Research Article

Numerical Investigation of the Effect of Magnetic Field on Natural Convection in a Curved-Shape Enclosure

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1. Introduction

The study of natural convection in horizontal annuli is of importance in many industrial and geophysical problems. This topic is of practical interest in several applications such as solar collector-receiver, underground electric transmission cables, vapor condenser for water distillation, and food processing. Mohammed et al. [1] experimentally investigated the forced and free convection for thermally developing and fully developed laminar airflow inside a horizontal concentric annulus. They showed that the Nusselt number is considerably greater for developing flow than the corresponding values for fully developed flow over a significant portion of the annulus. Kuehn and Goldstein [2] presented experimental and numerical studies of steady-state natural convection heat transfer in a horizontal concentric annulus. They studied parametrically the effects of the Rayleigh and Prandtl numbers and aspect ratio and proposed correlating equations. Natural convection between a square outer cylinder and a heated elliptic inner cylinder was studied numerically by Bararnia et al. [3]. They found that streamlines and isotherms strongly depend on the Rayleigh number and the position of the inner cylinder. Recently, several papers were published about natural convection [4–13].

Natural convection under the influence of a magnetic field is of great importance in many industrial applications such as crystal growth in liquid, cooling of nuclear reactor, electronic package, microelectronic devices, and solar technology. In the case of free convection of an electrically conducting fluid in the presence of a magnetic field, there are two body forces: buoyancy force and Lorentz force. They interact with each other and can influence heat and mass transfer. Thus, it is important to study the detailed characteristics of transport phenomena in such a process to have a better product with improved design. Magnetohydrodynamic natural convection in a vertical cylindrical cavity with a sinusoidal upper wall temperature was investigated by Kakarantzas et al. [14]. They concluded that the increase of Hartmann number results in a damping of the fluid motion, and thus heat conduction progressively dominates over convection heat transfer. Rudraiah et al. [15] investigated numerically the effect of a magnetic field on natural convection in a rectangular enclosure. They found that the magnetic field decreases the rate of heat transfer. Sheikholeslami et al. [16] studied the natural convection in a concentric annulus between a cold outer square and heated inner circular cylinders in the presence of a static radial magnetic field. They reported that the average Nusselt number is an increasing function
Effect of magnetic field on natural convection was considered by several authors [17–29].

Control volume-based-finite-element method (CVFEM) is a scheme that uses the advantages of both finite-volume and finite-element methods for simulation of multiphysics problems in complex geometries [30, 31]. Soleiman et al. [32] studied natural convection heat transfer in a semiannulus enclosure filled with nanofluid using CVFEM. They found that the angle of turn has an important effect on the streamlines, isotherms, and maximum or minimum values of the local Nusselt number. Sheikholeslami et al. [33] performed a numerical analysis for natural convection heat transfer of Cu-water nanofluid in a cold outer circular enclosure containing a hot inner sinusoidal circular cylinder in the presence of a horizontal magnetic field using CVFEM. They concluded that in the absence of a magnetic field, the enhancement ratio decreases as the Rayleigh number increases, while an opposite trend is observed in the presence of a magnetic field. Also, they found that the average Nusselt number is an increasing function of the nanoparticle volume fraction parameter, the number of undulations, and Rayleigh number, while it is a decreasing function of the Hartmann number. The applications of this method were introduced by different authors [34, 35].

The main goal of the present work is to conduct a numerical investigation of natural convection heat transfer in a curved-shape enclosure in the presence of a magnetic field using CVFEM. The numerical investigation is carried out for different values of the governing parameters.

2. Problem Formulation

The physical model along with the important geometrical parameters is shown in Figure 1(a). The width and height of the enclosure is $H$. The right and top walls of the enclosure are maintained at constant cold temperature $T_c$, whereas the inner circular hot wall is maintained at constant hot temperature $T_h$ and the bottom and left walls with the length of $H/2$ are thermally insulated. Under all cases, $T_h > T_c$ condition is maintained.

