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# LAMINAR AND TURBULENT NATURAL CONVECTION IN A POROUS CAVITY WITH DOUBLE-DIFFUSION EFFECTS

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***Abstract***. *This paper presents results for coupled heat and mass transport under laminar and turbulent flow regimes in porous cavities. Two driving mechanisms are considered to contribute to the overall momentum transport, namely temperature driven and concentration driven mass fluxes. Aiding and opposing flows are considered, where temperature and concentration gradients are either in the same direction or of different sign, respectively. Modeled equations are presented based on the double-decomposition concept, which considers both time fluctuations and spatial deviations about mean values. Turbulent transport is accounted for via a macroscopic version of the* $k-\varepsilon$ *model.*

***Keywords***:*Porous Media, Double-Diffusion, Turbulence Modeling, Natural Convection*

## 1. INTRODUCTION

The study of double-diffusive natural convection in porous media has many environmental and industrial applications, including grain storage and drying, petrochemical processes, oil and gas extraction, contaminant dispersion in underground water reservoirs, electrochemical processes, etc. The importance of double diffusive natural convection can be better appreciated by the volume of papers published in this field, which was reviewed by Nield and Bejan (1999).

Accordingly, double diffusive convection in a vertical cavity subject to horizontal temperature gradients has been investigated by Trevisan and Bejan (1985, 1986), Goyeau et al (1996), Mamou et al (1995, 1998), Mohamad and Bennacer (2002), Nithiarasu et al (1997), Bennacer et al (2001, 2003), among others. In most of the aforementioned papers, the intra-pore flow was assumed to be laminar and it was demonstrated that, depending on the governing parameters of the problem and on the thermal to solute buoyancy ratio, various modes of convection prevail. However, in some specific applications, the fluid mixture may become turbulent and difficulties arise in the proper mathematical modeling of the transport processes under both temperature and concentration gradients. Due to such difficulties, there seems to be a lack in the literature on turbulent solution of double-diffusive convection.

Motivated by the foregoing, in an earlier paper de Lemos and Tofaneli (2004) a mathematical framework for treating turbulent double-diffusive flows in porous media was presented, but no numerical simulations were published. That work was derived from a general mathematical model for turbulent flow in porous media Pedras and de Lemos (2003), which was developed under a concept called "double-decomposition" de Lemos (2005). Such concept considered time fluctuations of the flow properties in addition to spatial deviations, in relation to a volume-average, when setting up macroscopic equations for the flow. Using such concept, non-buoyant Rocamora and de Lemos (2000) as well as buoyant heat transfer has been considered Braga and de Lemos (2004, 2009) in addition to turbulent mass transfer de Lemos and Mesquita (2003). Application of such methodology to channel flows with porous inserts Assato and de Lemos (2005), Santos and de Lemos (2006), have also been presented. However, in none of the above applications, results for turbulent double diffusion in porous media were presented.

The purpose of this contribution is to show numerical results for turbulent double-diffusive in porous media, which are obtained with the mathematical model earlier proposed in de Lemos and Tofaneli (2004). To the best of the authors´ knowledge, no solutions for turbulent flow using the work of de Lemos and Tofaneli (2004), have been previously published. Here, both aiding and opposing cases are investigated.

## 2. MACROSCOPIC MATHEMATICAL MODEL

The problem considered here is showed schematically in Figure 1a and refers to a square cavity containing a saturated porous medium. The cavity of height $H$ , width $L$ and aspect ratio $A = H/L = 1$ is filled with a binary fluid. The enclosure is isothermally heated from the left and cooled from the opposing side. The top and bottom walls are kept insulated and the porous medium is considered to be rigid. The binary fluid in the cavity of Figure 1a is assumed to be Newtonian and to satisfy the Boussinesq approximation.

The equations used herein are derived in details in Pedras and de Lemos (2003), de Lemos (2005), de Lemos and Tofaneli (2004) and for that their derivation need not be repeated here. They are developed based on volume-averaging procedures which are fully described in the literature Hsu and Cheng (1990), Bear (1972), Whitaker (1966, 1967).

