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A New Solution for Viscosity Identification in a Polymer Production line via Convection Analysis

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Abstract. Some studies have demonstrated the interest of temperature measurements for in-line rheometry. Both viscous dissipation and convection can be used in viscosity identification via inverse method. However, the inlet temperature (of a device downstream of a screw) in a polymer production line has also been observed to be less under control. To overcome the inlet temperature uncertainties during an in-line thermo-rheological characterization and to further apply a differential convection method for an injection molding process, a concept of device designing is proposed in this work. An analytical and numerical investigation proves that the proposed concept can provide information on the viscosity of the material via thermal measurements, despite a poorly known inlet temperature.

Introduction

The need for process monitoring during the polymer fabrication is increasing to make production more flexible and adaptive to raw materials' various properties, such as the viscosity, which is one of the critical properties [1]. The classical way to identify the viscosity in a production line is to use pressure sensors to measure several values of apparent viscosity [2,3]. Some studies [4,5] reveal the possibility and the advantages of using thermal measurements for in-line viscosity characterization. By analyzing the convection and the pressure loss, an entire power law can be identified within one injection cycle, when the convection is dominant compared to the viscous dissipation [5]. When the viscous dissipation is dominant, the differential convection method based on two injection cycles can “erase” the viscous dissipation which “covers” the convection phenomenon [5]. However, the uncertainties of the inlet temperature profile [6] can cause problems for in-line thermo-rheological characterization methods.

In this paper, a concept of device designing is presented to further apply the differential convection method in a polymer production line. A model is built with power law [7,8] for an analytical and numerical investigation in order to verify the influence of a poorly known inlet temperature to the proposed method. The numerical simulation is also used to demonstrate the sensitivity of the convection phenomenon to the power-law parameters.

Concept Description

We propose an annular geometry (Fig. 1) with thermocouples installed on the surface $\Gamma_{fw,1}$ of the central axis as exemplified in a previous work [5] for in-line viscosity identification. The annular duct can be placed downstream of an injection unit and upstream of the mold.

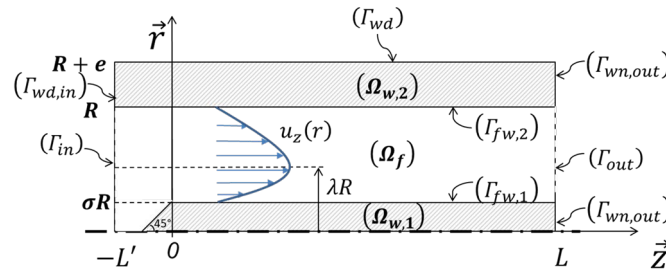


Figure 1: Illustration of the annular flow problem

Since the convection can be served as one of the key factors to identify the viscosity [5], to better study the convection in the annular duct, we can use a heating source (for example, an electric resistance) to raise the temperature of the central axis, and then observe how the polymer flow cools it down. We'd like to mention that the convection intensity is low when the temperature gap between the solid and the flow is small. For injection molding process with short injection cycles, it is not ideal to start heating the central axis after the injection started. In order to increase the sensitivity of thermal measurements to the convection during a short injection cycle, we should pre-heat the central axis to create a temperature gap compared to the incoming flow before the injection. In practice, the heating of the central axis can be done during the packing, the cooling and the reset time of the mold. We can thus achieve a repeatable heating-cooling cycle in the annular duct for the thermo-rheological characterization in an injection molding production line.

The differential convection method [5] consists in modifying a thermal boundary/initial condition, induce different convection intensities and compare the difference of thermal signals between two injection cycles. With a heating source at the central axis, we can modify the initial temperature field of the central axis and analyze ΔT the difference of temperature measurements at the central axis. Let's move to the modeling section to clarify the concept with equations.

Modeling

In Fig. 1, an annular axial laminar flow is presented in an axisymmetric cylindrical coordinate system. The central axis is represented by the domain $\Omega_{w,1}$. The channel is represented by the domain $\Omega_{w,2}$, with e as the outer wall thickness and L as the length of the annular part. The polymer (domain Ω_f) enters the duct at $z = -L'$ and is guided to the annular part by a 45° cone. When $z \geq 0$, the polymer flows between the outer radius R and the inner radius σR , with λR being the zero shear rate (maximum velocity) radial position [9].

