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Second Law Analysis in a Non-Newtonian Fluid Flowin a Circular Duct

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Abstract— **In this paper, mixed convection heat transfer and its associated entropy generation in a circular duct saturated with a Carreau non-Newtonian fluid has been numerically investigated. The influence of inlet pressure, thermal gradient and aspect ratio of the duct on the heat transfer entropy generation and frictional entropy generation is basically studied. The governing equations of the problem are solved numerically using the COMSOL software. Results show that the thermal and viscous irreversibilities are strongly affected by the increase in the inlet pressure and thermal difference temperature. A critical duct ratio equal to 3 after which, the duct ratio is with insignificant influence on irreversibility for all considered power indexes**

***Keywords*—non-Newtonianfluid,circularduct, mixed convection, entropy production,numerical methods.**

I. Introduction

Non-Newtonian fluid flows find a relatively new aspect in industrial fluid mechanics. The birth of new products, the interaction of heat exchange phenomena on viscosity, the search for new manufacturing processes encourages us to take stock of the industrial problems concerning the flow of this type of fluid. Grambode, et al. [1] studied the heat transfer in mixed convection of a non-Newtonian fluid flowing in a horizontal cylindrical pipe heated by a uniform heat flux density imposed on the wall and analyzed this problem using large-scale numerical simulation. Mecili and Mezaache [2] studied the forced convection of a power-law fluid flowing in a cylindrical pipe with a determined velocity profile. They then reduce the transport equations to a single energy equation. Houssem and Mohamed [3] carried out a numerical study solving the Navier-stokes equations and the energy equation using the finite volume method for the flow of an Ostwald fluid around a hot square cylinder. They showed that thermal buoyancy completely suppresses the recirculation zone behind the obstacle. Khelaf and Lauriat [4] dealt with the problem of forced convection in a cylindrical pipe between two parallel plates for a fully developed flow of a power-law fluid. Barletta and Zanchini [5] were interested in piston flow (constant velocity) in a cylindrical pipe. They analytically determined the temperature field and the local Nusselt number. Kaveh Yazdani et al. [6] numerically analyzed the production of thermal and viscous entropy caused by the natural convection of a fluid in power law in a

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trapezoidal cavity. They highlighted the effect of the power index on the production of entropy. Muhareem et al. [7] studied the production of entropy in a non-Newtonian shear thinning fluid between two infinite parallel plates and by adopting the Carreau model.

In this work we are interested in the study of the variation of the productions of thermal and viscous entropies according to the pressure of entry of the fluid, the thermal gradient and the index of power of the fluid. One of the strong points of this work manifests itself at the level of a dimensional calculation which, in our opinion, will allow us to have a real idea concerning the intensity of the irreversibilities encountered in such a flow.

II. Physical Model

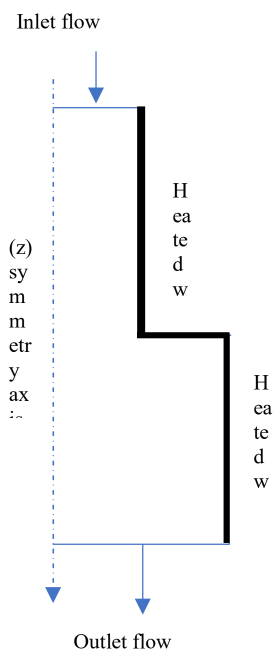

Figure 1: Geometry of the studied model

The non-Newtonian fluid under study is a polystyrene solution flowing in a vertical circular pipe. The fluid enters from the top with an inlet pressure and temperature (pin) and (Tin) respectively. The external wall of the pipe is subjected to a temperature higher than that of the noted fluid (T p). Thus, a horizontal temperature gradient is established between the fluid and the outer wall of the circular pipe. The study is reduced to half of the geometric configuration considered following the existence of an axis of symmetry along the direction (z).

