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Viscous dissipation influencing viscosity of polymer melt in micro channels †

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Abstract

Determination of melt rheological behavior within micro-structured geometry is very important for the accurate simulation modeling of micro-molding. Yet studies on the rheological behavior of polymer melts, flowing through micro channels, are complicated due to a large number of factors affecting the melt viscosity. One factor, viscous dissipation, is investigated in the current work through a novel experimental technique to determine the viscous dissipation of a polymer melt flowing through several micro channels with identical aspect ratio. Relative tests are conducted with the melt of high density polyethylene (HDPE) at different temperatures being extruded through the capillary dies with diameters 1000μm, 500μm and 350μm, respectively. It was found that the temperature rise due to viscous dissipation decreases significantly with the reduction of the characteristic size of micro channel at the same shear rate. In addition, based on the suggested model of radial temperature distribution, the influence of viscous heating on the melt viscosity is investigated. The results indicate that viscous dissipation does not play a significant role.

Keywords: Micro channels; Micro injection molding; Novel testing; Viscous dissipation; Viscosity of melt

1. Introduction

Micro injection molding is one of the mass production and great consistent molding methods for micro precision parts in the MEMS field. Many micro devices, such as micro sampling cells [1], micro heat exchangers [2] , micro pumps [3], wave guides [4], optical grating elements [5], etc. have been successfully injection molded. As micro-molding attracts more attention, the use of computer simulation to solve difficult molding problems becomes an inevitable trend. Recent studies [6-10] indicate that the existing simulation package is no longer sufficient to describe the filling flow behavior in micro-molding, especially for micro-parts with small dimensions. The inadequacy might be attributed to the rheological data used in the current simulation packages which are obtained from measurements of macroscopic scale. Recently, S. C. Chen, et al. [11-13] designed a mold with micro-channel of square cross-section that allowed sizes varying from 500μm to 300μm and 200μm to conduct melt rheological experiments. Results show that the polymer melt viscosity measured in micro channels is less than that measured by traditional capillary rheometer at the same shear rate. And the viscosity of polymer melt flowing through micro channel decreases with the reduction of characteristic size of micro channel. Chien [11] et al. assumed that the wall-slip effect was the reason for the reduction in viscosity and found that the ratio of slip velocity relative to mean velocity increases with decreasing size of micro-channels. However, no wall slip experiments were carried out. Meanwhile, no reasonable microscope viscosity of micro components was established and that finally leads to the inaccuracy of simulation. Therefore, the mechanisms of fluid flow are still not understood clearly, and it becomes increasingly urgent to investigate impacting factors on flow characteristics in micro channels. The influencing factors include viscous dissipation, micro scale effects, surface tension, and wall slip, etc. It is known that viscous dissipation effects are commonly neglected for macro scale measurement of viscosity. However, as the dimensions of channels approach the micro-level, viscous dissipation may become significant because of the existence of a large velocity gradient. Yao and Kim [9] simulated the temperature distribution in micro cavity and proposed that viscous dissipation effects result in a non-uniform temperature distribution, which affects the viscosity distribution. Yu et al. [14] simulated the polymer melt viscous dissipation effects of micro channel with PMMA and indicated that the viscous dissipation effects become significant and influence the temperature, pressure and velocity distribution in micro channels. As a result, it is essential to investigate viscous dissipation effects when polymer melts fill into micro channels.

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Because of the melt's high viscosity, viscous heating is appreciable, thereby causing a significant temperature rise of the melt within the die. In the past, many researchers [15, 16] concentrated on the changes in temperature and pressure of melt within dies which have an important effect on the parameters of melt, such as, in particular, viscosity and density. As we know, temperature rise depends on the melt viscosity and inversely the temperature rise affects the viscosity of melt. In micro channels, experimental observations indicate that the viscosity of polymer melt flowing through micro channels is altered with variation of characteristic size of micro channels, which indicates that the rheological behavior of polymer melt in micro scale is different from that in macro-scale. Accordingly, the viscous dissipation effects in micro scale differ from that in macro-scale. Therefore, the investigation of viscous dissipation in micro channels contributes to the understanding of the rheological behavior of melt in micro channels. On the other hand, several factors influence the viscosity of melt in micro channels, and in order to identify the important factors influencing the micro rheological behavior of melt, the accurately experimental study of viscous heating is significant, which is helpful for developing a micro scale viscosity model.

