Journal of Materials Processing Tech. 252 (2018) 680–687

Contents lists available at ScienceDirect

Journal of Materials Processing Tech.

journal homepage: www.elsevier.com/locate/jmatprotec

Research Paper

Effect of viscous dissipation in the prediction of thermal behavior of an elastomer cylindrical flow

Julien Launay*, Nadine Allanic, Pierre Mousseau, Rémi Deterre, Christophe Plot

Laboratoire GEPEA, UMR CNRS 6144, Université – IUT de Nantes, France

ARTICLE INFO

Keywords:
Polymer forming process
Extrusion
Intrusive thermal sensor
Rheometry
Viscosity

ABSTRACT

In this work, the thermal behavior of an elastomer flow all along a cylindrical runner placed at the outlet of an extruder is studied. A cylindrical runner thermally regulated and highly instrumented was designed. It is equipped with a new intrusive thermal sensor, developed in the lab and named thermal measurement cell (TMC). This device is used to measure temperature profiles at the inlet and the outlet of the flow. Several experiments are performed with an elastomer by varying the rotation speed of the screw. Experiments first show the influence of viscous dissipation on the thermal behavior of such a highly viscous flow. Then, the results are used to estimate the viscosity by taking into account the temperature profile of the flow. The comparison of the estimated viscosity with the viscosity measured in a capillary rheometer shows the importance to introduce a correction in rheometric characterization and to consider a non-isothermal behavior of the flow. Experimental results are also compared with model predictions. The model is then used to perform a sensitivity analysis. The influence of the correction on the viscosity and the impact of viscous dissipation on the thermal behavior prediction of the elastomer flow are discussed.

1. Introduction

Inside polymer melt flows, occurs an important viscous dissipation which involves a significant thermal gradient in the flow (Dinh and Armstrong, 1982). This coupling is an unavoidable fact of physics, often insufficiently known and thus commonly neglected or under-estimated, which might lead to design and/or characterization mistakes. If (Elgeti et al., 2012) assume a homogenous temperature of the process in their optimization study of profile extrusion dies, (Lebaal et al., 2009) consider at the opposite, a thermal dependence of viscosity. Their optimal geometry, chosen to help homogenization of the velocity profile, also homogenizes shearing heating. Thus, they show that the distribution of temperature at the exit of the die is more homogenous. Neglecting the viscous dissipation can yield a significant error, not only in the forming process modeling, but also during the viscosity measurement procedure. (Liang and Ness, 1997) have shown in their study, which compared the behavior of two polystyrene melts in a capillary rheometer, the influence of viscous dissipation at the entrance of the channel. Some authors have developed analytical calculations to quantify the influence of viscous dissipation on capillary viscosimetry. They have based their developments on the fact that the dissipative heating causes a temperature rise in the melt proportional to the pressure difference. Kamal and Nyun (1980) expressed viscosity with corrections of viscous heating based on the assumption of an adiabatic flow and an isothermal wall. They applied the treatment to a polystyrene sample. Laun (2003) characterized the rheology of a LPDE melt, by an analytical expression for the Bagley plot, which includes the combined treatment of viscous heating and pressure dependent viscosity in a rheometer. The method needs to identify parameters from experiments which is difficult due to experimental uncertainties on pressure measurement. In the case of elastomers, dissipative heating is more than significant, due to their high viscosity. The consequence could be an additional heating temperature or an unbalance in the filling channels of injection process (Agassant, 1991). In view of this, Beaumont (2004) suggests a specific geometry to favor thermal homogeneity in the runners and to avoid damages due to scorch arisen. This geometry is mostly a blending element whose aim is to limit the impact of viscous dissipation. Nevertheless, the viscous dissipation provides an efficient heating source within the flow which is not yet enough used in industrial process. The presence of peaks of temperature due to viscous heating, have been already shown in numerical studies (Zdanski and Vaz, 2006). Ha et al. (2008) modeled the coupled steady-state thermal flow of a rubber material in extrusion forming process for the automotive industry and presented numerical results showing significant variations of temperature of the flow. On the other hand, experimental studies were conducted to measure temperature profiles in thermoplastics extrusion

---

* Corresponding author.
E-mail address: julien.launay@univ-nantes.fr (J. Launay).

http://dx.doi.org/10.1016/j.jmatprotec.2017.10.035
Received 25 October 2016; Received in revised form 20 October 2017; Accepted 21 October 2017

process. Measurements are performed with a thermocouple mesh at the outlet of the screw where the flow diameter is relatively important (> 60 mm diameter). By this way, Vera-Sorroche et al. (2014) compare the thermal efficiency of several screw geometries. They measure a peak of temperature at the center of the flow which is due to shearing and also viscous dissipation near the screw. Abeykoon et al. (2016) also use this method to analyze motor energy consumption of a single screw extrusion. A low temperature shoulder region was observed for the lowest viscous polymers. These fluctuations of temperature are not present for the most viscous polymers. It confirms that the temperature at the outlet of the die is linked to the melting performance of the screw but also to the viscous dissipation near the screw.

The aim of this article is to experimentally and numerically analyze the thermal behavior evolution of a polymer melt flow and the impact of viscous dissipation. For this purpose, an original experimental device was designed in order to measure viscous heating peaks in the flow. It consists in a 10 mm diameter cylindrical runner equipped with a specific thermal sensor specifically developed in the lab (Launay et al., 2014). Placed inside the runner, it enables to obtain the thermal profile of the polymer melt flow. Experimental tests were conducted on an elastomer flow. In parallel, a numerical model of the thermal and rheological behavior of the flow in a cylindrical runner was developed. The model integrates a correction that takes into account the effects of the thermal sensor's presence. The characterization methods of the properties needed in the modeling are described. The simultaneous use of the experimental and numerical tools allows us to quantify the effects of the viscous dissipation on rheological characterization of the polymer. The viscosity is determined by considering the thermal profile measured in the flow. The confrontation with experimental results shows that the model with the corrected viscosity is reliable. Thus, a numerical study is performed to test the influence of viscous dissipation on the thermal behavior and characterization of the elastomer flow.

