Abstract: We examine the effects of different process parameter settings on variations in melt-filling pressure, viscosity index, and part weight based on the use of real-time pressure sensor readings of the inside of the injection melt flow path. In the experiment, widely used polypropylene materials and round-shaped molded parts are selected as the molding and study object. At the same time, pressure sensors are used at different positions to perform data acquisition to enable research into the variation process of the melt-filling pressure, allowing for a viscosity index equation to simultaneously calculate viscosity indexes and observe weight variations in the samples. The obtained data will be a basis for setting up smart manufacturing in the future. The research showed the following: (i) the installation of the real-time pressure sensing modules allowed the variation process of the melt-filling pressure to be monitored along a path from the injection barrel to the mold cavity; (ii) the viscosity index was subject to changing the melt temperature, the injection speed, and the V/P switch-over point of the screw; and (iii) the melt temperature change had a considerable impact on part weight and changes in the injection speed had a relatively significant impact on viscosity variation.

Keywords: scientific injection molding; sensor for thermoplastics; melting filling pressure real-time mechanism design; viscosity index; weight analysis

1. Introduction

Injection molding has seven stages: plasticization, clamping, injection, packaging, cooling, demolding, and ejection. Pressure during injection and packing may have a significant impact on the quality of products [1–10]. Kazmer et al. [1] mentioned that the variation of screw position and injection pressure is the factor to reduce the uncertainty of product quality. In addition to the screw position, injection speed is also important as a processing parameter of injection machines. Besides polymer materials, the relationship between pressure, volume, and temperature (P-V-T) influences the weight of the product significantly and is important in injection molding. By using the relationship between temperature and pressure to maintain a specific volume, the product is kept at a stable weight. Schreiber et al. [2] used the obtained feedback cavity pressure data and the P-V-T relationship of polymers for multiple cycles to control the product quality. Currently, there are many methods of controlling injection molding machines. For example, Chen et al. [3–5] found that there was a strong relationship between product weight and machine
clamping force as a criterion for adjusting the V/P switching position. The feedback data of cavity pressure with the P-V-T relationship is used to control the injection machine. Agrawal et al. [6] established a master curve based on the cavity pressure curve to ensure the maintenance of injection speed. Based on the above, this study aimed to create a real-time melt-filling pressure sensing system for measuring the variation process of the melt-filling pressure in the barrel, nozzle, and mold cavity of an injection molding system. Polypropylene was used as the material to be molded and the subject of this study. The viscosity index of the polypropylene was calculated by integrating the melt-filling pressure for time to investigate the effects of different process parameters on variations of the pressure and viscosity index of the injected melt and the variation of part weight.

2. Experimental Works

2.1. Sample and Equipment

To sense in real time and observe the melt-filling pressure of the PP, a round-shaped sample and an injection mold were designed and used, producing a round-shaped sample 100 mm in diameter and 4 mm thick. Injection molding machine 60-TX of the Chuan-Lih-Fa Machinery Works Co. Ltd., Tainan, Taiwan, with 60 tons mold clamp force was used as it is a curve-elbow toggle mechanism injection molding machine with a rate of injection of 115 cm$^3$/s. The maximum injection pressure was 170 bar.

2.2. Materials

Polypropylene (PP) was used for this experiment. PP was a material that was commonly used in the experiment. The model of the PP was PP-6331, which was manufactured by LCY GROUP (Taipei, Taiwan).

2.3. Test Method

2.3.1. Flow of Investigations

First, the data were collected in real time with a data acquisition system and analyzed to observe changes in raw plastic material pressure during plasticization under various process parameter configurations. The correlated molding conditions and parameters for the samples are listed in Table 1 and include injection speed, melt temperature, and V/P switch-over position. In this study, we used a real-time measurement system for the observation.

<table>
<thead>
<tr>
<th>Exp.</th>
<th>Melt Temperature (°C)</th>
<th>Injection Speed (%)</th>
<th>V/P Switch-Over Position (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>190</td>
<td>50</td>
<td>10</td>
</tr>
<tr>
<td>2</td>
<td>210</td>
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<td>9</td>
<td>210</td>
<td>50</td>
<td>12</td>
</tr>
</tbody>
</table>

The standard molding criteria were established based on the given parameters, and variations in individual parameters and calculated viscosity indices were explored to examine their impact on the final weight of the products using injection molding. The changes in barrel pressure during the injection stage were correlated with changes in part weight using a high-precision weighing scale. Figure 1 shows the research flow chart.
2.3.2. Melt-Filling Pressure of the Real-Time Mechanism

The injection barrel melt-filling pressure experiment was conducted using barrel/nozzle pressure sensors manufactured by American DYNISCO Corporation and mold cavity pressure sensors manufactured by Japanese FUTABA Corporation. The sensors were installed close to the injection-flow path and gate position (Figure 2) to detect a melt-filling pressure of the barrel–nozzle–cavity for PP. The sensors sensed the maximum peak of the pressure during filling and stabilized the condition during injection to change the material flow to be easier to measure.

