International Journal of Progressive Sciences and Technologies (IJPSAT)
ISSN: 2509-0119.

http://ijpsat.ijsht-journals.org
Vol. 23 No. 2 November 2020, pp. 660-666

Viscous Dissipation Effects on Thermodynamics Irreversibility in Mixed Convective Heat Transfer in a Lid-Driven Porous Cavity

Amira Chibani[2*], Ali Mchirgui[1], Mourad Magherbi[1,2]

[1]University of Gabes, Chemical and Process Engineering Department, National Engineering School of Gabes , Applied Thermodynamics Laboratory, Omar Ibn El Khattab Street, 6029 Gabes, TUNISIA,

[2]University of Gabes, Civil Engineering Department, High Institute of Applied Sciences and Technology, Omar Ibn El Khattab Street, 6029 Gabes, TUNISIA,

Abstract – This paper reports a numerical study about the viscous dissipation effect on steady sate of mixed convection in lid-driven porous square cavity. The analysis is performed using Darcy–Brinkman formulation with the Boussinesq approximation. The set of coupled equations of conservation of mass, momentum and energy are solved using the Control Volume Finite Element numerical method (CVFEM). The viscous dissipation model of Al-Hadhrami is used in this investigation and its expression is injected in the energy equation as a source term. Effects of viscous dissipation on thermal and Darcy viscous entropies generations are investigated. It was found that the heating effect, by viscous dissipation, significantly affects the thermodynamics irreversibility in the porous medium. Mainly more, results reveal that heat transfer irreversibility dominates for all Darcy number when viscous dissipation effect is taken into account.

Keywords – Mixed convection; cavity; viscous dissipation; porous media; entropy generation; Bejan number.

I. Introduction

During the last decades, the rate of investigations on convection in porous media continue to increase. Interest in this topic has been motivated by its importance in many industrial and technological applications, such as transport of pollutants in the soil, geothermal energy, ceramic engineering, mechanical engineering, and petroleum engineering. Sen [1] investigated natural convection in a Brinkman porous rectangular cavity with differentially heated sidewalls. Selamat et al. [2] numerically studied natural convection in a square porous cavity using finite difference method. They found that the time taken to reach the steady state considerably depend on the Rayleigh number. The problem of forced convection was studied analytically by Nield et al. [3] in a parallel-plate channel filled with a porous medium and numerically by Hooman and Gurgency [4] with different viscous dissipation models. Kuznetsov et al. [5] Studied the problem of forced convection in a duct of circular cross-section, with the temperature held constant at the walls by adding an axial conduction term and a viscous dissipation term to the thermal energy equation. mixed convection problem in a lid-driven enclosure filled with a fluid-saturated porous medium was investigated by Khanafer and Chamkha [6] and by oztop [7]. Some experimental investigations about mixed convection can be found in [8, 9 and 10] and Ghorbani et al.

As is commonly understood, entropy generation is a measure of the degraded energy of any given industrial system, improving the performance of any engineering processes during convection is related to entropy generation and its minimization. Convection includes phenomena that induce a non-equilibrium state, which means that a given evolution is described as irreversible that's why one can find in numerous studies the entropy generation associated with convection phenomenon. Varol et al. [11] 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. Abu-Hijleh and Heilen [12] investigated entropy generation due to mixed convection from an isothermal rotating cylinder. They found that that entropy generation considerably depends on Reynolds number and buoyancy parameter. Baytas [13] carried out a numerical study about the minimization of entropy generation in an inclined enclosure. Hooman et al. [14,15] analysed the first and the second laws characteristics of a fully developed a forced convection for different porous configuration. Singh et al. [16]. Carried out an analytical study about entropy generation in Al_2O_3–water nanofluid flow in micro-channel of different sizes. A good review about entropy generation and its minimization for different geometries, fluids and nanofluids was documented by Biswal and Basak [17], Marzougui et al.[18] and Oudina et al.[19]

In view of the above works which study the entropy generation in porous media, the study of the heating effect via the viscous dissipation model of Al-Hadhrami et al.[20] in not well investigate. In this context, this paper is interested on the investigation of the effect of viscous dissipation on entropy generation and the Bejan number in a saturated porous medium fluid flow under the Darcy-Brinkman formulation.