To assess the shape of inner circular and outer rectangular boundaries which consist of the right and top walls, an elliptic function can be used as follows:

$$\left(\frac{X}{a}\right)^{2\tilde{n}} + \left(\frac{Y}{b}\right)^{2\tilde{n}} = 1. \quad (1)$$

When $a = b$ and $\tilde{n} = 1$, the geometry becomes a circle. As $\tilde{n}$ increases from 1, the geometry would approach a rectangle for $a \neq b$ and square for $a = b$. It is also assumed that the uniform magnetic field ($\vec{B} = B_x \vec{e}_x + B_y \vec{e}_y$) of constant magnitude $B = \sqrt{B_x^2 + B_y^2}$ is applied, where $\vec{e}_x$ and $\vec{e}_y$ are unit vectors in the Cartesian coordinate system. The orientation of the magnetic field forms an angle $\gamma$ with horizontal axis such that $\gamma = B_y / B_x$. The electric current $J$ and the electromagnetic force $F$ are defined by $J = \sigma (\nabla \times \vec{B})$ and $F = \sigma (\nabla \times \vec{B}) \times \vec{B}$, respectively.

The flow is two-dimensional, laminar, and incompressible. The radiation, viscous dissipation, induced electric current, and Joule heating are neglected. The magnetic Reynolds number is assumed to be small so that the induced magnetic
field can be neglected compared to the applied magnetic field. Now using the Boussinesq approximation, the governing equations can be obtained in dimensional form as follows

\[
\begin{align*}
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} &= 0, \\
\frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} &= -\frac{1}{\rho} \frac{\partial P}{\partial x} + v \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) \\
&\quad + \frac{\sigma B^2}{\rho} \left( v \sin \lambda \cos \lambda - u \sin^2 \lambda \right), \\
\frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} &= -\frac{1}{\rho} \frac{\partial P}{\partial y} + v \left( \frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} \right) + \beta g (T - T_c) \\
&\quad + \frac{\sigma B^2}{\rho} \left( u \sin \lambda \cos \lambda - v \sin^2 \lambda \right), \\
\frac{\partial T}{\partial x} + v \frac{\partial T}{\partial y} &= \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right). 
\end{align*}
\]

The stream function and vorticity are defined as follows:

\[
u = \frac{\partial \psi}{\partial x}, \quad \omega = -\frac{\partial v}{\partial y} + \frac{\partial u}{\partial y}. \tag{6}
\]

The stream function satisfies the continuity equation (2). The vorticity equation is obtained by eliminating the pressure between the two momentum equations, that is, by taking the \( y \)-derivative of (3) and subtracting from it the \( x \)-derivative of (4). This gives

\[
\begin{align*}
\frac{\partial \psi}{\partial y} \frac{\partial \omega}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial \omega}{\partial y} &= v \left( \frac{\partial^2 \omega}{\partial x^2} + \frac{\partial^2 \omega}{\partial y^2} \right) + \beta g \left( \frac{\partial T}{\partial x} \right) \\
&\quad + \frac{\sigma B^2}{\rho} \left( -\frac{\partial v}{\partial y} \sin \lambda \cos \lambda + \frac{\partial u}{\partial y} \sin \lambda \cos \lambda \right) \\
&\quad + \frac{\partial u}{\partial x} \sin \lambda \cos \lambda - \frac{\partial v}{\partial x} \sin \lambda \cos \lambda \\
&\quad + \frac{\partial u}{\partial x} \sin \lambda \cos \lambda - \frac{\partial v}{\partial x} \sin \lambda \cos \lambda \\
\frac{\partial \psi}{\partial y} \frac{\partial T}{\partial x} - \frac{\partial \psi}{\partial x} \frac{\partial T}{\partial y} &= \alpha \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right), \\
\frac{\partial^2 \psi}{\partial x^2} + \frac{\partial^2 \psi}{\partial y^2} &= -\omega. \tag{7}
\end{align*}
\]

Nondimensional variables are defined as follows:

\[
\begin{align*}
X &= \frac{x}{L}, \quad Y = \frac{y}{L}, \quad \Omega = \frac{\omega L^2}{\alpha}, \quad \psi = \frac{\psi}{\alpha}, \\
\Theta &= \frac{T - T_c}{T_h - T_c}, \quad U = \frac{v L}{\alpha}, \quad V = \frac{v L}{\alpha}, \\
\end{align*}
\]

where \( L = r_{out} - r_{in} = r_{in} \) is the distance between the inner and outer radii. Using the dimensionless parameters, the equations now become as follows:

