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Research article

Determination of wall thickness effect of in-mold viscosity measurement under non-adiabatic, non-isothermal flow conditions

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Abstract. Measuring the viscosity of the melt contributes to the quality of injection molded products. Injection molding machines cannot give much feedback on the processes in the cavity, so pressure measurement inside the mold facilitates quality supervision. Our goal is to get more information about the viscosity of the material during filling in a traditional injection mold. A suitable and cost-effective method is to install cavity pressure sensors for the *in-situ* viscosity measurement. We prepared an experimental mold with variable wall thickness and 80×80 mm cavity dimensions. We implemented eight pressure sensors in each cavity. The wall thickness varied from 1 to 4 mm, and apparent viscosity was determined at different shear rates and mold temperatures. We measured non-isothermal and non-adiabatic flow during filling. The environment was quite different from that of standard measuring equipment. Based on the results, we effectively measured the material viscosity with a non-heated mold in the case of acrylonitrile-butadiene-styrene (ABS) and polypropylene (PP) material. The results were validated by measuring viscosity with a capillary rheometer and compared to our method using the non-heated mold, and the error was less than 10%. The results were accurate in a specific speed wall thickness range with PP and ABS.

Keywords: *injection molding, viscosity measurement, cavity pressure sensors, wall thickness variation, apparent viscosity, non-isothermal viscosity, non-adiabatic viscosity*

1. Introduction

Nowadays, plastics are widely used. As costs decrease, higher and higher part quality is expected. A considerable proportion of plastics are processed by injection molding, where machine control can only partially check the quality of the product [1–5]. As the number of cavities increases, machine control has less and less control over the quality of the products. Installing sensors in the mold provides information about the processes in the cavity. In most cases, temperature and/or pressure sensors are built into the mold [6]. The pressure curve as a function of time is closely related to the quality of the product and its structure. The application of these sensors only focused on finding short shots and process deviations in most of the cases. However, viscosity is one of the most important parameters in injection molding and determines the stability of the process [7–11]. A little change in the process conditions could result in mechanical property deviation [12].

Zhao *et al*. [13] highlighted advancements in measurement within injection molding, emphasizing real-time monitoring techniques. It underscores the importance of viscosity as a key parameter influencing flow

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resistance and molded product quality, advocating for its precise characterization during manufacturing. Bhattad [14] reviewed various viscosity measurement devices and methods, categorizing them into offline and inline techniques. The review underscored the growing preference for inline methods, such as capillary and oscillatory viscometers, for their ability to integrate with industrial processes and provide continuous, real-time data. Wappler *et al*. [15] introduced a nozzle capillary viscometer (NCV) for inline viscosity measurement, designed for series production applications. The NCV's design eliminated the need for interchangeable capillary channels while ensuring high precision in viscosity determination during production. Friesenbichler and coworker [16, 17] have shown that the viscosity measured by a capillary rheometer differs by 10% from the value determined during injection molding, between 3000 and 200 000 1/s shear rate. They developed a special heated rheo-mold with pressure sensors and IR transducers. Wu *et al*. [18] developed a thin wall (0.2; 0.5 mm) heated mold to measure the in-mold viscosity using cavity pressure sensors. They designed it to measure the material viscosity in a microinjection environment. In several research studies, a common slit-die rheometer was developed and used with an injection molding machine to measure the viscosity, and all of them used a heated flow channel.

In addition to rheometers, many other devices have been developed [19–26], making it possible to measure viscosity using different methods. Their common feature is that, in most cases, a slit geometry was used, and, in all cases, the whole slit was heated. Melt flow was provided by an extruder, an injection molding machine, or a device specially built for this purpose. These devices are referred to as 'slit die' rheometers in the literature.

Sykutera *et al*. [27] used a 4-cavity specimen mold to measure viscosity with 2 cavity pressure sensors. Based on their research, the measurement error tends to be reduced at high shear rates (above 1000 1/s). They identified the non-isothermal conditions as the root cause of the error. The mold and the cavity plate were not heated (40 °C). They used a non-uniform flow channel (specimen geometry) that could cause measurement errors and neglected the importance of wall correction.

Viscosity can be adequately measured with the presented heated slit-die rheometers and other devices, and measurement error is minimal. However, the measurement process requires the use of a separate device and a lot of preparation. Heating and cleaning can be time-consuming and cumbersome, and cleaning the device used for measurement is also complicated. The simplest solution for measuring viscosity can be a traditional injection mold, where no extra preparation, special modification, or cleaning is required. The injection molded product can be easily ejected from the mold. This research aims to investigate the viscosity measurement possibilities using non-isothermal and non-adiabatic conditions with an injection molding machine. Furthermore, we want to investigate the wall thickness effect for the measurement error as a first study.

2. Theory

The flow of melts following the power law is modeled as a laminar flow of incompressible stationary fluids, where the material does not slide on the wall of the pipe, and viscosity is determined by temperature and deformation rate. Viscosity is independent of the density of the material, but it greatly depends on material properties and injection molding conditions (Figure 1).

