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Mini Review

# Process Dependence of Specific Volume of Plastics in Injection Molding

**Jian Wang**[1,2*]

[1]State Key Laboratory of Organic-Inorganic Composites, Beijing University of Chemical Technology, China

[2]College of Mechanical and Electrical Engineering, Beijing University of Chemical Technology, China

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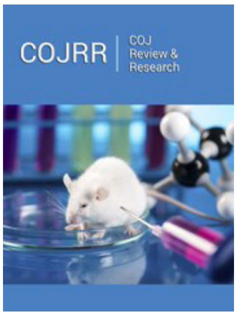


***Corresponding author:** Jian Wang, State Key Laboratory of Organic-Inorganic Composites, Beijing University of Chemical Technology, China

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**Abstract**

The specific volume (v) of plastics establishes a controllable relationship between material, process and product, and it is the key to improving the molding accuracy and production efficiency of injection molding. The specific volume is not only dependent on the pressure (p) and temperature (T) but also on the variation rate of pressure and temperature, which is defined as the process dependence of specific volume of plastics. The digitalization of pvT behavior of plastics for precision or intelligent injection molding is important. The pvT behavior of plastics has a strong process dependence, and process parameters such as cooling/heating rate, compression/decompression rate, and initial temperature/pressure have different effects. It is important to accurately measure the pvT data and establish a high-precision prediction model, and then the precision and intelligent injection molding process control can be realized. This mini-review presents the research progress on measurement, modeling, and control of process-dependent pvT behavior of plastics for injection molding. The challenges and perspectives for future research on the specific volume of plastics are discussed.

**Keywords:** Specific volume; Process dependence; Pressure; Temperature; Plastics; Injection molding

## Introduction

Injection molding is one of the most important and common manufacturing processes to produce plastic parts in high volume. The identification of the most critical process parameters influencing the dimensional accuracy of the injection molded parts cannot be separated from material properties. The specific volume (v) of plastics directly reflects the volume and shape/size quality of the molded product. The specific volume of plastics depends on the free volume and intermolecular interaction of the material. In injection molding, all plastic material variables are related to pressure (p), temperature (T), and time (t). These variables influence the specific volume of the plastic and the shape or dimensions of the products. The pressure-specific volume-temperature (pvT) relationship of plastics (Figure 1) is playing a very important role in plastics engineering; it is especially used for numerical simulation and process control of the injection molding. According to the pvT data and its model, the shrinkage and warpage of the injection molded parts can be predicted or controlled. The pvT models have been widely used in various simulation software (such as Moldflow, Moldex3D, Sigma soft, Cadmould, etc.). It has played an important role in mold design optimization. In addition, the online monitoring technology of injection molding and process optimization based on pvT relationship of plastics has also made great progress. However, the exact process control based on pvT diagrams is difficult. The traditional pvT diagrams and relative models are all based on the pvT data measured through isothermal or isobaric modes. The time-dependent behaviors have not been considered, which have significant influences on the pvT data. Therefore, the injection molding process control based on pvT is still waiting for the process-dependent pvT data and model.

