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Interest of an Annular Geometry Compared to Cylindrical One in the Thermo-Rheological Analysis of a Polymer Flow

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Abstract. The need for process monitoring on a polymer production line is increasing, especially in the face of new generation materials. In this paper, an analytical and numerical study is carried out to examine the possibility to measure the polymer's temperature increasing all along the annular channel due to the viscous dissipation in steady state. The results show that the annular geometry contributes to a high concentration of viscous dissipation at the central axis, compared to a cylindrical geometry subjected to the same external mechanical power. In addition, under the production conditions, the polymer flow with a large Graetz number isolates the central axis from external thermal disturbances. It is thus possible to measure robustly in the center of the flow the temperature variation with respect to the change in thermo-rheological parameters, which opens up new perspectives for an in-line/on-line characterization method.

INTRODUCTION

In polymer processing, it is necessary to have a good knowledge of the material's thermo-rheological properties and the processing conditions. However, the material's properties depend on the processing conditions [1], not to mention recycled and bio-sourced materials with fluctuating and poorly understood characteristics [2,3]. Moreover, the viscous heating of a polymer flow can modify the processing temperature. There is a real need for in-line/on-line thermo-rheological measurements to make production more flexible and responsive to raw materials' condition.

Currently, on a polymer production line (injection, extrusion...) [4,5], we only have access to the pressure measurements at the entrance of the flow. Sometimes they are completed by non-intrusive temperature measurements, which can be easily disturbed by the wall temperature of the tool. A few studies [6,7] reveal the interest and the difficulty to access to the thermal measurements of the polymer flow for in-line/on-line monitoring.

In this work, an annular geometry is proposed for a process monitoring device. Its ability to induce viscous dissipation is first analyzed. Then, a numerical study demonstrates the robustness of the thermal measurements in this geometry.

SENSITIVITY OF THE VISCOUS DISSIPATION - ANALYTICAL FORMULATION

A laminar axial flow in an annular channel is described in Figure 1. The polymer flows between the outer radius R and the inner radius σR . The velocity vector only has the component u_z in the z direction. At the position $r = \lambda R$, the flow velocity reaches its maximum value and the shear rate ($\dot{\gamma} = du_z/dr$) equals zero [8].

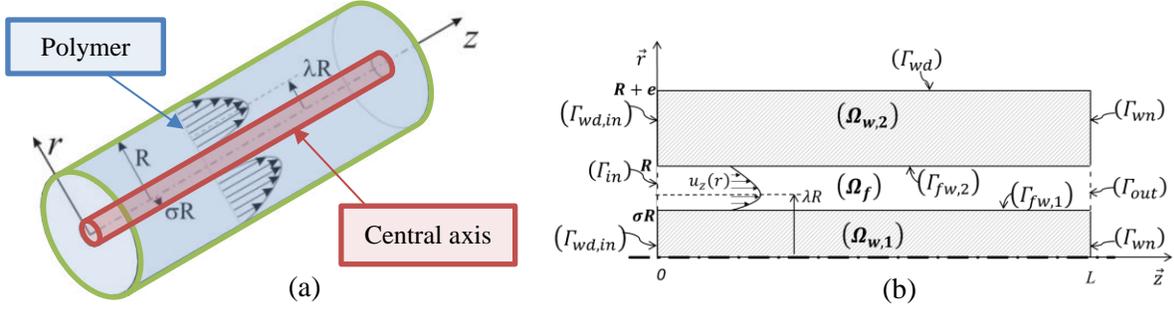


FIGURE 1. (a) 3D diagram and (b) 2D axisymmetric model of an annular flow

We suppose that the fluid is incompressible. Inertia terms are neglected thanks to the strong viscous nature of polymers [1]. The steady-state momentum conservation equation in the described flow can be written as equation (1), where p is the pressure and τ is the shear stress. By using the zero shear rate boundary condition at $r = \lambda R$, equation (1) can be integrated and becomes equation (2).

$$\frac{dp}{dz} = \frac{\tau}{r} + \frac{d\tau}{dr} \quad (1)$$

$$\tau = -\frac{1}{2} \frac{dp}{dz} \left(\frac{\lambda^2 R^2}{r} - r \right) \quad (2)$$

Power law [9,10] shown in equation (3) is used to describe our fluid, with η being the viscosity, K the consistency coefficient and n the power-law index ($0 < n < 1$ for pseudo-plastic materials such as polymer [11]).

$$\tau = \eta \dot{\gamma} = K |\dot{\gamma}|^{n-1} \dot{\gamma} \quad (3)$$

We can then obtain the shear rate profile by combining equations (2) and (3). The velocity profile can be obtained by integrating the shear rate profile. By integrating the shear rate profile twice, the expression (4) of the flowrate can be obtained as presented by Hanks & Larsen [12] in 1979.

$$Q = \frac{\pi n}{3n+1} \left(-\frac{1}{2K} \frac{dp}{dz} \right)^{\frac{1}{n}} R^{\frac{1+3n}{n}} \left[(1-\lambda^2)^{\frac{1}{n}+1} - \sigma^{1-\frac{1}{n}} (\lambda^2 - \sigma^2)^{\frac{1}{n}+1} \right] \quad (4)$$

It should be noted that when using power law in an annular flow model, the parameter λ can only be determined with numerical methods or approximated models [11]. When σ and λ tend to zero, the annuli turns into a cylinder, the expressions mentioned above become those of the cylindrical pipe [13].