In micro scale, several researchers [17, 18] with infrared thermal imager have studied the viscous dissipation of Newtonian fluid, for example, water. However, for non-Newtonian fluid, the investigation of viscous dissipation in micro channel for polymer melts is difficult due to the lack of commercial equipment and suitable devices. So far, no relevant experimental studies have been reported.

In this paper, a novel method is introduced to detect a melt's viscous dissipation effects in micro channels. Temperature rises are measured when polymer melt, such as high density polyethylene (HDPE), flows through several identical aspect ratio micro channels. Depending on the established model of radial temperature distribution and cross-WLF viscosity model, the impact of viscous dissipation on the viscosity of melt is analyzed.

2. Experimental work

2.1 Design of measurement method

The capillary rheometer, which is a common instrument for measuring the rheological properties of polymer melts, has a very stable and accurate temperature control. The temperature of melts in barrels can be kept static without extrusion. When polymer melts are extruded through a capillary die by the action of a piston which is driven at a constant speed, the temperature of extruded melts will rise. An instrument is designed on the base of a Rosand RH-7 capillary rheometer and the schematic of experimental device is shown in Fig. 1. A micro temperature transducer (Kistler, type 6193A) with 1000μm diameter of detection location is selected to be fitted into the right barrel of double-barrel capillary rheometer to measure the temperature of static melts and the other is mounted near the outlet of capillary die which is installed in the left barrel to measure the temperature of extruded melts directly. The gap between measurement location and the outlet of capillary die can be adjusted by thin pads to guarantee the measured temperature rapidly and accurately and avoid the transducer from being destroyed due to high-speed melt pressure. When the diameter of the capillary die is less than that of temperature transducer, the extruded melt can flow fully through the detection location immediately and the measured temperature is reasonable. As the piston moves downward, the melt in the left barrel flows through the micro capillary die and at the same time two sensors begin to measure the melt temperature. The melt temperature in the left barrel will rise due to shear friction. When the measured temperature of the right transducer is considered as the melt temperature of micro channel entrance, the measured temperature difference between the two sensors is the temperature rise due to viscous dissipation at certain shear rate. Then, the characteristics of the viscous dissipation effects in micro channel can be analyzed and discussed.

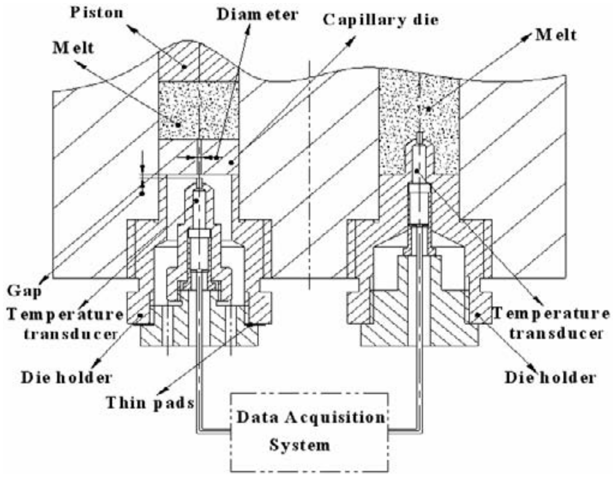

Fig. 1. The schematic of experimental device.

2.2 Experimental procedure

High-density polyethylene (HDPE 5070 Panjin Petrochemical Corporation, Liaoning) is used to investigate the viscous dissipation after three hours drying at 80℃. The diameters of capillary dies used are 1000μm, 500μm and 350μm, respectively, with the same aspect ratio, 16.

The experimental procedures commence by allowing the apparatus to warm up and the required temperature to stabilize. The capillary die and die holders are inserted onto barrels and the temperature transducers are fitted. The gap is adjusted to about 300μm. The barrels are charged with the polymer particles using a charging tool to regularly tamp the polymer. The piston is mounted. When the motor starts, the piston drive engages to compress the polymer slightly. The polymer is left in the barrels for ten minutes to allow the polymer to melt and consolidate. In the case of a moving piston at constant speed, the shear rate is stable and the polymer melt is extruded through the die. Meanwhile, the temperature curves (Fig. 2(a)

