

Online Pressure–Volume–Temperature Measurements of Polypropylene Using a Testing Mold to Simulate the Injection-Molding Process

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ABSTRACT: To obtain accurate prediction of service performance and service life of polymers and to optimize the processing parameters, a modified online measurement was used to measure the pressure–volume–temperature (PVT) properties of polymers under certain processing conditions. The measurement was based on an injection molding machine, and it was used to obtain the PVT data of polymers directly with a special testing mold under normal processing conditions. The PVT properties of a semicrystalline polymer, polypropylene, were measured through both an online testing mold and a conventional piston–die dilatometer. The PVT properties were correlated by a modified

two-domain Tait equation of state. The differences between the two groups of PVT data measured were investigated, and relative differences, especially in the rubbery state because of different cooling or heating measuring modes and sample forms, were observed. Numerical simulations of injection-molding processes were carried out by Moldflow software with both of the types of PVT data. The resulting online PVT data exhibited improvement in the accurate prediction of shrinkage and warpage. © 2010 Wiley Periodicals, Inc. *J Appl Polym Sci* 118: 200–208, 2010

Key words: injection molding; melt; molding; simulations

INTRODUCTION

The pressure–volume–temperature (PVT) relationships of polymers are important for both engineering and polymer physics. Molding defects, such as shrinkage, warpage, and sink marks, will cause thermally induced stresses and will affect both the dimensional accuracy and long-term dimensional stability. Software, such as Moldflow (Autodesk, Inc., San Rafael, CA), seeks to reduce the risk of producing parts with shrinkage or warpage in plastic components by providing quantitative predictions based on reliable data. In numerical simulations of the injection-molding process, one of the most important input data sets to these software packages is PVT data.¹ Process analyses have revealed that optimum processing conditions can be achieved by the application of PVT diagrams, particularly if PVT diagrams are used in conjunction with computer con-

trol of the process.² Therefore, it is necessary to obtain accurate PVT data for accurate prediction, evaluation, optimization, and calculation.

The use of a dilatometer is the most common technique for measuring the bulk-specific volume as a function of the temperature and pressure of polymers. There are two principally different conventional techniques for performing PVT measurements: the piston–die technique and the confining fluid technique.³ The advantage of the piston–die technique is the simplicity of the design that can be achieved, whereas the disadvantage is that the pressure applied is not hydrostatic because the material sticks to the wall.⁴ More problems include possible leakage between the piston and the die and the formation of voids in the sample during solidification. The advantages of the confining fluid technique are (1) the pressure is purely hydrostatic, as the sample is surrounded by the confining fluid in both the melted and solid state, and (2) there is an absence of leakage and friction. The disadvantages are that the volumetric changes measured are not those of the polymeric sample only, the difficulty of sealing the pressurized fluid, and that reactions may occur between the polymers and confining fluid. It has been shown that differences between the piston–die and confining fluid techniques in methods or measurement principles do not lead to differences in measured values of larger than 4%.⁵

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Conventional techniques can only be used at relatively low cooling rates. However, plastic processing, such as injection molding, is a rapid, high-pressure process where both the cooling rate and pressure play critical roles in the final component dimensions. Because high cooling rates are present during injection molding, some improved experimental techniques have been developed. In these studies, the cooling rate, the effect of pressure, sample forms, melt shearing, and so on the specific volume was investigated. Piccarolo⁶ measured the specific volume of semicrystalline polymers at high cooling rates to investigate the morphological changes in isotactic polypropylene (PP) as a function of cooling rate. Bhatt and McCarthy⁷ developed a PVT apparatus for computer simulations in injection molding. Imamura et al.⁸ determined PVT relationships at different cooling rates and verified their influence on computer simulations. Sato et al.⁹ developed a PVT testing device based on the confining fluid technique, and the effects of a sample cup and sample forms were investigated. Chakravorty¹⁰ in NPL developed the PVT equipment for measuring polymer properties at industrial processing conditions on the basis of the piston–die technique. Luyé et al.¹¹ discussed specific volume measurement methods for semicrystalline polymers to obtain reliable data and analyzed the effect of the cooling rate, taking into account the thermal gradient in a cylindrical sample. Zuidema et al.¹² built a setup based on the confining fluid technique and analyzed the influence of the cooling rate. van der Beek et al.^{13,14} developed a dilatometer to investigate the specific volume of polymers as a function of pressure, temperature, cooling rate, and shear rate. Kowalska¹⁵ obtained PVT behavior corresponding to the high cooling rate used in the molding process with differential scanning calorimetry measurements combined with PVT data measured during slow isobaric cooling.