II. Mathematical Modeling

The physical model given in Fig. 1 is a lid-driven saturated porous cavity filled with a Newtonian incompressible fluid. The vertical walls are isothermal, whereas the horizontal wall are well insulated. The right wall is kept at hot temperature (Th) and the left wall is kept at cold temperature (Tc). All the walls of the cavity are assumed to be rigid and impermeable. The density of the fluid which satisfies the Boussinesq approximation is given by:

$$\rho(T) = \rho_0[1 - \beta_T(T - T_0)] \quad (1)$$

The term β_T is the thermal expansion coefficients given by:

$$\beta_T = \frac{1}{\rho_0}\left(\frac{\partial p}{\partial T}\right)_p \quad (2)$$

The parameters ρ_0 and T_0 are the reference mass density and the reference temperature respectively. All other physical properties of the fluid are assumed to be constant

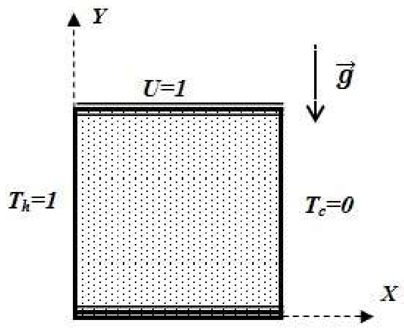

Fig.1 Mathematical model

Using Darcy–Brinkman formulation, the dimensionless conservation equations of mass, momentum and energy describing the phenomenon inside the cavity are given as follows:

$$\frac{\partial V_x}{\partial X} + \frac{\partial V_y}{\partial Y} = 0 \quad (3)$$

$$\rho_0\left[\frac{1}{\varepsilon}\frac{\partial V_x}{\partial t} + \frac{1}{\varepsilon^2}\left(V_x\frac{\partial V_x}{\partial X} + V_y\frac{\partial V_x}{\partial Y}\right)\right] = -\frac{\mu}{K}V_x - \frac{\partial P}{\partial X} + \mu_{eff}\left(\frac{\partial^2 V_x}{\partial X^2} + \frac{\partial^2 V_x}{\partial Y^2}\right) \quad (4)$$

$$\rho_0\left[\frac{1}{\varepsilon}\frac{\partial V_y}{\partial t} + \frac{1}{\varepsilon^2}\left(V_x\frac{\partial V_y}{\partial X} + V_y\frac{\partial V_y}{\partial Y}\right)\right] = -\frac{\mu}{K}V_y - \frac{\partial P}{\partial Y} + \mu_{eff}\left(\frac{\partial^2 V_y}{\partial X^2} + \frac{\partial^2 V_y}{\partial Y^2}\right) - \rho g \quad (5)$$

$$\sigma\frac{\partial T}{\partial t} + V_x\frac{\partial T}{\partial X} + V_y\frac{\partial T}{\partial Y} = \alpha_e\left(\frac{\partial^2 T}{\partial X^2} + \frac{\partial^2 T}{\partial Y^2}\right) + \frac{\Phi}{(\rho c)_p} \quad (6)$$

Were σ is the specific heat capacities ratio, μ_{eff} is the effective viscosity, μ is the fluid dynamic viscosity, K is the permeability and ε the porosity of the medium. The term (Φ) in the energy equation, is the contribution due to the viscous dissipation which is a local production of thermal energy and appears as an internal heat source in the porous media. Thus, heating effect by viscous dissipation arises as an additional term in the energy equation.

In this work we followed the viscous dissipation model of Al-Hadhrami et al. [20] which involves both Darcy fluid and clear fluid viscous frictions and which is given by:

$$\Phi = \mu\,\overline{\overline{K}}^{-1}V.V + \overline{\overline{\tau}}:\overline{\overline{\nabla}} \quad (7)$$

In the case of isotropic porous medium and for 2D system coordinates, Eq.7 is reduced to:

$$\Phi = \frac{\mu}{K}(Vx^2 + Vy^2) + \mu\left[2\left(\frac{\partial Vx}{\partial X}\right)^2 + 2\left(\frac{\partial Vy}{\partial Y}\right)^2 + \left(\frac{\partial Vx}{\partial Y} + \frac{\partial Vy}{\partial X}\right)^2\right] \quad (8)$$

Using the following dimensionless variables:

$$u = \frac{Vx}{W}\ ;\ v = \frac{Vy}{W}\ ;\ x = \frac{X}{h}\ ;\ y = \frac{Y}{h}\ ;\ \tau = \frac{t.W}{h};\ p = \frac{P-P_0}{\rho.W^2};\ \theta = \frac{T-T_0}{\Delta T}$$
$$\Delta T = T_h - T_c\ ;\ Pr = \frac{\upsilon}{W.a}\ ;\Lambda = \frac{\mu_{ef}}{\mu}\ ;\ Da = \frac{K}{h^2}\ ;\ Br = \frac{\mu.W^2}{k_m\Delta T}\ ;$$
$$Ra = \frac{g\beta_T\Delta T^{\ 3}}{\mu_{eff}};\ Re = \frac{hW}{V} \quad (9)$$

