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Liquid metal buoyancy driven convection heat transfer in a rectangular enclosure in the presence of a transverse magnetic field

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ABSTRACT

Liquid metal, an electrically conducting fluid, buoyancy driven convection heat transfer processes are fundamental problems in the design of the fusion reactor due to the influence of the large temperature difference and the strong magnetic field. An investigation of liquid metal buoyancy driven convection heat transfer is conducted in a rectangular enclosure with a square cross-section under the influence of a uniform horizontal magnetic field. Two opposite vertical walls are maintained at different temperatures and the other four walls are thermally insulating. The applied magnetic field is perpendicular to the temperature gradient. Ultrasound Doppler velocimetry measurement method is used to get natural convection velocity in different temperature difference and different magnetic field intensities. The flow is characterized by the external Grashof number, *Gr*, determined from the temperature difference of the side walls, and the Hartmann number, *Ha*, determined from the intensities of the imposed magnetic field. Two multiple linear regression models of the Nusselt number based on the Hartmann layers theory are summarized which indicate that the induced current's restraining influence determines the natural convection heat transfer process of viscous electric liquids in a strong magnetic field.

1. Introduction

Liquid metal is a kind of important energy transport carrier in the nuclear reactor, the accelerator driven sub critical system and the spallation neutron source device, etc. Especially the most promising method in the future fusion reactor is to use liquid metal lithium in the blanket to produce tritium. In the fusion reactor, there are large heat loads in the first wall of facing high temperature plasma to engender considerable temperature differences with the cladding walls to form natural convection of liquid metal. It is a buoyant driven convection of liquid metal under the influence of a strong magnetic field. As an electrically conducting fluid, the buoyant driven convection of liquid metal heat transfer process is an important topic for the design of the fusion reactor.

For transparent media, there were systematic analysis methods and measurement technologies [1–3]. Using Particle Image Velocimetry (PIV) method, the two-dimensional velocity distribution of air natural convection was gotten in a square enclosure [4]. It is easy to obtain the flow field inside the transparent liquid, and the velocity information can be used to analyze the heat transfer characteristics even with complex structure and complex heat transfer conditions.

When there is a magnetic field, containing the uniform and gradient magnetic field, there is a complex influence mechanism for the flow and heat transfer process. The electrically conducting fluid flows through a magnetic field to generate an induced current inside itself, which produces a Lorentz force $J \times B$ to promote or restrain the electrically conducting fluid flow.

Natural convection of salt water under the different directions of the magnetic field in a horizontal cylindrical annulus was numerically studied using lattice Boltzmann method. The computational results revealed the flow oscillations could be suppressed effectively by imposing an external horizontal magnetic field [5]. In a gradient magnetic field, researchers studied the salt solution natural convection and found that the gradient magnetic field could strengthen or weaken the heat transfer process [6]. Thermal convection magnetic control in electrically non-conducting or low-conducting paramagnetic fluids was studied showing magnetic field controlling the flow and heat transfer characteristic [7]. It is worth noting that the conductivity of liquid metal is much larger than that of the salt solution, so the induced current in the liquid metal is larger and the magneto hydrodynamic (MHD) effect is stronger.

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Nomenclature

A	heat transfer area, m^2
b	magnetic field, T
B	dimensionless magnetic field
E	electric field, V/m
Gr	Grashof number
H	Height of container, m
Ha	Hartmann number
j_x, j_y, j_z	electrical current, A
J_x, J_y, J_z	dimensionless current
L	length of container, m
N	Stuart number
Nu	Nusselt number
p	pressure, Pa
P	dimensionless pressure
Pr	Prandtl number
Q	heat quantity, W
Ra	Rayleigh number
t	time, s
T	temperature, K
u, v, w	velocities, m/s
U, V, W	dimensionless velocities
x, y, z	Cartesian coordinates, m
X, Y, Z	dimensionless coordinates
α	thermal diffusivity, m^2/s
β	thermal expansion coefficient, k^{-1}
θ	dimensionless temperature
υ	kinematic viscosity
ρ	density, kg/m^3
φ	electrical potential
σ	electrical conductivity, S/m
λ	thermal conductivity, $W/(m \cdot K)$

