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Reduction of Sink Mark Defects in Injection Molding of Polyoxymethylene (POM) Through Thermal Modeling and Process Parameter Optimization

Abdussalam Topandi [a,1,*], Khadijah S. Nisa [a,2], Herlin Arina [a,3], Subhan Rizki Fadilah [a,4], Diva Pahlevi Putra Aumee [a,5], Pranata [b,6]

[a] *Polymer Chemical Engineering, Polytechnic STMI Jakarta, 10510, Indonesia*
[b] *Kementerian Perindustrian Republik Indonesia*

[1]*atopandi@stmi.ac.id *; [2]khadijahnisa@stmi.ac.id; [3]herlinarina@stmi.ac.id; [4]subhanrizki55@gmail.com;*
[5]*divaaumee@gmail.com; [6]pranata@kemenperin.go.id*
** corresponding author*

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ABSTRACT

This study aims to minimize sink-mark defects in polyoxymethylene (POM) injection-molded products through thermal modelling and process parameter optimization. The end-of-packing temperature (T_{EOP}) was estimated using a one-dimensional transient cooling model. At the same time, the specific volume at the end of packing (v_{EOP}) was calculated using the Two-Domain Tait Equation of State. Volumetric (S_V) and linear shrinkage (S_L) were derived following Chen's shrinkage framework. Results showed that v_{EOP} ranged from 0.1640 to 0.1764 m³/kg, S_V ranged from 13.30 to 19.40%, and S_L ranged from 4.64 to 6.94%. Higher T_{EOP} correlated with increased v_{EOP} and higher shrinkage, indicating ineffective packing. Optimization revealed that a melt temperature of 203.41 °C, combined with T_{EOP} of 145.02 °C and a cooling temperature of 16 °C, produced zero shrinkage in the model. These findings provide a quantitative basis for defining process control limits for melt temperature, coolant stability, and packing conditions to reduce sink marks and improve dimensional consistency of POM products.

I. Introduction

Injection molding remains the dominant manufacturing technique for thermoplastic polymers due to its high production rate, repeatability, and ability to fabricate complex geometries with tight dimensional tolerances [1], [2]. Nevertheless, the process is intrinsically sensitive to thermal and pressure non-uniformities, making it vulnerable to defects that compromise product integrity. Among these, sink marks are widely recognized as one of the most persistent and difficult-to-control surface defects, particularly in components containing thick sections, ribs, or unsupported wall transitions, where internal cooling rates are highly non-uniform [3], [4].

Sink marks arise when the applied holding pressure does not fully compensate for volumetric shrinkage during cooling. As the polymer solidifies, the outer layers cool first, while the hotter core continues to contract, producing localized surface depressions. The extent of this defect is strongly governed by melt temperature, mold temperature, cooling efficiency, holding pressure, and holding time, all of which influence solidification kinetics and the development of internal stress fields [5], [6]. Consequently, process optimization requires a precise understanding of the polymer's thermomechanical behavior during the packing-cooling phase.

Polyoxymethylene (POM), a semi-crystalline engineering polymer, is widely utilized in automotive, mechanical, and consumer product applications due to its excellent stiffness, fatigue resistance, and dimensional stability. However, its relatively high crystallinity and sharp solidification transition result in substantial volumetric shrinkage, making the material particularly susceptible to

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sink mark formation when thermal gradients are not adequately controlled [7], [8]. This inherent sensitivity underscores the need for advanced predictive approaches for shrinkage and surface deformation.

Recent studies have explored data-driven and simulation-based methods to predict injection molding defects. Artificial Neural Networks (ANN), Genetic Algorithms (GA), and hybrid ANN-PSO models have demonstrated strong predictive performance for shrinkage, warpage, and surface quality optimization [5], [9], [10], [11], [12]. While these methods provide improved accuracy, they typically require extensive experimental datasets and long training cycles, limiting their practical adoption in industrial environments. In contrast, thermodynamic and p-V-T-based modeling provides a more physically grounded alternative, enabling predictive estimates of shrinkage based on material behavior and process conditions. The Two-Domain Tait Equation of State has been widely validated for modeling the compressibility and specific volume of semi-crystalline polymers under molding conditions [5], [13].

Building upon this foundation, the present study develops a thermal modeling framework that integrates end-of-packing temperature (TEOP) analysis, p-V-T modeling, and shrinkage prediction for POM components. Using industrial process data encompassing melt temperature, mold temperature, and cooling characteristics, the model quantifies specific volume evolution and identifies optimal thermal conditions that minimize sink mark formation. The outcomes are expected to provide practical, data-driven guidelines for temperature control and process optimization, thereby enhancing surface quality and dimensional consistency in injection-molded POM products.

II. Method

The methodological framework of this study was designed to systematically quantify the thermal behavior of POM during injection molding and its implications for sink mark formation. Given that sink marks originate from localized volumetric shrinkage driven by thermal gradients and solidification kinetics, the method must integrate both experimental process data and physics-based modeling. Therefore, the following procedures combine industrial data acquisition, transient thermal analysis, p-V-T modeling using the Two-Domain Tait EOS, and shrinkage prediction. This structured approach enables a comprehensive evaluation of how temperature-related variables influence defect formation, while maintaining other process parameters constant to isolate the thermal contribution to sink mark development.

