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Double-diffusive laminar free convection in a porous cavity simulated with the two-energy equation model

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ABSTRACT

Numerical simulations for laminar double-diffusive free convection in a porous square cavity using the Thermal Non-Equilibrium Model were presented. Vertical surfaces were maintained at constant temperature and concentration whereas horizontal walls were kept insulated. The cavity was filled with a rigid and isotropic porous matrix, which was saturated with an incompressible fluid. Transport equations were discretized by means of the control volume method leading to a coupled algebraic equation set that was solved via the SIMPLE method. Results pointed that both Nu_w and Sh_w are dependent on porosity ϕ and on the thermal conductivity ratio k_s/k_f. Nu_w decreases as ϕ decreases or k_s/k_f increases due to enhancement of conduction transport across the cavity. On the other hand, Sh_w and wall mass flux increases as porosity decreases or k_s/k_f increases. Such dependence of Sh_w arises from the intensification of recirculating motion in the cavity as ϕ is reduced or k_s/k_f is of a higher value, which affects heat exchange between phases and, consequently, wall mass fluxes. Finally, this study shows that both average Nusselt and Sherwood numbers diverge from published correlation when k_s/k_f>1 for same *Da* value.

Contents

1. Introduction

Processes involving coupled heat and mass transfer are found in various branches of science and engineering. When occurring within porous substrates, research on such double-diffusive systems have wide

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Nomenclature

Latin characters

c_F	*Forchheimer coefficient*
c_p	*Specific heat*
d	*Pore diameter*
$\mathbf{D}$	$\mathbf{D} = [\nabla\mathbf{u} + (\nabla\mathbf{u})^T]/2$, *Deformation rate tensor*
Da	*Darcy number*, $Da = \frac{K}{H^2}$
D	*Mass diffusion coefficient*
D_p	*Particle diameter*
$\mathbf{g}$	*Gravity acceleration vector*
h	*Heat transfer coefficient*
h_c	*Mass transfer coefficient*
H	*Square height*
$\mathbf{I}$	*Unit tensor*
J_y	*Mass flux of species* ℓ *along hot wall*
K	*Permeability*, $K = \frac{D_p^2\phi^3}{144(1-\phi)^2}$
k_f	*Fluid thermal conductivity*
k_s	*Solid thermal conductivity*
$\mathbf{K}_{disp}$	*Conductivity tensor due to the dispersion*
$\mathbf{K}_{tor}$	*Conductivity tensor due to the tortuosity*
L	*Cavity width*
Le	*Lewis Number*, $Le = \frac{\alpha_f}{D} = \frac{Sc}{\Pr}$
$\mathbf{n}_i$	*Unit vector normal to the* A_i
Nu	*Nusselt number*, $Nu = {}^{hL}/_{k_{eff}}$
Nu_w	*Average Nusselt number at hot wall*
Pr	*Prandtl number*
q_w^f	*Wall heat flux through the fluid phase*
q_w^s	*Wall heat flux through the solid phase*
Ra_f	*Fluid Rayleigh number*, $Ra_f = \frac{g\beta H^3\Delta T}{\nu_f\alpha_f}$
Ra_m	*Darcy-Rayleigh number*, $Ra_m = Ra_f \cdot Da = \frac{g\beta_\phi H\Delta TK}{\nu_f\alpha_{eff}}$
Re_D	*Reynolds number based on the particle diameter*, $\mathrm{Re}_D = \frac{\lvert\mathbf{u}_D\rvert D_p}{\nu_f}$.
Sc	*Schmidt number*, $Sc = \frac{\nu}{D}$
T	*Temperature*
$\mathbf{u}$	*Microscopic velocity*
$\mathbf{u}_D$	*Darcy or superficial velocity (volume average of* $\mathbf{u}$*)*
u,v	*Velocity components*
U,V	*Non-dimensional velocity components*
V_o	*Reference buoyancy velocity*

Greek characters

α_f	*Fluid hermal diffusivity*
β	*Thermal expansion coefficient*
ΔV	*Representative elementary volume*
ΔV_f	*Fluid volume inside* ΔV
μ	*Dynamic viscosity*
ν	*Kinematic viscosity*
ρ	*Density*
ϕ	*Porosity*, $\phi = {}^{\Delta V_f}/_{\Delta V}$