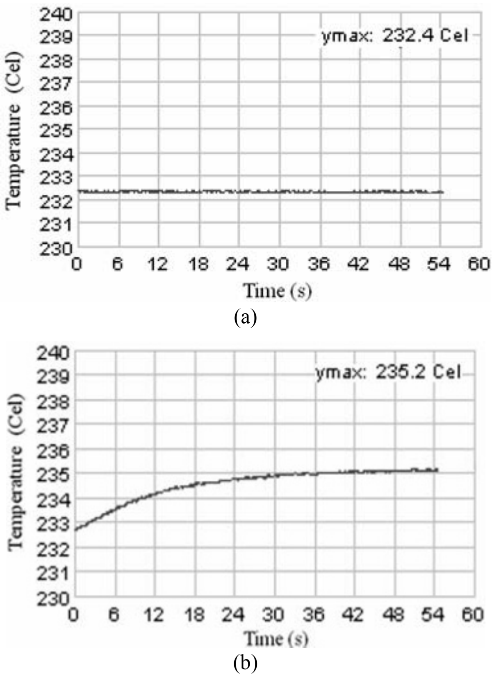

Fig. 2. (a) Temperature profile measured from right temperature transducer; (b) Temperature profile measured from left temperature transducer near outlet of capillary die with diameter 350μm at apparent shear rate of 6000 s^{-1}.

and 2(b)) are recorded simultaneously by a personal computer which is equipped with CoMo Injection (Switzerland) data acquirement system software. Because of non-extrusion, the measured temperature of the right temperature sensor (Fig. 2(a)) is invariable. According to Fig. 2(b), the generated heat due to viscous dissipation is dissipated by the die wall at the outset and the initial temperature rise is small. With the die wall heated by viscous dissipation, thr die temperature gradually increases and the extruded melt temperature rises slowly. When the heat exchange comes to a balance between the die wall and melt, the temperature of the extruded melt reaches a static peak value. Therefore, the stable temperature can be used to calculate the temperature rise caused by viscous dissipation.

Since the velocity gradient near wall is the biggest, the temperature rise of melt near the wall reaches a maximum value due to high shear rate. However, the temperature rise is unchanged in the center of the channel due to low shear rates. After extrusion, the temperature distribution of the melt near the outlet of capillary die is uneven. Since the sensor detecting location is a round plane, the perceived temperature is the general result of extruded melt. Hence, the measured temperature is considered as an average value of extruded melt.

3. Results and discussions

The capillary rheometer used is a constant shear rate rheometer and ten stages for every shear rate are set up in order to guarantee extruded melt temperature to reach static peak value.

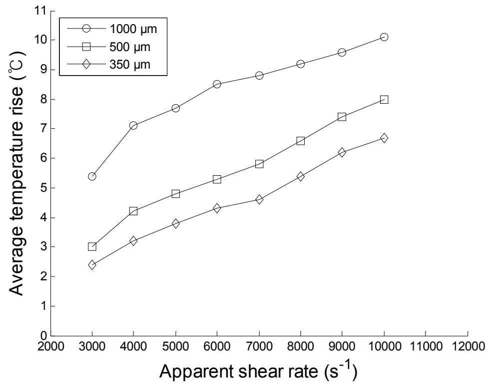

Fig. 3. Average temperature rise curves of micro channels at 213.7℃.

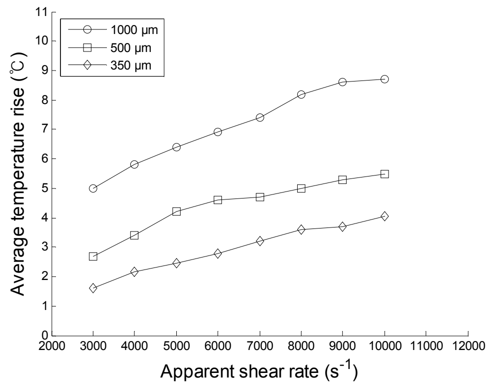

Fig. 4. Average temperature rise curves of micro channels at 232.4℃.