The flow domain (Ω_f) is supposed to be incompressible [10] and at mechanical steady state. The continuity equation and the equilibrium equation are written as Eq. 1 and Eq. 2:

$$\text{div}(\vec{u}) = 0, \quad (1)$$

$$-\overrightarrow{\text{grad}}p + \overrightarrow{\text{div}}(\vec{\tau}) = 0, \quad (2)$$

with \vec{u} the velocity vector, p the pressure and $\vec{\tau}$ viscous stress tensor. The inertial terms are neglected compared to the viscous stress [10]. The incompressible heat equation with viscous dissipation taken into account for the flow domain Ω_f is written as Eq. 3:

$$\rho_f C_{p,f} \left(\frac{\partial T}{\partial t} + \text{div}(T\vec{u}) \right) = \text{div}(k_f \overrightarrow{\text{grad}}T) + \phi_v, \quad (3)$$

where T is the temperature, t is time; ρ_f , $C_{p,f}$ and k_f are respectively the density, the isobar specific heat capacity and the thermal conductivity of the fluid. ϕ_v is the viscous dissipation power and can be calculated with Eq. 4:

$$\phi_v = \eta \dot{\gamma}^2 = \frac{\eta}{2} \left(\overline{\text{grad}(\vec{u})} + \left(\overline{\text{grad}(\vec{u})} \right)^T \right) : \left(\overline{\text{grad}(\vec{u})} + \left(\overline{\text{grad}(\vec{u})} \right)^T \right), \quad (4)$$

with η the viscosity and $\dot{\gamma}$ the generalized shear rate. We assumed that the polymer melt behavior follows the power law [7,8], shown in Eq. 5:

$$\eta = K \dot{\gamma}^{n-1}, \quad (5)$$

with K being the consistency coefficient and n being the power-law index ($0 < n < 1$ for pseudo-plastic materials such as the polymers). In the solid domains $\Omega_{w,1}$ (the central axis) and $\Omega_{w,2}$ (the channel), we solve the heat conduction problem Eq. 6 and Eq. 7:

$$\rho_s C_{p,s} \frac{\partial T}{\partial t} = \text{div}(k_s \overline{\text{grad}T}) + \phi_a, \quad (6)$$

$$\rho_s C_{p,s} \frac{\partial T}{\partial t} = \text{div}(k_s \overline{\text{grad}T}), \quad (7)$$

with ρ_s , $C_{p,s}$ and k_s being respectively the density, the isobar specific heat capacity and the thermal conductivity of the solids. ϕ_a is the heating power in the central axis given by an electric resistance.

The no-slip condition is applied on the fluid/solid interfaces $\Gamma_{fw,1}$ and $\Gamma_{fw,2}$ (Fig. 1), where perfect contacts are assumed between the fluid and the solid. A flow rate 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 $\Gamma_{wd,in}$, with a temperature T_w assigned on Γ_{wd} and a linear interpolation between the temperatures T_w and T_{in} on $\Gamma_{wd,in}$ to ensure the continuity of the temperature field. The initial temperature field is noted as $T_{init}(r, z)$.

Analytical Investigation on Differential Convection Method

When a differential convection characterization is carried out between two injections with two different initial temperature fields (and other boundary conditions, such as the flow rate Q and the heat source ϕ_a , remaining the same), we differentiate the temperature fields of those two injections. Eq. 3 becomes Eq. 8, with the variable T replaced by ΔT and the viscous dissipation term ϕ_v offset by the differentiation.

$$\rho_f C_{p,f} \left(\frac{\partial \Delta T}{\partial t} + \text{div}(\Delta T \vec{u}) \right) = \text{div}(k_f \overline{\text{grad} \Delta T}). \quad (8)$$

Eq. 6 and Eq. 7 become Eq. 9 by the same principle.

$$\rho_s C_{p,s} \frac{\partial \Delta T}{\partial t} = \text{div}(k_s \overline{\text{grad} \Delta T}). \quad (9)$$

The Neumann condition, on the flow outlet Γ_{out} and the outlet walls Γ_{wn} , becomes $[\partial \Delta T / \partial z = 0]$. The Dirichlet conditions have a value of zero kelvin. The initial temperature field becomes $\Delta T_{init}(r, z)$.

The new variable ΔT depends on the initial condition $\Delta T_{init}(r, z)$, the thermal diffusivities $[k / \rho C_p]$ of the materials and the velocity profile which itself depends on the flow rate and the power-law index n [5]. That is to say that, if the Dirichlet boundary conditions, including the inlet temperature, are the same for those two injections, we don't necessarily need to know the values of these boundary conditions. In the next section, numerical simulations are performed to verify our concept and confirm the analytical investigation.