\[
\begin{align*}
\frac{\partial \psi}{\partial Y} \frac{\partial \omega}{\partial X} - \frac{\partial \psi}{\partial X} \frac{\partial \omega}{\partial Y} &= \Pr \left( \frac{\partial^2 \omega}{\partial X^2} + \frac{\partial^2 \omega}{\partial Y^2} \right) + \frac{\beta g}{\alpha} \frac{\partial \omega}{\partial X} + \frac{\sigma B^2}{\rho} \frac{\partial \omega}{\partial Y} \\
&\quad \times \left( -\frac{\partial \psi}{\partial Y} \tan \lambda + \frac{\partial U}{\partial X} \tan^2 \lambda + \frac{\partial U}{\partial X} \tan \lambda - \frac{\partial \psi}{\partial X} \right), \\
\frac{\partial \psi}{\partial Y} \frac{\partial \Theta}{\partial X} - \frac{\partial \psi}{\partial X} \frac{\partial \Theta}{\partial Y} &= \left( \frac{\partial^2 \Theta}{\partial X^2} + \frac{\partial^2 \Theta}{\partial Y^2} \right), \\
\frac{\partial^2 \psi}{\partial X^2} + \frac{\partial^2 \psi}{\partial Y^2} &= -\Omega, \tag{9}
\end{align*}
\]

where \( \Pr = g \beta L^3 (T_h - T_c) / (\alpha \nu) \) is the Prandtl number, \( Ha = LB \sqrt{\mu / \sigma} \) is the Hartmann number, and \( \Pr = \nu / \alpha \) is the Prandtl number. The boundary conditions as shown in Figure 1 are

\[
\begin{align*}
\Theta &= 1.0 \quad \text{on the inner circular boundary}, \quad \Psi = 0.0 \quad \text{on all solid boundaries}, \\
\frac{\partial \Theta}{\partial n} &= 0.0 \quad \text{on the two other insulation boundaries}, \\
\end{align*}
\]

The values of vorticity on the boundary of the enclosure can be obtained using the stream function formulation and the known velocity conditions during the iterative solution procedure. The local Nusselt number along the hot wall can be expressed as

\[
\text{Nu}_{\text{loc}} = \frac{\partial \Theta}{\partial n} \bigg|_{\text{hot wall}}, \tag{11}
\]

where \( n \) is the direction normal to the inner circular wall. The average Nusselt number on hot wall is evaluated as

\[
\text{Nu}_{\text{ave}} = \frac{1}{\pi/2} \int_0^{\pi/2} \text{Nu}_{\text{local}} (\theta) \, d\theta. \tag{12}
\]

### 3. Numerical Procedure

The mesh of the enclosure used in the present CVFEM program is shown in Figure 1(b). Triangular elements are considered as the building block of the discretization using CVFEM. The values of variables are approximated with linear interpolation within each element. A control volume is created by joining the center of each element in the support to the midpoints of the element sides that pass through the central node \( i \), which creates a close polygonal control volume (see Figure 1(b)). To illustrate the solution procedure using the CVFEM, one can consider the general form of advection-diffusion equation for node \( i \) in integral form

\[
\int_Y Q \, d\Omega - \int_A k \nabla \phi \cdot n \, dA + \int_A (\nu \cdot n) \phi \, dA = 0 \quad \text{(13)}
\]
or point form

\[-\nabla \cdot (k \nabla \phi) + \nabla \cdot (v \phi) - Q = 0,\]

which can be represented by the system of CVFEM discrete equations as

\[[a_i + Q_{c,i} + B_{c,i}] \phi_i = \sum_{j=1}^{n_i} a_{i,j} \phi_{S_{ij}} + Q_{B_i} + B_{B_i}.\]

In the aforementioned, the \(a\)'s are the coefficients, the index \((i, j)\) indicates the \(j\)th node in the support of node \(i\), the index \(S_{ij}\) provides the node number of the \(j\)th node in the support, the \(B\)'s account for boundary conditions, and the \(Q\)'s account for source terms. For the selected triangular element which is shown in Figure 2, the approximation without considering the source terms leads to

\[-(a^k_i + a^u_i) \phi_i + (a^k_2 + a^u_2) \phi_{S_{i,3}} + (a^k_3 + a^u_3) \phi_{S_{i,4}} = 0.\]