The macroscopic continuity equation is then given by,

$$\nabla \bar{\mathbf{u}}_D = 0 \tag{1}$$

where the Dupuit-Forchheimer relationship, $\bar{\mathbf{u}}_D = \phi \langle \bar{\mathbf{u}} \rangle^i$ , has been used and $\langle \bar{\mathbf{u}} \rangle^i$ identifies the intrinsic (liquid) average of the local velocity vector $\bar{\mathbf{u}}$ . The macroscopic time-mean Reynolds equation for an incompressible fluid with constant properties is given as,

$$\rho \nabla . \left( \frac{\bar{\mathbf{u}}_D \bar{\mathbf{u}}_D}{\phi} \right) = -\nabla \left( \phi \langle \bar{p} \rangle^i \right) + \mu \nabla^2 \bar{\mathbf{u}}_D + \nabla \cdot \left( -\rho \phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i \right) \; - \rho \mathbf{g} \phi \left[ \beta_\phi \left( \langle \bar{T} \rangle^i - T_{ref} \right) + \beta_{C_\phi} \left( \langle \bar{C} \rangle^i - C_{ref} \right) \right] - \left[ \frac{\mu \phi}{K} \bar{\mathbf{u}}_D + \frac{c_F \phi \rho \left| \bar{\mathbf{u}}_D \right| \bar{\mathbf{u}}_D}{\sqrt{K}} \right] \tag{2}$$

where the last two terms in (2) represent the Darcy-Forchheimer contribution. The symbol $K$ is the porous medium permeability, $c_F$ is the form drag coefficient (Forchheimer coefficient), $\langle p \rangle^i$ is the intrinsic average pressure of the fluid, $\rho$ is the fluid density, $\mu$ represents the fluid viscosity and $\phi$ is the porosity of the porous medium. Buoyancy effects due to temperature and concentration variations within the cavity are also shown in Eq.(2). The macroscopic Reynolds stress $-\rho \phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i$ is modeled as,

$$-\rho \phi \langle \overline{\mathbf{u}'\mathbf{u}'} \rangle^i = \mu_{t_\phi} 2 \langle \bar{\mathbf{D}} \rangle^v - \frac{2}{3} \phi \rho \langle k \rangle^i \mathbf{I} \tag{3}$$

where

$$\langle \bar{\mathbf{D}} \rangle^v = \frac{1}{2} \left[ \nabla \left( \phi \langle \bar{\mathbf{u}} \rangle^i \right) + \left[ \nabla \left( \phi \langle \bar{\mathbf{u}} \rangle^i \right) \right]^T \right] \tag{4}$$

is the macroscopic deformation tensor, $\langle k \rangle^i = \langle \overline{\mathbf{u}' \cdot \mathbf{u}'} \rangle^i / 2$ is the intrinsic turbulent kinetic energy, $k$ and $\mu_{t_\phi}$, is the turbulent viscosity, which is modeled in de Lemos (2005) similarly to the case of clear flow, in the form,

$$\mu_{t_\phi} = \rho c_\mu \frac{\langle k \rangle^{i2}}{\langle \varepsilon \rangle^i} \tag{5}$$

Coefficients $\beta_\phi$ and $\beta_{C_\phi}$ in (2) are used to write the Grashof numbers associated with the thermal and solute drives, in the form,

$$Gr_\phi = \frac{g \beta_\phi \Delta T H^3}{\nu^2} \; , \; Gr_{C_\phi} = \frac{g \beta_{C_\phi} \Delta C H^3}{\nu^2} \tag{6}$$

where $\Delta T = T_1 - T_2$ and $\Delta C = C_1 - C_2$ are the maximum temperature and concentration variation across the cavity, respectively. One should note that for opposing thermal and concentrations drives, such maximum differences are of opposing sign. Also, the Rayleigh-Darcy number is a dimensionless parameter defined as $Ra^* = g \beta_\phi \Delta T H K / \nu \alpha_{eff}$ , with $\alpha_{eff} = \lambda_{eff} / (\rho c_p)_f$ .