There are also some other techniques for measuring the PVT behavior of polymers with the ultrasonic technique or X-rays. Kim et al.¹⁶ investigated the PVT relationship by the ultrasonic technique and its application for the quality prediction of injection-molded parts. Michaeli et al.¹⁷ developed a new method to determine the specific volume of polymers over a wide range of temperatures and pressures on the basis of X-ray attenuation. The devolution of the specific volume of isotactic PP at elevated pressures and cooling rates was investigated.

The PVT relationships were almost measured by a special dilatometer. Actually, the technology for measuring PVT relationships with an injection-molding machine (IMM), which can be called an online measurement, is a potentially powerful tool for programming process controllers because the normal

process conditions of injection molding can be obtained. However, only in a few studies^{18–21} did authors examine online measurements, and all of the results of those experiments were significantly limited by the machines; notably, the maximum pressures were only 9.646,¹⁸ 96.44,¹⁹ and 28 MPa.²⁰

In a previous study,²¹ we developed a novel method for testing PVT relationships of polymers on the basis of an IMM. The advantage of this testing approach is that it can be used to obtain the PVT data of polymers in a mold directly by a special testing mold; however, the temperature range was limited below 130°C, and the pressure range was limited up to 120 MPa.

In this study, a new testing mold with a small mold cavity was developed to elevate the temperature and pressure ranges of the online PVT equipment, and the heating rate was improved as well. The objective of this study was to obtain PVT data with the new testing mold and to confirm the accuracy improvement of the data in numerical simulation for the injection-molding process. The PVT properties of a semicrystalline polymer (PP) were measured through both the online testing mold and a conventional piston–die dilatometer. Both types of PVT data were used in numerical simulations for the injection-molding process. The simulation was carried out by Moldflow software, and the results of warpage and shrinkage prediction with different PVT data were compared and investigated.

EXPERIMENTAL

Apparatus

The modified online measurement of the PVT properties of polymers used a special testing mold (see Fig. 1). This testing mold was assembled onto an IMM to measure the PVT data under normal processing conditions. It used the mold cavity as a pressure chamber for determining the specific volume of polymers under various pressure and temperature conditions. The material was enclosed and pressurized in the rigid mold cavity with a core; the core was close fitting in the mold cavity. During the measuring cycle, the volume of the material was recorded by the measurement of the displacement of the core. Both the temperature and pressure could be varied. The frictional forces were reduced by application of a lubricant that was nonreactive with the polymer. Because any leakage, especially between the mold cavity and the core, had to be avoided, it was necessary that the mold cavity and the core had to fit to an accuracy of 0.001 mm over the whole pressure and temperature range. The special testing mold required a thermocouple and a heater band in the cavity plate, a cavity pressure