Pressure measured on the injection molding machine and in the mold is partially proportional to viscosity [28, 29]. The viscosity is most often determined by rotational, oscillating or capillary rheometers. Rheometers can determine viscosity as a function of shear rate, even at several different temperatures [30]. The geometric design of capillary rheometers can be a circle or a slot, where the most common is the circle-shaped capillary rheometer. The measured data depends on the geometry; several corrections are necessary for accurate viscosity results. In the slit capillary tool (Figure 2), the pressure difference is

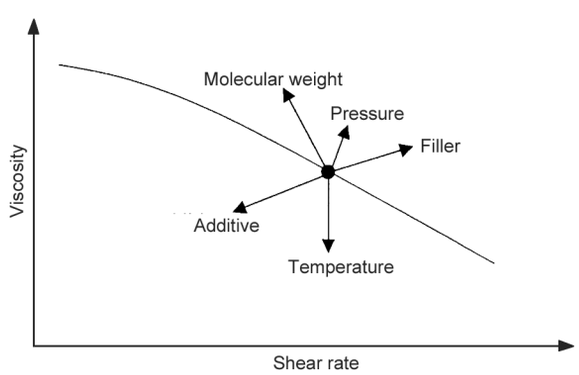

Figure 1. The most important material and technological parameters affecting viscosity [28].

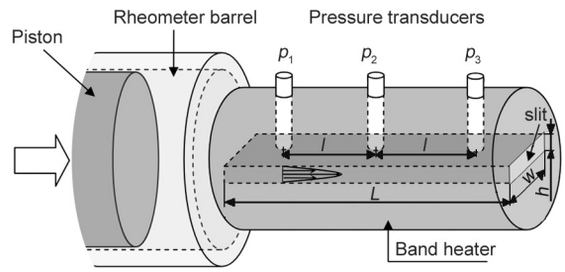

Figure 2. Measuring layout for slit capillary measurement [25].

measured over a given length L at a constant volume flow. Thickness is h, while the width of the slit is w. The slit and the rheometer barrel are heated, which ensures a properly controlled melt temperature. A piston presses the melt through the capillary. The uncorrected shear stress required to determine apparent, *i.e.* uncorrected, viscosity is calculated from the pressure differences ($\Delta P = p_2 - p_1$) (Equation (1)):

$$\tau_w = \frac{h\Delta P}{2L} \quad [\text{Pa}] \tag{1}$$

The uncorrected shear rate is determined from the volume flow (Equation (2)):

$$\dot{\gamma}_{wa} = \frac{6Q}{h^2 w} \quad [1/\text{s}] \tag{2}$$

where Q [m^3/s] is the volumetric flow of the material in the slit, h [m] is the thickness of the slit, and w [m] is the height. The boundary condition for the applicability of the equations is that the flow is stationary and isothermal, the measured pressure drop is the result of viscous flow, and the height of the slit is much smaller than its width (>1:10). In the case of polymer materials, the following rheological corrections are used to determine actual viscosity [10, 16, 22, 28, 30, 31]:

- **Bagley** – Correction of outlet and inlet losses – in capillary rheometers, pressure is typically measured before the capillary, so the pressure change must be calculated after the inlet.
- **Dissipative heat** – Correction of melt temperature increase in the capillary – at a speed of 10 000 1/s, the temperature increase inside the capillary can be up to 5–10 °C, which affects viscosity.
- **Mooney** – Wall slip correction – wall slip appears above the critical shear rate, which varies from material to material but is particularly characteristic of of high-density polyethylene (HDPE) and poly(vinil cloride) (PVC).
- **Weißenberg-Rabinowitsch** – It is used to determine real shear rate – in the flow of pseudoplastic melts, the shear rate in the cross-section changes along a distorted parabolic profile, compared to the Newtonian medium.

In the viscosity measurement of most high-viscosity polymer materials, only the Bagley and Weißenberg-Rabinowitsch corrections are performed (Figure 3). The Weißenberg-Rabinowitsch correction for a slit capillary (Equations (3) and (4)):

$$\dot{\gamma}_w = \frac{6Q}{h^2 w}\left(\frac{2n'+1}{3n'}\right) \quad [1/\text{s}] \tag{3}$$

where

$$n' = \frac{\mathrm{d}\log\tau_w}{\mathrm{d}\log\dot{\gamma}_{wa}} \quad [\text{Pa·s}] \tag{4}$$

that is, the corrected viscosity measured within the capillary (Equation (5)):

$$\eta = \frac{\tau_w}{\dot{\gamma}_w} = \frac{h\Delta P}{2L\frac{2n'+1}{3n'}\cdot\dot{\gamma}_{wa}} \quad [\text{Pa·s}] \tag{5}$$

In practice, a simpler but almost equally effective correction method was developed by Schümmer and