Using upwinding, the advective coefficients identified with the superscripts (\(^k\)) are given by

\[a^k_i = \max \{q_{f1}, 0\} + \max \{q_{f2}, 0\},\]

\[a^u_i = \max \{-q_{f1}, 0\},\]

\[a^u_2 = \max \{-q_{f1}, 0\},\]

\[a^u_3 = \max \{-q_{f2}, 0\},\]

and the diffusion coefficients, identified with the superscripts (\(^u\)), are given by

\[a^u_i = -k_{f1} N_{1x} \Delta \hat{y}_{f1} + k_{f1} N_{1y} \Delta \hat{x}_{f1} - k_{f2} N_{1x} \Delta \hat{y}_{f2} + k_{f2} N_{1y} \Delta \hat{x}_{f2},\]

\[a^u_2 = -k_{f1} N_{2x} \Delta \hat{y}_{f1} + k_{f1} N_{2y} \Delta \hat{x}_{f1} - k_{f2} N_{2x} \Delta \hat{y}_{f2} + k_{f2} N_{2y} \Delta \hat{x}_{f2},\]

\[a^u_3 = -k_{f1} N_{3x} \Delta \hat{y}_{f1} + k_{f1} N_{3y} \Delta \hat{x}_{f1} - k_{f2} N_{3x} \Delta \hat{y}_{f2} + k_{f2} N_{3y} \Delta \hat{x}_{f2}.\]

In (17), the volume flow across faces 1 and 2 in the direction of the outward normal is

\[q_{f1} = v \cdot n A_{f1} = v^{f1}_x \Delta \hat{y}_{f1} - v^{f1}_y \Delta \hat{x}_{f1},\]

\[q_{f2} = v \cdot n A_{f2} = v^{f2}_x \Delta \hat{y}_{f2} - v^{f2}_y \Delta \hat{x}_{f2}.\]

The value of the diffusivity at the midpoint of face 1 is

\[k_{f1} = [N_1 k_1 + N_2 k_2 + N_3 k_3]_{f1} = \frac{5}{12} k_1 + \frac{5}{12} k_2 + \frac{2}{12} k_3,\]

and at the midpoint of face 2 is

\[k_{f2} = [N_1 k_1 + N_2 k_2 + N_3 k_3]_{f2} = \frac{5}{12} k_1 + \frac{2}{12} k_2 + \frac{5}{12} k_3.\]

The velocity components at the midpoint of face 1 are

\[v^{f1}_x = \frac{5}{12} v_{x_1} + \frac{5}{12} v_{x_2} + \frac{2}{12} v_{x_3},\]

\[v^{f1}_y = \frac{5}{12} v_{y_1} + \frac{5}{12} v_{y_2} + \frac{2}{12} v_{y_3},\]

and on face 2 are

\[v^{f2}_x = \frac{5}{12} v_{x_1} + \frac{2}{12} v_{x_2} + \frac{5}{12} v_{x_3},\]

\[v^{f2}_y = \frac{5}{12} v_{y_1} + \frac{2}{12} v_{y_2} + \frac{5}{12} v_{y_3}.\]

These values can be used to update the \(i\)th support coefficients through the following equations:

\[a_i = a_i + a^k_i,\]

\[a_{i,3} = a_{i,3} + a^k_3,\]

\[a_{i,4} = a_{i,4} + a^k_4.\]

In (18), moving counterclockwise around node \(i\), the signed distances are

\[\Delta \hat{x}_{f1} = \frac{x_3}{3} - \frac{x_2}{6} - \frac{x_1}{6},\]

\[\Delta \hat{x}_{f2} = -\frac{x_2}{3} + \frac{x_3}{6} + \frac{x_1}{6},\]

\[\Delta \hat{y}_{f1} = \frac{y_3}{3} - \frac{y_2}{6} - \frac{y_1}{6},\]

\[\Delta \hat{y}_{f2} = -\frac{y_2}{3} + \frac{y_3}{6} + \frac{y_1}{6}.\]
the derivatives of the shape functions are
\[
N_{1x} = \frac{\partial N_1}{\partial x} = \frac{(y_2 - y_3)}{2V^{\text{ele}}}, \quad N_{1y} = \frac{\partial N_1}{\partial y} = \frac{(x_3 - x_2)}{2V^{\text{ele}}},
\]
\[
N_{2x} = \frac{\partial N_2}{\partial x} = \frac{(y_3 - y_1)}{2V^{\text{ele}}}, \quad N_{2y} = \frac{\partial N_2}{\partial y} = \frac{(x_1 - x_3)}{2V^{\text{ele}}},
\]
\[
N_{3x} = \frac{\partial N_3}{\partial x} = \frac{(y_1 - y_2)}{2V^{\text{ele}}}, \quad N_{3y} = \frac{\partial N_3}{\partial y} = \frac{(x_2 - x_1)}{2V^{\text{ele}}},
\]