When the setting temperatures of rheometer barrels are 215℃ and 235℃, respectively, the testing temperatures of static melts are 213.7℃ and 232.4℃, correspondingly. The spectrum of apparent shear rate varied from 3000 to 10000s^{-1}. The variations of average temperature rise of outlet location with apparent shear rate at different melt temperature rise are illustrated in Figs.3-4, respectively. From these figures, it can be seen clearly that the temperature rises of melt in micro-channel show much lower melt temperature rises in micro channels of 500μm and 350μm size than that in a micro channel with diameter 1000μm. The temperature rising curves for HDPE melt in Fig. 3-4 indicate that melt temperature rises in micro channels of 500μm and 350μm size are approximately 2-3℃, 3-5℃, correspondingly, lower than that obtained in 1000μm diameter micro channel at the same shear rate.

In a micro channel, the radial temperature distribution is non-isothermal while the experimental results are calculated by using the average temperature of melt. To construct the relationship between the two temperatures mentioned above, the following is the development of a model about radial temperature distribution.

The melt along x direction in micro channel is in a non-isothermal state and a micro wafer of any location along length direction is chosen as the research object, which is shown in Fig. 5. ΔH is thickness and R is radius. The stable laminar flow of micro channel is simplified as one-

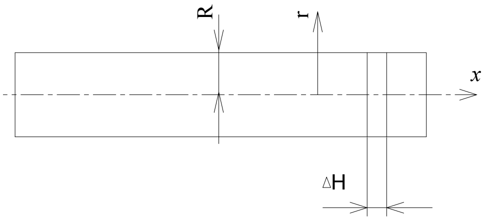

Fig. 5. The schematic of micro wafer.

dimensional shear flow. Then the flow along the axial direction is considered as isothermal flow, and the flow of radial direction is non-isothermal.

The rheological properties of melt in micro wafer are described by the power law:

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

where K' is the melt consistency and $\dot{\gamma}$ is the shear rate. n is the non-Newtonian index. Due to the non-isothermal property in radial direction, Xu [19] suggested that K' of the cross section average temperature is used to calculate viscous dissipation in order to make up for the errors due to variation of viscosity caused by temperature. Momentum equation along x direction is simplified as

$$\frac{\Delta p}{\Delta H} = \frac{1}{r}\frac{\partial}{\partial r}\left(r\tau_{rx}\right) \tag{2}$$

where $\Delta p/\Delta H$ is pressure gradient.

Energy Equation is simplified as

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rq_r\right) = \tau_{rx}\frac{\partial u}{\partial r} \tag{3}$$

where thermal conductivity flux q_r is described by

$$q_r = k\frac{\partial T}{\partial r} \tag{4}$$

and shear stress is calculated by

$$\tau_{rx} = K'\dot{\gamma}^n = K'\left(\frac{\partial u}{\partial r}\right)^n \tag{5}$$

where k is the thermal conductivity of polymer melt.

Eq. (5) is substituted into Eq. (3) to obtain

$$\frac{1}{r}\frac{\partial}{\partial r}\left(rk\frac{\partial T}{\partial r}\right) = K'\left(\frac{\partial u}{\partial r}\right)^n \frac{\partial u}{\partial r} \tag{6}$$

The velocity distribution for non-Newton fluid in micro tube is described as

$$u\left(r\right) = \frac{n}{1+n}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1}{n}} R^{\frac{n}{1+n}}\left[1-\left(\frac{r}{R}\right)^{\frac{1+n}{n}}\right] \tag{7}$$

The derivation of Eq. (7) is

$$\frac{\partial u}{\partial r} = -\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1}{n}} r^{\frac{1}{n}} \tag{8}$$

where the negative sign expresses the vector direction. For convenience of calculation, Eq. (8) is substituted into Eq. (6) with scalar quantity to obtain

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) = \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1+n}{n}} r^{\frac{2n+1}{n}} \tag{9}$$

The integration of Eq. (9) is calculated as

$$r\frac{\partial T}{\partial r} = \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1+n}{n}} \frac{n}{3n+1} r^{\frac{3n+1}{n}} + c_1 \tag{10}$$

According to boundary condition: $r = 0$ and $\partial T/\partial r = 0$, the flowing equation is obtained

$$c_1 = 0 \tag{11}$$

Eq. (10) is integrated again to obtain

$$T = \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1+n}{n}}\left(\frac{n}{3n+1}\right)^2 r^{\frac{3n+1}{n}} + c_2 \tag{12}$$

