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EFFECTS OF POLYMER MORPHOLOGY ON THE RHEOLOGICAL BEHAVIOR OF MELT WITHIN MICRO-CHANNELS

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ABSTRACT

Micro molding has shown great commercial potential in recent years and determination of the rheological behavior of the polymer melt within micro structured geometry is vital for accurate simulation modeling of micro molding. The lack of commercial equipment is one of main hurdles in the investigation of micro melt rheology. In this study, a melt viscosity measurement system for low and high density polyethylene polymer melt flowing through micro-channels was established using a micro channel mold operated at a mold temperature as high as the melt temperature. For measured pressure drop and volumetric flow rate, capillary flow model was used for the calculation of viscosity utilizing Rabinowitsch correction. The calculated results of low crystallinity LDPE resin were also compared with those of high crystallinity HDPE resin to discuss the effect of degree of crystallinity on the viscosity characteristics of polymer within micro-channels. It was found that the measured LDPE and HDPE viscosity values in the test ranges are significantly lower (about 40~56% and 22~29% for LDPE and HDPE, respectively, flowing through a channel size of 150 μ m) than those obtained with a traditional capillary rheometer. Meanwhile, the percentage reduction in the viscosity value and the ratio of slip velocity relative to mean velocity all increase with decreasing micro-channel size. In the present study we emphasize that the rheological behavior of the high crystallinity HDPE and low crystallinity LDPE resins in microscopic scale are all different from that of macroscopic scale but HDPE displays a less significant lower. The reason can be attributed to for LDPE resin within the micro-channel can create the higher extra bonding force between the bulk chains than HDPE resin. Thus, it will have the lower adhesive force between the bulk chains with the micro-channel wall, resulting in higher degree of wall slip.

Keywords: rheological behavior, polyethylene, micro-channel, wall slip

INTRODUCTION

Compared with other materials such as metals, ceramics and semiconductors, polymer-based materials have the advantages of low cost, mass production capability, disposability and biocompatibility. Hence, in recent years, polymer-based micro-fabrication techniques have been explored for applications in the field of micro-structured products such as biomedical and optical devices. Injection molding of plastics for microsystem products has displayed growing commercial potential. Many micro and micro-featured devices such as micro sampling cells [1], micro heat exchangers [2], micro pumps [3], biochip [4] and optical grating elements [5], have been successfully injection molded.

In the injection molding process, melt flow can be described as an ideal laminar flow under regular injection velocity and cavity geometry. Instability of melt flow occurs when the geometry is subjected to abrupt changes such as the location at gate area, thin-rib, etc. This can also happen if the melt is injected at ultra high speed. According to the literature [6], wall slip usually appears when flow instability and melt degradation occurs. The former case may be contributed to experimental setup and/or a special rheometer design. The latter case is mainly due to temperature rise resulting from viscous heating. The slip phenomenon may be attributed to the disentanglement of the bulk chains when attached to the wall [7-10]. To simulate this process realistically, a reliable determination of slip velocity is needed. The traditional method to determine the slip velocity of molten polymer is to use experimental data from a capillary rheometer and the classic Mooney method. A study from Rosenbaum et al. [11], who determined the slip velocity at high shear rates, accounted and

corrected the effects of viscous heating within capillary dies with three different diameters (of 0.508, 0.762, and 1.27 mm) at a constant L/D ratio equal to 40. It was found that the flow curve of wall shear stress and apparent shear rate that corresponds to the capillary of a smaller diameter deviates more significantly from the no-slip flow curve. This indicates that when flow geometry becomes smaller, the rheological behavior of the melt may be different from that measured in macroscopic scale.

As micro molding attracts more and more attention, using computer simulation tools to solve difficult molding issues is becoming an important trend. However, only a handful of experimental studies on polymeric flows in micro channels have been reported. Recent studies [12-15] indicate that existing simulation packages are no longer sufficient to describe all the effects in micro molding, especially for micro parts with small dimensions. The inadequacy may be attributable to the following issues in standard modeling. Rheological data used in current simulation packages are obtained from macroscopic scale measurements. The macroscopically measured viscosities may not be suitable for modeling melt flows through geometries at micro scale dimensions. Within micro scale geometries, surface tension may have a significant influence on melt flow, depending on the order of magnitude of the viscosity value. Roughness of cavity surface, wall slip conditions, or even heat transfer behaviors at the micro scale [13] are other characteristics that may affect rheological data as well. For example, viscoelasticity was found to be important when the melt flows through the gate [15]. Chen et al. [16] studies on thin-wall injection molding have shown that the prediction of injection pressure from the current simulation package may be higher 50% than practical injection pressure.