The governing equations, related to the fluid flow in the saturated lid-driven porous cavity, can be written in dimensionless form as:

$$div(v) = 0 \tag{10}$$

$$\frac{\partial u}{\partial \tau} + div(Ju) = -\varepsilon\frac{\partial p}{\partial x} - \varepsilon\frac{Pr}{Da.Re}u \tag{11}$$

$$\frac{\partial v}{\partial \tau} + div(Jv) = -\varepsilon\frac{\partial p}{\partial y} - \varepsilon\frac{Pr}{Da.Re}v + \varepsilon\frac{Ra}{Re.Pe}\theta \tag{12}$$

$$\sigma\frac{\partial \theta}{\partial \tau} + div(J\theta) = \frac{Br}{Pr.Re.Da}(u^2+v^2) + \frac{Br}{Pr.Re}\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right] \tag{13}$$

Where:

$$Ju = \frac{1}{\varepsilon}u.V - \frac{\Lambda\varepsilon}{Re}grad(u) \tag{14}$$

$$Ju = \frac{1}{\varepsilon}v.V - \frac{\Lambda\varepsilon}{Re}grad(v) \tag{15}$$

$$J\theta = \theta.V - \frac{1}{Pr.Re}grad(\theta) \tag{16}$$

The appropriate boundary conditions of the problem are:

For the top wall $u=1,\ v=0$.
For all other walls $u=v=0$.
For x=0 and $0 \le y \le 1$, $\theta = 1$.
For x=1 and $0 \le y \le 1$, $\theta = 0$.
For y=0 and $0 \le x \le 1, u = v = 0, \frac{\partial \theta}{\partial y} = 0$.
For y=1 and $0 \le x \le 1, u = 1, v = 0, \frac{\partial \theta}{\partial y} = 0$.

III. Entropy Generation Equation

Following Hooman et al.[20], Hidouri et al. [21] and Mchirgui et al. [22] the local entropy generation in a fluid flow in a porous mediumand for 2D system coordinates and using the dimensionless variables mentioned above (Eq.9), the local entropy generation equation can be written in dimensionless form as:

$$s_l = s_{Th} + s_D + s_F \tag{17}$$

In the right side of equation 17, the first term is the heat transfer irreversibility, the second is the Darcy viscous irreversibility while the third is due to the clear fluid viscous irreversibility. These terms are given by:

$$s_{Th} = \left[\left(\frac{\partial \theta}{\partial x}\right)^2 + \left(\frac{\partial \theta}{\partial y}\right)^2\right] \tag{18}$$

$$s_D = \frac{Br^*}{Da}(u^2+v^2) \tag{19}$$

$$s_F = Br^*\left[2\left(\frac{\partial u}{\partial x}\right)^2 + 2\left(\frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right)^2\right] \tag{20}$$

$Br^* = \frac{Br}{\Omega}$, is defined as the modified Darcy-Brinkman number.

Br and Ω are the Brinkman number and the temperature ratio respectively. They are given by:

$$Br = \frac{\mu W^2}{k_m \Delta T} and \Omega = \frac{\Delta T}{T_0} \tag{21}$$

The dimensionless total entropy generation for the entire lid-driven porous cavity is obtained by numerical integration of local entropy generation over the cavity volume A.

$$s_{tot} = \int_A s.dA \tag{22}$$

The average heat transfer through the heated wall is given in dimensionless term by Nusselt number as follow:

$$Nu = -\int_0^1 \left(\frac{\partial \theta}{\partial x}\right) dy \tag{23}$$

IV. Numerical Results And Validation

The used numerical method consists on the Control Volume Finite Element Method (CVFEM) of Saabas and Baliga [23]. Standard staggered grids were employed in the goal to calculate and store the velocity components. The SIMPLER algorithm of Patankar [24] is adopted to resolve the coupled pressure-velocity equations in conjunction with an alternating direction implicit (ADI) scheme for performing the time evolution. The used numerical code was described and validated in details in Abbassi et al. [25]. As mentioned, local entropy generation is obtained from the known gradients of temperature and velocity fields, which are calculated at any nodal point and any time t. Therefore the entropy generation can be a good convergence criterion. The convergence criteria is given by:

$$\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}\right) \le 10^{-5} \tag{24}$$

$$\text{Max}\left|\frac{\Gamma^{\Gamma+\Delta\Gamma}-\Gamma^{\tau}}{\Gamma^{\Gamma+\Delta\Gamma}}\right| \le 10^{-5} \tag{25}$$