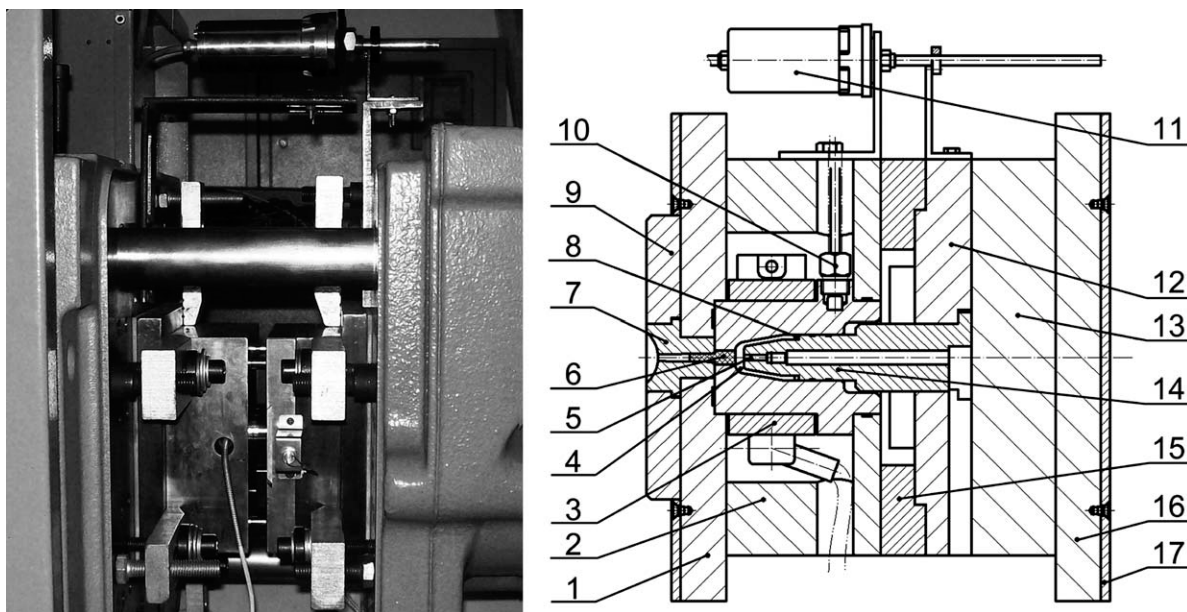


Figure 1 Picture and detailed outline of the special testing mold: (1,16) clamping plates, (2) cavity plate, (3) heater band, (4) mold cavity, (5) pressure transducer, (6) gate plug, (7) sprue bushing, (8) sealing ring, (9) locating ring, (10) thermocouple, (11) position sensor, (12) solid plate, (13) back plate, (14) core, (15) setting plate, and (17) thermal insulating sheet.

transducer, a gate plug, and a position sensor between both halves of the mold. The pressure transducer was located in the core where the probe of the transducer was kept in contact with the sample to measure the melt pressure immediately. The position of the core was measured by a position sensor during the measuring cycle.

A Kistler pressure transducer (Kistler Instrument Corp., Amherst, New York) (6158A) was used. The thermocouple (type L800) was acquired from Arburg Machinery Trading Co., Ltd. (Shanghai, China). The heater band was a Nozzle heater band 230V 600W DI 50 L38, also from Arburg Machinery Trading Co. The position sensor and data acquisition system were supported by KangYu Control System Engineering, Inc.; the testing accuracy of the position sensor was within 0.001 mm.

The IMM used was an Arburg Allrounder 270 S 500-60 with a maximum clamp force of 500 kN and a screw diameter of 18 mm. It was a precise hydraulic IMM suitable for sample compression. The pressure was determined to be the mold clamping force divided by the cross-sectional area of the mold cavity. The volume variation was determined by the position variation of the core during sample compression. The weights of the samples were measured by an electronic scale (JT 2003, Jinnuo Balance Instrument Co., Ltd., Yuyao City, China); the testing accuracy of the electronic scale was 0.1 mg.

In addition to the online measurements, the PVT data of the material were also determined with a conventional piston–die type dilatometer (type PVT-100, SWO Polymertechnik, Krefeld, Germany).

Materials and samples

The plastic material used in the experiment was PP (Beijing Yanshan Petrochemical Co., Ltd., Sinopec, Beijing, China), a semicrystalline polymer. The details of the material are given in Table I. The materials were molded into a cup sample by the IMM. The tail end of the cup sample was a 5-mm straight cylinder, which was suitable to be pressed horizontally during the experiment. The shape and dimensions of the cup sample are shown in Figure 2. The mold cavity was designed on the basis of the principle of injection-molding design, which enabled the PVT measurements to be carried out on injection-molded samples. The thickness of the sample was only 2 mm, so the PVT data generated would be closer to typical component-part thicknesses.

Procedure

When we used the online testing method, the sample was produced by the IMM and weighed by the electronic scale before the experimental measurement. The basic experimental procedure was as follows:

1. We put the gate plug into the gate runner and the sample and the sealing ring into the mold cavity.
2. We closed the mold, holding the gap length between the cavity plate and the solid plate at 4 mm by the setting plate.
3. We removed the setting plate.

TABLE I
Mechanical, Thermal, and Rheological Properties of the Material

Mechanical properties	
Elastic modulus (MPa)	1480
Poisson ratio	0.38
Shear modulus (MPa)	570
Transversely isotropic coefficient of thermal expansion data	
α_1 (1/°C)	1.07×10^{-4}
α_2 (1/°C)	1.07×10^{-4}
Stress at yield (MPa)	24.8
Strain at break (%)	45
Thermal properties	
Specific heat (J/kg °C) at a heating/cooling rate of -0.3333°C/s	
60°C	1757
100°C	2029
150°C	3158
160°C	5368
170°C	4886
200°C	2259
230°C	2364
Thermal conductivity data	
Temperature (°C)	250
Thermal conductivity (J/kg °C)	0.26
Rheological properties	
Cross-WLF viscosity model coefficients	
n	0.2065
τ^* (Pa)	57861
D_1 (Pa s)	2.25304×10^{14}
D_2 (K)	263.15
D_3 (K/Pa)	0
A_1	34.12
A_2 (K)	51.6
Transition temperature (°C)	135
Melt mass flow rate	
Temperature (°C)	230
Load (kg)	2.16
Measured mass flow rate (g/10 min)	45.0

n , A_1 , A_2 , s^* , α_1 , and α_2 are the model constant of Cross-WLF viscosity model.

