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Volumetric shrinkage of polymer parts during cooling

Yusupov Abdulaziz Abdullajonovich
Almalyk State Technical Institute
PhD in Technical Sciences, Associate Professor, Head of the Department of Mechanical Engineering Technology
E-mail: abdulaziz.yusupov1@tdtu.uz
Yo’ldashev Hayrullo Hasanboy o’g’li
Almalyk State Technical Institute
3rd-year PhD Student
E-mail: hayrulloh0411@gmail.com

Article History	Abstract
Received: 11th February, 2026 Accepted: 10th March, 2026	This paper investigates volumetric shrinkage phenomena occurring during the injection molding process of polymer materials and its influence on product quality. The study focuses on a washing machine tank manufactured from PP J-360 material. The effects of cooling system design and heat transfer conditions on volumetric shrinkage are analyzed both theoretically and experimentally. A mathematical model for evaluating volumetric shrinkage is developed based on temperature distribution, pressure variation, and pvT characteristics of the material. Different cooling channel configurations are compared to determine their influence on shrinkage and deformation behavior.

Keywords: Mold cooling, cooling system, optimization methods, heat exchange, natural cooling, thermal efficiency, polymer molding, cooling process, energy saving.

All polymers exhibit shrinkage when cooled from the melting temperature to the solid state. The two classes of thermoplastics, amorphous and semi-crystalline, show a linear dependency of the specific volume on the temperature in the melted state. In the solid state, the specific volume of the semi-crystalline polymers decreases exponentially whereas the amorphous polymer keeps a linear dependency, although with a different slope. This can be visualized by the pvT diagram, see Figure 11, where the specific volume is plotted as a function of the temperature for different pressures.

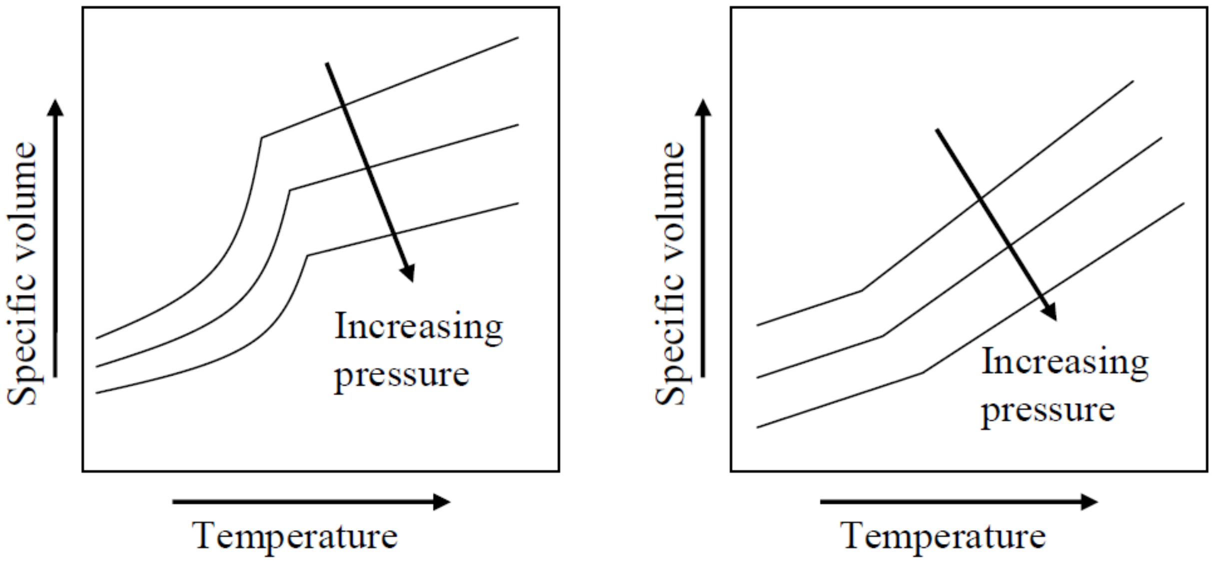

Figure 1. Example of pvT-diagram for semi-crystalline polymers (left) and amorphous polymers (right). The specific volume is plotted as a function of the temperature and for different pressures.

