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Second law analysis in double diffusive convection through an inclined porous cavity

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ABSTRACT

A numerical investigation of entropy generation in steady–unsteady double diffusive convection through an inclined porous enclosure is carried on. Expressions of different irreversibilities are firstly derived. Then, effects of the enclosure inclination angle, α, and the enclosure aspect ratio, A, on entropy generation, heat and mass transfer, and fluid flow are analysed. It was found that entropy generation exhibits an oscillatory behaviour for lower ($Da = 10^{-4}$) and higher ($Da = 10^{-2}$) medium permeability values, when $\alpha \neq 0°$. Minimum entropy generation is found at the aspect ratio $A = 0.5$ and 1, for $Da = 10^{-2}$ and 10^{-4}, respectively. More details about the influence of the above mentioned operating parameters on entropy generation, heat and mass transfer and fluid flow are discussed and graphically presented.

1. Introduction

Interest in studying double diffusive natural convection in a confined porous medium has many important fundamental considerations such as to develop a better understanding of physical processes, and many engineering applications, such as the moisture removing through the air contained in fibrous insulations, the migration of moistures in grain storage installations, the fuel storage pools, the heating and cooling buildings, the room ventilating, the underground disposal of nuclear wastes, the contaminant transport through water-saturated soil and so on. The resulting flows, induced by both temperature and concentration fields, are expected to be much more complicated than the purely thermal convection flow, especially when the two buoyancy forces are in opposite directions.

In literature, convection flows in porous media have received considerable interest in the last years. Many papers concerning the field of transport in porous media are available, namely those of Nield and Bejan [27] and Kaviany [17]. Mamou et al. [21] numerically studied double-diffusive natural convection in a fluid-saturated rectangular porous enclosure. They found that the flow pattern considerably depend on the buoyancy ratio, especially for the opposing flows. Goyeau et al. [11] simulated a solidification process by considering a Darcy–Brinkman model in a porous cavity saturated by a binary fluid subject to horizontal thermal and concentration gradients. Their results reported a significant effect of the permeability on heat transfer, which is more complex than in thermal convection. Getachew et al. [10] analytically and numerically studied double diffusive convection in a saturated porous cavity with non-Newtonian fluids. They found that average Sherwood and Nusselt numbers are sensitive to the Rayleigh and Lewis numbers, buoyancy ratio and the power-law index of the fluids. Compared to the Newtonian fluids, a decrease in the power-law index enhances the convection heat and mass transfer while an increase in the power-law index yields corresponding reductions. For non-Newtonian fluids, and for the case of heat transfer driven flow ($N = 0$), heat transfer results are independent on the Lewis number, while mass transfer results depend on Lewis number.

A numerical investigation of double-diffusive convection in a vertical porous annulus was carried out by Beji et al. [7]. They found that the buoyancy ratio for which flow transition and flow reversal occur, strongly depends on physical and geometrical parameters. Simultaneous heat and mass transfer by natural convection is numerically investigated by Benzeghiba et al. [8] for a vertical annular cavity partly filled with a porous medium. Results are presented for several situations involving the cavity geometry, the fluid type, the magnitude of driving forces as well as the characteristics of the porous matrix. It was demonstrated that

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Nomenclature

A	aspect ratio (h/l)
C	concentration (mol m^{-3})
D	molecular diffusivity (m^2 s^{-1})
Da	Darcy number (K/h^2)
g	gravitational acceleration (m s^{-2})
Gr_T	thermal Grashof number
Gr_S	solute Grashof number
h	height of the cavity (m)
k	thermal conductivity (W m^{-1} K^{-1})
K	porous medium permeability (m^2)
Le	Lewis number
l	width of the cavity (m)
N	buoyancy ratio (Gr_S/Gr_T)
Nu	Nusselt number
P	pressure (kg m^{-1} s^{-2})
p	dimensionless pressure
R	gas constant (J mol^{-1} K^{-1})
Pr	Prandtl number
Ra	Rayleigh number
Ra^*	thermal porous Rayleigh number
R_K	thermal conductivity ratio (k_m/k_f)
S	entropy generation rate (J s^{-1} K^{-1} m^{-3})
S_T	total dimensionless entropy generation
Sh	Sherwood number
T	temperature (K)
t	time (s)
u,v	dimensionless velocity components
U,V	velocity components along X, Y directions (m s^{-1})
x,y	dimensionless coordinates
X,Y	Cartesian coordinates (m)