- We built up the required parameters according to different measuring modes.
- We used the clamping system of the IMM to increase the pressure, the heater band to control the temperatures of the mold and the polymer, and the pressure transducer, position sensor, and thermocouple to acquire the PVT data.
- We performed data processing to obtain the PVT diagram by computer.
- We cooled the sample, opened the mold, and removed the sample and the gate plug.

For the piston–die dilatometer, the details of the experimental apparatus and procedures were described by Luyé et al.¹¹

Measuring modes

There are two different principal measuring modes: isobaric mode and isothermal mode. In the isobaric

mode, the volume is measured with a constant cooling or heating rate while a constant pressure is maintained and the temperature is varied. When the temperature scan is completed, another pressure is selected, and the temperature is varied again. In the isothermal mode, the volume is measured at selected temperatures while the pressure is varied.

In this article, the isothermal compression, taken in order of increasing temperatures, was applied as the experimental mode of the online measurement. For that, the specific volume was recorded along the isotherms (in order of increasing temperature) and at different pressures. This measuring mode is often considered the standard one. The isobaric cooling mode was used by the piston–die dilatometer. The specific volume was recorded along isobars with a fixed cooling rate.

RESULTS AND DISCUSSION

PVT results

The PVT data of the semicrystalline polymer PP were measured by online measurement in the temperature range 17–160°C at pressures from 50 to 200 MPa at a heating rate of 15°C/min; the data were measured by the piston–die dilatometer in the temperature range 30–260°C at pressures from 20 to 150 MPa at a cooling rate of 2°C/min. The experimental results are shown by gray lines and cross dots, respectively, in Figure 3.

The PVT relationships can be represented by the Tait equation of state (EOS):²²

$$V(T, P) = V_0(T) \left\{ 1 - C \ln \left[1 + \frac{P}{B(T)} \right] \right\} + V_1(T, P) \quad (1)$$

where $V(T, P)$ is the specific volume at temperature T and pressure P , $V_0(T)$ is the specific volume on the zero gauge pressure at temperature T , C is 0.0894 (a universal constant), and $B(T)$ represents the pressure sensitivity of the material at temperature T . Two temperature domains are required to model the PVT

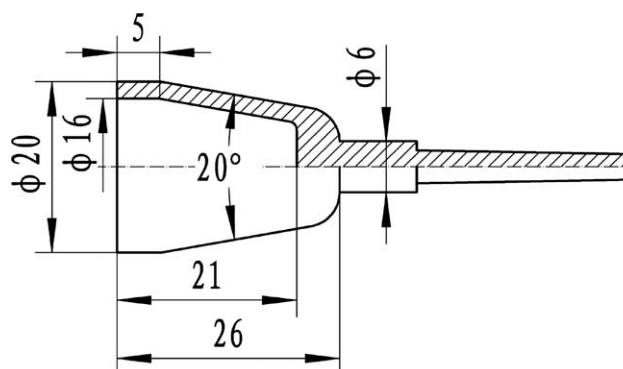


Figure 2 Shape and dimensions of the cup sample.

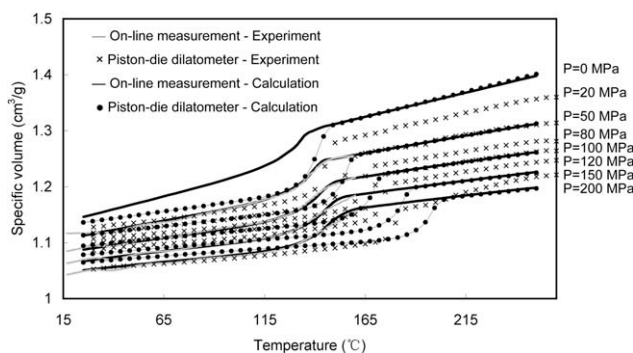


Figure 3 Experimental and correlation PVT diagrams of PP. The experiment using online measurements was performed at 17–160°C and at pressures of 50, 100, 150, and 200 MPa; the experiment using the piston–die dilatometer was performed at 30–260°C and at pressures of 20, 50, 80, 100, 120, and 150 MPa; and the correlation was determined with the Tait EOS at 20–250°C and at pressures of 0, 50, 100, 150, and 200 MPa.

relationship because the thermodynamic properties of polymers change at the transition to the solid state. The volumetric transition temperature at zero gauge pressure is denoted by b_5 , and the linear increase in the transition with pressure is denoted by b_6 . The specific volume obtained by extrapolation of the zero-isobar curve to the transition temperature is denoted by b_1 . This value is the same for both domains when the glass transition is crossed. However, when the material is semicrystalline, the transition due to crystallization is accompanied by an abrupt change in the specific volume, such that the melt-specific volume at b_5 and zero pressure (b_{1m}) is greater than b_{1s} (for b , the subscript m represents the melt state, and the subscript s represents the solid state). The temperature dependence of the specific volume is measured by b_2 , whereas b_3 and b_4 characterize $B(T)$ in the solid and melt states. The specific volume becomes more pressure sensitive with increasing temperature when b_4 is positive. The constants b_7 , b_8 , and b_9 characterize V_1 in the solid state.