When an amorphous polymer is heated, it moves from a glassy state, where the molecules are frozen in crumpled formations, to a liquid state where segments of the molecules change places by thermally activated jumps. The transition between these two states is called the glass transition temperature, often abbreviated as *Tg*. The thermal expansion during the glassy state is due to the increasing separation between the crumpled, but still immobile, molecules. When reaching *Tg*, the mixture of increasing separation between the molecules and position changes by discrete jumps yields a smooth transition. Beyond *Tg,* the increase of the thermal expansion coefficient is due to the thermally activated jumps by the molecule segments.

When cooling a semi-crystalline polymer below the melting temperature, crystallization is initiated at so called nuclei in the amorphous melt, on different locations. The crystallization proceeds by the growth of a spherulite around the nuclei and these spherulites are the result of the growth of many crystals which it comprises. More segments of the polymer chains disentangle from the melt and connect with the crystals until the spherulite impinges on its neighbors. During this process, some amorphous polymer is getting trapped between the crystals. Semi-crystalline grades suitable for injection molding often have a *Tg* below room temperature which implies that they exhibit toughness, as a result of the partial mobility of the amorphous parts, and strength, as a results of the crystalline portions. Crystals formed from the same polymer are rarely crystallized so that all the crystals are of precise equal thickness. Due to this variation, a melting range is observed instead of a melting temperature which a perfect crystalline material would exhibit.

The pvT behavior is an important key to produce parts with low shrinkage. The injection molding process can be depicted as in Figure 12. The cavity is filled during an increased pressure (1→2) and at about the same temperature, the compression phase is started (2→3). The polymer is steadily cooled down while the holding pressure (3→4) partly compensates the volumetric shrinkage. When the gate is frozen (point 4), an isochoric pressure drop takes place until normal pressure is reached (point 5). This point establishes the volumetric shrinkage and the volume of the plastic part is the same as the volume of the cavity. The isobaric cooling stage takes place and at point 6, the part is ejected and the constraints from the surrounding mold are no longer there. At point 7, the part has reached a thermal equilibrium.

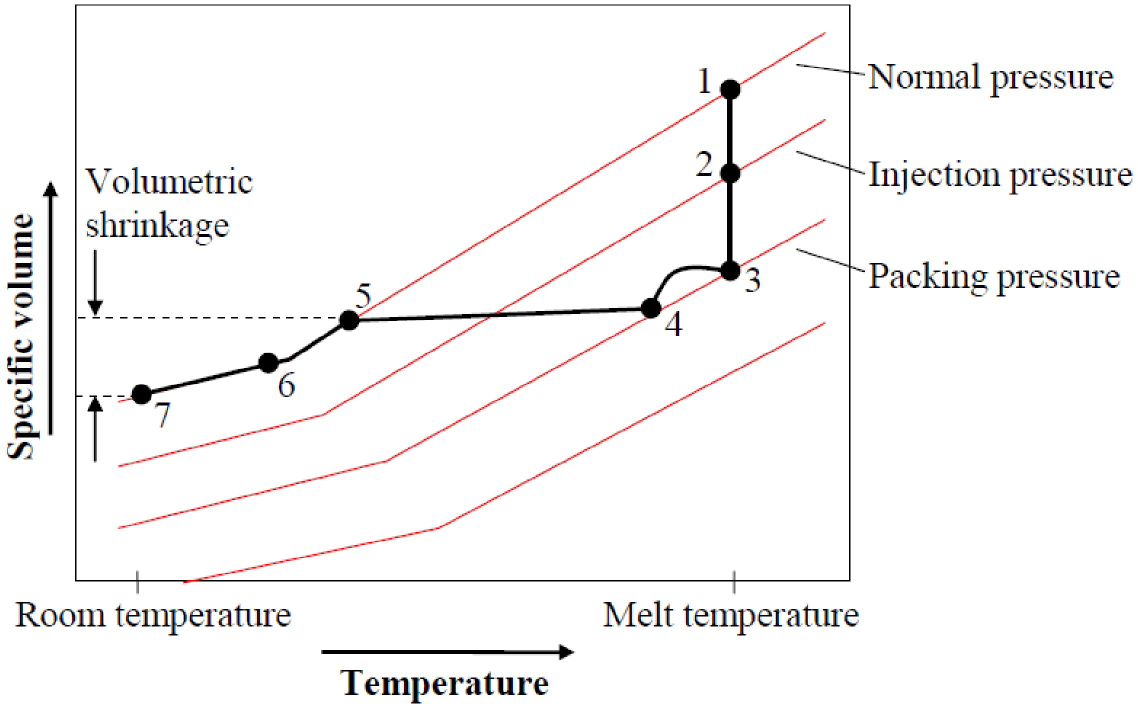

Figure 2. The different steps in injection molding depicted in the pvT diagram.