The viscous dissipation (equation (5)) in annuli can be calculated from equations (2) and (3). By introducing the flowrate expression (4), a mechanical power per unit of volume $[-Q dp / \pi R^2 dz]$ can be written explicitly in equation (5). We can thus introduce $\bar{\phi}_a$ the dimensionless viscous dissipation in annuli as shown in equation (6). $\bar{\phi}_t$ the dimensionless viscous dissipation in a cylindrical pipe with σ and λ equaling zero is presented in equation (7).

$$\phi_a = \tau \dot{\gamma} = \left(\frac{1}{K} \right)^{\frac{1}{n}} \left(-\frac{1}{2} \frac{dp}{dz} \left| \frac{\lambda^2 R^2}{r} - r \right| \right)^{\frac{1}{n}+1} = -\frac{Q dp}{\pi R^2 dz} \frac{3n+1}{2n} \frac{\left| \frac{\lambda^2 R}{r} - \frac{r}{R} \right|^{\frac{1}{n}+1}}{\left[(1-\lambda^2)^{\frac{1}{n}+1} - \sigma^{1-\frac{1}{n}} (\lambda^2 - \sigma^2)^{\frac{1}{n}+1} \right]} \quad (5)$$

$$\bar{\phi}_a = -\frac{\pi R^2 dz}{Q dp} \phi_a = \frac{3n+1}{2n} \frac{\left| \frac{\lambda^2 R}{r} - \frac{r}{R} \right|^{\frac{1}{n}+1}}{\left[(1-\lambda^2)^{\frac{1}{n}+1} - \sigma^{1-\frac{1}{n}} (\lambda^2 - \sigma^2)^{\frac{1}{n}+1} \right]} \quad (6)$$

$$\bar{\phi}_p = \frac{3n+1}{2n} \left(\frac{r}{R} \right)^{\frac{1}{n}+1} \quad (7)$$

The dimensionless viscous dissipation in annuli is compared to the one in a cylindrical pipe in Figure 2 for different values of n and σ . This dimensionless term can be considered as an index of conversion from the mechanical power per unit of volume $[-Qdp/\pi R^2 dz]$ to the viscous dissipation. We mention that in annuli, the polymer flows between $[r/R = \sigma]$ and $[r/R = 1]$.