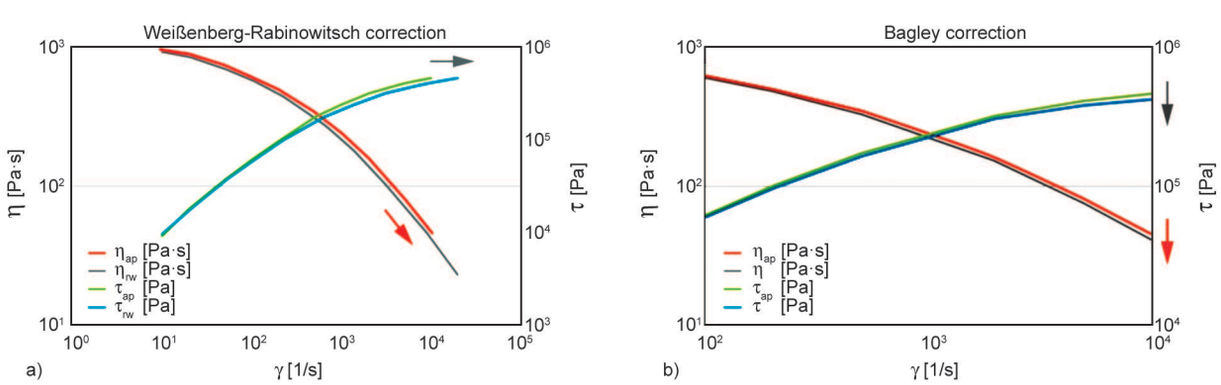

Figure 3. The effect of the Bagley and Weißenberg-Rabinowitsch corrections on apparent viscosity curves [28].

Worthoff [32], which was further developed by Brunn and Vorwerk [33].

The essence of the method is that the shear rate is determined at a distance from the center of the slit where real and apparent shear rates are equal. In practice, the following equation can be used, which only produces a minimal error for a significant part of materials but makes calculation simpler (Equations (6) and (7)):

$$\eta\left(x^{*}\dot{\gamma}_{f}\right)=\eta_{a}\left(\dot{\gamma}_{w}\right) \tag{6}$$

where

$$x^{*}=\left(\frac{2n+1}{3n}\right)^{n/(n-1)}\approx 0.79 \tag{7}$$

where x^{*} it the proportionality factor, n is the power-law index.

3. Experimental method and materials

3.1. Material and equipment

We used two materials for the experiments. The first is an acrylonitrile-butadiene-styrene (ABS, Terluran GP 35, Styrolution Group GmbH), a general-purpose polymer with an amorphous structure suitable for injection molding. The material was dried before processing to eliminate the absorbed water effect for viscosity change. The drying conditions were at a temperature of 80 °C for 3 h. The material can be processed well in a wide temperature range (220–260 °C). The flowability of the material is adequate, and it can also be used with a low injection rate.

Polypropylene (PP, Mol Tipplen H145F) was also used, which can be injection molded easily and processed in a wide range. Its melt flow index is 29 g/10 min (MFI, 230 °C/2.16 kg). The shear sensitivity of the material is considerable. Therefore, the viscosity dependence of the shear rate can be easily investigated (n = ~0.3). We dried the raw materials at a temperature of 80 °C using a hot air dryer according to the material datasheet. We measured the surface temperature of the mold with a J-type thermocouple. We performed the measurements on a fully electric Engel TL160 injection molding machine (Engel Austria GmbH, Schwertberg, Austria). Its maximum clamping force is 50 t, and the screw diameter is 25 mm. We used a Göttfert Rheograph (Göttfert Werkstoff-Prüfmaschinen GmbH, Buchen, Germany) to measure the material properties using capillaries with a diameter of 1 mm and lengths of 0.2 and 20 mm. We used the temperatures and materials defined in Table 1.

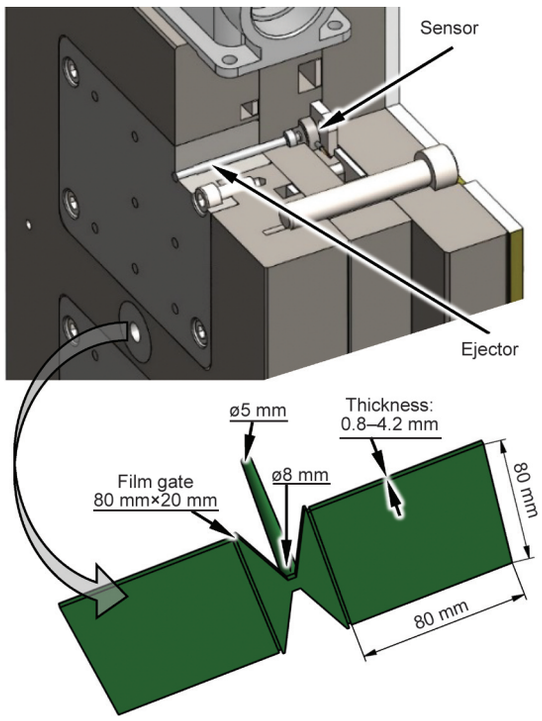

Figure 4. Installation layout of pressure sensors (up) and the injection molded product (down).

3.2. Mold

The cold runner mold used for the experiments has variable wall thickness and two cavities. The cavity is filled through a film gate with a thickness of 2 mm and a width of 80 mm. In the mold, wall thickness can be adjusted infinitely with a special mechanism, the position of which can be changed by turning a screw with a fine thread. By moving the wedge track, the rear position of the moving side inserts can be adjusted. Wall thickness can be changed between 0.8 and 4.2 mm. Changing the wall thickness does not affect the thickness of the film gate. Moreover, the film gate ensures the uniform filling of the cavities.

Internal pressure was measured with Cavity Eye indirect pressure sensors (Cavity Eye Hungary Kft, Kecskemét, Hungary). The sensors were installed in the stationary side of the test mold, directly behind the insert holder plate (Figure 4). A total of 16 sensors were installed in the mold. The diameter of the measuring pin is 3 mm, for which we used a 1 kN sensor. The measuring pins are located 10 mm from the outer edge of the mold cavity, so the distance between the two measuring points is 30 mm. We used the results of the lower cavity for evaluation. The maximum error of the pressure sensors in the tested

Table 1. Parameters used for injection molding.

