Rheological behaviour of low/high density polyethylene melt flowing through micro-channels

Chun-Sheng Chen

Department of Mechanical Engineering, Lunghwa University of Science and Technology, Taoyuan Country 33306, Taiwan, ROC; fax: 886(2) 29506385; e-mail: cschenme@yahoo.com.tw

(Received: 1 December, 2007; published: 11 March, 2008)

Abstract: The determination of the proper rheological behaviour of the polymer melt within micro structured geometry is vital for accurately simulating the micro moulding. The paucity of suitable equipments is one of main hurdles in the investigation of micro melt rheology. In the present study, a measurement system for the melt viscosity of low and high density polyethylene polymer melts flowing through micro-channels was established. The capillary flow model with Rabinowitsch correction was used in the calculations of the viscosity based on the measured pressure drop and volumetric flow rate. The effect of the morphology structure on the viscosity characteristics for both the LDPE and HDPE resins within micro-channels was investigated and discussed. It was found that the measured viscosity values for LDPE and HDPE in the test ranges are significantly lower (about 40~56% and 22~29% for LDPE and HDPE, respectively, flowing through a channel size of 150μm) than those obtained with a traditional capillary rheometer. Moreover, both the percentage reduction in the viscosity value and the ratio of the slip velocity to the mean velocity increase as the micro-channel size decreases. It can be observed that the rheological behaviours of the HDPE and LDPE resins in microscopic scale are different from those in macroscopic scale as a result of the wall slip effect. It also revealed that the wall slip occurs more easily for the LDPE resin within micro channels than HDPE resin due to enlarged effect of morphology structure.

Keywords: Rheological behaviour; Polyethylene; Micro-channel; Wall slip.

Introduction

Compared with metals, ceramics and semiconductors, polymer-based materials have the advantages of low cost, mass production capability, disposability and biocompatibility. Hence, in the past years, polymer-based micro-fabrication techniques have been explored for producing the micro-structured parts for applications in biomedical and optical devices. Injection moulding of plastics for products used in microsystem has showed a growing commercial potential. A great number of micro and micro-featured devices have been successfully injection moulded, which include micro sampling cells [1], micro heat exchangers [2], micro pumps [3], biochip [4] and optical grating elements [5].

In the injection moulding process, melt flow can be described as an ideal laminar flow under the regular injection velocity and cavity geometry. Instability of the melt flow occurs when the geometry is subjected to abrupt changes at the locations of gate area, thin-rib, etc. This can also happen if the melt is injected at ultra high speed. According to the literature [6], the wall slip usually appears when the flow instability and melt degradation occurs. The former case may be attributed to the experimental
setup and/or a special rheometer design. The latter case is mainly due to the temperature rise resulting from the 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 the slip velocity is needed. The traditional method to determine the slip velocity of the molten polymer usually utilizes the 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 much significantly from the no-slip flow curve. This indicates that when the flow geometry becomes smaller, the rheological behaviour of the melt may be different from that measured in macroscopic scale.

Recently, the demands of using computer simulation tools to solve micro moulding issues are increasing due to the trend towards the injection-moulded microsystem products. However, some studies [12-15] have showed that existing simulation packages are no longer sufficient to describe all the effects in the micro moulding of micro parts with small dimensions. The inadequacy may be attributable to the following issues in the conventional modelling. The rheological data used in current simulation packages are mainly obtained based on the measurements of macroscopic scale. The macroscopically measured viscosities may be improper for modelling melt flows through geometries with micro scale dimensions. Depending on the order of magnitude of the viscosity value, the surface tension might have a significant influence on the melt flow within micro scale geometries. Other characteristics such as roughness of cavity surface, wall slip conditions, or even heat transfer behaviours at the micro scale [13] may influence the rheological data as well. Meanwhile, the viscoelasticity was found to be of importance while the melt flows through the gate [15]. The studies on thin-wall injection moulding by Chen et al. [16] have shown that the predicted injection pressure from the current simulation package is 50% higher than the practical injection pressure.