Further, the transient behavior of material properties during fast molding times may exhibit certain differences with measurements taken close to an equilibrium state. Investigation of micro melt rheology is difficult due to the lack of commercial equipment and suitable devices. Thus far no relevant study has been reported, except for one for investigation into hot embossing of microstructures [14], which measures the transient extensional melt viscosity suitable for very small shear rates. A more recent study from Yao et al. [12], who used the simulation as an analysis tool, investigated the consequences of micro scale phenomena, particularly size-dependent viscosity, wall slip, and surface tension on the filling process of polymeric materials into micro channels. The micro channel geometry is a plate with a length to width to thickness ratio (L:w:2b) equal to 100:10:1, and the half thickness, b, is varied from 0.1 μm to 1000 μm . From the simulated result, they pointed out that the viscous heating effect is insignificant in the cavity with b less than 100 μm , i.e. almost no temperature variation occurs in micro cavities (less than half a degree for b=100 μm). The effect of micro scale viscosity becomes important when b is less than 1 μm . In addition, as thickness of mold cavity decreases, the slip effect dominated

the velocity. Though the simulation results of the wall-slip effect in the micro channels are helpful in understanding the rheological behavior of the melt in micro scale, and though there is some evidence indicating that the polymer melt flows in micro channels differ significantly from those in macro geometries, experimental data has been insufficient for robust quantitative conclusions. As a result, it is important to investigate and/or verify the slip phenomenon of the polymer melts flowing through micro-channels experimentally.

In our group's recent investigation, the measurement of melt viscosity within small dimension geometries was investigated using high-fluidity amorphous PS, ABS, and high/low density PE, as well as high crystallinity POM resin. A mold with micro channels of square cross section was constructed and operated at a mold temperature similar to the melt temperature. From the measured pressure drop obtained from pressure transducers and melt volumetric flow rate, one can calculate the viscosity values using a capillary flow model and slit flow model combined with Rabinowitsch and Walter corrections, respectively. For amorphous ABS and PS resin [17-18], it was found that as micro channel size decreases, the percentage reduction in viscosity value increases, when compared with data obtained from traditional capillary rheometer. The ratio of slip velocity relative to mean velocity was also found to increase as the size of the micro channels decreases. It seems that wall slip plays a dominant role when the melt flows through micro-channels, resulting in a greater apparent viscosity reduction when the size of micro channel decreases. In addition, the wall-slip effect becomes more significant as melt temperature increases. Our group's previous study, though providing a better understanding of amorphous polymer melt rheology in flow through micro-channels, is far more complete in the different degree of crystallinity polymer melt rheology. Consequently, in the present study, we use high density PE resin to investigate polymer melt rheological behavior when flowing through micro-channels to form the basis for improvements in computer simulation of micro injection molding. Meanwhile, the calculated results of high crystallinity HDPE resin was also compared with those of low crystallinity LDPE resin to understand the effects of degree of crystallinity on the viscosity characteristics of polymer within micro-channels.

CAPILLARY FLOW MODEL DESCRIPTION

Capillary flow model was used to analyze the rheological behavior and calculate the viscosity of the molten polymer melt flowing through micro-channels of square cross section. Capillary viscometer is the most common instrument used for measuring melt viscosity dependence on shear rate and temperature. In the test, the molten polymer in a reservoir is forced to flow by a piston under a given pressure through a capillary. From the amount of melt existing from the capillary per unit of time and the required pressure drop across the capillary one can calculate the melt viscosity at a specified

shear rate. The apparent shear rate ($\dot{\gamma}_{w(app)}$) and the apparent shear stress ($\tau_{w(app)}$) at the wall for Newtonian fluids is given by [19]

$$\dot{\gamma}_{w(app)} = \frac{4Q}{\pi R^3} \quad (1)$$

and

$$\tau_{w(app)} = \frac{\Delta P}{2L} R \quad (2)$$

respectively. In these equations, R is the radius of the capillary having length L , Q is the volumetric flow rate through the capillary under a pressure drop ΔP along the capillary. Furthermore, two corrections are commonly applied to capillary data in order to obtain the correct viscosity of polymeric fluids. The Rabinowitsch correction [19] corrects the rate of shear at the wall for non-Newtonian liquids. It changes equation (1) to

