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ORIGINAL ARTICLE

Numerical study of double diffusive buoyancy forces induced natural convection in a trapezoidal enclosure partially heated from the right sidewall

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Abstract A study of double-diffusive natural convection in a trapezoidal enclosure with a partial heated active right sidewall has been conducted numerically using the finite difference method. The length of the heated active part is equal to half of the inclined wall. Uniform different temperatures and concentrations are imposed along the active parts of the enclosure. The top and bottom boundaries of the enclosure, as well as inactive part of the right sidewall, are being insulated and impermeable. The species diffusivity of the fluid is considered to be constant, but the density varies linearly with the temperature and concentration. Double-diffusive convection for laminar two-dimensional incompressible flow with negligible radiation is expressed in terms of vorticity, temperature or energy, concentration and stream function. A Partial Differential Equation (PDE) technique is adopted to generate regular grid distribution in the physical space. The numerical results are reported for the effect of different heating cases, thermal Grashof numbers, and inclination angles on the contours of streamline, temperature, and concentration. Also, the relevant results for the average Nusselt and Sherwood numbers are demonstrated for several parameters including thermal Grashof number ($10^3 \leqslant Gr_T \leqslant 10^6$), Lewis number ($0.5 \leqslant Le \leqslant 10$), Prandtl number ($0.7 \leqslant Pr \leqslant 10$) at a fixed aspect ratio $Ar = 1$ and buoyancy ratio $N = -0.2$.

1. Introduction

A diversity of transport procedure in nature and numerous industrial applications encounters with the simultaneous heat and mass transfer. Fluid flows generated by combining thermal and solutal buoyancy forces are well known as double-diffusive

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Nomenclature

Ar	aspect ratio (H/L)
C	dimensional concentration $(\mathrm{kg/m^3})$
D	mass diffusivity $(\mathrm{m^2/s})$
g	acceleration of gravity $(\mathrm{m/s^2})$
Gr_S	solutal Grashof number, $Gr_S = g\beta_S \Delta C L^3/\nu^2$
Gr_T	thermal Grashof number, $Gr_T = g\beta_T \Delta T L^3/\nu^2$
h	length of heating section (m)
H	height of the cavity (m)
l	length of inclined wall (m)
L	length of the cavity (m)
Le	Lewis number, $Le = \alpha/D$
m	center of heating section (m)
N	buoyancy ratio, $N = \beta_C \Delta C/\beta_T \Delta T$
Nu	local Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure (Pa)
Pr	Prandtl number, $Pr = \nu/\alpha$
S	dimensionless concentration
Sc	Schmidt number, $Sc = \nu/D$
Sh	local Sherwood number
$\overline{Sh}$	average Sherwood number
T	temperature (K)
t	dimensional time (s)
u, v	velocity components (m/s)
U, V	dimensionless velocity components
x, y	dimensional coordinates (m)
X, Y	dimensionless coordinates

Greek symbols

α	thermal diffusivity $(\mathrm{m^2/s})$
β_S	coefficient of concentration expansion $(\mathrm{m^3/kg})$
β_T	coefficient of thermal expansion $(\mathrm{K^{-1}})$
θ	dimensionless temperature
ν	kinematic viscosity $(\mathrm{m^2/s})$
ρ	density $(\mathrm{kg/m^3})$
ω	vorticity (s^{-1})
ξ	dimensionless vorticity
ψ	stream function $(\mathrm{m^2/s})$
Ψ	dimensionless stream function
τ	dimensionless time

Subscripts

c	cold wall and low concentration
h	hot wall and high concentration

convection. This phenomenon can be seen in different natural fields such as geology, biology, astrophysics, and oceanography. Double-diffusive also happens in various engineering applications such as solar ponds, natural gas storage tanks, crystal manufacturing, material processing, and food processing. To have a general overview of the phenomenon see some relevant fundamental works [1–5]. An extensive overview of the literature was reported by [6–10].

In recent years, study of the double-diffusive phenomenon has been mainly restricted to square and rectangular enclosures, for instance see [11–17]. However, it could be more practical and efficient to design enclosures in non-rectangular shapes such as triangular in some engineering applications such as solar collectors or heat exchangers. The presence of sloping walls makes it difficult to analyze the phenomenon in such geometries rather than in rectangular cavities. One of the most interesting non-rectangular geometries is trapezoidal which is involved in several practical scientific applications, such as attic spaces in buildings [18], greenhouses [19] or sun drying of crops [20]. Unfortunately, minimal attention has been paid to this geometry in examinations in spite of the significant aspects and potential of the trapezoid in what involves heat and mass transfer performance. Iyican et al. [21,22] were the first to investigate natural convection heat transfer in a closed trapezoidal cavity, presenting both analytical and experimental results.

The problem of natural convection heat transfer in trapezoidal enclosures has been extensively analyzed in the literature, see [23–26]. However, less attention has been given to double-diffusive heat and mass transfer natural convection in this geometry. A preliminary investigation of double diffusive convection in the trapezoidal enclosure has been done by Dong and Ebadian [27]. They studied a cavity with 75° slopping walls and horizontal top and bottom boundaries. In their investigation results were obtained for $Pr = 7$ and $Le = 100$ (water) in both aiding and opposing flows. Boussaid et al. [28] studied double diffusive convection in the laminar-flow regime. In another work, Van der Eyden et al. [29] examined numerically a trapezoidal enclosure with horizontal top and bottom boundaries and slopping sidewalls at 45°. The configuration was encountered in underground coal gasification. In their examination, the flow was considered to be turbulent at thermal Grashof number $Gr = 2.6 \times 10^8$ and buoyancy ratio $N = 2.5$. The researchers demonstrated numerical results for the mixture argon/nitrogen with $Le = 1.16$ injected from the bottom as well as the sidewalls. The numerical results had a good agreement compared with experimental results. Papanicolaou and Belessiotis [30] analyzed natural convective heat and mass transfer in an asymmetric trapezoidal enclosure. They carried out the work for both opposing and assisting buoyancy forces with vertical temperature and concentration gradients.

The above literature surveys show that most of the works are concerned with the heat and mass transfer convection in rectangular geometries because of either complete thermal and solutal active horizontal or inclined walls. However, some engineering applications such as solar energy collection, prevention of subsoil water pollution, cooling of electronic components, and fluidized bed chemical reactor are subjected to partial heating and cooling zones. In fact, the complete active walls are not optimized for the heat and mass transfer in such practical applications. In other words, the relative setting of the hot and cold wall regions plays more significant role in optimizing heat and mass transfer rate in the cavity. Therefore, it is required to study the convective heat and mass transfer in the enclosures with partially active thermal and solutal walls to obtain the results that give a better understanding of these applications.