Figure 3 shows the curves of the melt-filling pressure level in different sensing positions and the reaction trend of the screw position. In this figure, area (I) is for mold closing, area (II) is for injection and packing, area (III) is for plasticizing and cooling, and area (IV) is for mold opening. Figure 4 shows pressure profiles amid the filling of the injection molding were measured with a sensor, and the results are presented in [10–12]. The sensing system was also used to measure the mold cavity melt-filling pressure in this system.
The viscosity index changes in the material during the melting process were calculated using Equation (1) and applying maximum pressure to the pressure peaks. The viscosity of the material was determined by considering the pressures in the barrel and nozzle cavity with the screw position displacement. The equation used to obtain the viscosity index includes the “screw position” term, which refers to the point where the V/P switch-over point [10,11].

\[
VI_{Injection} = \int_{\text{Screw Position}_1}^{\text{Screw Position}_2} P_{Melt}(t) \, dt 
\]  

(1)

3. Results and Discussion

3.1. Effect of Melt-Filling Pressure and Viscosity

- Effect of temperature of melt.

Figure 5 presents the variation trends of the melt-filling pressures at different sensing positions and different melt temperatures, the melt-filling process, and various trends of the corresponding viscosity indices of the melt. It was found that as the melt temperature setting was increased, the change in phase and temperature rise of the PP after it was plasticized, heated, and melted in the barrel increased the fluidity of the melt. The melt-filling pressure changed only slightly along the melt flow path, or more specifically, between

![Figure 3. Real-time melt-filling pressure curves at different sensing positions and molding stages.](image)

![Figure 4. Calculation of the viscosity index: (a) barrel position; (b) nozzle position; (c) cavity position.](image)
the nozzle and barrel. In contrast, when the melt temperature was lowered, flow resistance, as well as the viscosity of the material, increased during the melt-filling process due to the melt-filling pressures in the barrel and the nozzle. The corresponding viscosity indices became relatively high. In addition, after the melt was injected into the mold cavity, the melt-filling pressure in it was not instituted until the mold cavity was almost full. Therefore, when the temperature and, hence, the fluidity of the melt was increased, it was relatively easy for the melt to flow into and fill the mold cavity, thus inducing the mold cavity pressure. A relatively high melt temperature also resulted in a rise in melt-filling pressure due to the limited mold cavity volume and the material temperature.

![Figure 5](image-url)

**Figure 5.** Influence of the temperature of the melt on barrel–nozzle–cavity pressure peak and viscosity index for PP melt filling.

- **Effect of injection speed**

  Figure 6 depicts the variation trends in the melt-filling pressures and corresponding viscosity indices at different injection speeds over the filling stage, recorded from different sensing positions. It was found that by raising the injection speed, i.e., by raising the speed of advance of the screw mechanism in the injection barrel, the melt-filling pressure was also increased. Moreover, a relatively high injection speed caused the melt to apply a relatively high pressure when the mold cavity was full. In other words, melt-filling pressure in the mold cavity rose with injection speed. Alternatively, a relatively low injection speed led to a relatively large area under the integral curve for the melt-filling pressure with respect to time during the filling period, meaning the melt was subjected to relatively high flow resistance and had a relatively high viscosity index. When the injection speed was increased, flow resistance was experienced, and the viscosity of the melt was lowered as the area under the integral curve for the melt-filling pressure with respect to time during the filling period was reduced.

- **Effect of V/P switch-over position**

  Figure 7 presents the variation trends of the melt-filling pressures and corresponding viscosity indices resulting from different V/P switch-over position settings recorded from different sensing positions during the filling process. A change in the position resulted in a greater change in the trends of the pressures in the barrel, the mold cavity, and the nozzle, which caused a change in the melt temperature or the injection speed. This was because a change in the position affected the material volume with which the mold cavity was filled. More specifically, if the V/P switch-over position is set to occur too late, the mold cavity, even when full, keeps being filled with the melt before the screw mechanism in the barrel unit reaches the position corresponding to the V/P switch-over position. In that case, the melt keeps pushing the wall of the mold cavity because of the limited volume of the mold cavity. Therefore, the melt-filling pressures in the barrel and the nozzle are
affected by the reaction force acting on the melt in the overfilled cavity. The area under the integral curve for the melt-filling pressure with respect to time during the filling period increases, resulting in relatively high viscosity indices. A properly set V/P switch-over position, however, leads to a relatively small difference between the pressure peaks during the melt-filling process, as reflected by the variation trends of the viscosity indices.