Furthermore, the transient behaviour of material properties during the fast moulding process is significantly different from the measured one close to an equilibrium state. Because of the lack of commercial equipments and suitable devices, it is difficult to investigate the rheology of micro melt. Thus far no relevant studies have been reported, except for the one concerning the hot embossing of microstructures [14], in which the transient property of the extensional melt viscosity is measured under very small shear rates. Recently, Yao et al. [12] used the simulation as an analysis tool to investigate the effects of micro scale phenomena, particularly on the 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) of 100:10:1, and the half thickness, b, ranging from 0.1μm 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 significant when b is less than 1μm. In addition, as the thickness of mould cavity decreases, the slip effect dominates the velocity. The simulation results of the wall-slip effect in the micro channels are useful for better understanding of the rheological behaviour of the melt in micro scale, and some
evidence indicates that the polymer melt flows in micro channels behave significantly different from those in macro ones, but the existing experimental data has been insufficient for robust quantitative conclusions. Hence, it is important to investigate and/or verify the slip phenomenon of the polymer melts flowing through micro-channels experimentally.

In a series of studies by our group, the measurement of melt viscosity of polymer melts within channels with small dimensions was conducted on the high-fluidity PS, ABS, and high/low density PE, as well as POM resin. A mould with micro channels of square cross-section was constructed and operated at a mould temperature similar to the melt temperature. Based on the measured pressure drop from pressure transducers and melt volumetric flow rate, one can evaluate the viscosity values using a capillary flow model and slit flow model with Rabinowitsch and Walter corrections, respectively. For ABS and PS resin [17-18], it was found that the percentage reduction in viscosity value increases as the micro channel size decreases, when compared with the data obtained from the traditional capillary rheometer. The ratio of the slip velocity to mean velocity was also found to be increased as the decreased size of the micro channels. The wall slip seems to play a dominant role on the reduction of the apparent viscosity when the melt flows through micro-channels, which results in a greater apparent viscosity reduction when the size of micro channel is smaller. Meanwhile, the wall-slip effect is becoming more significant as the melt temperature increases. The above studies, though providing engineers a better insight in the melt rheology of polymers flowing through micro-channels, are still far more than complete regarding the melt rheology of polymers with different morphology structure. Hence, in the present study, the high density PE resins are used to experimentally investigate the polymer melt rheological behaviour when flowing through micro-channels, which will form the basis for improvements in the analytical simulation of micro injection moulding. Meanwhile, the calculated results of the HDPE resin is also compared with those of the LDPE resin to better understand the effects of the morphology structure on the viscosity characteristics of the polymer within micro-channels.

**Capillary flow model description**

The capillary flow model described next will be used to analyze the rheological behaviour and the viscosity of the molten polymer melt flowing through micro-channels of square cross section. The most widely used capillary viscometer is employed for measuring the melt viscosity dependence on the shear rate and temperature. In the test, the molten polymer in a reservoir is forced to flow into a capillary by a piston under a given pressure. Then the melt viscosity at a specified shear rate can be calculated based on the data of the amount of melt exiting from the capillary per unit of time and the required pressure drop across the capillary. For Newtonian fluids the apparent shear rate \( \dot{\gamma}_{w(app)} \) and the apparent shear stress \( \tau_{w(app)} \) at the wall are given as follows [19]

\[
\dot{\gamma}_{w(app)} = \frac{4Q}{\pi R^3}
\]

(1)

and

\[
\tau_{w(app)} = \frac{AP}{2L} R
\]

(2)
Here $R$ is the radius of the capillary with length $L$; $Q$ is the volumetric flow rate through the capillary under a pressure drop $\Delta P$ along the capillary.

However, in order to obtain the correct viscosity of polymeric fluids, Equations (1) and (2) are modified based on the Rabinowitsch correction and Bagley correction, respectively. The Rabinowitsch correction [19] corrects the shear rate at the wall for non-Newtonian liquids, which leads equation (1) to

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

(3)

where $b$ is the slope of log $\dot{\gamma}_{w(\text{app})}$ versus log $\tau_w$ in a bi-logarithmic coordinate system.