Special characters

φ	*General scalar variable*
$\langle\varphi\rangle^i$	*Intrinsic average*
$\langle\varphi\rangle^v$	*Volume average*
${}^i\varphi$	*Spatial deviation*
$\lvert\boldsymbol{\varphi}\rvert$	*Absolute value (Abs)*
$\boldsymbol{\varphi}$	*General vector variable*
φ_{eff}	*Effective value*, $\varphi_{eff} = \phi\varphi_f + (1-\phi)\varphi_s$
$\varphi_{s,f}$	*solid/fluid*
$\varphi_{H,C}$	*Hot/cold*
φ_ϕ	*Macroscopic value*

applications spanning from environmental flows to biomedical research.

Motivated by the foregoing, many studies have been published on laminar flow in porous media. The monographs of Nield and Bejan (1992) [1] and Ingham and Pop (1998) [2] fully documented the problem of laminar flow in porous medium. The works of Walker and Homsy (1978) [3], Bejan (1978) [4], Prasad and Kulacki (1984) [5], Beckermann et al. (1986) [6], Gross et al. (1986) [7], Manole and Lage (1992) [8] and Moya et al. (1987) [9] have contributed with important results to the problem of natural convection in a porous rectangular cavity.

When mass transfer is also considered, Trevisan and Bejan (1985) [10,11], Goyeau et al. (1996) [12], Mamou et al. (1995) [13] and Mamou et al. (1998) [14] investigated double-diffusive convection in a vertical cavity subjected to horizontal gradients of temperature and concentration. In all aforementioned works, the intra-pore flow was assumed to be laminar and they demonstrated that depending on the parameters employed and on the thermal to solute buoyancy ratio, several convection modes prevail. Bennacer et al. (2001) [15] studied the impacts of permeability and Lewis number on average Nusselt and Sherwood Numbers and pointed three distinct regimes depending of the permeability ratio of anisotropic porous media.

If fluctuations in time are also of concern due the existence of turbulence in the intra-pore space, a variety of mathematical models have been published in the literature in the last decade. One of such views, which entails simultaneous application of both time and volume averaging operators to all governing equations, has been published in a book [16] that describes, in detail, an idea known in the literature as the double-decomposition concept.

Further in the literature, the use of the two-energy equation model has also been considered for passive heat transfer across differentially heated cavities [17]. Recently, Carvalho and de Lemos (2014a) [18] used the two-energy equation model for analyzing laminar flows in cavities. Therein, only laminar regime was investigated. Following a systematic study on thermal non-equilibrium model in porous cavities, an extension of the work in [18] was presented for turbulent flow by Carvalho and de Lemos (2014b) [19].

Earlier, de Lemos and Tofaneli (2004) [20] presented a mathematical model for turbulent double-diffusive natural convection in porous enclosures and discussed the stability of mixtures under temperature and concentration gradients. Later, Tofaneli and de Lemos (2009) [21] studied the effects of opposing and aiding drives on double-diffusive convection, using laminar as well as k-ε high Reynolds turbulence models. They found that, for both models, aiding drives presents higher values for Nusselt and Sherwood parameters. However, the work in [21] was limited to one single porosity and one unique thermal conductivity ratio for the solid and fluid phases.

Therefore, this contribution combines two distinct models that have been developed on separate, namely the two-energy equation model for natural convection [18,19] and the double-diffusion model [20,21], both independently applied to porous enclosures. Here, these model are worked together and, by that, a larger number of practical engineering applications can be analyzed, broaden, as such, the numerical tool earlier developed [16]. Here, only laminar flows are considered.

2. Governing equations

The mathematical model here employed is based on the work of Reference [22], which includes the assumption of Local Thermal Non-Equilibrium (LTNE) or Two-Energy Equation Model for heat transfer calculations [18,19]. One should emphasize that in [22] no numerical results were reported. As most of the theoretical development of equations is readily available in the open literature, the governing equations will be just presented. For details about their derivations and formulations, the interested reader is referred to the above-mentioned papers. Essentially, local instantaneous equations are volume-