Parameters		Values
Wall thickness	[mm]	1; 2; 3; 3.5; 4
Average shear rate	[1/s]	46.875; 93.75; 187.5; 375; 562.5; 750
Mold temperature	[°C]	40; 80
Material and temperature	[°C]	PP H145F 235; 210 ABS GP35 245; 225
Screw rotation	[1/min]	100
Back pressure	[bar]	50

measuring range is below 1%. Before measuring, we checked the force measurable through the measuring pins with a manual calibration device.

3.3. Testing method

We performed the measurements using several wall thicknesses, materials, material temperatures, and mold temperatures. In all cases, we injection-molded the products with 100% volumetric filling, and after the filling, we applied 2 s of holding time. We used the measured values of the pressure sensors placed in the middle of the width of the product in the flow path to determine viscosity. The flow path between the pressure sensor near the gate and the pressure sensor at the end of the flow path is 60 mm. PP H145F and ABS GP35 materials were used for the tests. The material temperatures for injection molding were chosen in accordance with the viscosity curves determined with the rheometer. We determined injection rates as the function of wall thickness Equation (8) so the average shear rate was the same in case of all 4 ticknesses (Table 1). We used the Equation (8):

$$Q_{\text{injection}} = \frac{h^2 w \cdot \dot{\gamma}_{\text{wa}}}{6} \cdot 2 \quad [\text{m}^3/\text{s}] \tag{8}$$

We calculated every result for a 2-cavity layout, so that is the reason why the values doubled. Before deciding the appropriate shear rate, we checked that the injection molding machine can have the required injection rate with the given wall thickness. At the beginning of the injection molding process, while the injection molding machine accelerates to the desired speed, the sprue is filled, so the flow rate inside the cavity corresponds to the desired values.

We checked the mold temperature with a type J surface thermometer on both the stationary and the moving side of the mold. We changed the set temperature on the tempering devices in accordance with the specified mold temperature of 40 and 80 °C. We also checked the temperature of the melt with

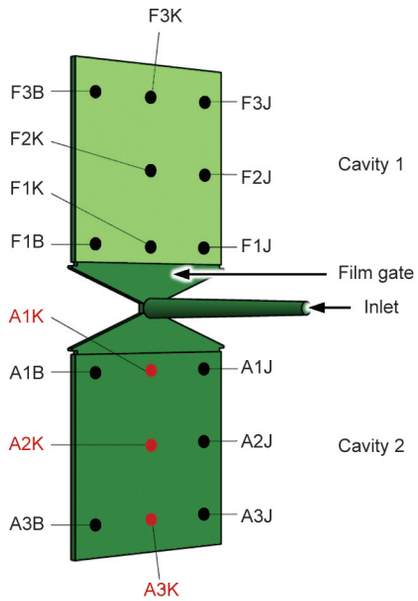

Figure 5. Schematic diagram of pressure measurement points (black dots) and in-mold viscosity measurement points (red dots, A1K, A2K, and A3K).

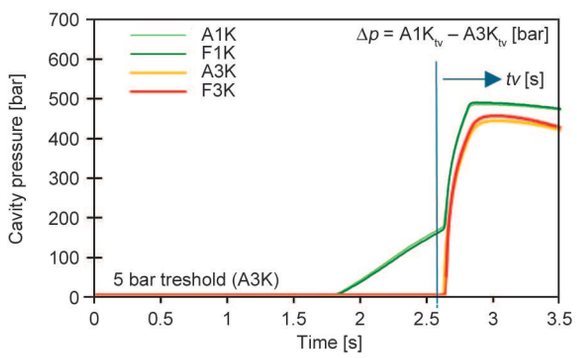

Figure 6. Determination of Δp by the measured pressure curves with a 5 bar treshold vaule (tv).

type J thermocouple and in all cases, it corresponded to the set value within ±4 °C. Therefore we did not define the barrel temperatures just the melt value. Our tests were focused on the filling phase, so holding pressure and holding time were determined individually for each setting so that the injection molding machine did not intervene in the process before complete filling. To simplify the rheological corrections, we used the measured values of the sensors in the middle of the cavity, so the correction of the wall effect was negligible since the width of the slit is much larger than its thickness (>10:1). For the measurements, we used the values of the A1K, A2K, and A3K sensors, and the viscosity was calculated from the pressure difference of A3K and A1K (Figure 5). We calculated the pressure difference of A3K and A1K when the value measured with the A3K sensor was 5 bar during the cycle (Figure 6).