$$\dot{\gamma}_{w(real)} = \frac{4Q}{\pi R^3} \left(\frac{3}{4} + \frac{1}{4}b \right) \quad (3)$$

where b is the slope of $\log \dot{\gamma}_{w(app)}$ versus $\log \tau_w$ (correlated in a bi-logarithmic coordinate system). In addition, the Bagley correction [19] takes care of non-ideality arising from viscous and elastic effects at the entrance to the capillary. The effective length of the capillary is greater than its true length. The shear stress at the wall of equation (2) becomes

$$\tau_{w(real)} = \frac{\Delta P}{2\left(\frac{L}{R} + e\right)} = \frac{\Delta P - P_0}{\frac{2L}{R}} \quad (4)$$

where e is Bagley correction factor and P_0 is the pressure drop corresponding to a capillary of zero length for a given rate of shear, respectively. After correction, the real viscosity of molten polymer can be obtained by dividing the real shear stress by real shear strain rate as follows:

$$\eta_{(real)} = \frac{\tau_{real}}{\dot{\gamma}_{real}} \quad (5)$$

For typical $\log \eta$ and $\log \dot{\gamma}$ curve, over the usual accessible shear rate range, the viscosity decreases nearly linearly with shear rate. This is known as the shear-thinning behavior and is usually described by the power law

$$\eta = m \dot{\gamma}^{n-1} \quad (6)$$

where m is the consistency index, and n is the power law index.

EXPERIMENTAL WORK

The determination of the rheological behavior of the melt flowing through micro-channels is a very difficult task mainly because of the high strength requirement of the micro-channel device to bear very high pressures when melt is forced through

the micro-channel. In addition, the pressure must also be large enough to drive the melt flowing through micro channels. Traditional capillary viscometer does not satisfy this requirement. As a result, on-line measurement using an injection molding machine as a plunger and a metal mold with micro channel design becomes the practical way. However, there is also a need to solve the high mold temperature problem during measurements. In our study, in order to determine the rheological behavior of the melt flowing through micro-channels, a mold designed with micro-channel of square cross-section that allowed sizes varying from 500 μm to 300 μm and 150 μm was used (Fig. 1). The surface roughness of micro-channel is in the range of 0.2 to 0.4 μm . The Sodick EH30 microinjection molding machine combined with a mold temperature control unit capable of heating coolant to 300°C was utilized as a pressure source to conduct the experiment. High and low density PE (Polyethylene) resins are used in this study. LDPE (grade Paxothene NA248, with density of 0.916 g/cm^3) and HDPE (grade Unithene LH523, with density of 0.956 g/cm^3) supplied by USI Corporation. The extrusion experiments of the polymer melt were conducted at test temperatures of 200°C, 220°C and 240°C for LDPE/HDPE resins and the screw speed allowed apparent shear rates ranging from approximately 7×10^2 to $4 \times 10^4 \text{ s}^{-1}$ (injection pressures are 5, 10 and 15 MPa, respectively). The mold with micro channels were operated at a mold temperature same as the melt temperature. In addition, the mold insert is sealed up by an asbestos board (Fig. 1.) to stabilize the mold temperature. On the core side, two pressure transducers (Kisler, type 6159A) were flush mounted near the inlet and outlet positions of the micro-channels as shown in Fig. 2 to measure the pressure drop when the polymer melt is flowing through the micro-channel. The pressure can be recorded, analyzed and displayed by interface developed using @Labview software. The pressure will reach a static peak value when melt exits the outlet of the cavity end as seen in Fig. 3a. The total pressure drop (ΔP_{total}) was composed of inlet pressure drop (ΔP_{inlet}), pressure drop within micro channel ($\Delta P_{micro-channel}$) and outlet pressure drop (ΔP_{outlet}). The pressure will rise very sharply in the micro channel due to the great flow resistance whereas the pressure variation is smooth in both the inlet and outlet of micro channel area. This is clearly seen in Fig. 3b. Assuming inlet pressure drop ΔP_{inlet} equal to outlet pressure drop ΔP_{outlet} , the $\Delta P_{micro-channel}$, pressure drop within the micro channel, can be obtained by deduction of ΔP_{inlet} and ΔP_{outlet} from the total pressure drop. Another method to determine the total pressure drop is to record the time when melt arrives at the second pressure transducer. The difference of pressure values between the two embedded sensors determines the total pressure drop. Calibrations of pressure sensors were also performed by switching positions between the two sensors. In both these methods, the measured pressure drops have a difference of less than 3%. Therefore, the former method is used for the

subsequent analyses. Finally from the measured data of flow rate and pressure drop, using capillary flow model, one can obtain the dependence of the true melt shear viscosity (η_w) on the shear rate ($\dot{\gamma}_w$) for the polymer melt at the test temperature.