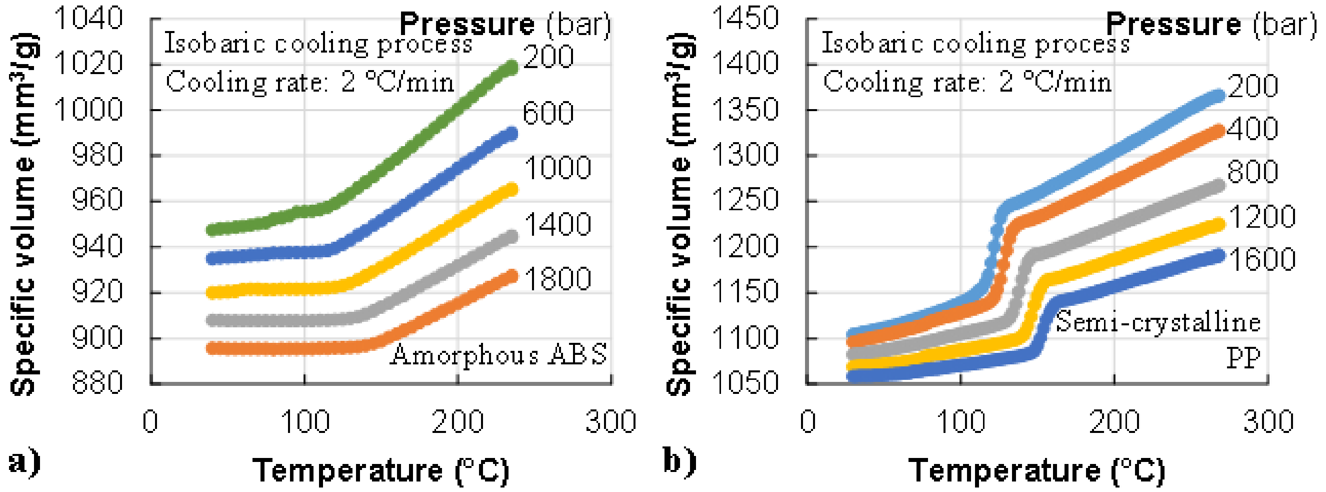


**Figure 1:** Typical pvT diagram of plastics: (a) amorphous polymer and (b) semi-crystalline polymer.

### Investigations

The pvT data are typically determined by measuring the specific volume depending on defined pressure and temperature. In addition to the effects of pressure and temperature, the specific volume of polymers has a great dependence on the time history of pressure and temperature [1,2]. Influencing factors are mainly pressure, temperature, and their respective different increasing or decreasing rates. Figure 2 shows the typical process dependence of specific volume of the two typical plastics (amorphous and semi-crystalline polymers). Firstly, heating the polymer leads to a different pvT behavior in comparison with the cooling process. As the heating/cooling rate increases, the difference becomes larger. Secondly, the pvT diagram is different during compression and decompression as well as it is related to the volume relaxation characteristics of the material. In addition, our recent investigations [3] have also shown that the starting temperature and pressure affect the pvT measurements a lot. The process dependence of polymer pvT behavior may be an important reason why the existing commercial software simulations are not accurate. It inevitably affects the development of intelligent injection molding systems based on pvT relationships. Therefore, the accurate description of pvT behavior of plastics should consider the process dependence.

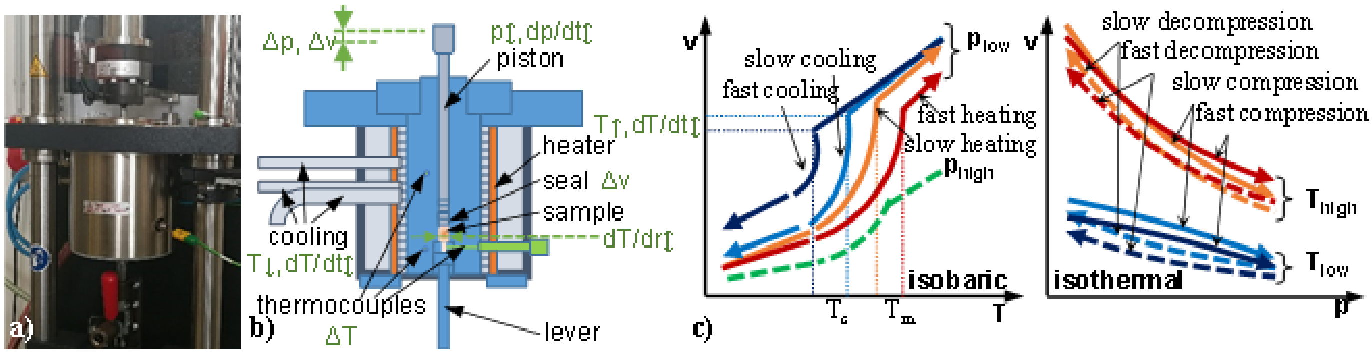


**Figure 2:** PvT testing device (a) [1,2] and its schematic with related process dependent parameters (b), process-dependent pvT behavior of a semi-crystalline polymer (c) [1].

## Techniques and Applications

### Measurement

Two measuring modes can be performed by the pvT testing devices: isobaric and isothermal [4,5]. The pvT measurements were standardized in ISO 17744 [6]. However, recent research finds that the properties of polymer materials are process-dependent [7]. Testing standards are long outdated. There are many differences in the specific volume of the material when it is processed for the measurements in the laboratory. Although some influencing factors such as the cooling rate and the shear rate on the specific volume of polymers were investigated [8], many other influencing factors cannot be neglected. Suarez et al. [9] reviewed the most representative pvT measurement methods and devices and pointed out that pressure distribution and compression speed should be considered. Besides compression, the decompression related to volume relaxation at different pressure and temperature of samples is also important, as it determines the dimensional stability of all industrial plastic products. We conducted measurements of specific volume of polymers under simulated injection molding processes [3]. Results provided important information on the phase transition and the shrinkage behavior of plastics. The starting temperature has a great effect on the specific volume but has little effect on the part shrinkage. The specific volume decreases nonlinearly with decreasing cooling rate during the shrinkage stage. Accordingly, the accuracy of pvT testing devices should be improved by considering the process dependence.