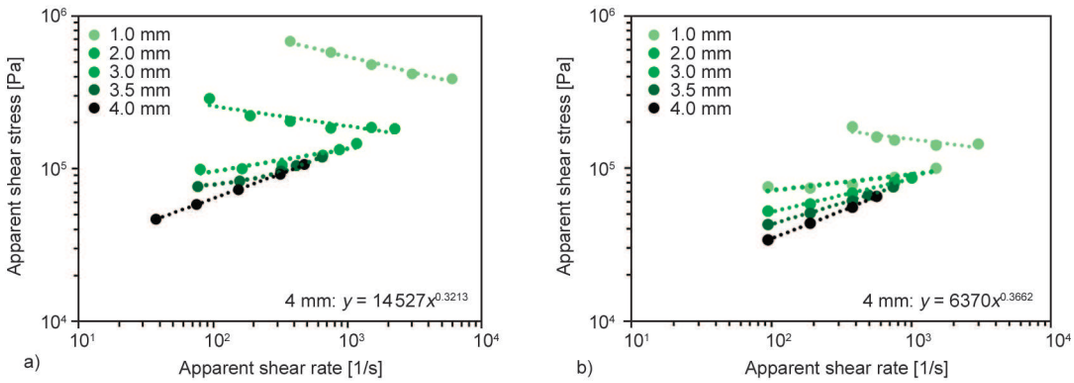

Figure 7. a) ABS GP35 flow curve as a function of shear rate for each wall thickness (40 °C mold temperature, 245 °C melt temperature) b) PP H145F flow curve as a function of shear rate for each wall thickness (40 °C mold temperature, 210 °C melt temperature).

We used cavity 2 for evaluation and compared the results with cavity 1. The measured pressure value differences were neglectable between the two cavities (under 0.2%), so we used cavity 2 for further evaluations.

4. Results and discussion

Typical polymer materials have pseudoplastic behavior, so when describing the flow curve with a power law, its exponent is between 0 and 1 ($0 < n \leq 1$). With ABS, when flow curves are calculated from the pressures measured in the mold, the slope of the flow curve is negative for small wall thicknesses (Figure 7). In the case of a negative exponent, increasing the shear rate results in an increasingly smaller apparent shear stress. Regarding pressure curves, a higher injection rate may result in a lower fill pressure.

As wall thickness increases, the shear sensitivity value also increases and closely approximates the value characteristic of the material determined by the rheometer. The difference between the results without correction calculated with the rheometer and the cold runner mold is less than 14% ($\eta_{\text{rheometer, ABS}} = 0.375$, $\eta_{\text{4 mm wall thickness, ABS}} = 0.323$).

As wall thickness is increased, cooling and the ratio of the frozen skin layer decreases, so the pressure-increasing effect is significantly reduced with a wall thickness of 4 mm. We did not correct the effect of temperature decrease (cooling) during the tests, but it can be seen that as wall thickness increases, the difference caused by cooling gets smaller compared to the results measured with the rheometer. We also performed experiments using the PP H145F material, where we experienced the same phenomena as with ABS (Figure 7). The difference in the shear sensitivity exponent in the case of PP was less than 5% ($\eta_{\text{rheometer, PP}} = 0.364$, $\eta_{\text{4 mm wal thickness, PP}} = 0.335$)

4.1. Apparent and corrected viscosity – ABS

The apparent viscosity curve determined from the ratio of the apparent shear stress and the apparent shear rate shows that the results measured with a wall thickness of 4 mm best approximate the corrected

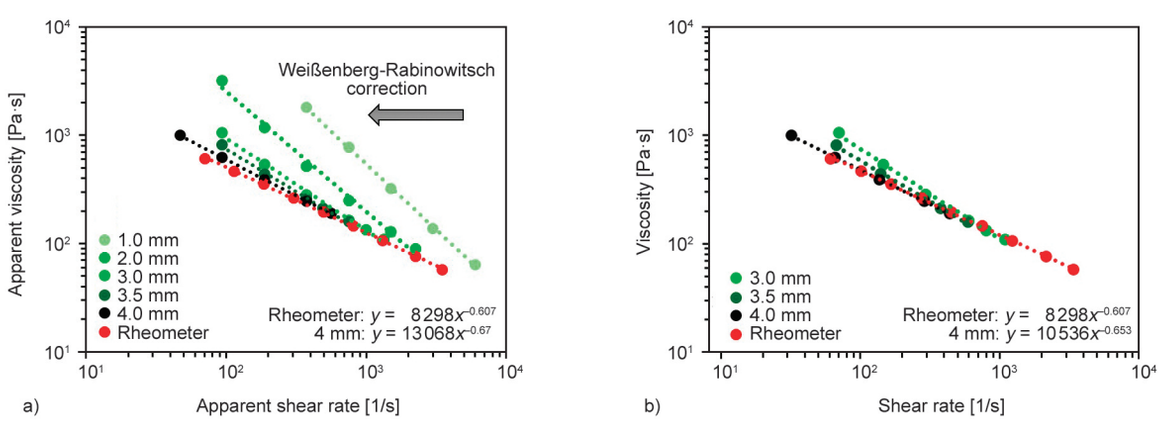

Figure 8. a) ABS GP35 – Apparent viscosity (40 °C mold temperature, 245 °C melt temperature) before rheological corrections, and b) after the corrections.

results measured with a capillary rheometer (Figure 8). The results obtained with the cold runner mold compared to the corrected viscosity determined with a rheometer (red curve) in each case. Using the results of the apparent viscosity curve, we made the necessary rheological corrections (Figure 8). Since we measured inside the capillary and the material did not exit it, we did not perform the Bagley correction. The wall-edge effect caused by the wall did not occur since the width of the gap is much greater than its thickness. We used the Rabinowitsch-Weißenberg correction to determine the actual shear rate. The use of the shear rate correction method provided by Giesekus [33] significantly shortened the calculations and caused only a 1% error compared to the traditional correction method. We didn't use this method further, but it works well in practice.