The Bagley correction [19] takes care of the non-ideality arising from viscous and elastic effects at the entrance to the capillary. Thus, the effective length of the capillary is greater than its true length. By considering the Bagley correction, the shear stress at the wall becomes

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

(4)

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

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

(5)

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

$$\eta = m \dot{\gamma}^{n-1}$$

(6)

Here $m$ and $n$ is the consistency index and the power law index, respectively.

Results and discussion

In order to adopt the capillary flow model, an equivalent radius of the square cross-sectional micro-channel must be determined first. The equivalent radii for square micro-channels with widths of 500 $\mu$m, 300 $\mu$m and 150 $\mu$m are 281 $\mu$m, 168.6 $\mu$m and 84.3 $\mu$m, respectively. In addition, the obtained equivalent radius must be modified by multiplying a shape factor of 1.117 because the higher surface area of the square cross-section will result in a higher flow resistance than that of the equivalent circular cross-section. Table 1 presents the Rabinowitsch correction $b$ values for both LDPE and HDPE resins, which are calculated from the slopes of the curves of the apparent shear rate against the wall shear stress. Figure 1 illustrates the variation of the LDPE melt viscosity with the shear rate at a melt temperature of 200 °C using the capillary flow model and traditional capillary rheometer. It can be clearly seen in Figure 1 that the viscosities of melt in micro-channel of 500 $\mu$m, 300 $\mu$m and 150 $\mu$m size are approximately 6~9%, 17~24%, and 53~56%, respectively, lower than those obtained from a traditional capillary rheometer at the same shear
It can also be found that the reduction in the viscosity of the polymer flowing through micro channel increases with the decreasing dimension of micro channels.

**Tab. 1.** Rabinowitsch correction values for capillary flow.

<table>
<thead>
<tr>
<th>Resin</th>
<th>Temperature (°C)</th>
<th>Channel size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>150</td>
</tr>
<tr>
<td>LDPE</td>
<td>200</td>
<td>1.30</td>
</tr>
<tr>
<td></td>
<td>220</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>1.07</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>1.54</td>
</tr>
<tr>
<td>HDPE</td>
<td>220</td>
<td>1.42</td>
</tr>
<tr>
<td></td>
<td>240</td>
<td>1.34</td>
</tr>
</tbody>
</table>

**Fig. 1.** Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temperature 200 °C.

Figures 2 and 3 show the plots of the melt viscosity against the shear rate for LDPE at the melt temperature 220 °C and 240 °C, respectively. Similarly, the viscosities of melt in micro-channel size of 500 μm, 300 μm and 150 μm are also smaller than those measured by the traditional capillary rheometer. Especially for the viscosity in micro channel 150 μm, it shows approximately 46%~56% lower values than that obtained from the traditional capillary rheometer at the same shear rate. This reveals that the rheological behaviour of the polymer melt flowing through the micro channels is significantly different from that when measured using a traditional capillary rheometer. According to the previous study on rheological behaviours of polymer melts flowing through the micro-channel, four factors are believed to have a significant influence on the melt viscosity, which include (1) surface tension, (2) size-dependent viscosity, (3) viscous heating and (4) wall slip. The correlation of the viscosity of the melt in micro-channel to these factors is quite a complicated issue. However, the effects of the surface tension and size-dependent viscosity can be safely neglected for the channel between 150 μm to 500 μm based on the study of Yao et al. [12]. Although the viscosity values obtained from the traditional capillary rheometer may not be appropriate for the micro moulding simulation, the simulation...
indicates only 1°C melt temperature rise within the micro channels. WLF equation [19] was used to check the variation of the melt viscosity against the 1 °C melt temperature change. When the melt temperature was varied from 240 °C to 241 °C, 220 °C to 221 °C, and 200 °C to 201 °C, the viscosity decreases 6%, 8% and 10%, respectively. Meanwhile, because of the short length of the micro channel in the current mould, the viscous heating effect seems to be less significant in the present study and can be neglected in the calculations of the viscosity. Moreover, the simulation results by Yao et al. [12] showed that the increased thermal diffusion effect results in the uniform temperature distribution inside the micro cavity, which is actually the same as the mould temperature. Hence, the viscous heating effect in micro moulding seems to be negligible, and the melt inside the micro cavity can be well assumed to be under the isothermal condition.

Fig. 2. Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temperature 220 °C.