For $T < b_5 + b_6P$

$$V_0 = b_{1s} + b_{2s}(T - b_5) \quad (2)$$

$$B(T) = b_{3s} \exp[-b_{4s}(T - b_5)] \quad (3)$$

$$V_1 = b_7 \exp[b_8(T - b_5) - b_9P] \quad (4)$$

For $T > b_5 + b_6P$

$$V_0 = b_{1m} + b_{2m}(T - b_5) \quad (5)$$

$$B(T) = b_{3m} \exp[-b_{4m}(T - b_5)] \quad (6)$$

$$V_1 = 0 \quad (7)$$

b_5 , b_6 , b_{1m} , b_{2m} , b_{3m} , b_{4m} , b_{1s} , b_{2s} , b_{3s} , b_{4s} , b_7 , b_8 , and b_9 were determined by fitting the experimental PVT

data with a nonlinear regression at temperatures from 20 to 300°C and pressures from 0 to 200 MPa. SPSS software (SPSS Inc., Chicago, Illinois) was used for the nonlinear regression. Before this, the experimental data was divided into two phases with the transition temperature. With the transition temperature at different pressures, b_5 and b_6 were calculated first; then, b_{1m} , b_{2m} , b_{3m} , and b_{4m} in melt state and b_{1s} , b_{2s} , b_{3s} , b_{4s} , b_7 , b_8 , and b_9 in the solid state were calculated separately. The characteristic parameters are listed in Table II. The correlation PVT results of both the online measurement and piston–die dilatometer calculated by the Tait EOS are shown by solid lines and dots, respectively, in Figure 3.

As shown in Figure 3, the specific volume of online measurement at 20°C and 0 MPa was 0.64% higher than that of the piston–die dilatometer. The specific volume data of online measurement increased more with temperature in comparison with those of piston–die dilatometer in a rubbery state, whereas the volume change at the melting point of online measurement was less than that of the piston–die measurement. Above the melting point, although the specific volume of the online measurement was slightly higher than that of the piston–die dilatometer, the difference in the specific volume between them was not significant; the PVT data of the two measurements gave good agreement within 0.045%.

The reason for the significant difference in the rubbery state must have been related to many factors. Because the principles of both of the measurements were similar, the main differences between them were the different procedures and sample forms. For the procedures, the influence of the cooling rate or heating rate was the most important factor. The heating rate of the online measurement was 15°C/min, whereas the cooling rate of the piston–die dilatometer was only 2°C/min. The resulting

TABLE II
Correlated Parameters for the Tait EOS

Parameter	Online	Piston–die
b_5 (K)	403	417.64
b_6 (K/Pa)	0.00000015	3.022×10^{-7}
b_{1m} (m ³ /kg)	0.001295	0.001306
b_{2m} [m ³ /(kg K)]	8.588×10^{-7}	9.019×10^{-7}
b_{3m} (Pa)	77,200,000	74,300,000
b_{4m} (1/K)	0.003487	0.004006
b_{1s} (m ³ /kg)	0.001242	0.001195
b_{2s} [m ³ /(kg K)]	9.153×10^{-7}	4.929×10^{-7}
b_{3s} (Pa)	63,200,000	131,900,000
b_{4s} (1/K)	0.006881	0.003355
b_7 (m ³ /kg)	0.00002616	0.00009623
b_8 (1/K)	0.0714	0.1338
b_9 (1/Pa)	3.355×10^{-9}	3.973×10^{-8}

