International Journal of Thermal Sciences 125 (2018) 52–65

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Thermomagnetic convection of oxygen in a square enclosure under non-uniform magnetic field

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ARTICLE INFO

Keywords:
Thermomagnetic convection
Permanent magnet
Optimal position
Heat transfer enhancement

ABSTRACT

The effects of magnet position and magnet strength on the thermomagnetic convection of gaseous oxygen in a square enclosure under combined magnetic and gravity fields are numerically studied. The magnetic field is provided by a Neodymium-Iron-Boron permanent magnet which has a high magnetic energy product. The results show that the thermomagnetic convection is significantly affected by the relative location of the permanent magnet. Both the heat transfer and buoyancy driven flow near the lower part of the vertical hot wall are greatly enhanced when the magnet is placed near the hot wall. The largest local Nusselt number is enhanced by 152.7% for the studied largest magnet strength. The corresponding largest average Nusselt number also increases by 17.9%. The overall heat transfer increases with the increase of magnet strength when the magnet is placed near the hot wall, while the heat transfer increases first and then decreases with the increase of magnet strength when the magnet is placed near the cold wall. Optimal position of permanent magnet exists for best heat transfer enhancement.

1. Introduction

Natural convection in an enclosure has attracted much research over the years due to its many practical applications, such as electronic equipment cooling, heat exchanger, gas-cooled reactor, solar energy collection, and flows in rooms [1,2]. The thermomagnetic convection which has a great potential for better heat transfer than natural convection is of considerable interest recently in many engineering applications, such as electronic cooling devices, heat exchanger, crystal growth and pure magnetic convection in space engineering [3]. The magnetic field can be supplied by permanent magnet or superconducting magnet which can provide a strong magnetic induction up to 10 T or more. In the fields of fluid mechanics and heat transfer engineering, the control of natural convection of fluids with high magnetic susceptibility under high magnetic field has been an active research topic [3].

Carruthers and Wolfe [1] theoretically and experimentally studied the thermomagnetic convection of oxygen in a rectangular container. They found that the convection inside the enclosure heated from one vertical wall and cooled from opposing wall was suppressed by horizontal magnetic field and the convection in the rectangular enclosure heated from below and cooled from above could be enhanced or suppressed by the horizontal magnetic field. Braithwaite et al. [2] found that buoyancy-driven convection in a solution of gadolinium nitrate can be enhanced or suppressed by a magnetic field depending on the relative orientation of magnetic field and temperature gradient. Yamaguchi et al. [4] reported that magnetic convection of ferrofluid is apparently greater than ordinary natural convection. Wakayama [5–7] found that the magnetic field can enhance or suppress combustion flames and also can accelerate or decelerate magnetic gas flow. Krakov and Nikiforov [8,9] numerically studied the effect of uniform magnetic field on natural convection in a square enclosure heated and cooled from opposing walls for cases with gravity and non-gravity. Their results showed that increasing the magnetic field could both enhance and suppress heat transfer. Bednarz et al. [10–12] studied the effect of magnetic field supplied by an electric coil on natural convection of paramagnetic fluid in a cubic enclosure and found that the inclined angle and location of electric coil have an important influence on heat transfer. Goharkhah et al. [13] experimentally studied the effect of external magnetic field generated by electromagnets on the heat transfer of ferrofluid. Their results showed that the magnetic field intensity increases the heat transfer. A maximum heat transfer enhancement of 24.9% by the application of constant magnetic field was reported. Yu et al. [14] numerically investigated the thermomagnetic convection in a rectangular cavity under uniform magnetic field with different directions at different angles with respect to horizontal plane.

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https://doi.org/10.1016/j.ijthermalsci.2017.11.012
Received 9 March 2017; Received in revised form 21 October 2017; Accepted 15 November 2017

Nomenclature

$\mathbf{A}$	vector potential (Wb/m)
$\boldsymbol{B}$	magnetic flux density (T)
Br	residual magnetic flux density of permanent magnet (T)
$\boldsymbol{f}_{\mathrm{m}}$	magnetizing force (N/m^3)
$\boldsymbol{g}$	acceleration coefficient of gravity (m/s^2)
$\boldsymbol{H}$	magnetic field strength (A/m)
L	length of cavity (m)
$\boldsymbol{M}$	magnetization (A/m)
Nu	Nusselt number (−)
p	pressure (Pa)
p_0	reference pressure without convection of gas (Pa)
Pr	Prandtl number (−)
r	distance from magnet to the field point (m)
$\boldsymbol{r_1}$	unit vector (−)
Ra	Rayleigh number (−)
R_g	Gas constant (J/kgK^{-1})
t	time (s)
T	temperature (K)
$\boldsymbol{u}$	velocity vector (m/s)
u, w	velocity components (m/s)
U	dimensionless velocity equals uL/α (−)
W	dimensionless velocity equals wL/α, (−)
x, z	coordinate (m)