III. Mathematical formulation

The equations governing the flow in a two-dimensional cylindrical coordinate system are written as follows:

-Continuity equation

$$\frac{1}{\mathrm{r}}\frac{\partial}{\partial \mathrm{r}}(\mathrm{rV_r}) + \frac{\partial \mathrm{V_z}}{\partial z} = 0 \quad (1)$$

- Conservation equation of momentum

$$\rho\left(V_r\frac{\partial V_r}{\partial r} + V_z\frac{\partial V_r}{\partial z}\right) = -\frac{\partial p}{\partial r} + \left(\frac{\partial}{\partial r}\mu_a\left(\frac{1}{r}\frac{\partial}{\partial r}(rV_r)\right)\right) + \frac{\partial}{\partial r}\left(\mu_a\frac{\partial V_r}{\partial z}\right) \quad (2)$$

$$\rho\left(V_r\frac{\partial V_z}{\partial r} + +V_z\frac{\partial V_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \rho g_z + \frac{1}{r}\frac{\partial}{\partial r}\left(\mu_a r\frac{\partial V_z}{\partial r}\right) + \frac{\partial}{\partial z}\left(\mu_a\frac{\partial V_z}{\partial z}\right) \quad (3)$$

-Equation of heat

$$\rho c_p\left(V_r\frac{\partial T}{\partial r} + +V_z\frac{\partial T}{\partial z}\right) = k\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial z^2}\right) \quad (4)$$

Equation of entropy production

The entropy generation equation is given by [8]:

$$S_{th} = \frac{k}{T^2}\left[\left(\frac{\partial T}{\partial r}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2\right] \quad (5)$$

$$S_{vis} = \frac{\mu_a}{T}\left\{2\left[\left(\frac{\partial V_r}{\partial r}\right)^2 + \left(\frac{\partial V_z}{\partial r}\right)^2\right] + \left(\frac{\partial V_z}{\partial r} + \frac{\partial V_r}{\partial z}\right)^2\right\} \quad (6)$$

$$S_{totale} = S_{vis} + S_{th} \quad (7)$$

The viscosity model adopted in this work is given by the following law:

$$\mu_a = \mu_\infty + (\mu_0 - \mu_\infty)[1 + (\lambda\dot{\gamma})^2]^{\frac{n-1}{2}} \qquad (8)$$

This work is focused on the study of entropy production in a non-Newtonian fluid flowing in mixed convection in a circular pipe. The effects of the inlet pressure (pin), the temperature difference between the pipe wall and the fluid ΔT

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(Tp-Tin) and the aspect ratio (A) of the pipe on the thermal and viscous irreversibilities.

IV. Numerical procedure and validation

In the dimensional form and considering the initial and the boundary conditions, the flow governing equations were solved using COMSOL Multiphysics software which is based on the discretization of equations by the finite element method, commonly known as the Petrov-Galerkin method that ensures the stabilization of pressure.

A numerical calculation code written under the COMSOL platform has been established for the resolution of the Navier-Stokes and energy equations in dimensional form and considering the initial conditions and the limits considered above. In a first step, the results given by the COMSOL code were validated with the numerical results, obtained by a FORTRAN code elaborated in our laboratory of Applied Thermodynamics at the National Engineering School of Gabes-Tunisia, related to the work of Magherbi et al. [11] in terms of isentropic lines and in the case of a power low index equal unity (Newtonian fluid). In a second step, another validation was carried out with the work of other authors. Our numerical results obtained by COMSOL are in good agreement with those obtained from other works.

V. Results and discussion

1. Effect of input pressure (pin)

Figure 1 illustrates the variation of the thermal entropy production (Sith) as a function of the power index (n) for different values of the inlet pressure (pin). The temperature of the fluid at the inlet is assumed to be constant and has a difference of 40K with the temperature of the pipe wall. The power index is taken as variable from 0.5 to 1.2.

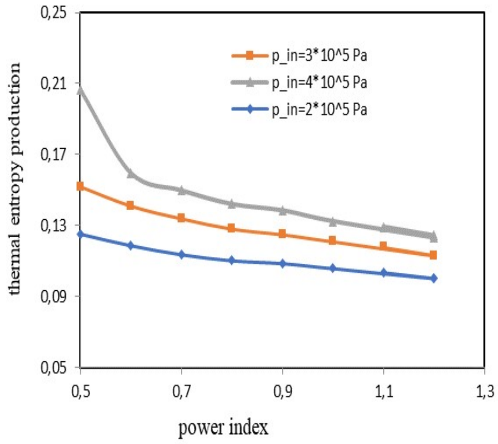

Figure1: Effect of inlet pressure and power index(n) on the total thermal entropy generation rate (ΔT=40K, A=2)