Fig. 3. Comparison of LDPE and HDPE melt viscosities analyzed from capillary flow model and measured by traditional capillary rheometer at a melt temperature 240 °C.
As previously described, the viscosity of the polymer melts flowing through micro-channel is lower than that obtained from a traditional capillary rheometer due to the wall slip effect. To analyze the wall slip phenomenon, one can make a reasonable hypothesis that the total volumetric flow rate flowing through the micro channel equals to the sum of the volumetric flow rate without slip and volumetric flow rate due to wall slip,

\[ Q_{total} = Q_{no-slip} + Q_{slip} \]  

(7)

A schematic comparison between the viscosities obtained from the experimental test on micro channels and measured by a traditional capillary rheometer is made in Figure 4. In order to analyze the wall slip effect, the volumetric flow rate is resolved into two components, namely, plug flow and laminar flow, which corresponds to \( Q_{slip} \) and \( Q_{no-slip} \), respectively, as depicted in Figure 5.

![Figure 4](image)

**Fig. 4.** Schematic representation of \( \dot{\gamma}_{i} \) and \( \dot{\gamma}_{c} \).

Basically, the plug flow will not introduce any shear rate since the direction of the melt flow along the cross-sectional area is uniform. As shown in Figure 4, the solid line correlating the viscosity \( \eta_{c} \) and the associated shear rate \( \dot{\gamma}_{i} \) is obtained by using Equation (3) assuming the fully laminar flow condition (no wall-slip condition). This is also the basic assumption used in the traditional capillary rheometer measurement. However, if the wall-slip occurs when the melt flows through the micro channel, the true volumetric flow rate must be obtained by subtracting the plug flow component, \( Q_{slip} \). Therefore, the shear rate \( \dot{\gamma}_{i} \) should also be corrected to obtain the true shear rate. The wall slip effect will reduce the viscosity of the melt within the micro channel, so for the same viscosity there exists a difference in the shear rate between the traditional case (\( \dot{\gamma}_{i} \)) and the case with wall slip (\( \dot{\gamma}_{c} \)), which can be contributed to \( Q_{slip} \).

Thus from this difference one can calculate the wall-slip velocity. According to equation (3), the volumetric flow rate without slip leading to \( \dot{\gamma}_{c} \) is

\[ Q_{no-slip} = \frac{\pi R^{3}}{4\left(\frac{1}{4} + \frac{1}{b}\right)} \dot{\gamma}_{c} \]  

(8)
and the total volumetric flow rate with no wall-slip leading to an apparent shear rate $\dot{\gamma}_t$ is given as

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

For the same viscosity $\eta_c$, the difference between the $Q_{\text{total}}$ and $Q_{\text{no-slip}}$ value (equations (8) and (9)) leads to the volumetric flow rate with wall slip, $Q_{\text{slip}}$,

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

![Schematic of melt flow due to plug flow (wall-slip) and laminar flow.](image)

**Fig. 5.** Schematic of melt flow due to plug flow (wall-slip) and laminar flow.

The no-slip velocity, mean velocity and slip velocity for the melt in the micro channel is defined by $V_{\text{no-slip}} = Q_{\text{no-slip}} / A$, $V_{\text{mean}} = Q_{\text{total}} / A$ and $V_{\text{slip}} = Q_{\text{slip}} / A$, respectively, in which $A$ is the cross-sectional area of the micro-channel. Substituting the values given by equations (8), (9) and (10) for the $Q_{\text{no-slip}}$, $Q_{\text{total}}$ and $Q_{\text{slip}}$, we obtain

$$V_{\text{no-slip}} = \frac{\pi R^3}{4 A(\frac{1}{4} + \frac{1}{4}b)} \dot{\gamma}_c$$  \hspace{1cm} (11)

$$V_{\text{mean}} = \frac{\pi R^3}{4 A(\frac{1}{4} + \frac{1}{4}b)} \dot{\gamma}_t$$  \hspace{1cm} (12)