The ratio of Grashof numbers defines the buoyancy ratio, $N$, in the form

$$N = \frac{Gr_{C_\phi}}{Gr_\phi} = \frac{\beta_{C_\phi}\Delta C}{\beta_\phi \Delta T} \tag{7}$$

giving for equation (2),

$$\begin{aligned} \rho\nabla\cdot\left(\frac{\overline{\mathbf{u}}_D\overline{\mathbf{u}}_D}{\phi}\right) &= -\nabla(\phi\langle\overline{p}\rangle^i) + \mu\nabla^2\overline{\mathbf{u}}_D + \nabla\cdot\left(-\rho\phi\langle\overline{\mathbf{u}'\mathbf{u}'}\rangle^i\right) - \rho\mathbf{g}\phi\beta_\phi\left\{(\langle\overline{T}\rangle^i - \overline{T}_{ref}) + N\frac{\Delta C}{\Delta T}(\langle\overline{C}\rangle^i - \overline{C}_{ref})\right\} \\ &\quad -\left[\frac{\mu\phi}{K}\overline{\mathbf{u}}_D + \frac{c_F\phi\rho|\overline{\mathbf{u}}_D|\,\overline{\mathbf{u}}_D}{\sqrt{K}}\right] \end{aligned} \tag{8}$$

Either $\beta_{C_\phi}=0$ or $\Delta C=0$ results in $N=0$, or say, only thermal drive applies. Also, for $\beta_{C_\phi}=0$ and $\Delta C\neq 0$ in (8), although no concentration drive is modeled, a distribution of C within the field will occur due to the flow established by the thermal drive.

The additional transport equations can also be found in de Lemos and Tofaneli:

## ***Heat transport***

$$(\rho c_p)_f\,\nabla\cdot(\overline{\mathbf{u}}_D\langle\overline{T}\rangle^i) = \nabla\cdot\{\mathbf{K}_{eff}\cdot\nabla\langle\overline{T}\rangle^i\} \tag{9}$$

$$\mathbf{K}_{eff} = \underbrace{[\phi\lambda_f + (1-\phi)\lambda_s]}_{\lambda_{eff}}\mathbf{I} + \mathbf{K}_{tor} + \mathbf{K}_t + \mathbf{K}_{disp} + \mathbf{K}_{disp,t} \tag{10}$$

## ***Mass transport***

$$\nabla\cdot(\overline{\mathbf{u}}_D\langle\overline{C}\rangle^i) = \nabla\cdot\mathbf{D}_{eff}\cdot\nabla(\phi\langle\overline{C}\rangle^i) \tag{11}$$

$$\mathbf{D}_{eff} = \mathbf{D}_{disp} + \mathbf{D}_{diff} + \mathbf{D}_t + \mathbf{D}_{disp,t} \tag{12}$$

$$\mathbf{D}_{diff} = \langle D\rangle^i\mathbf{I} = \frac{1}{\rho}\frac{\mu_\phi}{Sc}\mathbf{I} \tag{13}$$

$$\mathbf{D}_t + \mathbf{D}_{disp,t} = \frac{1}{\rho}\frac{\mu_{t_\phi}}{Sc_t}\mathbf{I} \tag{14}$$

Transport equations for $\langle k\rangle^i$ and its dissipation rate $\langle\varepsilon\rangle^i = \mu\langle\overline{\nabla\mathbf{u}':(\nabla\mathbf{u}')^T}\rangle^i/\rho$ including additional effects due to temperature and concentration gradients are proposed in Pedras and de Lemos (2003):

$$\rho\nabla.\left(\overline{\mathbf{u}}_D\langle k\rangle^i\right) = \nabla.\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_k}\right)\nabla\left(\phi\langle k\rangle^i\right)\right] + P^i + G^i + G^i_\beta + G^i_{\beta_C} - \rho\phi\langle\varepsilon\rangle^i \tag{15}$$

$$\begin{aligned} \rho\nabla.\left(\overline{\mathbf{u}}_D\langle\varepsilon\rangle^i\right) &= \nabla.\left[\left(\mu+\frac{\mu_{t_\phi}}{\sigma_\varepsilon}\right)\nabla\left(\phi\langle\varepsilon\rangle^i\right)\right] + \\ &\quad \frac{\langle\varepsilon\rangle^i}{\langle k\rangle^i}\left[c_1P^i + c_2G^i + c_1c_3\left(G^i_\beta + G^i_{\beta_C}\right) - c_2\rho\phi\langle\varepsilon\rangle^i\right] \end{aligned} \tag{16}$$

where $c_1$, $c_2$, $c_3$ and $c_k$ are constants. The generation rate of k due to buoyancy is represented by $G^i_\beta$ and $G^i_{\beta_C}$ for both the thermal and solute drives, respectively de Lemos and Tofaneli (2004).