Subscripts

x, y, z	x, y, z-direction
0	reference state
h, l	high temperature and low temperature

Unlike conventional working fluids, it is difficult to measure bubble velocity in an opaque liquid metal. Due to the opacity and electrical conductivity of liquid metal, the application of conventional optical and contact electrical measurement methods are limited to measure the velocity. Therefore, it is expected to use acoustic technology to measure the internal velocity of liquid metal. Ultrasonic Doppler Velocimetry (UDV) is used to measure the velocity of opaque liquids utilizing the acoustic reflection receiving technology, and has advantages over conventional techniques such as PIV or LDV [8–10]. In the measuring speed technology, the ultrasonic Doppler velocimetry technique is a very effective technique, by receiving the echo signal to obtain the velocity of reflection particle in different depth along the transducer emitting ultrasonic direction by the Doppler analysis without influence on the liquid metal internal velocity. Comparing with the traditional velocity measurement method, the technique has outstanding advantages on comprehensive flow field information, flexibility for opaque system and the instantaneous flow field.

For the natural convection of liquid metal under the influence of the magnetic field, Tagawa and Ozoe [11] simulated free convection in a differentially heated cube in the presence of a magnetic field perpendicular to the isothermal walls. All walls were assumed to be electrically non-conducting (the same configuration studied in the present work). It was found that, under these conditions a weak magnetic field (Hartmann number up to 100–200) was found slightly to enhance heat transfer, causing the average Nusselt number to increase by 5–7%. The moderate increase in heat transfer was also confirmed by the experiments conducted by the same authors in liquid gallium. Both effects were explained by the electric current pattern established near the edges between the *Ha* walls and the isothermal walls, which combined with the imposed magnetic field so as to assist the buoyant flow and to contrast the viscous forces exerted by the walls. Only for Hartmann number >200 the decelerating effects of the Lorentz forces near the central regions of the hot and cold walls became dominant, and both peak velocities and heat transfer rates decreased with Hartmann number. The buoyancy-driven magneto hydrodynamic flow in a liquid-metal filled cubic enclosure was investigated by Piazza and Ciofalo using three-dimensional numerical simulation method in which a uniform magnetic field was applied orthogonal to the temperature gradient and to the gravity vector (characteristic of Pb–17Li at 573 K) [12,13]. Increasing the Hartmann number suppressed convective motions and exalted the square shape of the circulation cells in which there would be the quasi-two-dimensionality of the flow in this case. An analogy was observed between stream function and electrical potential in the mid-plane orthogonal to the magnetic field, due to the fact that the component of vorticity in the magnetic field direction acts as a source term in the electrical potential equation. There studies attributed to that the convective heat transfer induced electric field E and $V \times B$ term gave a circulating electric current and large Lorentz force was resulted in suppressing the natural convection of liquid metal. The reason of moderate magnetic field to suppress the heat transfer can be explained reasonably, and the reason of heat transfer enhancement in a weak magnetic field needs further analysis and discussion.

An important mechanistic explanation is derived from the buoyant fully-established flow in long vertical enclosures in the presence of a strong horizontal magnetic field by Moreau et al. [14,15]. Numerical computations and experiments (mercury in the experiments) buoyant convection in a long vertical rectangular enclosure were studied under the presence of a uniform horizontal magnetic field. The applied magnetic field was either perpendicular or parallel to the temperature gradient. In both configurations, if it was large enough, it damped out the buoyant flow and ensures a conductive heat flux, but with different scaling laws: Gr/Ha for the perpendicular case, Gr/Ha^2 for the parallel case. Analytical solutions were derived and serve as a reference to validate the numerical results. The magnetic damping in the perpendicular case was much less than in the parallel case. Even in the moderate magnetic field, the velocity and the temperature fields were still convective and oscillatory when the *Gr* was large. The average heat transfer *Nu* increased due to the transition of the flow from three-dimensional to two-dimensional and oscillations were still present. This numerical result agreed fairly well with the experimental data which exhibited the maximum Nusselt number at $Ha = 200–300$. This transition might be characterized by a critical value of the interaction parameter, which was proportional to the $Ha/Gr^{1/4}$. When the magnetic field was applied parallel to the temperature gradient, the Lorentz force damped out more efficiently the velocity field