with rectangular and square roughness elements, the observations are contradicting. At present, no rational conclusion can be drawn without fully understanding the role of many different shapes of roughness. Therefore, in the present study, the effect of frequency and dimensionless amplitude of sinusoidal roughness elements on the hot, and both the hot and cold walls simultaneously has been investigated. Numerical study was performed by using single relaxation time Bhatnagr–Gross and Krook (BGK) model of Lattice Boltzmann method (LBM) for a Newtonian fluid of the Prandtl number 1.0 in a two-dimensional square cavity. The range of Ra number explored was 10^3–10^6 for a differentially heated rough square cavity.