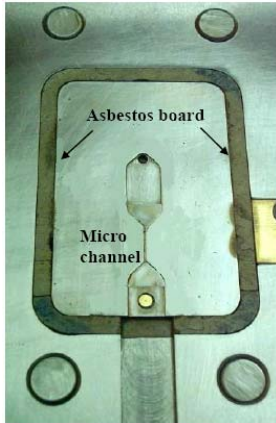


Fig. 1 Mold with micro channel insert sealed up with an asbestos board.

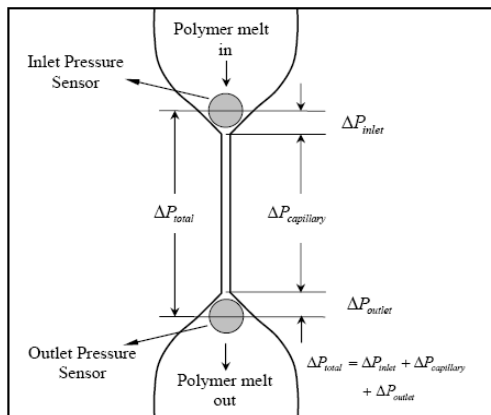


Fig. 2 Schematic of pressure drop when melt is flowing through the micro channel.

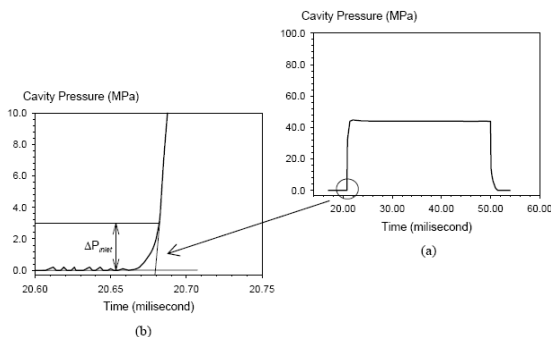


Fig. 3 (a) Cavity pressure profile measured from pressure sensor at inlet position. (b) Enlarged cavity pressure variation at inlet region of micro channel.

RESULTS AND DISCUSSION

Micro-channel of square cross-section must be converted into an equivalent radius if capillary flow model was adopted. The calculated equivalent radii are 281 μm , 168.6 μm and 84.3 μm , respectively, for square micro-channels with widths of 500 μm , 300 μm and 150 μm . In addition, the equivalent radius must be a multiple of the shape factor of 1.117, due to the higher surface area of the square-cross section than the circular cross section, resulting in higher flow resistance. Table 1 show the Rabinowitsch correction b values for LDPE and HDPE resin, respectively, obtained from the slope of the plot of apparent shear rate versus wall shear stress. Variation of LDPE viscosity with shear rate using capillary flow model at a melt temperature of 200°C is illustrated in Fig. 4. From this figure, it can be clearly seen that the viscosities of melt in micro-channel of 500 μm , 300 μm and 150 μm size shows approximately 6~9%, 17~24%, and 53~56%, respectively, lower values than those obtained from a traditional capillary rheometer at the same shear rate. It was found that the reduction in viscosity of polymer flowing through micro channel increases with decreasing dimension of micro channels. Figs. 5 and 6 show the variation of viscosity with shear rate using capillary flow model at melt temperatures 220°C and 240°C, respectively. The viscosities of melt in micro-channel size of 500 μm , 300 μm and 150 μm also show a lower value than those measured from the traditional capillary rheometer. Generally, viscosity in micro channel 150 μm shows approximately 46%~56% lower values than that obtained from the traditional capillary rheometer at the same shear rate. This indicates that the polymer melt flowing through the micro channels show significantly different rheological behavior from that of traditional capillary rheometer. According to the previous study on rheological behavior flowing through micro-channel, four factors are believed to play a significant role, i.e. the effect of (1) surface tension, (2) size-dependent viscosity, (3) viscous heating and (4) wall slip. The correlation of the viscosity in micro-channel to these factors is quite a complicated issue. The effects of surface tension and size-dependent viscosity can be safely neglected for the channel between 150 μm to 500 μm from the study of Yao et al. [12]. Although the viscosity values obtained from the traditional capillary rheometer may not be appropriate for micro molding simulation, the simulation indicates only 1°C melt temperature rise within the micro channels. WLF equation [19] was used to check change in viscosity due to temperature changes (1°C). When melt temperature was varied from 240°C to 241°C, 220°C to 221°C, and 200°C to 201°C, viscosity decreases to 6%, 8% and 10%, respectively. Meanwhile, due to the short length of the micro channel in the current mold, the viscous heating effect seems to be insignificant in the present study and can be neglected during the viscosity calculations. In addition, according to the simulation results by Yao et al. [12], the increased thermal diffusion effects results in uniform temperature inside the micro cavity, which is actually the same as the mold temperature,