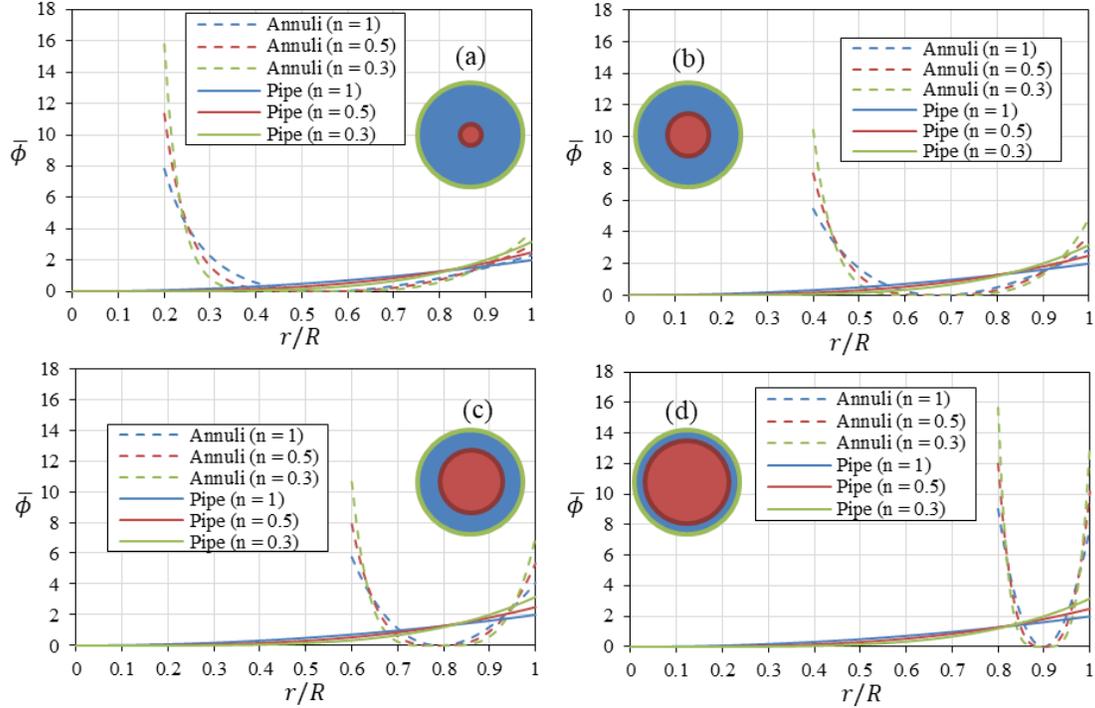


FIGURE 2. Dimensionless viscous dissipation in annuli and in a cylindrical pipe for $n = 0.3, 0.5$ and 1 with $\sigma =$ (a) 0.2 , (b) 0.4 , (c) 0.6 and (d) 0.8

Figure 2 shows that the viscous dissipation is concentrated at $[r/R = \sigma]$ in annuli, compared to the one in a cylindrical pipe for all values of n observed. The viscous dissipation is more important at $[r/R = \sigma]$ when σ is small. In fact, it tends to infinity on the surface of the central axis when σ tends to zero. When σ equals zero, there is no central axis and no viscous dissipation in the center of the flow. The viscous dissipation becomes also more important at $[r/R = \sigma]$ and $[r/R = 1]$ when σ is close to 1 . If the goal is to measure the viscous dissipation, sensors should be installed on the surface of the central axis at $[r/R = \sigma]$, where the viscous dissipation is sensitive in all cases observed.

ROBUSTNESS OF THE THERMAL MEASUREMENTS - DIGITAL SIMULATION

A numerical model is created to simulate a non-isothermal annular flow in a duct having an outer wall thickness e and a length L (Figure 1b). The domain (Ω_f) represents the polymer fluid in Figure 1b. The rheological equations including the viscous dissipation are already presented in the previous section. The steady-state heat equation can be written as equation (8), where T is the temperature; ρ , C_p and k_f are the density, the isobar specific heat capacity and the thermal conductivity of the fluid. The steady-state heat conduction problem (9) is solved in the solid domains $\Omega_{w,1}$ and $\Omega_{w,2}$, with k_s being the thermal conductivity of the solids.

$$\rho C_p u_z \frac{\partial T}{\partial z} = \text{div}(k_f \overrightarrow{\text{grad}} T) + \phi_a \quad (8)$$

$$0 = \text{div}(k_s \overrightarrow{\text{grad}} T) \quad (9)$$

The no-slip condition is applied on the surface ($\Gamma_{fw,1}$) of the central axis and on ($\Gamma_{fw,2}$) inside the channel at radius R . The temperature and the heat flux are supposed to be continued across the fluid/solid interfaces. A flowrate Q_{in} and a temperature T_{in} are assigned on the flow inlet (Γ_{in}). The Neumann condition [$\partial T/\partial z = 0$] is applied on the flow outlet (Γ_{out}) and the outlet walls (Γ_{wn}). Dirichlet conditions are applied on the side wall (Γ_{wd}) and the inlet wall of the duct ($\Gamma_{wd,in}$). The temperature T_w is assigned on (Γ_{wd}) for $r = R + e, z \in [0, L]$. The temperature T_{in} is assigned on ($\Gamma_{wd,in}$) for $z = 0, r \in [0, \sigma R]$. A linear interpolation between the temperatures T_w and T_{in} is used on ($\Gamma_{wd,in}$) for $z = 0, r \in [R, R + e]$ to keep the continuity of the temperature field.

The geometric parameters are: $L = 50$ mm, $e = 20$ mm and $R = 10$ mm which are commonly used flow dimensions on a polymer production line. The parameter σ is set to 0.4 to show one of the less efficient cases in terms of viscous dissipation in Figure 2. The material of the solid domains ($\Omega_{w,1}$) and ($\Omega_{w,2}$) is steel with a thermal conductivity of $49 \text{ W.m}^{-1}.\text{K}^{-1}$. The properties of Polypropylene are used for the polymer flow domain (Ω_f) with a thermal conductivity of $0.23 \text{ W.m}^{-1}.\text{K}^{-1}$, a density of 900 kg.m^{-3} and a specific heat capacity of $2800 \text{ J.kg}^{-1}.\text{K}^{-1}$. The rheological behavior of Polypropylene is simulated by a power law with $K = 4636 \text{ Pa.s}^n$ and $n = 0.332$.