Γ stands for the variables $(u, \vartheta, \theta, s)$. This means that the continuity equation should verify the first convergence criterion at each time step of calculation, and the variable Γ should verify the second criterion at each point of the cavity and at each time step. To test the accuracy of the present numerical study, the average values of Nusselt number for a square porous cavity (A=1), submitted to natural convection are given in Table 1 and compared with those of Kramer et al. [26] and Lauriat et al. [27]. As shown in Table 1, the obtained results are in good agreements with those given by the literature.

Table 1: Average values of Nusselt number (Ra*= Ra.Da =100)

Da	10^{-1}	10^{-2}	10^{-3}	10^{-4}
Present study	1.067	1.72	2.42	2.84
Kamer et al.	1.08	1.70	2.43	2.83
Lauriat et al.	---	1.70	2.41	2.84

Table 2: Total entropy generation values versus grid sizes (Ra*=Ra.Da=100)

A	Grid size	S_T Da=10^{-2}	Er(%) Da=10^{-2}	S_T Da=10^{-4}	Er(%) Da=10^{-4}
0.5	21*21	3.98	-	-	-
	31*31	4.13	3.34	38.97	-
	41*41	4.21	1.93	41.04	5.31
	51x51	4.26	1.18	41.65	1.48
1	21*21	4.01	-	-	-
	31*31	4.18	4.23	41.93	-
	41*41	4.25	1.67	42.97	2.48
	51x51	4.30	1.1	43.46	1.14

In order to ensure that the calculated results are grid independent, we calculate the total entropy generation for the following four grid size: 21x21; 31x31; 41x41; 51x51. For the grid independency calculation, the used Darcy numbers are 10^{-2} and 10^{-4} and the porous Rayleigh number is equal to 100. Table 2 illustrates the variation of total entropy generation values versus grid sizes in steady state for different grid distributions, and for the value of the thermal porous Rayleigh number Ra_T*=100. We adopted the relative error given by Eq. (26) as a criterion for choosing the grid size. The relative error is calculated when we pass from (n*n) to (n+10 x n+10) nodal points. Grids are chosen for relative error less than 1.5%.

$$Er(\%) = \frac{|S_{T(n+10,n+10)} - S_{T(n,n)}|}{S_{T(n,n)}}.100 \qquad (26)$$

From Table 2, it can be seen that the use of grid with 51*51 nodal points is sufficiently enough, for square porous cavity with aspect ratio A= 1, to calculate the entropy generation in the porous medium fluid flow for all selected Darcy numbers.

V. Results And Discussion

This paper concerns the study of thermal irreversibility, Darcy viscous irreversibility and Bejan number in a saturated lid-driven porous cavity. The porous medium properties Λ and ε are constant and respectively equal to 1 and 0.8.

4.1. Viscous dissipation effect on thermal irreversibility

Figure 2 illustrates the variation of the thermal entropy generation with the Darcy number for the specified viscous dissipation model. In this figure, logarithmic scale is used for x and y axis. The Prandtl, Reynolds and Rayleigh numbers are fixed respectively at 7, 10 and 10^5.

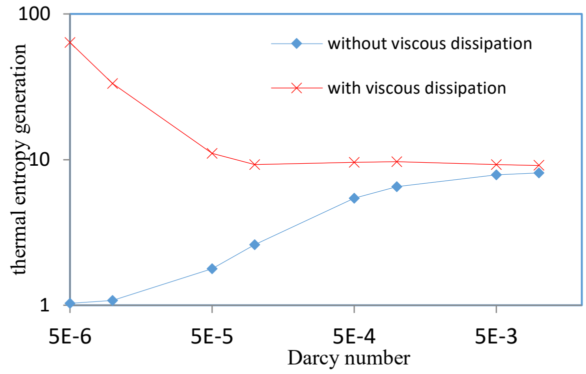

Fig.2 Thermal entropy generation versus Darcy Number with and without viscous dissipation

As can be seen from Fig. 2 for small Darcy number, plot linked to the case without viscous dissipation shows that the thermal entropy generation is quite equal to unity which indicates the existence of a conduction regime in the porous media. Indeed, in this case the permeability of the medium is very low and the porous matrix is dominant, thus giving a behavior close to a solid medium characterized by a pure conduction heat transfer. For this same plot, one can see a slight increase of the thermal irreversibility with the Darcy number. This is the result of an enhancement of the convection in the porous cavity as the permeability increases, resulting from the transition of the system from a solid behavior to a clear fluid one. This involves an increase in the thermal gradients and therefore in the thermal entropy generation.