Numerical Simulations

In the section, we use a numerical finite element model, with common flow dimensions in a polymer production line: $L = 76$ mm, $e = 20$ mm, $R = 10$ mm and $\sigma = 0.4$. The model is longer than the studied zone, which is limited to $z = 50$ mm, to reduce the influence of the outlet boundary conditions on the studied zone. The material of the solid domains $\Omega_{w,1}$ and $\Omega_{w,2}$ is austenitic stainless steel with a thermal conductivity of $15 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, a density of $7900 \text{ kg}\cdot\text{m}^{-3}$ and a specific heat capacity of $500 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$. The properties of Polypropylene are used as reference for the polymer flow domain Ω_f with a thermal conductivity of $0.23 \text{ W}\cdot\text{m}^{-1}\cdot\text{K}^{-1}$, a density of $900 \text{ kg}\cdot\text{m}^{-3}$ and a specific heat capacity of $2800 \text{ J}\cdot\text{kg}^{-1}\cdot\text{K}^{-1}$. It should be noted that the thermophysical parameters (especially the diffusivity) vary little for stainless steel [11] and for currently used polymers in the molten state [12], when these materials go through a temperature variation of 20 K at 473.15 K (200 °C). Four virtual thermocouples are installed on the surface of the central axis at $r = \sigma R$, from $z = 6$ mm to $z = 34$ mm with equidistance between them.

Pre-heating of the central axis. Firstly, the initial temperature T_{init} and the boundary temperature T_{in} and T_w are set to 473.15 K. A volumetric heat source (ϕ_a in Eq. 6) of $8 \text{ MW}\cdot\text{m}^{-3}$ is applied at the central axis for $0 \leq z \leq L$ and for $t \geq 0$. The total power of the heating source is 30.6 W. The temperature field after 12 s of heating is presented in Fig. 2a and the temperature profile on the surface of the central axis (at $r = \sigma R$, along z direction from 0 to 0.05 m) is presented in Fig. 2b for instants $t = 1, 4, 8$ and 12 s.

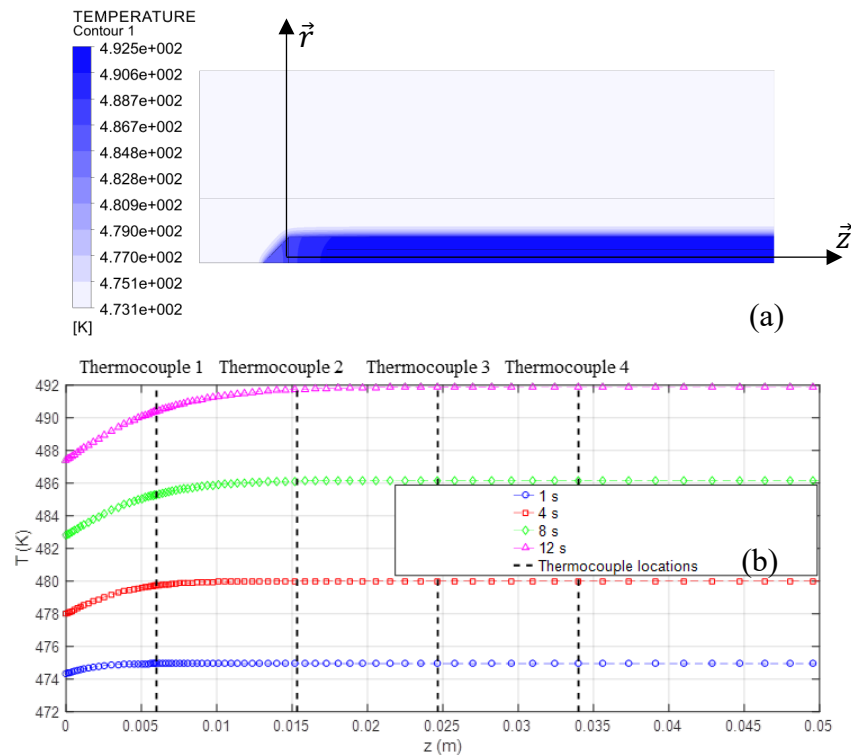


Figure 2: Temperature variation during the pre-heating step (a) over the whole annular system at $t = 12$ s and (b) at $r = \sigma R$ for $t = 1, 4, 8$ and 12 s

Although the upstream side of the axis is less heated due to our boundary conditions, the temperature variation (final temperature compared to the initial one at 473.15 K) can reach over 13–18 K after 12 seconds of heating. This is a reasonable temperature gap for the convection study.