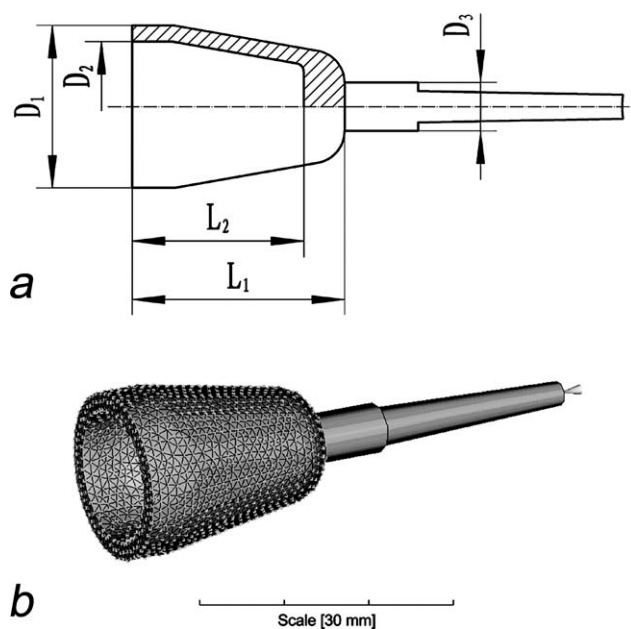


Figure 4 (a) Principal dimensions and (b) FE mesh of the sample.

specific volume in the solid state clearly increased with increasing heating rate.

For the sample forms, the sample of the piston-die dilatometer was a pillar with a diameter of 7.4 mm and a weight of 0.5–1 g, and the sample of the online measurement was a cup with a length of 26 mm, a thickness of 2 mm, and a weight of 2.2–2.4 g. To measure the PVT properties accurately, a large amount of samples had to be put into the dilatometer.⁹ Actually, a sample with a large length-to-diameter ratio is the best one for measurement because it is more convenient and accurate to get the displacement, even with a position sensor with low precision. The thickness of the sample used by online measurement was only 2 mm. The PVT data thus generated was closer to a typical component-part thickness. So the cup sample with a length of 26 mm and a thickness of 2 mm was better for testing than the pillar sample.

Numerical validation

The PVT relationships of the polymers are the most important factors influencing the shrinkage and warpage of polymer products. To verify the reliability of the PVT results obtained with the online measurement and the piston-die dilatometer, the prediction of sample shrinkage and warpage was carried out with Moldflow Plastics Insight 6.1. The approach implemented took advantage of finite element (FE) analysis to simulate component fabrication and to investigate the main causes of defects. The basic idea was to create a model of the geometry or mold to be analyzed, as Figure 4 shows.

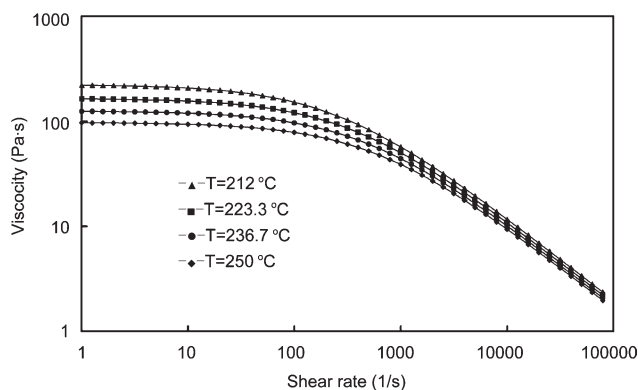


Figure 5 Flow curves of PP with the Cross-WLF model.

To get an accurate prediction, a three-dimensional numerical simulation was used to simulate the injection-molding process. Figure 4(a) shows the location of the five characteristic dimensions (D_1 , D_2 , D_3 , L_1 , and L_2) where results were analyzed, and Figure 4(b) shows the FE mesh of the sample. The calculation mesh number was 54,338, and the mesh type was a four-node tetrahedral element.

Efforts were made to reduce differences in the prediction, except the different PVT data, the other input material data such as rheological, thermal, and mechanical properties, were all measured through the appropriate instruments and kept identical in the simulation. These data are referred to in Table I and were provided by Beijing Yanshan Petrochemical Co., Ltd., Sinopec. For the PVT data, the modified Tait EOS was used. For viscosity, the Cross/Williams-Landel-Ferry (Cross-WLF) model was used, and the flow curves are given in Figure 5. Similarly, the processing conditions were all identical. As a result, it was possible to focus solely on the PVT data differences. According to the recommended and experimental processing, the process parameters used are reported in Table III.

The influence of the PVT data on shrinkage and warpage prediction of the sample was examined. The results for shrinkage and warpage with Moldflow are given in Figure 6, where displacements are amplified by a factor of 5. The behavior of the shrinkage and warpage was observed from the change in the dimensions of the sample. Table IV

TABLE III
Process Parameters

Parameter	Value
Volumetric injection rate (cm^3/s)	30
Mold temperature ($^{\circ}\text{C}$)	70
Melt temperature ($^{\circ}\text{C}$)	230
Hold pressure (MPa)	1.8
Hold time (s)	10
Cooling time (s)	20