2.2.2 Linearized shrinkage

The linearized shrinkage is developed as the melt flows in the cavity. These flow-induced effects can be attributed to shear forces and extensional forces induced to the polymer during filling and packing.

The filling stage is characterized by a so-called fountain flow, see Figure 3. A shear field is developed due to the variations in the velocity field and the shear field makes the molecules oriented in the direction of the main strain direction. If there is time, and if the polymer would be kept in its molten state, this orientation is recovered. When the melt closest to the mold solidifies, the molecules keep their orientation in the flow direction as well as their molecular elongation. Hence this layer has a tendency to shrink in the direction of orientation. The molecules in the centre of the melt on the other hand, are insulated from the cold metal which allows them to relax from their stretched orientation. In this way, they will have more time to recover from the oriented state. They will therefore have less frozen in orientation and will also have less tendency to shrink relative to flow direction. This gradient of oriented molecules causes the skin to be in compression while the core is in tension and consequently a warpage effect arises. The variations of the cooling rate, the direction and the velocity of flow, part thicknesses, etc., over the part geometry make this shrinkage effect complex. The balance of the strains and their directions results in so called "residual stress" which in its turn can contribute to warpage.

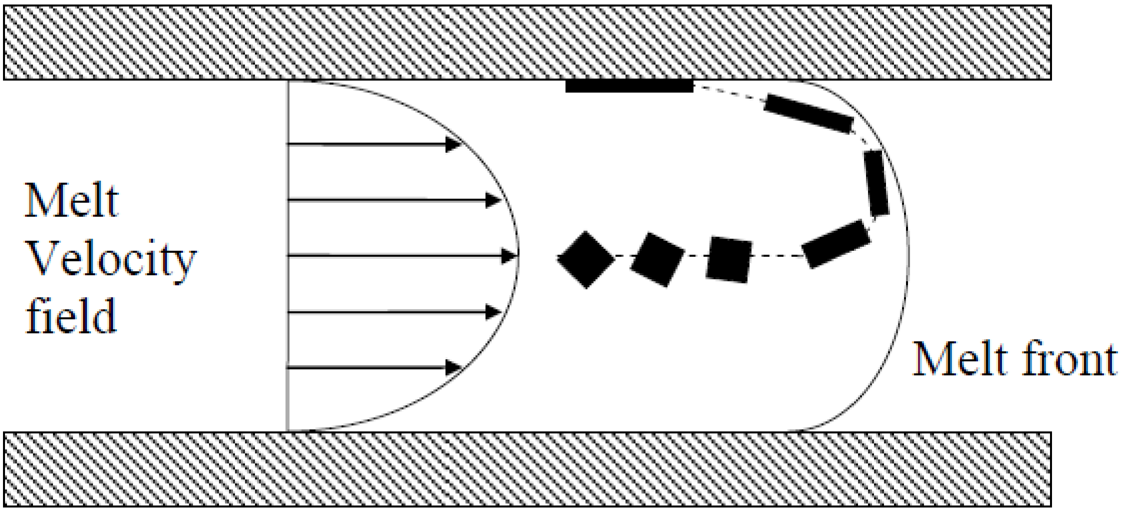

Figure 3. The fountain flow near the melt front. The deformation and orientation of a material element is depicted as it gets closer to the melt front.

As discussed above, the flow is almost linear in a long narrow part causing only shear forces but when diverging and converging flows are introduced, other components of strains are also present in the flow field. A typical example is the flow in a centered-gated disk where the flow expands outwards as it fills the cavity but at the same time, the flow also has a component in the perpendicular direction of the flow. This is referred to as extensional flow. In contrast to the shear-dominant flow, the outermost layer, the one closest to the mold, exhibits a random orientation of the molecules since the flow is not subjected to any shear forces. The next layer is subjected to high shear forces and will therefore have an orientation in the radial direction whereas the next layer is subjected to both shear and extensional flow effects and will show a random orientation. In the innermost layer, the shear forces are almost zero and the molecules will be subjected to high extensional forces and will be oriented in the perpendicular direction of the flow. The variations of the thicknesses of these layers as well as their magnitudes will affect the part differently and this is also a contributor to the residual stress.

