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Three-dimensional natural convection of molten Lithium in a differentially heated rotating cubic cavity about a vertical ridge

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ABSTRACT

Laminar natural convection heat transfer in three-dimensional molten Lithium filled differentially heated enclosure, rotating about the vertical ridge is studied numerically. Computations are performed for a wide range of dimensionless parameters including the rotational Rayleigh number, and Taylor number while the values of Rayleigh number and Prandtl numbers are maintained constant at $Ra = 2 \times 10^4$ and $Pr = 0.0321$, respectively. The results indicate that Coriolis forces seem to have a dominant role to suppress the thermal buoyancy driven effects. Transverse velocity isovaleurs show three-dimensional characteristics of the flow. By increasing, the Taylor number, the maxima of heat transfer gradually reduced about 55%. In the contrast, high rotational Rayleigh number values are found to significantly alter the flow patterns by increasing mixing which turn enhances the heat transfer.

1. Introduction

Rotating flows have wide range of technological applications, e.g. centrifugal pumps, manufacturing of crystal for semiconductor industries and numerous metallurgical processes, turbo-machinery [1], as well as in geophysical and astrophysical concerns over a large range of scales [2]. Due to rotation the heat transfer characteristic of the flow becomes complex and thereby, makes it very challenging in terms of numerical and experimental investigations especially in confined enclosures where bifurcations and transition to turbulence phenomena are imminent [3].

Both Coriolis and centrifugal forces with the rotation of the container containing fluids affect the flow. Especially in scientific fields like geology, oceanography and climatology, lots of intensive research regarding convection in rotating systems have been conducted [4]. Cavity is sometimes rotated to stabilize the flow as well as heat transfer. This phenomenon is particularly very important concerning the flow of liquid metals inside an enclosure. In fact, rotating liquid metals ensure the manufacture of higher quality crystals in the semiconductor industry [1,5].The literature pertaining to rotational fluid dynamics is well documented in both bi and three-dimensional configuration.

Baig and Masood [6] have carried out a numerical study of two-dimensional natural convection in a rotating and differentially heated square enclosure. The cavity is rotated at a constant angular speed about an axis orthogonal to the gravity axis and passing through the center of the cavity. It was found that a significant enhancement in heat transfer is achieved due to rotational effects. At a particular Ra, increase in Ta results in an increase in frequency of oscillations. Two-dimensional unsteady numerical studies were made on an air-filled enclosure rotated about its horizontal axis with an array of three rows of heat sources on one of the walls have been conducted by Jin et al. [7]. The evolutionary process of flow field and natural convection characteristics from stationary to rotating situation is studied. The authors showed that rotation reduces oscillation in Nusselt number, but in contrast, it improves heat transfer in the weak stages. Baig and Zunaid [8] have also studied natural convection of liquid metals in differentially heated enclosure undergoing orthogonal rotation. They have noticed that at higher values of Ta and Ra_w, two horizontally aligned counter-rotating rolls are occurred. Furthermore, results revealed that the rotational effects, especially influenced by centrifugal force, could achieve significant increase or decrease in heat transfer rates. Tso et al. [9] investigated the effects of Coriolis force, centrifugal force, and thermal buoyancy force numerically on an air-filled, differentially heated enclosure, with the enclosure rotated about its horizontal axis. They validated their numerical results with the experimental results of Hamadi et al. [10]. They have concluded that the effects of Coriolis force and centrifugal force on the natural convection are small and are differentiated from those of other forces. Recently, Saleh et al. [11] investigated the rotation effects on non-Darcy convection in an enclosure filled with porous medium. In their study, they assumed the centrifugal force weaker than the Coriolis force. It was found that the global quantity of the heat transfer rate increases by increasing the porosity and the Darcy number and decreases by increasing the Taylor number.

All the above works pertain only bidimensional natural convection flows subjected to rotation. Advances in computational speed and numerical methods now allow numerical simulation of three-dimensional,

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Nomenclature

L	height of the enclosure, m
k	thermal conductivity, W m^{-1} K^{-1}
r	position vector, m
$\dot{\mathbf{r}}$	velocity vector (dr/dt), m s^{-1}
u	x-velocity component, m s^{-1}
U	dimensionless X-velocity component, u L/ν
v	*y*-velocity component, m s^{-1}
V	dimensionless Y-velocity component, v L/ν
V	velocity vector, m s^{-1}
w	*z*-velocity component, m s^{-1}
W	dimensionless Z-velocity component, w L/ν
Ω	speed of rotation, rad/s
x	x-Cartesian coordinate, m
X	dimensionless X-Cartesian coordinate, x/L
y	*y*-Cartesian coordinate, m
Y	dimensionless Y-Cartesian coordinate, y/L
z	z-Cartesian coordinate, m
Z	dimensionless Z-Cartesian coordinate, z/L
ΔT	reference temperature difference, $T_H - T_C$, K
$\overline{Nu}$	average Nusselt number
$\overline{Nu}_Z$	Z-direction average Nusselt
p	pressure, N m^{-2}
P	dimensionless pressure, $pL^2/\rho_0\,\nu^2$
Pr	Prandtl number, ν/α
Ra	Rayleigh number, $g\beta\,\Delta T\,L^3\,/\,\nu\,\alpha$
Ra_w	rotational Rayleigh number, $\beta\,\Omega^2\,\Delta T\,L^4/\nu\alpha$
Ta	Taylor number, $\Omega^2\,L^4/\nu^2$
T	dimensional temperature, K
T_C	temperature of cold (vertical right) wall, K
T_H	temperature of hot (vertical left) wall, K
t	dimensional time, s
E_C	kinetic energy
COR	Coriolis force magnitude, $2\,Pr\sqrt{Ta(U^2+V^2)}$
CEF	centrifugal force magnitude, $Ra_w\,Pr\theta\sqrt{(X^2+Y^2)}$
TBF	thermal buoyancy force magnitude, TBF = Ra Pr θ