2. Material and techniques

2.1. Material characterization

The study is performed on an elastomer flow. The base of the elastomer is a commercial EPDM (ethylene propylene diene monomer) denoted Keltan 2340. It has an ethylene content of 53 parts per hundred of rubber. Carbon black (SFR-HS) and oil are added with a respective content of 100 and 70 parts per hundred of rubber. To avoid any damages on the experimental device, experiments were performed with the elastomer without vulcanization additives. The thermal properties of the blend, expressed as a function of temperature, are given in Table 1. The thermal properties are measured on samples without vulcanization additives. The thermal conductivity was measured with a Hot Disk TPS 2500 (He, 2005). With this method, two elastomer samples with dimensions of 50 × 50 mm and a 6 mm thickness are placed around a 2 mm diameter Kapton probe. A power of 0.01 W is applied during 20s. The elastomer temperature increase remains lower than 7 °C. The value of the measured thermal conductivity is 0.339 W m^{-1} K^{-1} at 20 °C and is 0.364 at 150 °C. The thermal capacity was determined by differential scanning calorimetry with a METTLER TOLEDO DSC1 device. The analysis was performed from 40 to 180 °C. A heating ramp of 2 °C/min is imposed. As Cheheb et al. (2012) previously made for the thermal characterization of a natural rubber, the TOPEM method is used. This method mathematically described by Wunderlich et al. (1994) is based on the analysis of the sample's temperature answer of a periodic temperature modulation. The thermal capacity varies linearly with temperature, which is consistent with work of Dippel et al. (2015) on rubber. The elastomer density was determined by a pycnometric density method at ambient temperature. It was also measured at the extrusion temperature range (at 100 °C, 120 °C and 140 °C) with a Melt flow Index device by the evaluation of the ratio mass flows versus volumetric flow rate in accordance with (ASTM, 1970).

Table 1
Thermal properties of the elastomer.

Thermal properties (T in K)		
c_p	J kg^{-1} K^{-1}	$3.0194\,T + 780.4$
ρ	kg m^{-3}	$-1.982 \times 10^{-3} T^2 + 8.579 \times 10^{-1} T + 1.009 \times 10^3$
λ	W m^{-1} K^{-1}	$1.62 \times 10^{-4} T + 0.297$

The viscosity of the elastomer was measured with a capillary rheometer ROSAND RH2000 of MALVERN. Equipped with two 12 mm diameter channels, this rheometer enables to test two different capillaries of 1 mm diameter at the same time. The first one is 16 mm length. The second one has a length close to zero. To improve the accuracy of measurement in a rheometer, the Bagley correction is commonly used (Agassant, 1991). The aim is to qualify the entrance pressure drop to correct the shear stress. The Bagley correction needs to perform many tests with several ratio length/diameter of the capillary. In this work, to avoid additional tests, we assume that the pressure drop in the capillary corresponds to the zero pressure drop, and thus to the entrance pressure drop. The Rabinowitsch correction (Agassant, 1991) is directly included in the data treatment of the rheometer software. The measurements were performed for three temperatures (100 °C, 120 °C and 140 °C) and for shear rates between 1 s^{-1} and 10,000 s^{-1}. We showed that the studied elastomer has a pseudoplastic behavior all along the shear rate range. Moreover, we didn't detect any singularity on the shear stress curve versus shear rate that could be an indication of the occurrence of wall slip. Thus, the rheological behavior of the elastomer is described as usually by a power law expression (Lenk, 2012):

$$\eta = K \cdot \dot{\gamma}^{n-1} \tag{1}$$

This simple rheological model is commonly used since it describes well the behavior of polymer melt flow at high shear rate. Ha et al. (2008) has already used it to predict the behavior of a rubber during an extrusion forming process. This model is used in this work, since the power law index n presents small variations in the shear rate range. The thermal dependence is integrated by an Arrhenius law (Lenk, 2012):

$$\mathrm{K} = K_0 e^{-CT} \tag{2}$$

with C the thermodependance parameter.

By using the results obtained with capillary rheometer, the rheological parameters are first identified to be $C = 0.00945\ ^{\circ}\mathrm{C}^{-1}$, $K_0 = 60100$ Pa s^{n} and $n = 0.293$.

However, when using a capillary rheometer, the melting temperature is supposed to be constant. This hypothesis is in all probability wrong, because of the rise of temperature due to viscous heating, which becomes non-negligible in the case of low diameter dies (Kang and Jayaraman, 2002). Taking into account viscous dissipation effects in capillary rheometer implies a substantial treatment of experimental results (Laun, 2003). Thus, the experimental device developed to study the thermal behavior of the polymer was also instrumented to be able to estimate the viscosity of the polymer in the shear rate range of processing.

2.2. Instrumented die

Global views of the experimental device and a focus on its instrumentation are given in Fig. 1. It is a straight cylindrical runner having a 300 mm length, a 50 mm outer diameter and a 10 mm internal diameter, mounted on a single-screw rubber extruder. The extruder barrel is instrumented with a thermocouple (T_{ext}) placed inside the material flow and a pressure sensor (P_{ext}).

2 mm diameter hot wires with a 750 W nominal power are used to regulate the temperature along the runner. They are fixed by matting in