and

$$V_{\text{slip}} = \frac{\pi R^3}{4 A(\frac{1}{4} + \frac{1}{4}b)} (\dot{\gamma}_t - \dot{\gamma}_c)$$  \hspace{1cm} (13)
Hence, from the fraction of $\dot{\gamma}_s - \dot{\gamma}_c$ to $\dot{\gamma}_s$, one can calculate the ratio of the wall slip velocity $V_{slip}$ relative to the mean flow velocity $V_{mean}$. Figures 6-8 depict the percentage of the slip velocity to mean velocity for the polymer melt flow through micro channels of 500 μm, 300 μm and 150 μm, at the temperature 200, 220, and 240 °C, respectively. As can be seen, the percentage of the slip velocity relative to mean velocity increases with the 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 the viscosity of HDPE melt with the shear rate at a melt temperature of 200 °C is also illustrated in Figure 1. It shows that for 500 μm channel size the viscosity of HDPE melt is only slightly lower, approximately less than 2% in percentage reduction, than that obtained from a traditional capillary rheometer. However, for the 300 μm channel size the viscosity of HDPE melt is approximately 5~6% lower than that measured by 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 the viscosity value of HDPE polymer flowing through micro channel increases as the decreasing micro channel dimension. Figures 2 and 3 show the variation of the viscosity of HDPE melt against the shear rate at a melt temperature of 220 °C and 240 °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. In general, the value for the viscosity of the HDPE melt in the 150 μm micro channel is 22~29% lower than that obtained by the traditional capillary rheometer at the same shear rate. This demonstrates that the HDPE polymer melt flowing through the micro channels also displays significantly different rheological behaviour from that when measured with a traditional capillary rheometer.

![Fig. 6. Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 200 °C.](image)

Next, the effect of the morphology structure on the percentage reduction in the viscosity of the melt flowing through micro-channels will be investigated and discussed. It can be clearly seen in Figures 1-3 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 those measured with a traditional capillary rheometer and that the viscosity values of LDPE melt in the 500 μm, 300 μm and 150 μm micro-channels are 6–9%, 17–24% and 53–56%, respectively, lower than those obtained by a traditional capillary rheometer.

**Fig. 7.** Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 220 °C.

**Fig. 8.** Comparison of the percentage of slip velocity to mean velocity for LDPE and HDPE resin at a melt temperature of 240 °C.

From the comparison between the results of LDPE and HDPE melts, it shows that the LDPE resin has a significantly higher percentage reduction in viscosity values than the HDPE resin. The reason can be attributed to that the viscosity of LDPE resin is lower than HDPE resin by traditional capillary rheometer due to the difference of morphology structure (compared dashed line for HDPE with solid line for LDPE shown as Figures 1, 2 and 3); thus when these resins within the micro-channel can enlarge the effect of morphology structure resulting in percentage reduction in the viscosity value of LDPE resin being larger than the HDPE resin, especially for smaller micro-channel size. Hence, the ratio of the wall slip velocity to the mean velocity for
the LDPE polymer melt is significantly greater than that for the HDPE resin. As can be seen in Figures 6-8, the percentage of the slip velocity to the mean velocity increases as the micro-channel size is decreased. This also indicates that the slip phenomena are increasingly important when the micro-channel size is reduced, especially for LDPE resins.

**Conclusions**

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

It was observed that the measured viscosity values of LDPE and HDPE melts 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. The percentage reduction in the viscosity value and the ratio of the slip velocity to mean velocity all increase with the decreasing micro-channel size, and those of the LDPE resin are more significantly affected by the micro-channel size when compared with those of the HDPE resin. The experimental results reveal that the wall slip has a significant effect on the reduction of the melt viscosity when the melt flow through the currently used micro-channels with proposed sizes. It also indicates that the wall slip occurs more easily for the LDPE melt within micro channels. The reason is that when these resins within the micro-channel can enlarge the effect of morphology structure resulting in percentage reduction in the viscosity value of LDPE resin being larger than the HDPE resin, especially for smaller micro-channel size. The present study also indicates that the proper modelling of the rheological behaviour of the melt within the micro-structures is important for the accurate simulation the micro-moulding.