Therefore, the viscous heating effect in micro molding can be ignored, and the melt inside the micro cavity can be well assumed to be under isothermal conditions.

As previously described, the viscosity of the polymer melts flowing through micro-channel is lower than from a traditional capillary rheometer where, wall slip plays a dominant role. To analyze the wall slip phenomenon, one can make a reasonable hypothesis that the total volumetric flow rate flowing through micro channel equals to the sum of volumetric flow rate without slip and volumetric flow rate due to wall slip, i.e.

$$Q_{total} = Q_{no-slip} + Q_{slip} \quad (7)$$

A schematic comparison of viscosity obtained from experimental data and that measured by traditional capillary rheometer is made in Fig. 7. In order to analyze the wall slip effect, we assume that the volumetric flow rate resulting from two components, namely, plug flow and laminar flow, corresponds to Q_{slip} and $Q_{no-slip}$, respectively. This is described in Fig. 8. The plug flow will not introduce any shear rate since the direction of melt flow along each section is uniform. However, in Fig. 7, η_c and the associated $\dot{\gamma}_t$ located in the solid line are analyzed assuming the fully laminar flow condition (no wall-slip condition) based on Eq. (3). This is also the condition assumed in the traditional capillary rheometer measurement. Now, if wall-slip occurs when melt flows through the micro channel, the true volumetric flow rate must be obtained by subtracting plug flow component, Q_{slip} . Therefore, $\dot{\gamma}_t$ should also be corrected to the true shear rate. The wall slip effect is assumed to be the reason for the reduction in viscosity within the micro channel, hence for similar viscosities the difference in shear rate between the traditional case ($\dot{\gamma}_t$) and the case with wall slip flow ($\dot{\gamma}_c$) is contributed by Q_{slip} . Thus from this difference one can calculate wall-slip velocity. According to equation (3), the volumetric flow rate (laminar) leading to $\dot{\gamma}_c$ is

$$Q_{no-slip} = \frac{\pi R^3}{4(\frac{3}{4} + \frac{1}{4}b)} \dot{\gamma}_c \quad (8)$$

and the volumetric flow rate (assuming no wall-slip) leading to an apparent shear rate $\dot{\gamma}_t$ is given as

$$Q_{total} = \frac{\pi R^3}{4(\frac{3}{4} + \frac{1}{4}b)} \dot{\gamma}_t \quad (9)$$

The difference between Q_{total} and $Q_{no-slip}$ under the same η_c value results from wall slip. Then Q_{slip} becomes

$$Q_{slip} = Q_{total} - Q_{no-slip} = \frac{\pi R^3}{4(\frac{3}{4} + \frac{1}{4}b)} (\dot{\gamma}_t - \dot{\gamma}_c) \quad (10)$$

The mean velocity for melt in micro channel is defined by $V_{mean} = Q_{total}/A$. Thus from the fraction of $\dot{\gamma}_t - \dot{\gamma}_c$ to $\dot{\gamma}_t$, one can calculate the ratio of the wall slip velocity (V_{slip}) relative

to mean flow velocity, V_{mean} . Figs. 9, 10, and 11 depict the percentage of slip velocity to mean velocity for the polymer melt flow through micro channel of 500 μm , 300 μm and 150 μm , at temperature 200, 220, and 240 $^{\circ}\text{C}$, respectively. As can be seen, the percentage of slip velocity relative to mean velocity increases with decreasing size of the micro-channel. This indicates that the slip velocity becomes more and more important when the micro-channel size is reduced.