### Modeling

Modeling polymer pvT behaviors considering process dependence and achieving accurate prediction of pvT data is another important task. The existing pvT models used for injection molding are mainly two-domain equations of state (EoS) such as Tait and Schmidt models. It is reported that these empirical models still have some problems such as the discontinuity at the transition state and the low fitting accuracy at the crystallization state of semi-crystalline polymers [10,11]. Therefore, the understanding of the pvT relationship across the entire injection molding process cycle is essential. We have derived new models [10-12]. The discontinuity problem was resolved. The effect of the cooling rate was also considered. The machine-learning based Artificial Neural Networks (ANN) method was also successfully developed [13]. However, the pvT model is based on the experimental data measured by the pvT device. The prediction accuracy beyond the experimental data range is lower, especially since the prediction ability for high cooling rates is low due to the limited availability of pvT data at high cooling rates. Moreover, the effects of compression/decompression rate and starting temperature/pressure should be considered in the pvT modeling. Therefore, a more precise pvT modeling is still necessary to accurately describe the pvT behaviour of polymers considering the process dependence.

### Control

Simultaneous recording of pressure and temperature in the mold cavity makes it possible to illustrate their variation on the pvT diagram [14]. By tracing the specific volume path in the pvT diagram, we can exactly obtain the material's thermal history under a defined set of injection molding process conditions at a specific location of the molded part and mold cavity. The specific volume difference during the process represents the amount of volume shrinkage of the molded part. The adjustment or control of the specific volume difference can determine the shrinkage of the part and thus improve the part quality. By means of pvT diagrams, it is possible to realize a uniform volume shrinkage along the whole part. In addition, the resultant pvT diagram should be repeated from shot to shot inside the mold, and then the process proficiency can be confirmed and optimized. By means of real-time process optimization techniques, the most robust set of injection molding process conditions can be developed. The ideal state is to make each pvT path pattern of each location of molded part repeatable from shot to shot and from time to time, resulting in consistent molded part quality for long-term production (Figure 3).

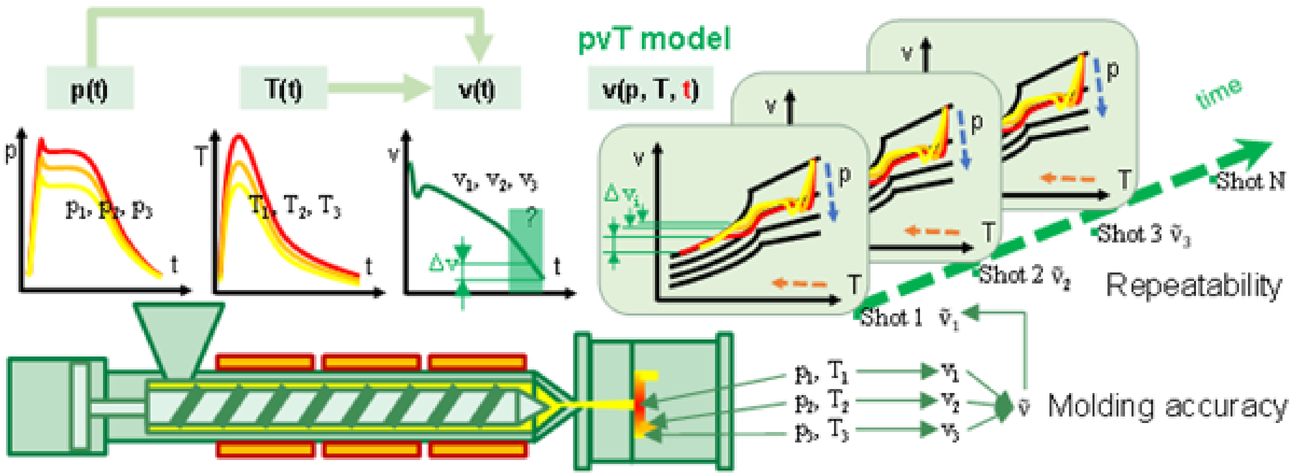


**Figure 3:** Schematic of online process control technology for injection molding based on pvT relationship of plastics.

## Summary and Future Perspectives

In summary, the process dependence of specific volume of plastics should be considered in precision and intelligent injection molding. To apply the pvT data in the real injection molding process, the process-dependent pvT measurement, modeling, and control are all needed to be conducted. The distribution and variation of specific volume of the plastics in the mold cavity during the injection molding process cannot be predicted or tested accurately. It presents a scientific question corresponding to the spatial and temporal evolution mechanism of specific volume of plastics. The question of how to improve the prediction and control accuracy of specific volume of thermoplastic polymers during the rapid injection molding process is still subject to ongoing research. The effects of process parameters on the specific volume should be investigated, and then the rules of specific volume changing with pressure, temperature, and time can be explored. Process-dependent pvT models considering the effects of cooling/heating rate, compression/decompression rate, and initial temperature/pressure are necessary. The model validation method is also needed to adapt to other thermal analysis results considering the process dependence. The process-dependent pvT model can be applied in numerical simulation and real-time process optimization. A precise regulation mechanism of the plastic specific volume in the intelligent injection molding process can be established. The research results can be the scientific basis for establishing a more effective intelligent injection molding system.

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