According to boundary condition: $r = 0$ and $T = T_c$ where T_c is the temperature of center line

$$c_2 = T_c \tag{13}$$

Therefore the radial temperature distribution can be expressed as

$$T = \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{1+n}{n}}\left(\frac{n}{3n+1}\right)^2 r^{\frac{3n+1}{n}} + T_c \tag{14}$$

When r is equal to R, the temperature near wall reaches a maximum value:

$$T_R = T_c + \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{\Delta p}{\Delta H}\right)^{\frac{n+1}{n}}\left(\frac{n}{3n+1}\right)^2 R^{\frac{3n+1}{n}} \tag{15}$$

Therefore the average temperature of the outlet location is given as

$$\begin{aligned} T_{ave} &= \int_0^{2\pi}\left[\left(\int_0^R Trdr\right)\right]d\theta \Big/ \pi R^2 \\ &= T_c + \frac{1}{2k}\left(\frac{1}{2K'}\right)^{\frac{1}{n}}\left(\frac{Dp}{DH}\right)^{\frac{n+1}{n}}\left(\frac{n}{3n+1}\right)^2 \frac{2n}{5n+1} R^{\frac{3n+1}{n}} \end{aligned} \tag{16}$$

Since the center shear rate of micro channel melt is zero, the melt temperature is unchanged. We can obtain

$$T_{in} = T_c \tag{17}$$

where T_{in} is the inlet temperature of the melt of the micro channel. Hence, depending on Eqs. (15), (16) and (17), the ratio of maximum temperature rise near wall to the average temperature rise of the cross section can be described as

$$\frac{T_R - T_{in}}{T_{ave} - T_{in}} = \frac{5n+1}{2n} \tag{18}$$

Then the wall temperature is calculated as

$$T_R = \frac{5n+1}{2n}\left(T_{ave} - T_{in}\right) + T_{in} \tag{19}$$

When the micro wafer is located in outlet location, Eq. (19) is reasonable yet and can be used to calculate the wall temperature of the outlet location.

It is well known that the velocity gradient near wall is the biggest; the temperature rise of melt near wall approaches a maximum value due to high shear rate, while the temperature rise is unchanged in the center of the channel due to low shear rates. At the same time, since the fluid viscosity is a function of temperature, it follows that the viscosity of melt near wall changes most markedly. As the wall temperature changes along the tube, the fluid viscosity varies along the tube. This means the viscosity distribution in the tube changes along the flow direction. Therefore, the local viscosity may not be useful in micro-scale flow since the information about the local flow parameters is not available in experimental measurements of the micro fluidics, and the average viscosity near wall should be used for experimental presentations. We define the average viscosity is calculated with the average temperature rise of melt near wall, $T_a = \left(T_R + T_{in}\right)/2$. According to Eq. (19), the wall average temperature is calculated with

$$T_a = \frac{5n+1}{4n}\left(T_{ave} - T_{in}\right) + T_{in} \tag{20}$$

The rheological behavior of melt was described by a 7-constant modified-cross model with WLF equation, which is represented as follows:

$$\eta(\dot{\gamma},T) = \eta_0(T,p)\Bigg/\left(1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}\right) \tag{21}$$

$$\eta_0\left(T,p\right) = D_1\, exp\left\{\frac{-A_1\left(T-T^*\right)}{A_2+\left(T-T^*\right)}\right\} \tag{22}$$

$$T^*\left(p\right) = D_2 + D_3 p \tag{23}$$

$$A_2 = \tilde{A}_2 + D_3 p \tag{24}$$

Table 1. The parameters of HDPE.

Parameter	Value
D_2/K	393.15
D_3	0
A_1/K	9.6
$\tilde{A}_2$/K	51.6
n	0..2037

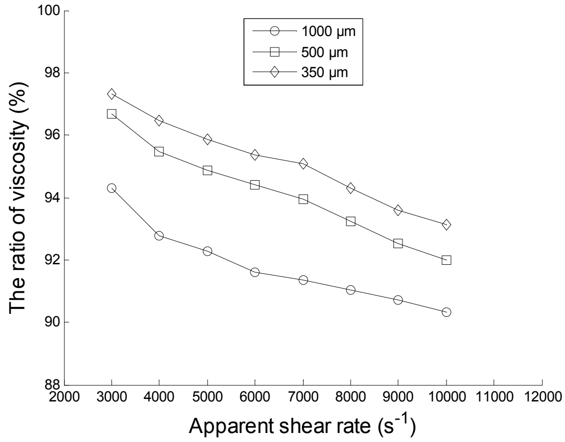

Fig. 6. The effects of viscous dissipation on viscosity at 213.7℃.