Taking into account heating by the viscous dissipation effect and at fixed Darcy number, Fig. 2 illustrates an increase in heat transfer irreversibility compared with the basic model. This increase is as amplified as the Darcy number is smaller. The largest discrepancy between the results from the viscous dissipation case and non-viscous one is identified for small number of Darcy (5.10^{-6}). In this context, one can observe that thermal entropy generation is important (superior to unity) at small Darcy number, then it decreases to take a minimum value at critical Darcy number, from which it begins to increase until it reaches a constant value at relatively high Darcy number. The important value of heat transfer entropy generation at small Darcy number is due to the important quantity of internal calorific energy received by the fluid due to the local production of thermal energy generated by the mechanism of viscous stress. This phenomenon can be the result of a relatively complex flow characterized by a micro-convection effect established at the pores scale of the porous medium that rises thermal gradients and thereafter increases thermal entropy generation. The decrease in the generation of thermal entropy to a minimum value, when the Darcy number increases, can be explained by a decrease in the internal heat energy of the fluid when the permeability of the porous medium increases. The increase in thermal entropy generation from the critical value of Darcy number can be explained by the birth of a convection phenomenon resulting of the clear fluid behavior dominance. At high Darcy number, figure 2 shows that thermal irreversibility takes almost a constant value which approaches the value in the non viscous dissipation case. This observation indicates that the viscous dissipation, although it exists, stay very slight at high permeability values. Remark that in this case the difference between the two values at Da=5.10^{-3} is about 11%.

4.2. Darcy Viscous entropy generation

Figure 3 illustrates the evolution of the Darcy viscous entropy generation as a function of Darcy number in the cases with viscous dissipation (Red curve) and without viscous dissipation (blue curve). In this figure, the logarithmic scale is used for x-axis. The Prandtl, Reynolds and Rayleigh number are fixed respectively at 7, 10 and 10^5.

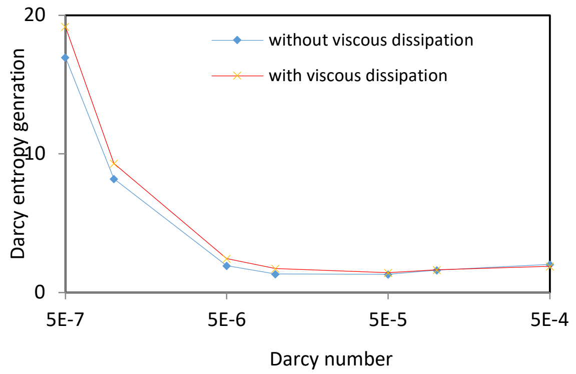

Fig. 3 Darcy viscous entropy generation versus Darcy Number with and without viscous dissipation

As shown in this figure and in absence of heating by viscous dissipation, Darcy viscous dissipation takes important value at low Darcy number. This is principally the result of the kinetic energy acquired by the fluid via works done by the inertial forces induced by the driven wall of the cavity. Also in the case without viscous dissipation, Fig. 3 shows that the Darcy viscous irreversibility decreases when Darcy number increases. This is principally due to an intrinsic effect of the Darcy number in Darcy viscous irreversibility equation (Eq.19). As Darcy number increases and takes relative important values, Darcy viscous irreversibility takes practically constant value. In fact at relatively high Darcy number the mixed convection in the porous medium is well developed and consequently the Darcy number becomes without noticeable effect. In fact, its intrinsic effect which tends to reduce Darcy irreversibility is counterbalanced by the enhancement of the convection in the cavity via the thermal buoyancy force which tends to increase the velocity. As a result and taking into account that Rayleigh and Reynolds numbers are kept constant, Darcy viscous irreversibility remains almost stable.

Taking into account viscous dissipation effect, one can observe from Fig.3 that Darcy viscous irreversibility plot deviate from the case without viscous dissipation. This deviation between the two cases (with and without viscous dissipation effect) is as important as Darcy number is smaller and one can count a value close to 12% at Darcy number equal to 5.10^{-7}.