fixed inlet pressure value, Figure 1 shows that an increase in the power index (n) leads to a decrease in the rate of thermal entropy production. This reduction being small, at a low value of the inlet pressure, becomes increasingly significant for low values of the power index, and this at inlet pressures greater than or equal to 4.10^{5}. Indeed, this decrease in the production of entropy as a function of the power index is mainly due to an increase in the dynamic viscosity which generates a shear-thickening character of the fluid which is accompanied by an increase in the forces of viscous friction and consequently reduces the phenomenon of convection in the cavity. The decrease in convection leads to a decrease in temperature gradients which in turn leads to a decrease in the thermal entropy production. For a given value of n, Figure 1 shows that the thermal entropy production increases with the inlet pressure of the fluid. This increase, in the case of a constant aspect ratio, can be explained by the emergence of fluid recirculation zones just in the vicinity of the widening zone of the circular pipe. Indeed, the existence of recirculation zones in these places leads to an increase in thermal gradients and consequently to the thermal entropy production. It should be noted that the greatest increase in thermal irreversibilities was observed for power indices below 0.6. Indeed, when the power index goes from 0.6 to 0.5, the thermal entropy production undergoes an increase of almost 25%.

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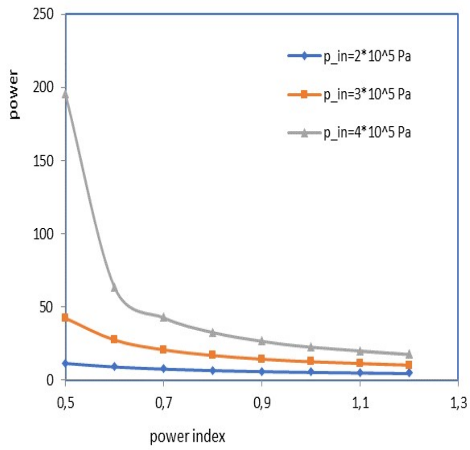

Figure2: Effect of inlet pressure and power index on the viscous entropy production (ΔT=40K, A=2)

Figure 2 illustrates the variation of the viscous entropy production rate (Siv) as a function of the power index (n) for different values of the inlet pressure (Tin). For a relatively low fluid inlet pressure (less than 2.10^{5}) increasing the power index (n) has virtually no effect on the rate of viscous entropy production. This is due to the insignificant character of the velocity gradients whose influence on the viscosity of the fluid remains minimal and whose effect on the viscous entropy production remains negligible.

As illustrated in Figure 2, the variation of viscous entropy as a function of the power index becomes more and more remarkable, while increasing the inlet pressure of the fluid. This may be the result of an increase in fluid viscosity via increasing velocity gradients. It is important to note that this increase is more significant as the power index is low. Indeed, this case corresponds to a decrease in viscosity which induces an improvement in convection in the pipe. It is important to note that an increase in the viscosity of the fluid is a cause which manifests itself by two effects. The first effect is extrinsic and results in an increase in viscous friction forces which tend to oppose and slow down the flow and consequently reduce viscous irreversibilities. The second effect is intrinsic through the expression of viscous entropy and is manifested by an increase in viscous irreversibilities. These two totally opposite effects, result of the same cause, are in competition which depends on the quantities characterizing the flow as well as on the geometry of the pipe.

Figure 2 also shows that a decrease in the power index (n) is accompanied by an increase in the rate of viscous entropy production. This increase is very remarkable for power indices between 0.5 and 0.6. This is explained by the transition of the fluid from a shear-thinning character (n<1) where the dynamic viscosity becomes very low, generating lower viscous forces compared to a shear-thickening fluid (n>1). Finally, let us note that when the power index takes on relatively large values, the viscous entropy production practically converges towards the same value for all the input pressures considered. Indeed, in this context the non-Newtonian fluid takes on a shear-thickening character which is close to that of a solid.

2. Effect of temperature difference (ΔT)

Figure 3 illustrates the variation of thermal entropy production (Sith) as a function of the power index (n) for different values of the temperature difference between the wall and the fluid at the inlet thermal gradient (**Δ**T)

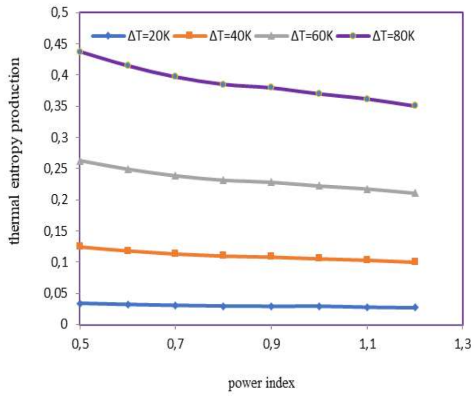

Figure3: Effect of temperature difference and power index on the thermal entropy production for(A=2, pin=2.10^{5} Pa)