![Graph](image1.png)

**Figure 6.** Effect of injection speed on barrel–nozzle–cavity pressure peak and viscosity index for PP melt filling.

3.2. **Trend of Viscosity Index and Final Weight**

By changing the injection conditions, i.e., by setting the injection speed, melt temperature, and V/P switch-over position differently, the melt-filling pressures at different sensing positions changed during the melt-filling process depending on changes in the melt fluidity, the limited volume of the mold cavity, whether the mold cavity was filled sooner than expected, and whether pressure was exerted on the melt in the mold cavity. This implies that a change in the injection conditions has a huge impact on the melt-filling pressure and indirectly changes the viscosity of the melt. Therefore, to fully understand the variation trends of the viscosity and pressure of the melt in the filling stage and the product quality by the solidification of the melt filling the mold cavity, it is necessary to measure the weight of injection-molded products and analyze the relationship of the part weight with viscosity. As there is relatively little literature on the effect of the pressure variation or

![Graph](image2.png)

**Figure 7.** Effect of V/P switch-over position on barrel–nozzle–cavity pressure peak and viscosity index for PP melt filling.
viscosity index variation in the barrel of an injection unit on part weight, the correlation between viscosity index variation and part weight was observed by changing the injection molding conditions and then measuring the barrel pressure and calculating the viscosity index in this study.

- **Variation in the melt temperature**

  Figure 8 describes that the change in the melt temperature affected the viscosity and part weight. An increase in the melt temperature lead to a lower viscosity index, lower resistance against melt flow, a lower melt density, a higher specific volume of the material, and lower weight. This indicates that a higher melt temperature leads to lower resistance against melt flow, greater ease with which the screw can push the melt into the mold cavity, and, therefore, a lower required molding pressure, as reflected by part weight.

![Figure 8](image-url)  
**Figure 8.** Variation in the melt temperature on viscosity index obtained from the barrel and injection-molded part weight.

- **Variation in the injection speed**

  Figure 9 illustrates the change in the injection speed on the viscosity and part weight. A decrease in flow resistance during the melt-filling process and a lower melt viscosity were observed with an increase in injection speed. The mold cavity was filled up sooner with the melt, with the material in the mold cavity having a lower density. An increase in the injection speed resulted in a lower viscosity index and lower product weight. The weight reduction trend in the injection-molded product is reflected by the establishment of pressure in the mold cavity, which is directly affected by the speed at which the screw reaches the V/P switch-over position. A faster filling rate of the melt in the mold cavity is achieved as the screw approaches the V/P switch-over position earlier.

- **Variation in the V/P switch-over position**

  Figure 10 presents the impact of changes in the V/P switch-over position on the viscosity index and product weight. When the position occurred too early, the mold cavity was unable to be filled with the melt, and the weight of the molded product was therefore affected, i.e., reduced. Conversely, when the position took place too late, the mold cavity was filled with excessive melt such that both material density and product weight were increased.
The melt-filling pressures in the mold cavity, injection barrel, and nozzle changed (i.e., injection speed, melt temperature, and V/P switch-over position) was analyzed. The viscosity index of the melt was calculated by integrating pressure to time to find and observe correlations between the changes in each of the aforesaid process conditions and part weight. A real-time pressure sensing system was also created for this study. The creation of the real-time pressure sensing system allowed the variation process of the melt-filling pressure to be monitored along a path from the injection barrel to the mold cavity. The results of the research are as follows:

1. The melt-filling pressures in the mold cavity, injection barrel, and nozzle changed with the process parameters. The injection speed had a relatively significant impact on the variation in the barrel pressure.

2. Research into the correlation between the viscosity index variation in the injection barrel and part weight in response to different process parameters shows that changes

![Figure 9. Variation in the injection speed on viscosity index obtained from the barrel and final injection-molded part weight.](image1)

![Figure 10. V/P switch-over position on viscosity index obtained from the barrel and injection-molded part weight.](image2)

4. Conclusions

The variation process of the melt-filling pressure in the injection barrel, nozzle, and mold cavity of an injection molding system in response to different process conditions (i.e., injection speed, melt temperature, and V/P switch-over position) was analyzed. The viscosity index of the melt was calculated by integrating pressure to time to find and observe correlations between the changes in each of the aforesaid process conditions and part weight. A real-time pressure sensing system was also created for this study. The creation of the real-time pressure sensing system allowed the variation process of the melt-filling pressure to be monitored along a path from the injection barrel to the mold cavity. The results of the research are as follows:

1. The melt-filling pressures in the mold cavity, injection barrel, and nozzle changed with the process parameters. The injection speed had a relatively significant impact on the variation in the barrel pressure.

2. Research into the correlation between the viscosity index variation in the injection barrel and part weight in response to different process parameters shows that changes
in the melt temperature had a relatively significant impact on part weight and that changes in the injection speed had a relatively significant impact on viscosity variation.


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References

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