and the volume of the element is
\[
V^{\text{ele}} = \frac{(x_2y_3 - x_3y_2) + x_1(y_3 - y_1) + y_1(x_3 - x_2)}{2}. \tag{27}
\]

The obtained algebraic equations from the discretization procedure using CVFEM are solved by the Gauss-Seidel method.

Boundary conditions for the present problem can be applied using \(B_{B_i}\) and \(B_{C_i}\) as follows.

Insulated boundary:
\[
B_{B_i} = 0, \quad B_{C_i} = 0. \tag{28}
\]

Insulated boundary:
\[
B_{B_i} = 0, \quad B_{C_i} = 0. \tag{29}
\]

Fixed value boundary:
\[
B_{B_i} = \phi_{\text{value}} \times 10^{16}, \quad B_{C_i} = 10^{16}, \tag{30}
\]
where \(\phi_{\text{value}}\) is the prescribed value on the boundary. The volume source terms can be applied to (15) as
\[
\sum_{j=1}^{\text{elements}} \int_{V_j} Q \, dV \approx Q_i V_i \tag{31}
\]
or after linearizing the source term
\[
Q_i V_i = -Q_{C_i} \phi_i + Q_{B_i}. \tag{32}
\]

### 4. Grid Testing and Code Validation

A mesh testing procedure was conducted to guarantee the grid independency of the present solution. Various mesh combinations were explored for the case \(Ra = 10^5, Ha = 100, r/L = 0.75\), and \(Pr = 0.025\) as shown in Table 1. The present code was tested for grid independence by calculating the average Nusselt number on the inner circular wall. In harmony with this, it was found that a grid size of \(81 \times 2.1191\) ensures a grid-independent solution. The convergence criterion for the termination of all computations is
\[
\max_{\text{grid}} \left| \Gamma^{k+1} - \Gamma^{k} \right| \leq 10^{-7}, \tag{33}
\]

### 5. Results and Discussion

In this study, natural convection heat transfer in a curved-shape enclosure in the presence of a magnetic field is investigated numerically using CVFEM. Calculations are made for various values of the Hartmann number, \(Ha = 0, 10, 100\), and Rayleigh number, \(Ra = 10^5, 10^6, 10^7\).

Figures 3 and 4 show the isotherms and streamlines contours for different values of Rayleigh number and Hartmann number. At \(Ra = 10^7\), the isotherms are parallel to each other and take the shape of the enclosure which are the main characteristics of conduction heat transfer mechanism. At \(Ra = 10^5\), the circulation of the flow shows that the main eddy is divided into two eddies. Also, as Rayleigh number increases, the isotherms become more distorted and the stream function values are enhanced which is due to the domination of convective heat transfer mechanism at higher Rayleigh numbers. At this Rayleigh number, a thermal plume appears over the hot surface at \(\gamma = 50^\circ\). At \(Ra = 10^7\), one small counterclockwise eddy appears between two clockwise eddies. It is worthwhile mentioning that the effect of magnetic field is to decrease the value of the velocity magnitude throughout the enclosure because the presence of magnetic field introduces a force called the Lorentz force, which acts against the flow if the magnetic field is applied in the normal direction. This type of resisting force slows down the fluid velocity. Increasing Hartmann number has no significant
Effect on isotherms and streamlines at low Rayleigh number. At $Ra = 10^3$, as Hartmann number increases, secondary eddies disappear and the core of voracity moves upward. At $Ra = 10^3$, increasing Hartmann number up to $Ha = 10$, two othercounter clockwise eddies appear. But in higher values of Hartmann number, it can be seen that all secondary eddies vanish. Also, it can be seen that in the presence of magnetic field, thermal plumes disappear.