Greek symbols

α	inclination angle (°)
α_f	thermal diffusivity (m^2 s^{-1})
β_T	thermal volumetric expansion coefficients (K^{-1})
β_C	solute volumetric expansion coefficients (m^3 mol^{-1})
Λ	viscosity ratio ($\mu_{e_{ff}}/\mu$)
ε	medium porosity
μ	fluid dynamic viscosity (kg m^{-1} s^{-1})
$\mu_{e_{ff}}$	viscosity in the Brinkman model (kg m^{-1} s^{-1}).
ν_f	kinematic viscosity (m^2 s^{-1}).
ϕ	dimensionless concentration
ρ	fluid density (kg m^{-3})
σ	specific heat ratio [$(\rho c)_m/(\rho c)_f$]
θ	dimensionless temperature
τ	dimensionless time

Subscripts

0	reference
c	cold side
h	hot side

the flow structures are quite complex when buoyancy effects are articulated with the porous matrices. This only combination adds complexity and substantially alters the flow patterns and the heat and mass transfer regimes. It was concluded that double diffusion occurs in a wider range of buoyancy ratio values for Darcian flow conditions. Moreover, the numerical results show that partly porous cavities ensure better filtration performance and superior thermal insulation behaviour when compared to a fully porous cavity. Recently, Hadidi et al. [12] numerically investigated double-diffusive convection in an inclined rectangular collector filled with two parallel porous layers. The study concerns heat and mass transfer and convective motion behaviours versus the permeability ratio. The effects of a discrete source of heat and solute on the fluid flow and heat and mass transfer rates were discussed. Abaiebaghri et al. [1] developed a numerical simulation of a two-dimensional steady state double diffusive natural convection inside a porous enclosure that is heating from below and salting from the top wall. The Darcy–Brinkman–Forchheimer extended model has been used to model the flow inside the porous medium. The effects of different parameters such as Rayleigh, Darcy and Lewis numbers on the flow field, heat and mass transfer characteristics and the Nusselt and Sherwood numbers have been studied. Results show that, due to the symmetrical boundary conditions and geometry, two symmetric contours of temperature, concentration and flow are generated for the entire range of the above mentioned parameters. The heat transfer from heated element to the fluid domain increases as Rayleigh number increases. For small Darcy numbers, the flow penetration and the heat and mass transfer within the enclosure are much less than at higher Darcy number values. The increase of Lewis number yields the increase of average Sherwood number. When Darcy number is too small, the resistance of the porous medium becomes large and it has a solid behaviour. The conduction heat transfer is the dominating mechanism in the porous medium.

For real systems, entropy generation is proportional to the destroyed exergy (available energy) as mentioned by Bejan [5]. The destroyed exergy or the generated entropy is responsible for the energy loss of a system that is associated with the reversible processes hypothesis. According to Bejan [6], one can draw the map of exergy destruction distribution in a system by exergy accounting in smaller subsystems. Knowing the components that destroy the most exergy, one can improve the efficiency by setting the optimised layout of the system in such a way that the minimum entropy be generated. This is called entropy generation minimisation, which is a popular method among those who are interested in optimal design of applied systems for real-life use.

Varol et al. [30] presented a numerical study of entropy generation due to natural convection in enclosures bounded by vertical solid wall. They found that the total entropy generation rate increases with the thermal conductivity ratio. Ilis et al. [16] studied the effect of the aspect ratio on entropy generation in rectangular cavities with the same area. It was found that heat transfer and fluid friction irreversibilities in a cavity considerably depend on the aspect ratio. Makinde [22], Makinde [23] analytically studied the entropy generation encountered due to a variable-viscosity fluid flow through a channel with non-uniform wall temperature (2008a) and with convective cooling at the walls (2008b). The study leads to the determination of volumetric entropy generation from known analytical expressions of temperature and velocity. Makinde [24] reported an analytical and numerical study about the irreversibility for variable viscosity liquid film along both isothermal- and isoflux-heated inclined plate surfaces with convective cooling at the liquid free surface. Results show that a minimum entropy generation is obtained, which can be used for a suitable system design with the proper choice and the appropriate combination of various thermophysical parameters. Makinde and Maserumule [25] investigated the same problem in the flow of a variable viscosity fluid through a cylindrical pipe with