As shown in Figure 3, for constant ΔT, the increase in the power index (n) is accompanied by a slight decrease in the thermal entropy generation rate. This decrease is insignificant for low values of the temperature difference (ΔT less than 20k). Indeed, in this case the flow is not very affected, and the thermal gradients remain practically unchanged, such that the effect of an increase in the power index remains insignificant on the production of entropy. This decrease

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becomes more and more remarkable for relatively large ΔT, because of the large value taken by the thermal entropy production at low values of the power index. Indeed, for low power indices and a significant temperature difference, the convection effect on the shear-thinning fluid becomes visible in the circular pipe. Figure 3 shows that for a constant power index the thermal entropy production increase when the temperature difference increases. This increase is all the greater when the power index is low. indeed, for a low power index, the shear thinning fluid has a low viscosity, the convection phenomenon becomes more and more developed as the temperature difference increases, thus causing an increase in the thermal gradients and consequently in the production thermal entropy.

Figure 4 illustrates the variation of viscous entropy production (Sith) as a function of the power index (n) of the temperature difference between the wall and the fluid at the inlet thermal gradient (**Δ**T)

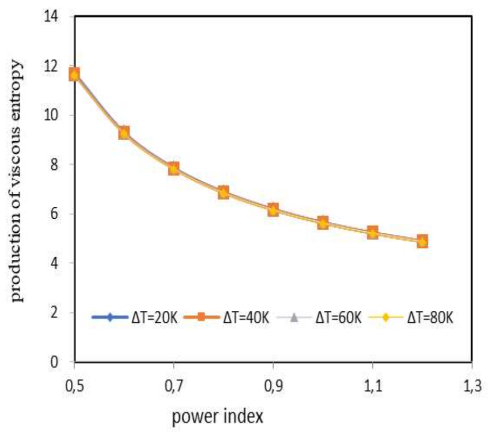

Figure3: Effect of temperature difference and power indexon viscous entropy production for (A=2, pin=2.10 ^{5} Pa)

This figure highlights the total non-dependence of the variation of the viscous entropy with the thermal gradient. This can be explained by the insignificant effect of the temperature difference on the velocity gradients and hence on the viscous entropy production. It should be noted that for all the considered values of the temperature difference, the viscous entropy production decreases considerably as a function of the power index. In this context, we observe a decrease in the viscous entropy production of more than 50%, when the power index goes from 0.5 to 1.2

3. Effect of the duct aspect ratio

In this paragraph we are interested in the study of the effect of the aspect ratio of the pipe on the thermal and viscous entropy productions plotted respectively in Figs. 5 and 7. At first sight as shown in figure 5, the thermal entropy production takes on very low values, and this for all the values of the power index and of the aspect ratio of the conduit considered. As illustrated in Figure 5 and as explained above, for a constant aspect ratio, the thermal entropy production decreases as a function of the power index. On the other hand, for a constant power index, Figure 5 shows that the thermal entropy production decreases when the aspect ratio increases. This decrease can be explained by the decrease in heat transfer between the hot wall of the pipe and the non-Newtonian flow following the birth of a thermo- convective cell which increases as the aspect ratio increases (Fig. 6). This can cause a decrease in thermal gradients and therefore a decrease in the thermal entropy production in the pipe.

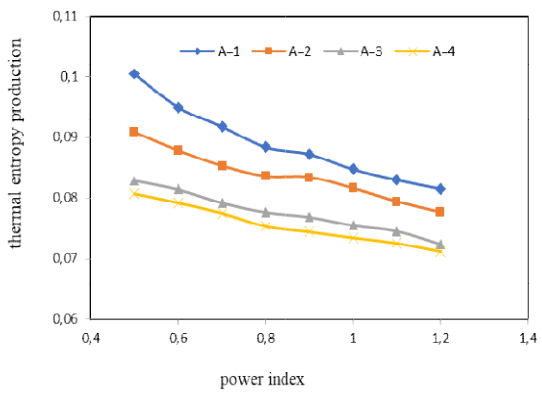

Figure 5: Effect of aspect ratio and power index on thermal entropy production for (ΔT=40K, pin=2.10 ^{5} Pa)

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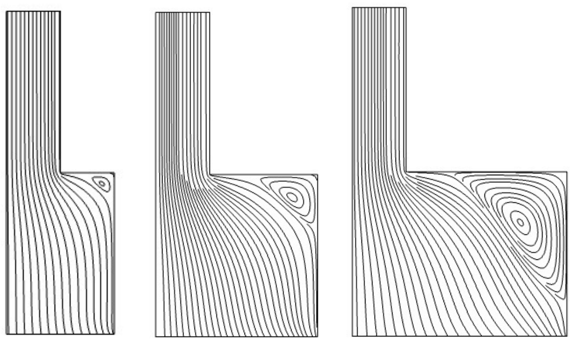