To determine the corrected shear rate, we used the results where the slope of the flow curve is positive at both materials. Therefore, we present the results obtained with a wall thickness of 3 mm and above. After using the corrections, the difference between the viscosity curve determined with the rheometer and the measured results further decreased in the investigated deformation speed range. Using the 4 mm wall thickness, we got the smallest difference compared to the corrected results obtained with the rheometer.

The obtained results show that the viscosity curves measured for each wall thickness intersect the rheometer results in all cases. The point of intersection is shifted towards higher shear rates as wall thickness increases. This is explained by the change in shear heat generation and cooling rate (skin–core layer ratio). At a low deformation speed, if wall thickness increases, the cooling rate decreases, and the ratio of the core layer increases. However, if the deformation speed increases, the average shear heat generation in the melt also increases significantly. Therefore, a lower viscosity can be measured since the material average temperature increased.

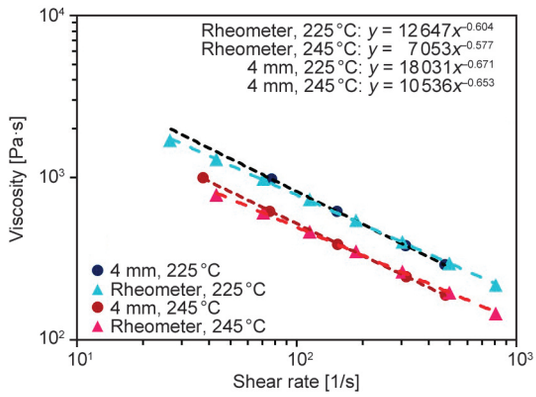

Figure 9. ABS GP35 corrected viscosity curves (40 °C mold temperature, 225 and 245 °C melt temperature).

4.2. Effect of melt temperature – ABS

When the melt temperature was reduced to 225 °C with ABS, the differences between the results measured with a wall thickness of 4 mm and the results obtained with the rheometer slightly increased compared to the melt temperature of 245 °C (Figure 9).

The difference is only 3–4% in terms of the value of the shear sensitivity factor. If the melt is colder, the thickness of the skin layer can also be greater, affecting the measurable differences. This is also confirmed by the fact that the intersection points of the viscosity curves measured with the mold and the rheometer shifted to higher shear rates. Therefore,

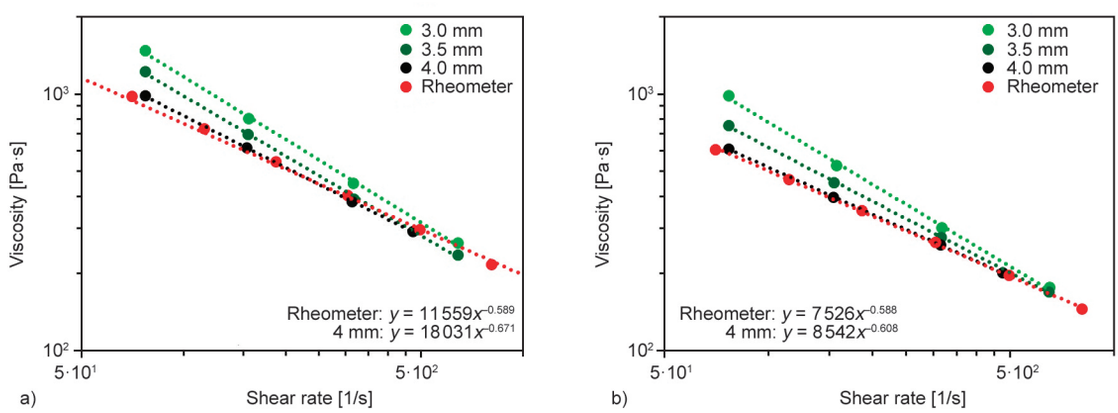

Figure 10. a) Corrected viscosity curve measured with reduced material temperature, ABS GP35, (40 °C mold temperature, 225 °C melt temperature), and b) corrected viscosity curve measured with increased material temperature, ABS GP35, (80 °C mold temperature, 225 °C melt temperature).

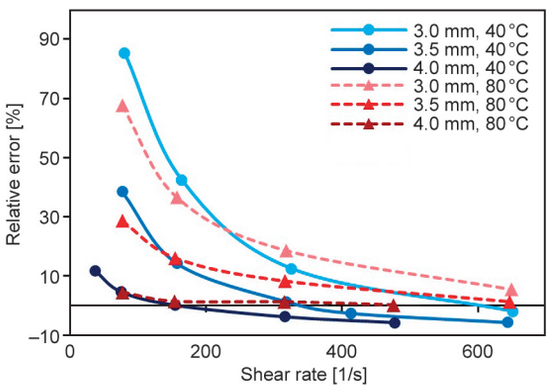

Figure 11. Relative error of viscosity measurement as a function of apparent shear rate, ABS GP35(40 and 80 °C mold temperature, 245 °C melt temperature).