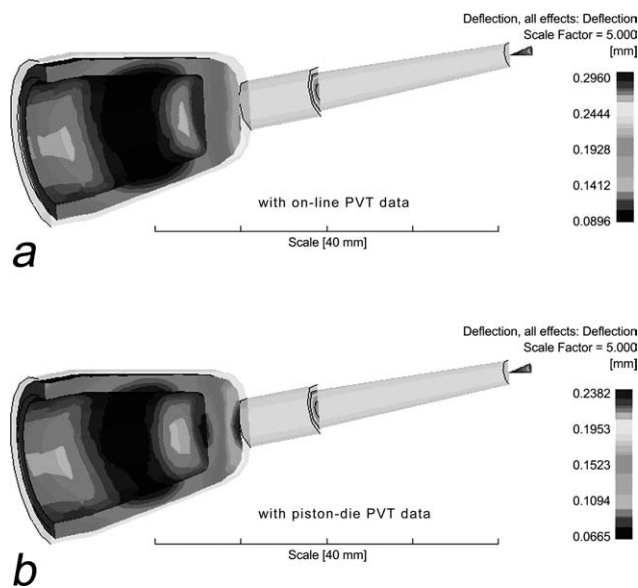


Figure 6 Numerical simulation of the shrinkage and warpage of the sample with (a) online PVT data and (b) piston-die PVT data.

indicates the principal dimensions of the sample measured by a micrometer. The experimental shrinkage was 5.3038%; the shrinkage was calculated as follows:

$$\text{Shrinkage} = 1 - V_{\text{molding}}/V_{\text{cavity}} \quad (8)$$

where V_{molding} is the molding volume (calculated with the five average dimensions in Table IV) and

V_{cavity} is the cavity volume (calculated with the dimensions of the mold cavity).

The experimental results for the shrinkage and warpage of the final parts were compared with the analysis results of the Moldflow software. The shrinkage of the sample is shown in Figure 7. The quantitative results of shrinkage, 4.557%, calculated by Moldflow with the online PVT data were observed as being somewhat underestimated in this study, and it was larger than 2.183%, as analyzed with the piston-die PVT data, but was much closer to the experimental shrinkage, 5.3038%.

The warpage of the sample measured by a micrometer and analyzed by Moldflow with both the online and piston-die PVT data is shown in Figure 8, and Table V indicates the experimental and analyzed deviation value of the principal dimensions. The qualitative description of warpage in this study was sufficiently comparable with the experimental results. The quantitative results were found to be slightly underestimated because the factors that resulted in warpage were not all considered. Several factors affect the shrinkage and warpage of molded parts, including molecular orientation, the nonequilibrium state of the polymer PVT behavior, the effect of the flow field on the polymer crystallization, the anisotropy of material properties, and so on, which are considered to accurately describe the real conditions of injection molding and to predict the real shrinkage and warpage of molded parts.^{23–26}

For both PVT data types, the warpage predictions were very different. Overall, as Figure 8 shows, the warpage prediction with the online PVT data was

TABLE IV
Principal Dimensions of the Samples Measured with a Micrometer

Sample	D_1 (mm)	D_2 (mm)	D_3 (mm)	L_1 (mm)	L_2 (mm)
1	19.60	15.52	5.66	25.42	20.38
2	19.44	15.50	5.72	25.60	20.50
3	19.42	15.44	5.68	25.60	20.56
4	19.48	15.46	5.72	25.50	20.60
5	19.42	15.44	5.64	25.40	20.50
6	19.60	15.56	5.66	25.44	20.50
7	19.42	15.52	5.62	25.62	20.62
8	19.62	15.58	5.56	25.44	20.34
9	19.52	15.54	5.70	25.50	20.58
10	19.40	15.40	5.68	25.60	20.70
11	19.46	15.50	5.62	25.50	21.00
12	19.50	15.40	5.62	25.12	20.48
13	19.48	15.50	5.70	25.50	20.50
14	19.58	15.54	5.50	25.16	20.74
15	19.46	15.50	5.78	25.56	20.46
16	19.46	15.50	5.70	25.52	20.54
17	19.50	15.50	5.72	25.58	20.48
18	19.46	15.50	5.64	25.50	20.60
Maximum	19.62	15.58	5.78	25.62	21.00
Minimum	19.40	15.40	5.50	25.12	20.34
Average	19.49	15.49	5.66	25.48	20.56
Cavity	20.00	16.00	6.00	26.00	21.00

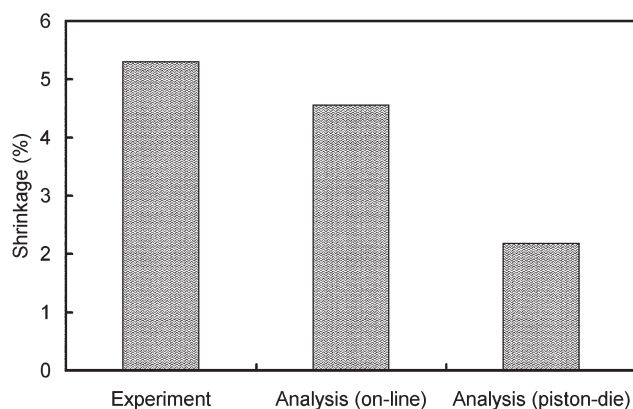


Figure 7 Shrinkage of the sample.

closer to the experimental results than the piston–die testing data.