Another important factor affecting the shrinkage is fibers. These fibers are used in the material in order to reinforce the part and like the molecules in the polymer, the fibers are oriented in the direction of the flow. The shrinkage in the direction of the fibers are counteracted since these fibers are very stiff and instead a fiber-reinforced polymer has a substantial shrinkage in the cross-flow direction. As before, the orientation of these fibers is varied in reference to flow direction, part thickness, and other process variations. Hence, it is a complex but important contributor to part stiffness and residual stresses.

Conclusion

This study has comprehensively investigated the phenomenon of volumetric shrinkage in polymer materials during the injection molding process, with particular emphasis on a washing machine tank produced from PP J-360. The results confirm that volumetric shrinkage is a complex thermo-mechanical process governed by the interaction of temperature distribution, pressure evolution, and the pvT characteristics of the material.

The developed mathematical model has demonstrated that accurate prediction of shrinkage requires simultaneous consideration of cooling rate, holding pressure, and phase transitions occurring within the polymer. It was established that the design and configuration of the mold cooling system play a decisive role in controlling heat transfer conditions, thereby directly influencing shrinkage magnitude, residual stresses, and final product deformation.

Comparative analysis of different cooling channel configurations revealed that optimized cooling layouts обеспечивают более равномерное распределение температуры по объёму изделия, что приводит к снижению градиентов усадки и уменьшению коробления. In particular, enhanced thermal efficiency and controlled heat exchange contribute to improved dimensional stability and reduced cycle time, supporting energy-saving manufacturing strategies.

Furthermore, the study highlights the importance of material structure, distinguishing between amorphous and semi-crystalline polymers, whose pvT behavior and crystallization kinetics significantly affect shrinkage patterns. Flow-induced molecular and fiber orientation, as well as non-uniform cooling conditions, were identified as key factors contributing to residual stresses and anisotropic shrinkage behavior.

In conclusion, the integration of optimized cooling system design, advanced modeling approaches, and a thorough understanding of material behavior enables effective control of volumetric shrinkage in injection-molded parts. These findings provide a scientific and practical basis for improving product quality, minimizing defects, and enhancing the overall efficiency of polymer processing technologies.

References

1. Rakhimov, A. A., & Sattorov, M. Sh. (2020). Technology of Plastics Processing. Tashkent: TTYMI Publishing House. — Covers the technological fundamentals of plastic injection, cooling, and molding processes.
2. Usmonov, B. S., & Jurayev, I. M. (2019). Fundamentals of Mechanical Engineering Technology. Tashkent: “Fan va texnologiya” Publishing House. — Provides practical approaches to mold materials, cooling systems, and thermal processes.
3. Toshpolatov, D. A. (2018). Modeling of Technological Processes. Tashkent: “Muhandis” Publishing House. — Presents theoretical foundations of digital modeling and optimization methods.
4. Rakhmonov, S. N. (2021). Thermal Engineering and Cooling Systems. Tashkent: TDPU Publishing House. — Describes heat transfer, natural convection, and cooling efficiency issues.
5. Gulomov, A. T. (2017). Computer-Aided Engineering Analysis (CAE Systems). Tashkent: “Innovatsiya” Publishing House. — A practical guide to thermal analysis using SolidWorks, ANSYS, and other CAE systems.
6. Xu, G., & Wang, G. (2015). Optimization design of conformal cooling channels in injection molds based on numerical simulation. Applied Thermal Engineering, 87, 398–408.
7. Li, H., Zhao, G., & Liu, X. (2018). Analysis of temperature field and cooling time in injection molding process. Polymers, 10(9), 1047.
8. Yusupov, A. A., Yuldashev, X. X. Composite Materials: Scientific-Technical and Applied Journal. — Improving the cooling efficiency of molds in the production of complex-shaped plastic parts.
9. Yusupov, A. A., Yuldashev, X. X., Juraqulov, I. Ch. (2024). Current Issues of Innovative Technologies in Materials Science, Welding Production, and Material Processing in Mechanical Engineering. — Mathematical modeling of the cooling process in manufacturing complex-shaped plastic parts (p. 513).

10. Yusupov, A. A., Yuldashev, X. X. (2024). Current Issues of Innovative Technologies in Materials Science, Welding Production, and Material Processing in Mechanical Engineering. — The importance of cooling channels in the production of complex-shaped plastic parts.
11. Yusupov, A. A., Yuldashev, X. X. OPTIMIZATION OF POLYMER INJECTION MOLDING PROCESSES Published by International journal of Social Sciences & Interdisciplinary Research., under Volume: 15 Issue: 03 in March-2026