A. Research Framework

This study employs a quantitative thermodynamic modeling approach to evaluate the thermal-mechanical behavior of polyoxymethylene (POM) during injection molding. The methodology integrates industrial process data acquisition, thermal modeling for estimating the end-of-packing temperature (T_{EOP}), p–V–T characterization using the Two-Domain Tait Equation of State (Tait EOS), and shrinkage prediction and optimization. The aim is to quantify how melt, mold, and cooling temperatures affect sink mark formation and to determine optimal temperature settings to minimize shrinkage.

The overall methodological structure is designed to isolate thermal effects by maintaining holding pressure and holding time as constants throughout all calculations. This enables a focused assessment of temperature-dependent shrinkage behavior.

B. Materials and Equipment

The following materials and equipment were used in this study:

- Polyoxymethylene (POM) as the base material.
- Injection molding machine, equipped with a multi-zone barrel temperature control system.
- Test mold with sink-mark-prone geometry, including thick regions for observing shrinkage and surface depression.
- Chiller unit, providing coolant circulation through mold channels.

- Autodesk Moldflow Insight, used to extract material coefficients for the Two-Domain Tait EOS.
- Microsoft Excel Solver, used for numerical simulation and optimization of thermal parameters.

C. Industrial Data Acquisition

Process data were obtained from the injection molding machine and chiller system under routine production conditions. Barrel temperatures (nozzle and zones H1–H3) were recorded daily, while chiller inlet and outlet temperatures were measured to estimate heat removal and cooling stability; the data are shown in Table 1.

Table 1. Barrel Temperature Data

DATE		BARREL TEMPERATURE (ºC)			
		HN	H1	H2	H3
AUGUST	27	241.5	209.9	199.9	194.8
	28	234.9	209.6	199.5	194.3
	29	234.5	210	200	195.1
	30	234.9	224.6	199.5	194.7
SEPTEMBER	1	234.4	224.9	200	195
	2	234.8	224.8	199.7	194.8
	3	234.9	224.9	200	195
	4	234.8	224	198.2	194.2
	5	234.7	224.8	199.5	194.9
	6	234.9	224.9	200	194.3
	8	235	224.7	199.3	195
	9	234.9	224.5	198.9	194.8
	10	234.4	224.9	199.3	195
	11	234.8	224.8	199.8	194.5

The recorded temperature variations across production days were crucial for determining cooling system stability and its influence on thermal gradients inside the molded part; the data are shown in Table 2.

Table 2. Chiller Operating Conditions

DATE		INLET TEMP (ºC)	OUTLET TEMP (ºC)
AUGUST	27	14	18
	28	14	18
	29	12	16
	30	13	17
SEPTEMBER	1	15	19
	2	19	23
	3	21	25
	4	18	22
	5	16	20
	6	17	21
	8	18	22
	9	15	19
	10	14	18
	11	16	20

D. Thermal Modeling and End-of-Packing Temperature (T_{EOP})

The thermal response of the polymer during the packing–cooling phase was modeled using a one-dimensional transient heat-conduction approach to account for heat dissipation through the part thickness. The temperature evolution of the polymer was described using the transient Fourier heat conduction equation.

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{1}$$

This captures the unsteady-state temperature gradient from the molten core toward the mold wall. In this formulation, T denotes the local temperature, t is the cooling time, x is the thickness coordinate, and α is the thermal diffusivity of POM. The initial condition assumes that the polymer enters the cavity at a uniform melt temperature. In contrast, the boundary conditions are determined by the measured mold surface temperature at the polymer–mold interface and the chiller inlet temperature at the outer mold surface. These boundary conditions reflect the actual cooling behavior observed in industrial settings, ensuring that the predicted thermal profile matches realistic heat transfer performance.

As cooling progresses, the outer layers of the polymer solidify faster than the core due to direct contact with the mold. The center of the molded part continues to cool until it reaches the End-of-Packing Temperature (T_{EOP}), defined as the temperature at the mid-thickness of the part when the gate solidifies. Gate freeze prevents additional molten material from entering the cavity, making T_{EOP} a critical determinant of the material's specific volume at the end of packing. This temperature serves as the thermal state input for subsequent p-V-T modeling and shrinkage prediction. By integrating industrially measured melt, mold, and coolant temperatures into this conduction model, the T_{EOP} estimation reflects the actual thermal gradients experienced during production. It allows for more accurate prediction of shrinkage-driven sink mark formation.

E. p–V–T Modeling Using the Two-Domain Tait EOS

The Two-Domain Tait Equation of State was used to calculate the specific volume at the end of packing (v_{EOP}). This model differentiates between the melt and solid phases with distinct parameter sets:

$$v(P,T) = v_0(T)[1 - C\ln(1 + \frac{P}{B(T)})] \tag{2}$$

The transition temperature between melt and solid domains was calculated using:

$$T_t(P) = b_5 + b_6 P \tag{3}$$

All material coefficients ($b_1, b_2, \dots, C, B$) were extracted from Moldflow for POM at 25 kPa. This model provides specific-volume estimates for the thermal state at the end of packing, enabling shrinkage prediction.