Variation of HDPE viscosity with shear rate at a melt temperature of 200 $^{\circ}\text{C}$ is illustrated in Fig. 4, which shows only slightly lower values for viscosity (approximately less than 2% in percentage reduction for 500 μm channel size) than those obtained from a traditional capillary rheometer. However, the 300 μm channel size shows approximately 5~6% lower values than those obtained from a traditional capillary rheometer at the same shear rate. For the 150 μm channel size, the difference can reach approximately 28~29%. Examination of this data showed that the percentage reduction in viscosity value of HDPE polymer flowing through micro channel increases as the micro channel dimension decreases. Figs. 5 and 6 show the variation of HDPE viscosity with shear rate at a melt temperature of 220 $^{\circ}\text{C}$ and 240 $^{\circ}\text{C}$, respectively. The viscosities of the melt at micro-channel sizes of 500 μm , 300 μm and 150 μm also show a lower value than those measured using a traditional capillary rheometer. Generally speaking, the value for the viscosity in the 150 μm micro channel is 22~29% lower than that obtained from the traditional capillary rheometer at the same shear rate. This indicates that the HDPE polymer melt flowing through the micro channels also displays significantly different rheological behavior than when measured with a traditional capillary rheometer.

At this point it is worthwhile to discuss the effect of degree of crystallinity (i.e. low or high crystallinity) on percentage reduction in viscosity when flowing through micro-channels. A schematic comparison of the viscosity obtained from experimental data (for micro-channel size 500, 300, and 150 μm) and that measured by a traditional capillary rheometer for LDPE and HDPE resin at a melt temperature of 200, 220, and 240 $^{\circ}\text{C}$, are made in Figs. 4, 5, and 6, respectively. It can be clearly seen in Fig. 4 that the values for the viscosities of the HDPE melt in micro-channels of 500 μm , 300 μm , and 150 μm are 1~2%, 5~6% and 28~29%, respectively, lower than values measured with a traditional capillary rheometer. The LDPE melt similarly displays viscosity values in the 500 μm , 300 μm and 150 μm micro-channels that are 6~9%, 17~24% and 53~56%, respectively, lower than those measured with a traditional capillary rheometer. Examination of the data shows that the low degree of crystallinity LDPE resin has a significantly higher percentage reduction in viscosity values than the high degree of crystallinity HDPE resin. The reason can be attributed to the different adhesive force between the polymer melt with the wall when polymer melt flowing through micro-channels. For low degree of crystallinity LDPE resin in the micro-channel, it will shorten the distance of the bulk

chains and create the higher extra bonding force at the same time. Consequently, it will weaken the adhesive force between the melt and the wall resulting in the wall slip speed increased. The high degree of crystallinity HDPE resin also has weakened adhesive force in the micro-channel but displays a less significant. So, the ratio of wall slip velocity relative to mean velocity in the low degree of crystallinity LDPE polymer melt that is significantly greater than in the high degree of crystallinity HDPE resin. Figs. 9, 10, and 11 depicts the percentage of slip velocity to mean velocity for LDPE and HDPE polymer melt (flowing through the 500, 300 and 150 μm micro-channels) at a melt temperature of 200, 220, and 240 $^{\circ}\text{C}$, respectively. As can be seen, the percentage of slip velocity relative to mean velocity increases as the micro-channel decrease in size. This also indicates that the slip phenomena are increasingly important when the micro-channel size is reduced, especially for low crystallinity LDPE resins.

Table 1 Rabinowitsch correction values for capillary flow

Resin	Temperature ($^{\circ}\text{C}$)	Channel size (μm)		
		150	300	500
LDPE	200	1.30	2.05	2.40
	220	1.10	1.84	2.18
	240	1.07	1.67	2.00
HDPE	200	1.54	2.17	2.41
	220	1.42	2.03	2.29
	240	1.34	1.87	2.16

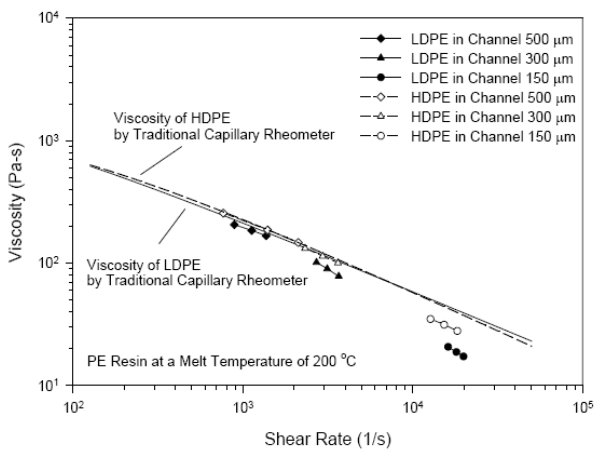


Fig. 4 Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temp. 200 $^{\circ}\text{C}$.