For the case with viscous dissipation effect, the Darcy fluid viscous irreversibility decreases when the Darcy number increases. It's perceptible that for fixed size system, when the Darcy number increases the permeability of the porous medium increases and the resistance of the porous matrix to the flow gradually decreases and the behavior of the system tend towards a clear fluid one. The Darcy viscous force becomes feeble that induces inexistent effect of the Darcy viscous dissipation term. Also, heating effect due to Al-Hadhrami term still weak due, firstly to insignificant velocity gradients even at high Darcy number and secondly to the selected small value of Brinkman number.

It's important to note that for high Darcy number, curves in the plot of Fig. 3 are almost confused, since the contribution of the local heat source terms in the energy equation has insignificant effects. In this context, the fluid has the ability to move more freely through the porous matrix, thereby generating a decrease in the local calorific energy due to the viscous forces.

4.3. Bejan Number variation with Darcy number

The study of different irreversibility competition is given by the Bejan number (Be), which is the ratio of heat transfer irreversibility to the total entropy generation, can be mathematically expressed as:

$$Be = \frac{S_{Th}}{S_{Total}} \tag{26}$$

Bejan number ranges from 0 to 1. Accordingly, Be=1 is limit at which the heat transfer irreversibility dominates. Be =0 is the opposite limit at which the irreversibility is dominated by fluid viscous effects. The case when Be=1/2 is which heat transfer irreversibility is equal to fluid friction irreversibility. Figure 4 illustrates the variation of the Bejan number versus the Darcy Number under viscous dissipation models cited above. The Reynolds and Rayleigh numbers are equal to 10 and 10^5 respectively. The Darcy number is varying from 5.10^{-6} to 10^{-2}.

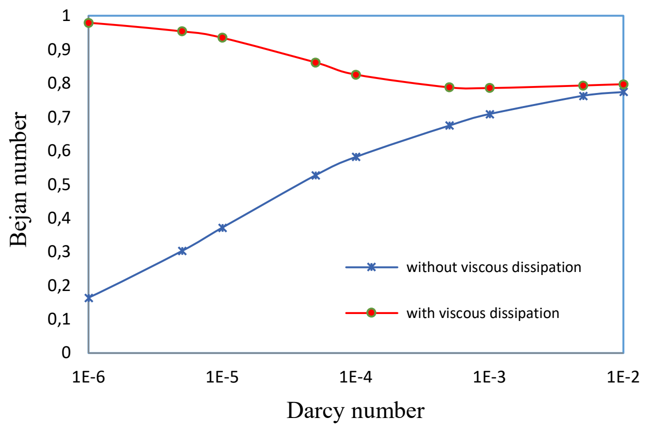

Fig. 4 Influence of Darcy number on Bejan number with and without viscous dissipation

As can be seen from Fig.4 and for no viscous dissipation effect, viscous fluid irreversibility is preponderant at small Darcy number. In fact in this case (small Da), as explain above, the viscous irreversibility is more important than the heat transfer irreversibility.

Consequently viscous irreversibility through its Darcy term is dominant. As the Darcy number increases the Bejan number increases and the dominance of viscous irreversibility decreases. Beyond the value Da=5.10^5, for which viscous and heat transfer irreversibilities are equal, the Bejan number becomes greater than 0.5 indicating the dominance of heat transfer irreversibility. In this case and for relatively high Darcy number, the permeability of the medium increases inducing a decrease in the Darcy viscous irreversibility and consequently a dominance of heat transfer irreversibility. In the case with viscous dissipation effect and as can be seen from Fig. 4, heat transfer irreversibility dominates for all Darcy numbers. In this case the dominance of heat transfer irreversibility is due to the heating process in the porous medium via the viscous dissipation effect at small Darcy number and due to the increase of heat transfer via the enhancement of convection phenomenon at high Darcy number.

VI. CONCLUSION

This study concerns the effect of viscous dissipation on entropy generation and Bejan number in a lid-driven porous cavity filled with Newtonian and incompressible fluid. The porosity of the medium is fixed at the value 0.8. The Prandtl and Rayleigh number are fixed at 7 and 10^5 respectively. The Navier–Stokes and energy equations are modeled under the Darcy-Brinkman formulation. Three models of viscous dissipation, added as source term in the energy equation, are studied. The influences of Darcy and Reynolds numbers on the thermodynamic irreversibility related to each one of the three viscous dissipation models are studied and compared with the basic case of non-viscous effect. The most important notice points given by the present investigation are the following:

1.In the case without viscous dissipation and for small Darcy number, the thermal entropy generation is quite equal to unity which indicates the existence of a conduction regime in the porous media. a slight increase of the thermal irreversibility is seen when the Darcy number increases.