Greek symbols

α	thermal diffusivity, $m^2\,s^{-1}$
β	thermal expansion coefficient, K^{-1}
Δ	difference value
ν	kinematic viscosity, $m^2\,s^{-1}$
μ	dynamic viscosity, N s/m^2
θ	dimensionless temperature, $(T - T_C)/\Delta T$
ρ	fluid density, kg/m^3
ρ_0	reference density, kg/m^3
τ	dimensionless time, t ν/L^2
ϕ	generic variable (U, V, W, P or θ)
ψ	dimensionless stream-function

Subscripts

max, min	maximum, minimum
H	hot
C	cold

low-Prandtl-number rotating natural convection. Lee and Lin [12] reported an early study of transient three-dimensional convection of air in a differentially heated rotating cubic cavity about a vertical axis through the cavity center. According to their numerical results, the centrifugal and Coriolis forces were found to exhibit significant effects on the flow and heat transfer in the cavity when they are high enough. They have also noticed that the effects of the cavity inclination are unimportant in a centrifugal force dominated flow whereas a flow transition through the Hopf bifurcation instability was observed. A combined numerical and experimental study was carried out by Ker and Lin [13] to investigate the flow stability in an inclined differentially heated cubic cavity filled with air and subject to rotation about an axis which is normal to the insulated bottom wall and through the geometric center of the cavity. The numerical results clearly revealed the complex multicellular flow structure in a vertical cavity at low rotation rates in which the mutual interactions of the thermal buoyancy, Coriolis force and rotational buoyancy are important. The experimental data suggested that the airflow could be stabilized by the cavity rotation when the rotation rate is low. However, at high rotating speed the cavity rotation produced destabilizing effects. Lin et al. [14] performed a combined experimental and three-dimensional conjugated heat transfer analysis of vortex flow development in mixed convection of air in a horizontal rectangular duct. Both the experimental and numerical results clearly showed the generation of the longitudinal vortex rolls in the entry region of the duct and the merging of the rolls downstream. Tang and Hudson [15] conducted experiments on a rotating fluid heated from below. The influence of rotation on heat transfer and on the onset of gravitational instabilities was determined. The turbulent Rayleigh–Bénard convection flow subject to various rotation rates was addressed by numerical investigations in the work of Kunnen et al. [16]. Steady rotation is applied about the vertical axis. The main results show, that at appropriate rotation rates, the heat flux through the fluid layer is increased relative to the non-rotating case. At sufficiently rapid rotation, however, the heat flux through the fluid layer is strongly attenuated. Three-dimensional direct numerical simulation of turbulent flow and combined convective heat transfer in a square duct with axial rotation have been carried out by Yang et al. [17]. The results show that thermal boundary conditions have significant effects on the topology of secondary flows. Sedelnikov et al. [18] have performed a three-dimensional numerical study of natural convection in a cubical cavity heated from below and rotating about its vertical axis of symmetry. The onset of convection is investigated for moderate values of the Rayleigh number. However, at higher values of Ra transitions to steady regimes of convection occur, at least as long as the Coriolis parameter is not too large. Stevens et al. [19] have also studied, both numerically and experimentally, the rotating Rayleigh–Bénard convection. Special attention was given to the influence of the aspect ratio on the rotation rate that is required to get heat transport enhancement. In addition, the authors discussed the relation between the heat transfer and the large-scale flow structures that was formed in the different regimes of rotating Rayleigh-Bénard convection. These regimes have been identified in experiments and simulations. Recently, the coupling effects between centrifugal acceleration and temperature field in a closed cavity have been studied through numerical simulation and experiments by He and Xu [20]. The results show that thermal buoyancy, centrifugal buoyancy and Coriolis force affect the temperature distribution obviously. Moreover, the convective heat transfer is enhanced by the centrifugal acceleration.

In the above-mentioned studies, both numerical and experimental models were used to simulate heat and mass transfer in rotating ducts for cases of either air or water. The literature was relatively scarce in what concerns research work dealing with rotating convection flow especially inside cubical enclosures undergoing rotation, for low Prandtl number fluids. However, depending on the nature of the fluid in the rotating cavity, significant three-dimensional effects can arise [21–22]. Lithium has gained attention as a candidate plasma facing material in several experiments, both as a solid and as a liquid [23–24]. Among these applications, we find thermal equipment for cooling and efficient regeneration of liquid Lithium in the type of plasma reactors and the production of high quality crystals [25].

Liquid metals are the extensively used as coolants in nuclear reactors. Heat transfer plays an important role in determining the efficiency of the reactor, the choice of the coolant for a particular application is a major aspect of design [26]. Lithium alloys seem to have several attractive thermo-physical properties that would make them potentially