**Experimental**

It is a very difficult task to determine the rheological behaviour of the melt flowing through micro-channels. The reason results from the high strength requirement of the micro-channel device in order to bear the very high pressures needed to drive the melt to flow through the micro-channel. Traditional capillary viscometer does not meet this requirement. Therefore, the on-line measurement on a metal mould with micro channel using an injection moulding machine as a plunger seems to be the practical way. However, the high mould temperature problem during measurements still needs to be solved. In the present study, in order to determine the rheological behaviour of the melt flowing through micro-channels, a mould designed with micro-channel with square cross-section of sizes varying from 500 μm to 300 μm or 150 μm was used as shown in Figure 9. The surface roughness of micro-channel is ranging from 0.2 to 0.4 μm. The Sodick EH30 microinjection moulding machine integrated with a mould temperature control unit capable of heating the coolant up to a temperature of 300 °C was utilized as a pressure source to carry out the experiment.

High and low density PE (Polyethylene) resins were used in this study. Both LDPE of grade Paxothene NA248 with density of 0.916 g/cm³ and HDPE of grade Unithene
LH523 with density of 0.956 g/cm$^3$ were supplied by USI Corporation. The extrusion experiments on the polymer melt of LDPE/HDPE resins were conducted at test temperatures of 200 °C, 220 °C and 240 °C and apparent shear rates ranging from approximately $7 \times 10^2$ to $4 \times 10^4$ s$^{-1}$ (injection pressures were 5, 10 and 15 MPa, respectively) controlled by the screw speed. The mould with micro channels were operated at a mould temperature same as the melt temperature. In addition, the mould insert was wrapped up with an asbestos board (Figure 9) to keep the mould temperature as required. On the core side, two pressure transducers (Kisler, type 6159A) flush-mounted near the inlet and outlet positions of the micro-channels as shown in Figure 10 were used to measure the pressure drop while the polymer melt was flowing through the micro-channel. During the test the cavity pressure was recorded, analyzed and displayed through the human-machine interface developed using @Labview software.

![Mould with micro channel insert sealed up with an asbestos board.](image1)

**Fig. 9.** Mould with micro channel insert sealed up with an asbestos board.

![Schematic of pressure drop when melt is flowing through the micro channel.](image2)

**Fig. 10.** Schematic of pressure drop when melt is flowing through the micro channel.
As can be seen in Figure 11a, the cavity pressure reached a static peak value when the melt exited the outlet of the cavity end. The total pressure drop ($\Delta P_{\text{total}}$) mainly consisted of the inlet pressure drop ($\Delta P_{\text{inlet}}$), pressure drop within micro channel ($\Delta P_{\text{micro-channel}}$) and outlet pressure drop ($\Delta P_{\text{outlet}}$). It could also be observed in Figure 11 that the pressure rose very sharply in the micro channel as a result of the great flow resistance whereas the pressure variation was smooth in both the inlet and outlet regions of the micro channel. If the inlet pressure drop $\Delta P_{\text{inlet}}$ was assumed to equal the outlet pressure drop $\Delta P_{\text{outlet}}$, the pressure drop within the micro channel $\Delta P_{\text{micro-channel}}$ could be obtained by the deduction of $\Delta P_{\text{inlet}}$ and $\Delta P_{\text{outlet}}$ from the total pressure drop. Alternative method to determine the total pressure drop was to record the time when the melt arrived at the second pressure transducer. The difference of pressure values between the two embedded pressure sensors determined the total pressure drop. Calibrations of pressure sensors were also conducted by switching the positions of the two sensors. The difference between the measured pressure drops obtained by both methods was less than 3%. Therefore, the former method was used for the subsequent analyses. Based on the measured data of the flow rate and pressure drop, and the capillary flow model, one could investigate the dependence of the true melt shear viscosity ($\eta_\gamma$) on the shear rate ($\dot{\gamma}$) for the polymer melt at the test temperature.

![Cavity Pressure Profile](image)

**Fig. 11.** Cavity pressure profile measured from pressure sensor at inlet position (a) and enlarged cavity pressure variation at inlet region of micro channel (b).

**Acknowledgements**

The author acknowledges Dr. S.C. Chen and Dr. R.D. Chien of Research and Development Centre for Mould and Moulding Technology, Chung Yuan Christian University, Taiwan, who provided the equipments and expertise.

**References**