Greeks

α	thermal diffusivity of gas (m^2/s)
β	volumetric thermal expansion coefficient (1/K)
λ	thermal conductivity of oxygen (W/(m·K))
μ	dynamic viscosity (kg/(m·s))
μ_{m}	magnetic permeability of free space (H/m)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
ρ_0	density of gas at a reference state of no convection (kg/m^3)
χ	mass magnetic susceptibility of oxygen (m^3/kg)

Subscripts

0	reference state
c	cold wall
h	hot wall
max	maximum value
min	minimum value

They concluded that both the magnetic field strength and inclination angle affect the heat transfer and the inclination angle plays a great role on flow and heat transfer when the aspect ratio is less or more than 1.0. Tagawa et al. [15] and Bednarz et al. [16,17] numerically and experimentally carried out extensive studies about the effect of magnetic field on natural convection in an enclosure at different boundary conditions. Their results showed that the heat transfer inside the enclosure can be controlled by the application of gradient magnetic field supplied by a superconducting magnet. Afifah et al. [3] recently gave a review of recent investigation in the field that focuses on magneto-viscous effect and thermomagnetic convection of magnetic fluids which has promising prospect in advanced applications.

Besides the magnetic fields supplied by superconducting magnet or electric coil, the gradient magnetic fields supplied by one or several permanent magnets with high residual magnetic flux density are also been used to study the thermomagnetic convection [18–25]. Song et al. [18] numerically studied the natural convection of air in a square enclosure under a nonuniform magnetic field supplied by a permanent magnet. Two kinds of the expressions for the magnetizing force are considered and compared in the numerical computations. Their numerical results revealed that the natural convection inside the enclosure does not depend on the types of the expressions for magnetizing force. Yang et al. [19] investigated the thermomagnetic convection of air in an enclosure by using the magnetic quadrupole field and pointed out that the magnetic force acting on the air in the magnetic quadrupole field exhibits a centrifugal character and the free convection induced by the centrifugal-form magnetic force exhibits different flow and heat transfer characteristics from the gravitational free convection. Jiang et al. [20,21] numerically investigated the thermomagnetic convection of air in a two-dimensional porous square enclosure under a permanent magnetic quadrupole field and reported that the magnetic field intensity and Rayleigh number have a significant effect on the flow field and heat transfer. Szabo et al. [22] experimentally investigated the thermomagnetic convection of a cavity filled with magnetic liquid under the influence of a permanent magnet that provided a spatial nonuniform magnetic field. Taslimifar et al. [23] studied the effect of ceramic magnet on the heat transfer characteristics of ferrofluidic open loop pulsating heat pipes and reported that the thermal performance could be adjusted by the application of magnetic field in different locations. Tangthieng et al. [24] studied the heat transfer of a ferrofluid in the presence of magnetic field supplied by a permanent magnet placed on the top of the square box and reported that the enhancement of Nusselt number is as high as 45% for the largest magnetic field of the permanent magnet. Ashouri et al. [25] numerically studied the magnetic convection heat transfer in a two-dimensional square cavity induced by magnetic field supplied by a permanent magnet located near the bottom wall. A correlation for the overall Nusselt number on the hot wall is introduced.

Referring to the above mentioned literature, the magnetic field is usually supplied by superconducting magnet or using uniform magnetic field for most of the research about thermomagnetic convection. Only few researches are focused on application of permanent magnetic field. With the continuous increase of residual magnetic flux density of permanent magnet, there must be plenty of applications of permanent magnet in engineering field in the near future. As to the thermomagnetic convection, no reports have focused on the effect of permanent magnet position on thermomagnetic convection yet. Thus, more studies are required for a better understanding of thermomagnetic convection in the nonuniform magnetic field supplied by permanent magnet, which is of importance for both scientific research and practical application. In this paper, the effect of permanent magnet position on the thermomagnetic convection is numerically carried out. The numerical results may provide more reliable information about thermomagnetic convection in a square enclosure under nonuniform magnetic field.

2. Physical model

Natural convection in a square enclosure with two vertical walls at different temperatures and two adiabatic horizontal walls is the most considered configuration because of its relative simplicity and practical importance. Fig. 1 shows the schematic view of the physical model considered in this paper. The square enclosure filled with gaseous oxygen is heated isothermally on the left vertical wall and cooled isothermally on the right vertical wall. While the horizontal walls are adiabatic. A square permanent magnet with the pole parallel to the z-direction is placed under the bottom wall of the square enclosure. The gravitational force acts in the direction opposite to z-direction.

The length of the square enclosure is $L = 0.05$ m. The length of the magnet is $0.4L$. The gap between the magnet and the enclosure is