Figure 6: Effect of aspect ratio (A) on current function (ΔT=40K, n=0.5, pin=2.10^5 Pa)

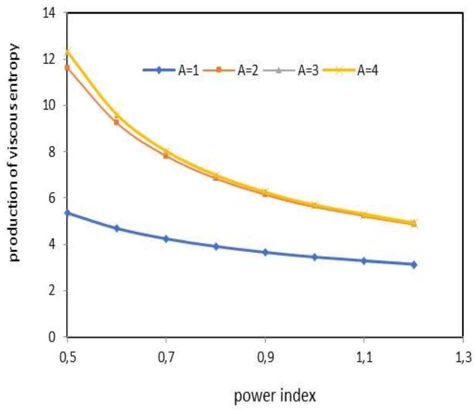

Figure 7: Effect of the aspect ratio and power indexon the viscous entropy production for (ΔT=40K, pin=2.10^5 Pa)

Contrary to the thermal entropy production, figure 7 shows that the viscous entropy production increases with the aspect ratio. Note that this increase is relatively pronounced for low power indices and aspect ratios less than 3. In this case, this increase is mainly intrinsic, via the viscous entropy production equation, following the increase in velocity gradients essentially localized in the region of pipe widening. It should also be noted that the aspect ratio no longer has any effect on the viscous entropy production, when the aspect ratio exceeds a critical value Ac=3, and this for all the power indices.

VI. . Conclusion

The production of thermal and viscous entropy within a non-Newtonian Carreau fluid in mixed convection flowing in a vertical cylindrical pipe was studied numerically using the commercial software COMSOL. The study concerned the influence of inlet pressure, temperature difference and aspect ratio on the production of thermal and viscous entropy. The main results found are summarized in the following points:

1. An increase in the power index (n) leads to a decrease in the rate of thermal entropy production. This reduction being small, at a low value of the inlet pressure, becomes increasingly significant for low values of the power index for inlet pressures greater than or equal to 4.10 ^{5}.
2. Thermal entropy production increases with fluid inlet pressure and the greatest increase in thermal irreversibility occurs for power indices below 0.6.
3. For a relatively low fluid inlet pressure (less than 2.10 ^{5},) increasing the power index (n) has almost no effect on the viscous entropy production rate.
4. The variation of the viscous entropy production according to the power index, becomes more and more remarkable, while increasing the inlet pressure of the fluid.
5.A decrease in the power index (n) is accompanied by an increase in the rate of viscous entropy production. This increase is very remarkable for power indices between 0.5 and 0.6.
6. When the power index takes relatively large values, the viscous entropy production practically converges towards the same value for all the input pressures considered.
6. The increase in the power index (n) is accompanied by a slight decrease in the rate of generation of thermal entropy. This decrease is insignificant for low values of the temperature difference (ΔT less than 20k).
7. For a constant power index, the thermal entropy production increase when the temperature difference increases. This increase is all the greater when the power index is low.
8. The thermal entropy production takes on insignificant values, and this for all the values of the power index and of the aspect ratio of the pipe considered.

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9.Viscous entropy production increases with aspect ratio. This increase is relatively pronounced for low power indices and aspect ratios less than 3. The viscous entropy production becomes independent of the aspect ratio when the latter exceeds a critical value equal to 3, and this for all power indices.

Nomenclature

μ_a : apparent viscosity of the fluid (Pa.s^n).
μ_∞: infinite shear viscosity (Pa.s).
μ_0 : zero shear viscosity (Pa.s).
λ : time constant(s)
$\dot{\gamma}$: shear rate (s $^{-1}$)
n: fluid power index. (SU)
Tin: fluid inlet temperature (K).
Tp: temperature of the pipe walls (K).
Pin: fluid inlet pressure (Pa).
A: aspect ratio of the duct.
ΔT: temperature difference (ΔT= Tp-Tin) (K).
S: entropy production (W/(m ^{3} .K)).
k: thermal conductivity of the fluid (W/(m.K))
Greek symbols
ρ: density of the fluid (Kg/m ^{3})
μ_a: dynamic viscosity of the fluid (Pa.s^n)

subscripts
th: thermals
vis: viscous

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