### 2.1 Integral Parameters

The local Nusselt number on the hot wall of the square cavity (x = 0) is defined as,

$$Nu_y = hL/\lambda_{eff} \therefore Nu_y = \left(\frac{\partial\langle T\rangle^i}{\partial x}\right)_{x=0} \frac{L}{T_1 - T_2} \tag{17}$$

where $T_1$ and $T_2$ refers to the temperature limits imposed at the cavity lateral walls.

The average Nusselt number is then given by,

$$Nu = \frac{1}{H}\int_0^H Nu_y \, dy \tag{18}$$

Likewise, the local Sherwood number on the wall where the highest concentration prevails, or say, at $x = 0$ for adding drives and at $x = L$ for opposing cases, can be defined as,

$$Sh_y = h_c L/D \therefore Sh_y = \left(\frac{\partial\langle C\rangle^i}{\partial x}\right)_{x_{wall}} \frac{L}{C_1 - C_2} \tag{19}$$

Here also 1 and 2 are subscripts referring to the maximum and minimum concentration values, respectively, and $h_C$ is a film coefficient for mass transfer. The average Sherwood number is then given by,

$$Sh = \frac{1}{H}\int_0^H Sh_y \, dy \tag{20}$$

The variables $h$ and $h_c$ are local film coefficients for heat and mass transfer, respectively.

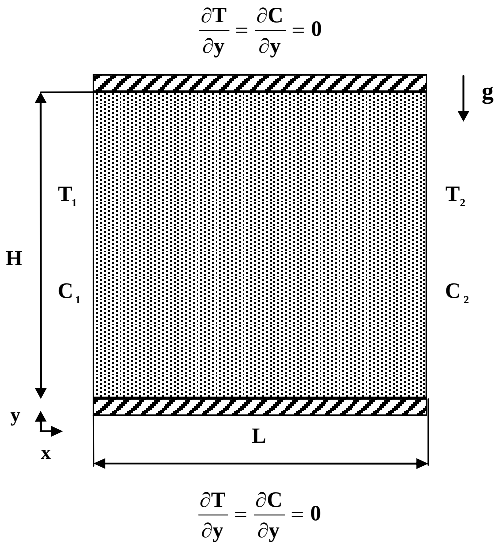
### 2.2 Numerical Details

The numerical method employed for discretizing the governing equations is the control-volume approach. A hybrid scheme, which includes both the Upwind Differencing Scheme (UDS) and the Central Differencing Scheme (CDS), was used for interpolating the convection fluxes. The well-established SIMPLE algorithm Patankar and Spalding (1972), was followed for handling the pressure-velocity coupling. Individual algebraic equations sets were solved by the SIP procedure of Stone (1968). In addition, concentration of nodal points closer to the walls reduces eventual errors due to numerical diffusion which, in turn, are further annihilated due to the hybrid scheme here adopted. Calculations for laminar and turbulent flows used a $80 \times 80$ stretched grid for all cases (Figure 1b). For turbulent flow calculations, wall log laws were applied.

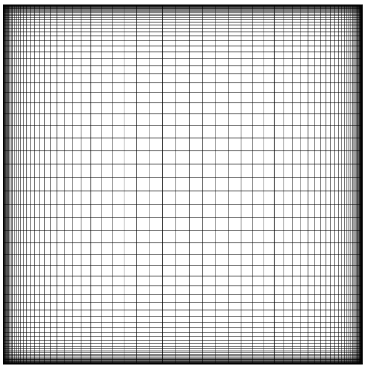
## 3. RESULTS AND DISCUSSION

As mentioned, this work refers to the study of natural convective flows in a porous cavity of height $H$ , width $L$ and aspect ratio $A = H/L$ =1 saturated by a binary fluid. The flow is incompressible and two dimensional steady state was assumed. Horizontal temperature and concentration differences were specified between the vertical walls (Figure 1a).

The validation of the numerical code has been performed over a large range of parameters for purely thermal natural convection in porous media. Table 1 shows average Nusselt e Sherwood numbers for laminar flow compared with those by Trevisan and Bejan (1985) and Goyeau et al (1996). Results in the table consider mass transfer caused by thermal convection only ( $N = 0$ ). In this configuration, the solute buoyancy force is not present but mass transfer across the cavity occurs due to the thermally driven flow. The table shows good agreement with similar computations presented in the literature and indicates correct programming of the numerical code developed.