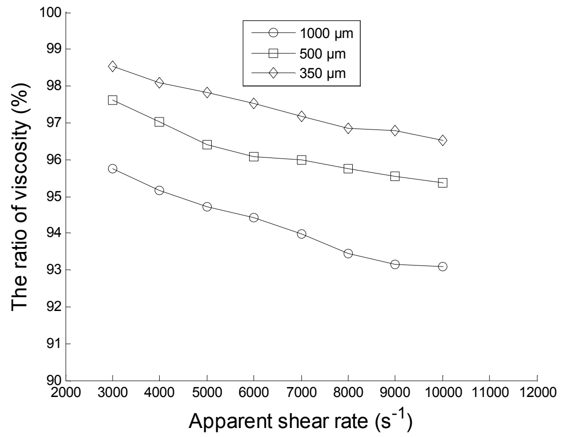

Fig. 7. The effects of viscous dissipation on viscosity at 232.4℃.

where D_1, D_2, D_3, A_1, τ^* and $\tilde{A}_2$ are material constants, n is the Non-Newtonian index.

When the shear rate is high, Eq. (21) can be approximately simplified as

$$\eta\left(\dot{\gamma},T\right) = \eta_0\left(T,p\right)\Bigg/\left(1+\left(\frac{\eta_0\dot{\gamma}}{\tau^*}\right)^{1-n}\right) \approx \eta_0\left(T,p\right)^n\Bigg/\left(\frac{\dot{\gamma}}{\tau^*}\right)^{1-n} \tag{25}$$

According to Eqs. (22), (23), (24) and (25), when the shear rate is identical, the ratio of viscosity between two temperatures can be expressed as

$$\frac{\eta_1(\dot{\gamma},T_1)}{\eta_2(\dot{\gamma},T_2)}=\left(\frac{\eta_0(T_1,p)}{\eta_0(T_2,p)}\right)^n\times 100\%$$
$$=\left\{exp\left[\frac{-A_1(T_1-T^*)}{A_2+(T_1-T^*)}-\frac{-A_1(T_2-T^*)}{A_2+(T_2-T^*)}\right]\right\}^n\times 100\% \tag{26}$$

Based on the above relationship, the impact of viscous dissipation on the viscosity can be calculated. Depending on the data in Figs.3-4 and the parameters in Table 1, the ratio of viscosity at static temperature to that at temperature due to viscous dissipation can be obtained depending on Eq. (26). The results are shown in Figs.6-7. From these figures, it can be clearly seen that the viscosity due to viscous dissipation is reduced less in a 350μm size micro channel, while decreases much in a 1000μm size micro channel.

Recently, Chen S.C [11-13] reported that the values for the viscosities of several polymer melts in micro-channels of 500 μ m, 300μ m, and 150μ m are lower than those measured with a traditional capillary rheometer in the testing shear rate range. In our prior work [20], we also found that for HDPE, the viscosity in micro channels of 500 μ m and 350 μ m size is approximately 15%-18%, 25%-34%, respectively, lower than those obtained in 1000 μ m diameter micro channel at the same shear rate. According to Figs.6-7, the difference of the percentage reduction in the viscosity value of identical shear rate due to viscous dissipation between micro channels is not more than 5%. Compared with the variation of viscosity, the changing viscosity due to viscous dissipation is little. Meanwhile, with micro-channel characteristic size decreasing, the percentage reduction in viscosity increases at the same shear rate while changing viscosity due to viscous heat is reduced. Therefore, viscous dissipation effects do not play a significant role.

4. Conclusions

The viscous dissipation of polymer melt flowing through micro channels is investigated with HDPE through a novel technique of viscous dissipation measurement. For the same aspect ratio micro channel, the temperature rises drop obviously with the reduction of characteristic size of micro channel, which is different from macro scale. Meanwhile, a radial temperature distribution model is developed. Based on the model, the influence of viscous heating on melt viscosity is studied. Compared with the variation of viscosity in different micro channels, the impact of viscous dissipation effects on viscosity is less and the results indicate that viscous dissipation is not the main reason.

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