Advantages of the online testing method

Compared with conventional PVT measurements, the technology for measuring PVT relationships with the IMM is a potentially powerful technique. The online testing method realized the principle of PVT measurement with the IMM. The advantages of this method are

1. The use of the clamping system of the IMM to control the pressure of the sample directly;
2. The simplicity in design that can be achieved.
3. It is feasible to set parameters directly on the IMM and provide industrial processing conditions.
4. The sample is molded and tested directly in an IMM.

The disadvantage is that the pressure applied is not hydrostatic. Additionally, there is possible leakage at the mold joint and bubbles in the sample during testing. All of the disadvantages are similar to those of the piston–die technique.

CONCLUSIONS

This article describes a modified online testing mold based on an IMM to measure the PVT data under injection-molding processing conditions. The PVT properties of a semicrystalline polymer, PP, were

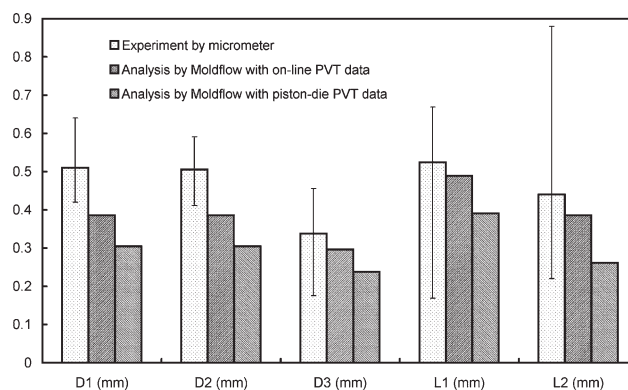


Figure 8 Comparison of the deviation values of the principal dimensions.

measured in the temperature range from 17 to 160°C and under pressures from 50 to 200 MPa. As a comparison, a conventional piston–die dilatometer was used to measure the PVT data as well. Both types of PVT data were correlated by a modified two-domain Tait EOS. The differences between both types of PVT data were investigated, with relative differences observed, especially in the rubbery state. The significant difference was attributed to the different procedures and sample forms. Numerical simulations of injection-molding processes were carried out by Moldflow software with both types of PVT data. The behaviors of the shrinkage and warpage were observed from the change in the dimensions of the parts. The quantitative results of shrinkage, 4.557%, analyzed by Moldflow with the online PVT data were observed as being somewhat underestimated in this study and were larger than the 2.183% calculated with the piston–die PVT data but were much closer to the experimental shrinkage, 5.3038%, which was calculated with the principal dimensions measured by a micrometer. The qualitative description of warpage in this study was sufficiently comparable with the experimental results. The quantitative results were found to be slightly underestimated. Overall, compared with the results of the piston–die PVT data, the warpage prediction with the online PVT data was closer to the experimental results.

This research confirmed that the choice of the correct PVT data was crucial to assessment of the influence of the process parameter variation on part manufacturability; this suggests possible adjustments for improving part quality. The resulting online PVT

TABLE V
Deviation Values of the Principal Dimensions

	D_1 (mm)	D_2 (mm)	D_3 (mm)	L_1 (mm)	L_2 (mm)
Experiment with a micrometer	0.5100	0.505556	0.337778	0.524444	0.4400
Analysis by Moldflow with online PVT data	0.3856	0.385600	0.296000	0.488800	0.3856
Analysis by Moldflow with piston–die PVT data	0.3046	0.304600	0.238200	0.390500	0.2617

data exhibited a significant improvement in the accurate prediction of shrinkage and warpage. We also demonstrated that the online PVT data are useful for injection-molding technology, although the warpage of the part could be more significant.

Consequently, a new PVT database of polymers could be established to aid in the further development of commercial plastics processing software packages. These PVT data will be used to predict shrinkage or warpage behavior in plastic components by software such as Moldflow. It can also help the plastics industry to gain a better understanding of the shrinkage and warpage behavior in their products from these new industrial PVT data and to optimize the injection-molding processing parameters.

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