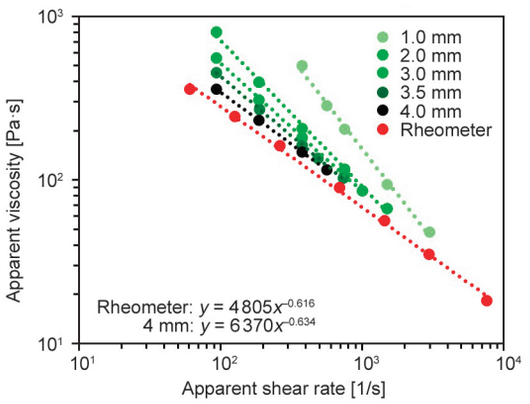

Figure 12. PP H145F apparent viscosity curves, (40 °C mold temperature, 210 °C melt temperature).

shear heat appears less in the average temperature increase of the melt when the deformation speed is the same but the melt temperature is different.

4.3. Effect of mold temperature – ABS

As the mold temperature increases, the cooling rate decreases, and the thickness of the frozen layer decreases, which can be seen as less pressure needed to fill up the cavity. Therefore, the differences between the viscosity curves measured with the rheometer and the mold are reduced (Figure 10). If the temperature of the mold is increased to the same temperature as that of the material, the measured viscosity curves should coincide regardless of the measurement method.

A comparison of the corrected viscosity curves with the results measured with the rheometer shows that increased wall thickness can significantly reduce the measurement error when ABS GP35 material is used (Figure 11). As the shear rate increases, the relative error decreases. However, shear heat generation can occur at lower mold temperatures, leading to more significant deviations at higher shear rates. This effect is more significant with smaller wall thicknesses, resulting in higher shear rates and increased heat generation. For accurate measurements, smaller wall thicknesses should be avoided. The best results are achieved with higher mold temperatures and greater wall thicknesses, where the error remains minimal.

4.4. Apparent and corrected viscosity and mold temperature effect – PP

Using the PP H145F material, the measured apparent viscosity curves are similar to those of the ABS material (Figure 12). As wall thickness is increased, the measured value gets closer to the viscosity curve determined with the capillary rheometer. We got the best results using the biggest wall thickness.

After the necessary rheological corrections, the corrected viscosity curves show a similar deviation compared to the results determined with the rheometer (Figure 13), just as in the case of ABS. ABS is more

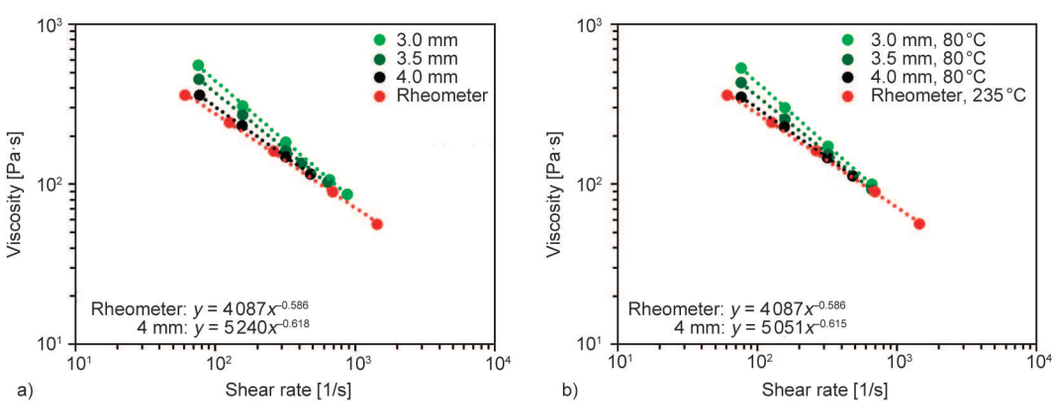

Figure 13. a) PP H145F corrected viscosity curves, (40 °C mold temperature, 210 °C melt temperature) b) PP H145F corrected viscosity curves, (80 °C mold temperature, 210 °C melt temperature).

sensitive to shear heat than PP, but there is no significant differencebetween the obtained deviations.

4.5. Effect of mold temperature – PP

In the case of cold runner molds, the wall thickness has a more significant effect on the measurable viscosity than the shear heating. As wall thickness increases, the differences between the viscosity curves determined by the mold and the rheometer decrease. Increasing mold temperature also reduces the error between the viscosity measured with the mold and the rheometer, similar to previous results with ABS, but not to a significantly noticeable extent. (Figure 13). The best results were obtained with a wall thickness of 4 mm and an 80 °C mold temperature in the tested range.

4.6. Effect of melt temperature – PP

When the melt temperature increases to 235 °C, the measurable difference is insignificant – it is in the range of 2–3%, as with ABS (Figure 14). In contrast,

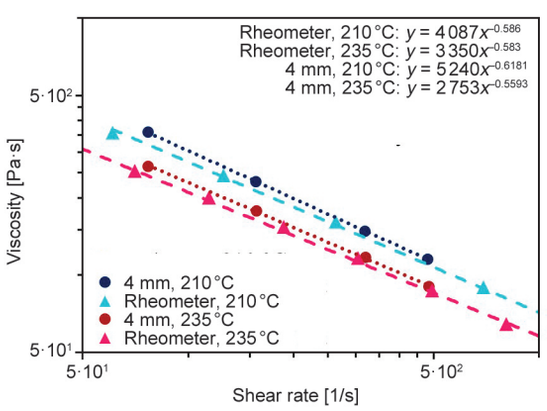

Figure 14. PP H145F corrected viscosity curves, (40 °C mold temperature, 210 and 235 °C melt temperature).