Effects of the Rayleigh number and Hartmann number on local Nusselt number are shown in Figure 5. At $Ra = 10^3$, the local Nusselt number profiles are symmetric with respect to $\gamma = 45^\circ$, which indicates the domination of conduction heat transfer mechanism. For higher Rayleigh number, local Nusselt number profiles are not symmetric and have extremums because of presence of thermal plumes. At $Ra = 10^4$, in absence of magnetic field, the local Nusselt number profile has one local minimum at $\gamma = 50^\circ$. Increasing Hartmann number shifts this minimum point to $\gamma = 45^\circ$. At $Ra = 10^3$, in the absence of magnetic field, the local Nusselt number profile has three local minima but as Hartmann number increases, these extrema disappear because of domination of conduction mechanism.

Figure 6 shows the effects of the Rayleigh number and Hartmann number on average Nusselt number and
maximum value of stream function. As Rayleigh number increases, buoyancy force increases so that both thermal and velocity boundary layer thicknesses decrease. Increasing Rayleigh number leads to increase in average Nusselt number and $|\Psi_{\text{max}}|$. When the magnetic field is imposed on the enclosure, the velocity field is suppressed owing to the retarding effect of the Lorentz force. As Hartmann number increases boundary layer thicknesses increase, and in turn the average Nusselt number and $|\Psi_{\text{max}}|$ decrease.

**Figure 4:** Streamlines contours for different values of Rayleigh number and Hartmann number at $r/L = 0.75$ and $Pr = 0.025$.

**Table 3:** Average Nusselt number versus different Grashof numbers under various strengths of the magnetic field at $Pr = 0.733$.

<table>
<thead>
<tr>
<th>Ha</th>
<th>$Gr = 2 \times 10^4$</th>
<th>$Gr = 2 \times 10^5$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Present</td>
<td>Rudraiah et al. [15]</td>
</tr>
<tr>
<td>0</td>
<td>2.5665</td>
<td>2.5188</td>
</tr>
<tr>
<td>10</td>
<td>2.26626</td>
<td>2.2234</td>
</tr>
<tr>
<td>50</td>
<td>1.09954</td>
<td>1.0856</td>
</tr>
<tr>
<td>100</td>
<td>1.02218</td>
<td>1.011</td>
</tr>
</tbody>
</table>
6. Conclusion

In this study, natural convection heat transfer in a curved-shape inclined enclosure in the presence of magnetic field is investigated numerically using the control volume-based finite element method (CVFEM). From the numerical investigation, it can be concluded that the Hartmann number can be a control parameter for heat and fluid flow. In addition, it can be found that the Nusselt number and maximum value of stream function are increasing functions of Rayleigh number and decreasing functions of Hartmann number.

Nomenclature

\( C_p: \) Specific heat at constant pressure
\( \text{Gr:} \) Grashof number \( (= g\beta \Delta T L^3 / \nu^2) \)
\( \text{Ha:} \) Hartmann number
\( \text{Nu:} \) Nusselt number
\( \text{Pr:} \) Prandtl number \( (= \nu / \alpha) \)
\( T: \) Fluid temperature
\( u, v: \) Velocity components in the \( x \)-direction and \( y \)-direction
\( U, V: \) Dimensionless velocity components in the \( X \)-direction and \( Y \)-direction

Figure 5: Effects of the Rayleigh number and Hartmann number on local Nusselt number.
Figure 6: Effects of the Rayleigh number and Hartmann number on (a) average Nusselt number and (b) maximum value of stream function at $r/L = 0.75$ and $Pr = 0.025$.

X, Y: Dimensionless space coordinates
r: Nondimensional radial distance
k: Thermal conductivity
L: Gap between inner and outer boundaries of the enclosure $L = r_{out} - r_{in}$
$\vec{g}$: Gravitational acceleration vector
Ra: Rayleigh number ($= g\beta TL^3/\alpha v$).

Greek Symbols
$\zeta$: Angle measured from the insulated right plane
$\alpha$: Thermal diffusivity
$\sigma$: Electrical conductivity
$\mu$: Dynamic viscosity
$\nu$: Kinematic viscosity
$\psi$ & $\Psi$: Stream function and dimensionless stream function
$\Theta$: Dimensionless temperature
$\rho$: Fluid density
$\beta$: Thermal expansion coefficient.

Subscripts
C: Cold
H: Hot
loc: Local
ave: Average
in: Inner
out: Outer.

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