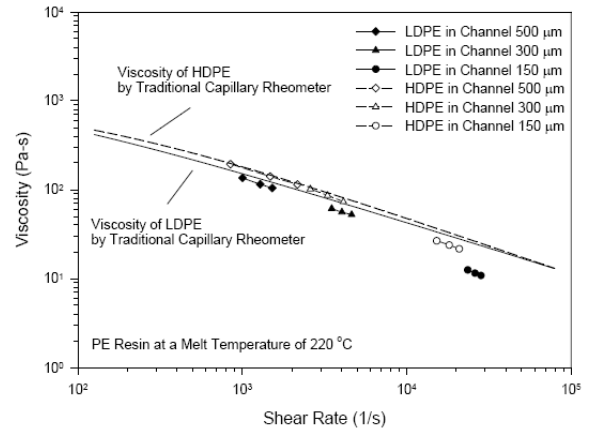


Fig. 5. Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temp. 220 $^{\circ}\text{C}$.

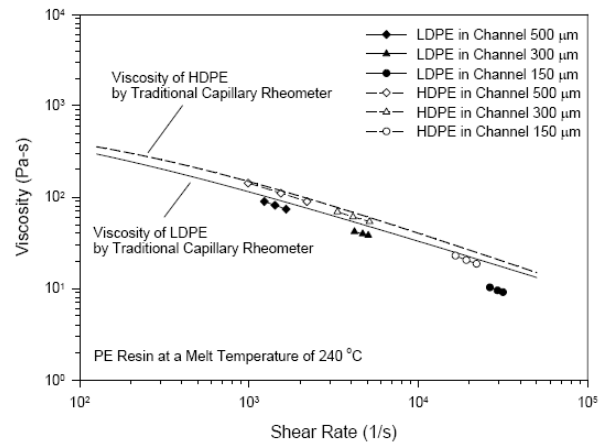


Fig. 6 Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temp. 240 $^{\circ}\text{C}$.

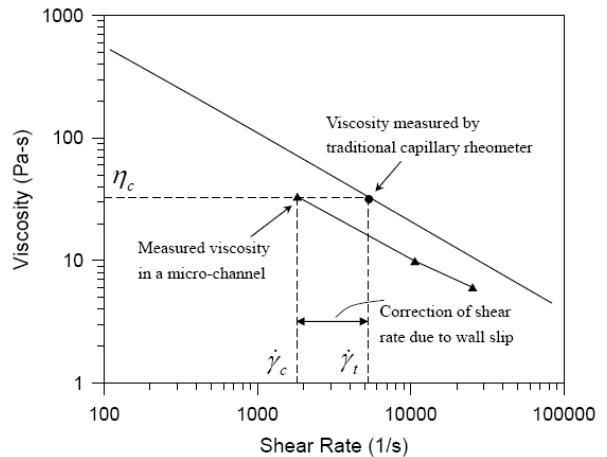


Fig. 7 Schematic representation of $\dot{\gamma}_t$ and $\dot{\gamma}_c$.

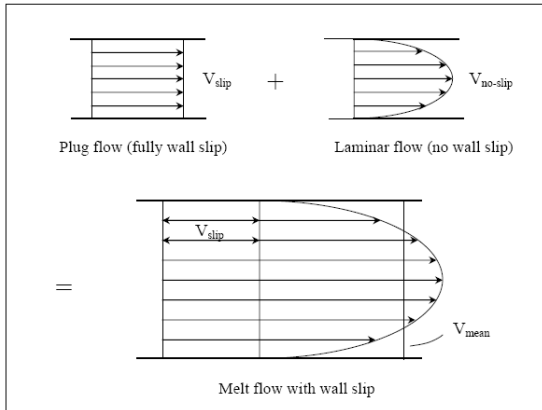


Fig. 8 Schematic of melt flow due to plug flow (wall-slip) and laminar flow.