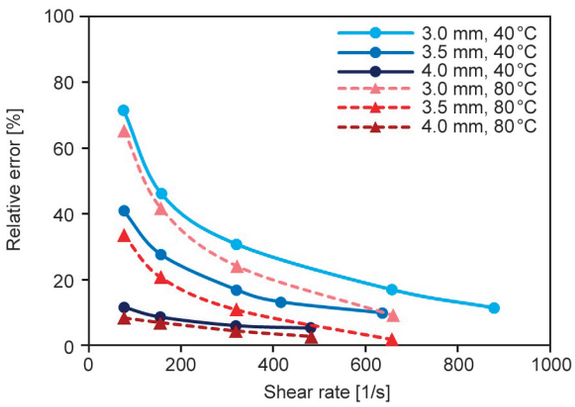

Figure 15. Relative error of viscosity measurement as a function of shear rate, PP H145F, (40 and 80 °C mold temperature, 245 °C melt temperature).

with ABS, we measured smaller differences at higher temperatures. The measurement results between the rheometer and the mold are smaller at a lower melt temperature. This can be explained by a difference in material and technological properties, such as filling pressure, shear heat, and heat transfer coefficient.

As mold temperature increased, the differences between viscosity measured with the mold and viscosity determined with the rheometer generally decreased, regardless of shear rate (Figure 15). This is because PP produces less shear heat than ABS. With increased wall thickness and deformation speed, measurement error decreases.

4.7. Comparison between capillary rheometer and mold-measured viscosities

In the case of PP and ABS, we have also demonstrated that there is a good correlation between traditional rheometer measurements and viscosity measurements using sensors in the mold cavity. Increasing the wall thickness further reduces the error (Figure 16), so

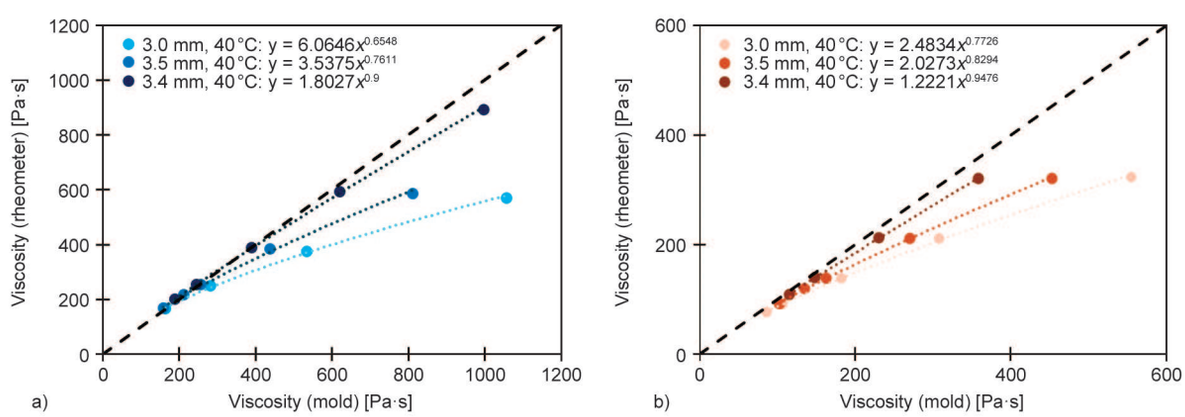

Figure 16. The viscosity results of the capillary rheometer as the function of the measured viscosity with the mold a) ABS, b) PP.

even in the case of measurements in the mold at multiple wall thicknesses, the true viscosity can be calculated with a good approximation especially in lower viscosity rates.

5. Conclusions

Several studies have focused on slit-die rheometry with injection molding machines in a heated environment. In this study, we have demonstrated that it is possible to find the viscosity of polymer melts using a simple, non-heated, slit cavity type mold equipped with pressure sensors without complex and expensive equipment. In a non-heated environment (where there is a more than 100 °C difference between the melt and the slit temperature) the slit thickness (wall thickness) is an important variable. With the proper rheological corrections, viscosity can be determined with less than 10% error from the pressure measured within the mold cavity. The observed errors are primarily due to the formation of a skin-core layer (continuous cooling) and shear-induced heat. Increasing mold temperature generally improves measurement accuracy. The average measurement error of viscosity decreases with increasing wall thickness for both tested materials, PP and ABS. The viscosity curves measured with the mold were compared to those obtained with a capillary rheometer across the examined shear rate, and the average error was calculated. The results show that increasing wall thickness consistently reduces average measurement error. This research is focused on the effect of wall thickness on the viscosity in non-isothermal, non-adiabatic flow conditions. A non-heated mold could be a much simpler approach to determine the mold viscosity in the production environment than the lab equipment. This study is a solid base for further investigation of the required corrections to measure viscosity in non-heated slit-die environment efficiently.

Therefore, we conclude that with a simple cold-runner mold with pressure sensors, the viscosity of polymer melts can be measured with satisfactory accuracy. This method offers a cost-effective solution for showing differences between material shipments quickly and efficiently.

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