2.Taking into account heating by the viscous dissipation effect and at fixed Darcy number, results show heat transfer irreversibility increases compared with the non viscous case. This increase is as amplified as the Darcy number is smaller.

3. The important value of heat transfer entropy generation at small Darcy number is due to the important quantity of internal calorific energy received by the fluid due to the local production of thermal energy generated by the mechanism of viscous stress.

4. The viscous dissipation effect still exists even at High permeability (high Darcy number) and one can count a difference between the two values of thermal entropy generation (with and without viscous dissipation) of about 11% at Da=5.10^{-3}.

5.The effect of viscous dissipation on Darcy viscous irreversibility is important at small Darcy number whereas it becomes insignificant at relatively high Darcy number. The most important gap between the two cases is seen at Da=5.10^{-7} and reaches11%.

6. For the non viscous dissipation case, viscous fluid irreversibility is preponderant at small Darcy number. In contrast, heat transfer irreversibility dominates for all Darcy number when viscous dissipation effect is taken into account,

REFERENCES

[1] A. K. Sen , Natural convection in a shallow porous cavity-the Brinkman model, int. J. Heat Mess Tran., 5. pp. 855-868. May1987.

[2] M. S. Selamat, I. Hashim, M. K. Hasan, transient Natural Convection in Porous Square Cavity Heated and Cooled on Adjacent Walls, Math. Prob. in Eng.Vol 2012, jan. 2012.

[3] D. A. Nield , A. V. Kuznetsov, M. XIiong: Effects of Viscous Dissipation and Flow Work on Forced Convection in a Channel Filled by a Saturated Porous Medium, Transport in Porous Media 56: 351–367, 2004.

[4] K. Hooman · H. Gurgenci : Effects of viscous dissipation and boundary conditions on forced convection in a channel occupied by a saturated porous medium, Transp Porous Med (2007) 68:301–319.

[5] A. V. Kuznetsov, M. XIiong, D. A. Nield : Thermally Developing Forced Convection in a Porous Medium: Circular Duct with Walls at Constant Temperature, with Longitudinal Conduction and Viscous Dissipation Effects Transport in Porous Media 53: 331–345, 2003.

[6] K.M. Khanafer, A.J. Chamkha, Mixed convection flow in a lid-drive enclosure filled with a fluid-saturated porous medium, Int. J. Heat Mass Transfer 42 (1999) 2465–2481.

[7] H.F. Öztop, Combined convection heat transfer in a porous lid-driven enclosure due to heater with finite length, Int. Commun. Heat Mass Transfer 33 (2006) 772–779.

[8] M. Dogan, M. Sivrioglu, Experimental investigation of mixed convection heat transfer from longitudinal fins in a horizontal rectangular channel, Int. J. Heat Mass Tran. 53 (2010) 2149 – 2158.

[9] A. Zöllner, E.R.F. Winter, R. Viskanta, Experimental studies of combined heat transfer in turbulent mixed convection fluid flows in double-skin-facades, Int. J. Heat Mass Tran. 45 (22) (2002) 4401–4408

[10] N. Ghorbani, H. Taherian, M. Gorji, H. Mirgolbabaei, Experimental study of mixed convection heat transfer in vertical helically coiled tube heat exchangers, Exp. Therm. Fluid Sci. 34 (7) (2010) 900–905.

[11] Varol Y, Oztop HF, Koca A. Entropy generation due to conjugate natural convection in enclosures bounded by vertical solid walls with different thickness. Int Commun Heat Mass Transfer 2008;35:648–56.

[12] Abu-Hijleh B. A. K. and Heilen, W. N., entropy generation due to laminar natural convection over a heated rotating cylinder. Int. J. Heat and Mass Transfer 1999, 42, 4225-4233.

[13] Baytas, A.C.: optimisation in an inclined enclosure for minimum entropy generation in natural convection. J. Non-Equilib. Thermodyn. 22, 145–155 (1997)

[14] Hooman, K., Gurgenci, H., Merrikh, A. A. Heat transferandentropy generationoptimizationofforced convection ina porous-saturatedduct ofrectangular cross-section. International Journal ofHeatandMass Transfer 2007;50:2051-2059.