*a*)

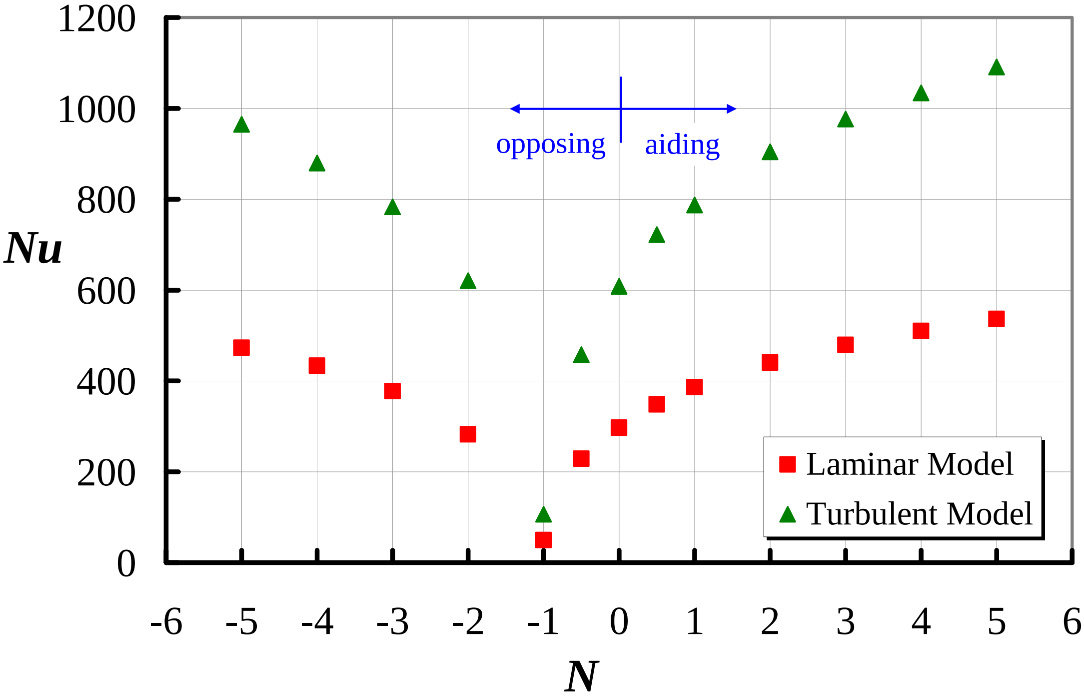


*b*)

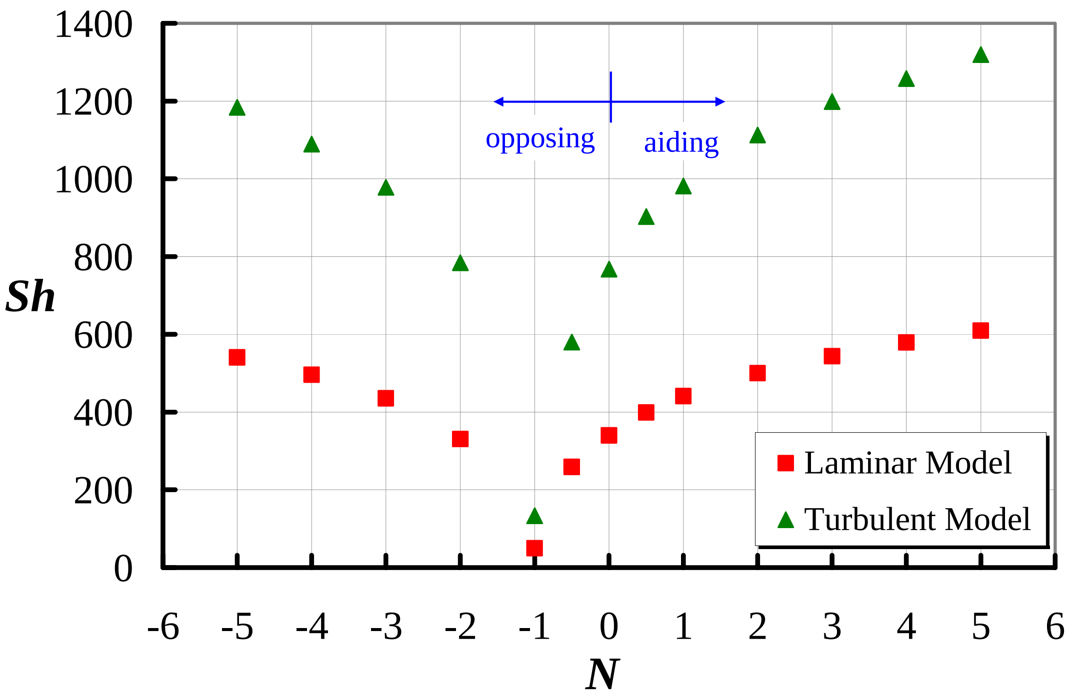
Figure 1: Configuration investigated: a) geometry and boundary conditions, b) stretched grid.