We'd like to mention that we don't need to spend 12 s between every two injection cycles to heat up the central axis. It depends on the degree of the temperature drop after each injection. We can perform two injection cycles without heating the central axis in between, to create a ΔT_{init} for the

differential convection characterization. We can also make one characterization every ten injection cycles so that we can heat up the central axis during for example, eight injection cycles.

Differential convection simulation. Injection simulations are performed at a flow rate of $30 \text{ cc}\cdot\text{s}^{-1}$. The heating source at the central axis is cut off ($\phi_a = 0$ in Eq. 6) during the following injection simulations. Two different initial temperature fields are considered. The first uses the result of the pre-heating simulation (Fig. 2) at $t = 12 \text{ s}$, as if we start the injection directly after the twelve-second heating. The second initial temperature field is homogeneous at 473.15 K . The differentiated temperature field ΔT of those two configurations (the first configuration minus the second one) is calculated for different couples of power-law parameters. n varies from 0.2 to 1 with a step of 0.025 and $\ln(K)$ varies from 4 to 10 with a step of 0.1875 (K varies from 54.6 to 22 026.5 $\text{Pa}\cdot\text{s}^n$), to cover a wide range of commonly used polymers. The values of ΔT revealed by each virtual thermocouple (Fig. 2b) after 2 seconds of injection are presented in Fig. 3.

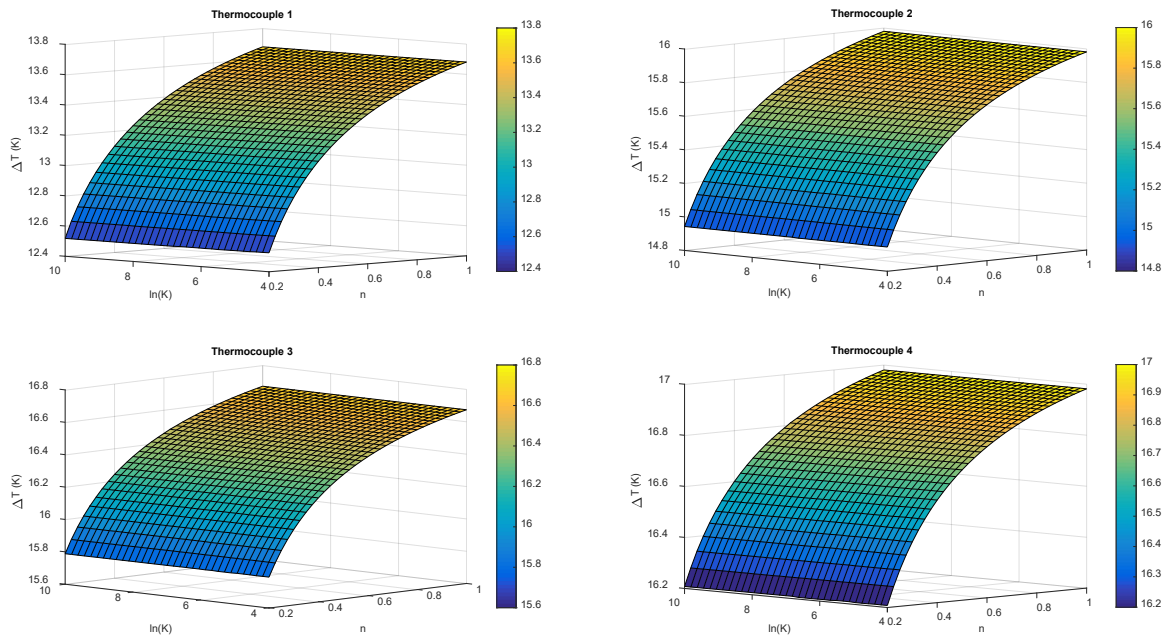


Figure 3: ΔT after 2 seconds of injection at a flow rate of $30 \text{ cc}\cdot\text{s}^{-1}$

In Fig. 3, the smaller n is, the smaller the residual temperature gap, the greater the intensity of convection cooling. When the heated axis is exposed to the injection flow, the temperature drop due to the convection is not significant since the temperature gap remains at 12-17 K after the injection. Fig. 3 also confirms that the differential convection method is sensitive only to the variation of the power-law index n and not to the consistency coefficient K . This characteristic can help to decouple the power-law parameters. Once the power-law index n has been identified, the consistency coefficient K can be calculated from a pressure measurement at one constant flow rate (with or without thermal dependency), which is an advantage for in-line application without hindering the production cadence.