The flowrate Q_{in} is set to 60 cc.s^{-1} (mean velocity $\bar{u}_z = 0.23 \text{ m.s}^{-1}$) in the first place. The Graetz number [$\rho C_p \bar{u}_z (R - \sigma R)^2 / (k_f L)$] reaches 1793.6, which means that the radial heat conduction in the flow is insignificant compared to the axial heat advection. When thermocouples are installed at the central axis to measure the temperature variation due to the viscous dissipation, thanks to the large Graetz number, the polymer flow around the central axis can render these temperature measurements unsusceptible to external thermal disturbances at [$R \leq r \leq R + e$].

The temperature T_{in} and T_w are set to 473.15 K for the reference simulation, which is compared to another simulation with T_w being at 453.15 K (20 K below the reference one to produce an external thermal disturbance). The results are presented in Figure 3a and Figure 3b. Figure 3a shows that the thermal disturbance from the outer wall of the duct stops at a position r/R between 0.9 and 0.1. Figure 3a also confirms that the temperature variation due to the viscous dissipation at [$r/R = \sigma = 0.4$] is more important than any other position in the r/R direction. Figure 3b shows the temperature variation due to the viscous dissipation along the z direction on the surface of the central axis. Thanks to the large Graetz number, the measurements at the central axis are unsusceptible to the external thermal disturbance.

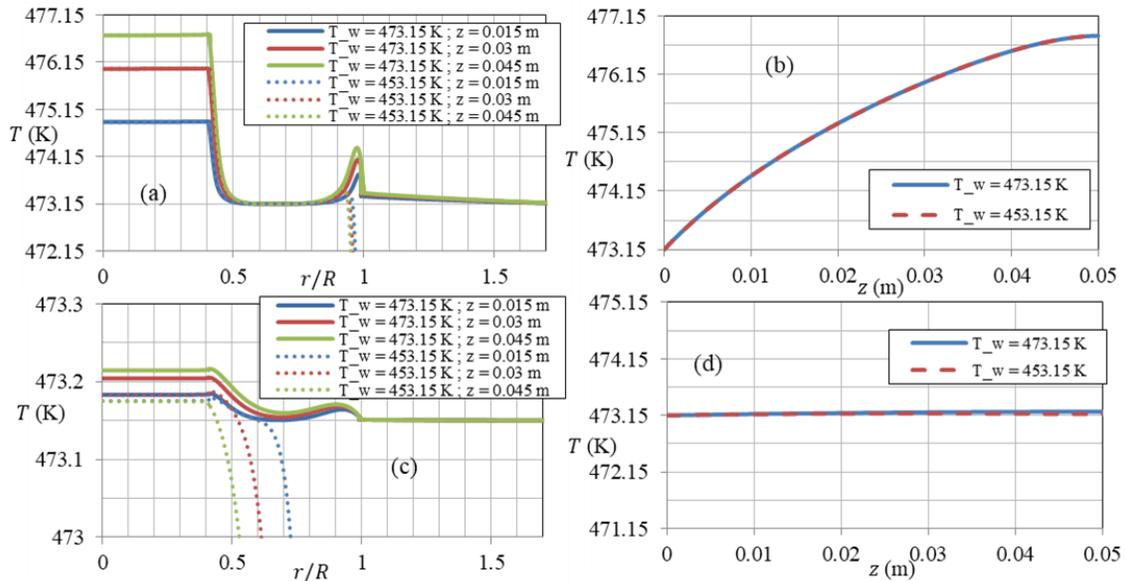


FIGURE 3. Temperature measurements with a Graetz number of 1793.6 (a) for different z positions, (b) at the central axis [$r/R = \sigma$]; with a Graetz number of 17.936 (c) for different z positions, (d) at the central axis [$r/R = \sigma$]

Then, the same comparison is carried out with a lower flowrate to find out a critical Graetz number with which the disturbance reaches the central axis. Figure 3c and Figure 3d show that the temperature measurements at the central axis are slightly influenced by the external thermal condition, when the Graetz number drops to 17.936 (with a flowrate of $0.6 \text{ cc}\cdot\text{s}^{-1}$). In this case, the thermal disturbance starts from the outer wall of the duct and reaches the central axis as the polymer flows from the entrance to the outlet (Figure 3d). When the flowrate drops to $0.6 \text{ cc}\cdot\text{s}^{-1}$, the temperature is barely increased along the z direction by the viscous dissipation.

CONCLUSION

We studied the sensitivity of the viscous dissipation in annuli compared to the one in a cylindrical pipe. The results show that an annular duct has better efficiency to induce viscous dissipation on the surface of the central axis. It provides a good solution for the viscous dissipation measuring and opens up new perspectives for an in-line/on-line characterization method which uses the viscous heating as information [6]. Besides, some numerical simulations show that the polymer flow under the processing conditions with a large Graetz number can keep thermal measurements at the central axis from external thermal disturbances to a certain extent. This advantage can further ensure the robustness of the in-line/on-line measurements when using an annular duct.

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