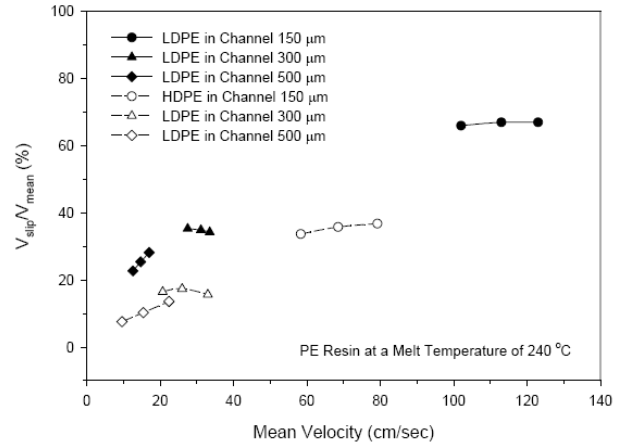


Fig. 11. Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 240°C.

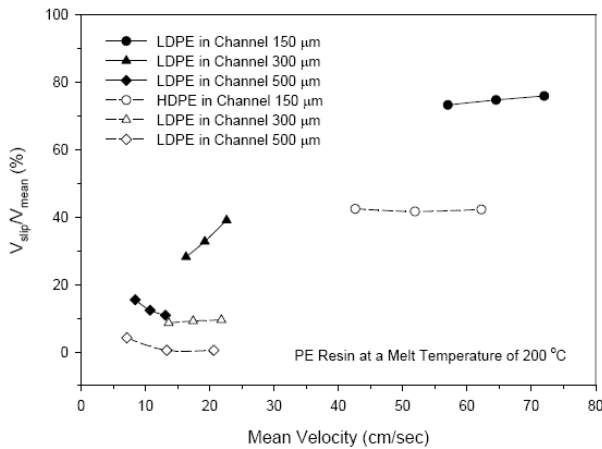


Fig. 9 Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 200°C.

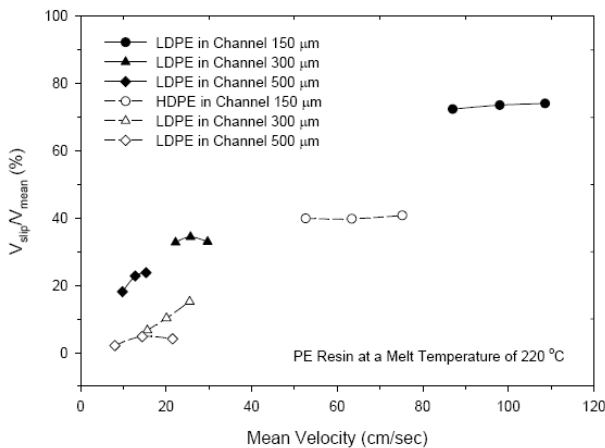


Fig. 10 Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 220°C.

CONCLUSIONS

In the present study, a measurement system of melt rheological property flowing through micro channels was established. Capillary flow model was used to analyze the measured data. Calculated results of viscosity from capillary model at various melt temperatures were compared with the viscosity values obtained from traditional capillary rheometer. The wall slip phenomenon of the polymer melt flowing through micro-channels were analyzed and correlated. Influence of degree of crystallinity on the melt viscosities within micro-channels was also investigated.

It was found that the measured LDPE and HDPE viscosity values in the test ranges are significantly lower (about 40~56% and 22~29%, respectively, for a channel size of 150 μm) than those obtained with a traditional capillary rheometer. Meanwhile, the percentage reduction in the viscosity value and the ratio of slip velocity relative to mean velocity all increase with decreasing micro-channel size, and LDPE resin shows more significantly when compared with HDPE resin. Within the proposed size of micro-channels currently used, the experimental results indicate an important effect due to wall slip on the reduction of melt viscosity. Wall slip occurs more easily in micro channels, especially with low crystallinity LDPE resin. This is due to for low crystallinity LDPE resin within micro-channel can create the higher extra bonding force between the bulk chains than high crystallinity HDPE resin. Thus, it will have the lower adhesive force between the bulk chains with the micro-channel wall, resulting in higher degree of wall slip. The study also indicates that proper modeling of the rheological behavior of the melt within the micro-structured geometry is vital for accurate micro-molding simulation.

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