Inlet temperature uncertainty. The same differentiation procedure is carried out with an inlet temperature of 493.15 K (20 K higher than the previous case). The results are noted as ΔT_{+20} and compared to ΔT of the previous section. We define: $\delta\Delta T = \Delta T - \Delta T_{+20}$. Fig. 4 shows the value of $\delta\Delta T$ as a function of $\ln(K)$ and n after 2 seconds of injection measured by each virtual thermocouple (Fig. 2b).

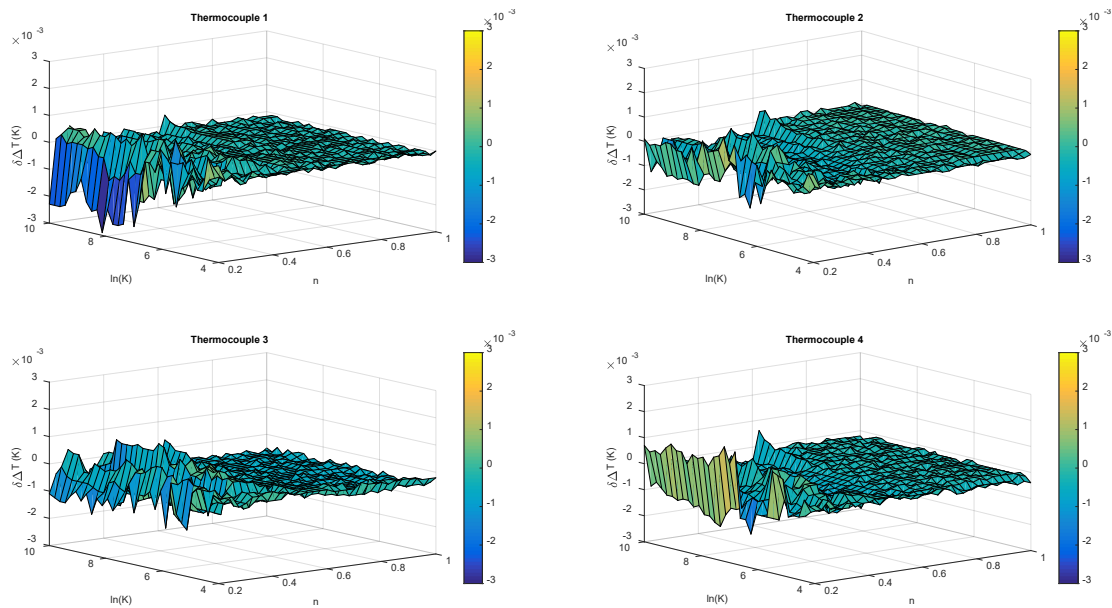


Figure 4: $\delta\Delta T$ after 2 seconds of injection at a flow rate of $30 \text{ cc}\cdot\text{s}^{-1}$

With a maximal absolute value under 0.003 K , we can confirm that the 20 K of increase on the inlet temperature has no influence on our differential convection method. This characteristic ensures the performance of our thermo-rheological method in a production line where it is difficult to accurately obtain the inlet temperature, as long as the inlet temperature is repeatable during two injections.

Conclusion

Based on the differential convection method of previous work [5], we proposed a concept of an annular in-line device to achieve viscosity identification during the injection molding process. A strategy with heating-cooling cycles at the central axis of the device is also introduced to further adapt the method to the injection production rhythm.

An analytical and numerical study justified and confirmed the sensitivity of the method to the power-law index n of the material. The method has also been proven to be insensitive to the inlet temperature of the flow, as long as the inlet temperature is repeatable for two injections. By adding a pressure measurement, the proposed concept makes it possible to identify the viscosity without the need to know precisely the inlet temperature or to modulate the production flow rate.

In this study, the thermophysical parameters took constant values. Further analysis is required to investigate the effect of thermal dependence of those parameters on the proposed method.

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