Table 1: Average Nusselt and Sherwood numbers for thermal drive only, $N = 0$ with $\beta_{C_\phi} = 0$, ( $Le = 10, A = 1$ ).

| $Ra^*$ | Imposed conditions | | 100 | 200 | 400 | 1.000 | 2.000 |
|---|---|---|---|---|---|---|---|
| *Nu* | $\frac{\Delta C}{\Delta T} = 1,$ $\beta_{C_\phi} = 0$ | Present Results | 3.11 | 4.90 | 7.65 | 13.22 | 19.54 |
| | | Goyeau et al (1996) | 3.11 | 4.96 | 7.77 | 13.47 | 19.90 |
| | | Trevisan and Bejan (1985) | 3.27 | 5.61 | 9.69 | - | - |
| *Sh* | | Present Results | 14.76 | 22.02 | 32.55 | 53.37 | 76.58 |
| | | Goyeau et al (1996) | 13.25 | 19.86 | 28.41 | 48.32 | 69.29 |
| | | Trevisan and Bejan (1985) | 15.61 | 23.23 | 30.76 | - | - |




a)




b)

Figure 2: Comparison of integral parameters as functions of the buoyancy ratio $N$ for turbulent and laminar model solutions, $Ra^* = 2\times10^6$, $Gr_\phi = 2.25\times10^{10}$, $Da = 8.88\times10^{-6}$, $\lambda_{eff} = \lambda_s = \lambda_f$ and $\phi = 0.8$: a) Nusselt number; b) Sherwood number.

Simulations considering laminar and turbulent flow for $\phi = 0.8$, $Ra^* = 2\times10^6$, $\Pr = 10$, $Gr_\phi = 2.25\times10^{10}$, $Da = 8.88\times10^{-6}$, $\lambda_{eff} = \lambda_s = \lambda_f$ and $Le = 1.0$ are shown next. The buoyancy ratio $N$ was varied from -5 to 5, for both model solutions.

Figure 2 shows the average Nusselt and Sherwood numbers at the heated wall as a function of $N$. For aiding flows ($N > 0$), $Nu$ and $Sh$ increase with $N$. The figure also shows that there are significant variations between the laminar and turbulent model solutions, with integral values nearly doubling when turbulence is considered, at least for the particular conditions presented in the figure.

The case for $N = 0$ indicates that convection is sole due to thermal buoyancy. However, since the C-equation is also solved, the flow mixes the concentration field and a corresponding Sherwood is computed. The value of $Nu$ is at minimum when $N = -1$, when the two driving mechanisms oppose each other with equal strength. Under such circumstances, conduction prevails across the cavity.

The Figure 2 further indicates that as $N$ is decreased below -1, negative buoyancy forces due to species distribution acts vertically downward, along the heated wall, thereby opposing the vertically upward thermal buoyancy drive. For that, transport rates are lower for $N < -1$ when compared with aiding cases having the same numerical value of $|N|$. That is, laminar $Nu$ and $Sh$ for $N = +4$ are 15% higher than for $N = -4$, for example. For turbulent solution, such differences for the same values of $N$ are around 23% for both $Nu$ and $Sh$.

## 4. CONCLUSIONS

This work presents numerical computations for laminar and turbulent flows using a macroscopic $k-\varepsilon$ model with wall functions. Double-diffusive natural convection in a square cavity, totally filled with porous material, was simulated. The cavity was heated from the left and cooled from the opposing side. For aiding laminar flows, predicted integral parameters were 15% higher when compared with flows with similar but opposing conditions. For adding turbulent flows, $Nu$ and $Sh$ values are roughly 23% higher than for the cases of opposing flows, at least for the conditions here simulated.

## 5. ACKNOWLEDGEMENTS

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