[15] Hooman,K.,Hooman,F., Mohebpour,S. R.Entropy generation for forced convection in a porous channel with is of luxor isothermal walls. International Journal ofExergy2008;5:78-96.

[16] P.K. Singh, K.B. Anoop, T. Sundararajan, S.K. Das, Entropy generation due to flow and heat transfer in nanofluids, Int. J. Heat Mass Transfer 53 (2010) 4757– 4767.

[17] Entropy generation vs energy efficiency for natural convection based energy flow in enclosures and various applications: A review Pratibha Biswal, Tanmay Basak.Renewable and Sustainable Energy Reviews 80 (2017) 1412–1457

[18]S.Marzougui, A.Mchirgui ,M. Maghrebi. Double diffusive natural convection and entropy generation through a trapezoidal porous cavity: January 2020 Special Topics and Reviews in Porous Media

[19]F.Oudina. Entropy Generation on Magneto-Convective Flow of Copper-Water Nanofluid in a Cavity with Chamfers: April 2020 Journal of Thermal Analysis and Calorimetry

[20] Al-Hadhrami, A.K., Elliott, L., Ingham, D.B.: A new model for viscous dissipation in porous media across a range of permeability values. Trans. Porous Media 53, 117–122 (2003).

[21] Hooman, K., Gurgenci, H., Merrikh, A. A.: Heat transfer and entropy generation optimization of forced convection in a porous-saturated duct of rectangular cross-section. Int. J. Heat and Mass Trans. 50, 2051-2059 (2007).

[22] Hidouri, N., Abbassi, H., Magherbi, M., Ben Brahim, A.: Entropy generation in double diffusive convection in presence of the Soret effect. progress in computational fluid dynamics, 7, 5 , 237 – 246 (2007).

[23] Mchirgui A. , Hidouri N., Mourad M. , Ben Brahim A.: Entropy Generation in Double-Diffusive Convection in a Square Porous Cavity using Darcy–Brinkman Formulation. Transport in Porous Media, 93, 223 – 240 (2012).

[24] H. J. Saabas, B.R. Baliga, Co-located equal-order control-volume finiteelement method for multidimensional incompressible fluid flow. Part I: Formulation. Numer. Heat Transfer Pt. B-Fund.vol 26, 381–407, Jan. 1994.

[25] Patankar SV. Numerical heat transfer and fluid flow. In computational methods in mechanics and thermal sciences. NY, USA: Hemisphere /Mac Graw-Hill; 1980.

[26] Abbassi H,Turki S,Ben Nasrallah S . Numerical investigation of forced convection in a plane channel with a built-in triangular prison. Int J Therm Sci 2001;40:649-58.

[27] Kramer J, JecI R, Skerget L. Boundary domain integral method for the study of double diffusive natural convection in porous media. Eng Anal Bound Elem 200;31:897-905.

[28] Lauriat G, Prasad V., Natural convection in a vertical porous cavity: a numerical study for Brinkman-extended Darcy formulation . J Heat Transfer 1987;109:688-96.

Nomenclature

Symbol	Description	Unit
Da	Darcy number	K/h^2
g	gravitational acceleration	$m \cdot s^{-2}$
h	height of the cavity	m
K	thermal conductivity	$W.m^{-1}.K^{-1}$
K	Porous medium permeability	m^2
Nu	Nusselt number	
P	Pressure	$kg \cdot m^{-1}.s^{-2}$
P	dimensionless pressure	
R	gas constant	$J.mol^{-1}.K^{-1}$
Pr	Prandtl number	
Ra	Rayleigh number	
Re	Reynolds number	
S	entropy generation rate	$J.s^{-1}.K^{-1}.m^{-3}$
S_T	total dimensionless entropy generation.	
T	temperature	K
t	time	s
u, v	dimensionless velocity components	
U, V	velocity components along *X*, *Y* directions	$m \cdot s^{-1}$
x, y	dimensionless coordinates	
X, Y	cartesian coordinates	m

Greek letter

α_f	thermal diffusivity	$m^2.s^{-1}$
β_T	thermal volumetric expansion coefficients	K^{-1}
Λ	viscosity ratio	μ_{eff}/μ
ε	medium porosity	
μ	fluid dynamic viscosity	$kg.m^{-1}.s^{-1}$
μ_{eff}	Effective viscosity	$kg.m^{-1}.s^{-1}$
ν_f	kinematic viscosity	$m^2.s^{-1}$
Φ	viscous dissipation function	
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	Th	thermal
c	cold	f	fluid
h	hot	D	Darcy
l	local	T	total