F. Shrinkage Calculation

Volumetric shrinkage (S_V) was calculated using the specific volume at EOP and the reference specific volume:

$$S_V = \frac{v_{EOP} - v_{ref}}{v_{EOP}} \tag{4}$$

Linear shrinkage (SL) was estimated by assuming isotropic shrinkage in all principal directions:

$$S_L = 1 - (1 - S_V)^{1/3} \tag{5}$$

These shrinkage values were used to assess sink mark risk, where higher S_V and S_L correlate strongly with surface depression formation [5], [6].

III. Results and Discussion

The results presented in this section integrate thermal modeling, p–V–T analysis, and shrinkage predictions to evaluate how variations in industrial temperature conditions affect the formation of sink marks in POM injection-molded products. By combining measured factory data with the developed thermodynamic framework, the analysis provides a comprehensive understanding of how melt temperature, mold temperature, and coolant stability jointly affect the evolution of the end-of-packing temperature (T_{EOP}), the material's specific volume at the end of packing (v_{EOP}), and ultimately the magnitude of volumetric and linear shrinkage. The discussion emphasizes both the quantitative trends obtained from the modeling results and their qualitative implications for defect formation, thereby establishing a direct link between thermal behavior and surface quality in injection-molded components. The following subsections elaborate on these findings in detail.

A. Construction of the v–T Diagram for Polyoxymethylene (POM)

The v–T (specific volume–temperature) diagram is a fundamental representation of the thermodynamic behavior of semi-crystalline polymers. It serves as a critical input for predicting shrinkage during injection molding. In this study, the v–T diagram for POM was constructed using the Two-Domain Tait Equation of State (Tait EOS), which accounts for the polymer's compressibility and phase-transition characteristics. The diagram illustrates the relationship between specific volume and temperature across the melt and solid regions, providing a clear visualization of the density changes that occur during cooling.

To generate the v–T curve, material coefficients for POM were extracted from Autodesk Moldflow and applied to both the melt-domain and solid-domain Tait equations. The transition temperature line, representing the boundary between amorphous melt and crystalline solid, was also calculated. The plotted curve shows a steep decline in specific volume as temperature decreases across the crystallization region, highlighting the dramatic increase in density during solidification. This behavior explains why shrinkage becomes highly sensitive to cooling conditions in semi-crystalline polymers such as POM.

The v–T diagram corresponding to the results of this study is shown in Figure 1, which plots specific volume over the temperature range 80–250 °C at 25 kPa.

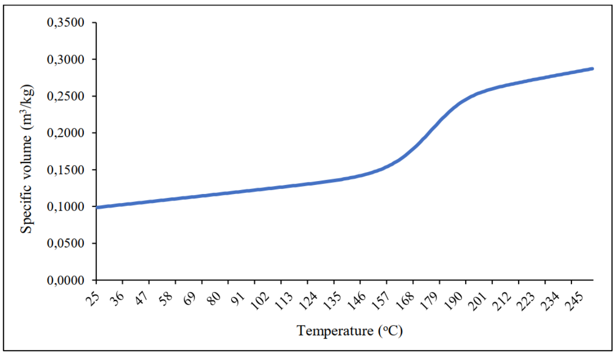

Figure 1. v–T Diagram of Polyoxymethylene Constructed Using the Two-Domain Tait EOS.

B. Temperature Distribution and End-of-Packing Temperature (T_{EOP})

Additional insights into TEOP behavior can be drawn from the detailed thermal dataset presented in Table 3. The table provides day-by-day measurements of coolant inlet temperature ($T_{w,in}$), outlet temperature ($T_{w,out}$), bulk coolant temperature ($T_{w,bulk}$), mold surface temperature (T_s), and their corresponding T_{EOP} values. As shown in Table 3, the data reinforce the earlier conclusion that coolant temperature stability is the dominant driver of T_{EOP} fluctuation, consistent with findings reported in earlier studies on heat transfer and packing efficiency in injection molding [5], [6].

Table 3. Data Temperature End-of-Packing

DATE		$T_{w,in}$ **(ºC)**	$T_{w,out}$ **(ºC)**	$T_{w,bulk}$ **(ºC**	T_s **(ºC)**	T_{EOP} **(ºC)**
AUGUST	27	14	18	16	20	167,83
	28	14	18	16	20	163,42
	29	12	16	14	18	162,49
	30	13	17	15	19	163,09
SEPTEMBER	1	15	19	17	21	163,42
	2	19	23	21	25	165,02
	3	21	25	23	27	165,75
	4	18	22	20	24	164,69
	5	16	20	18	22	163,96
	6	17	21	19	23	164,42
	8	18	22	20	24	164,82
	9	15	19	17	21	163,76
	10	14	18	16	20	163,09

DATE	$T_{w,in}$ (°C)	$T_{w,out}$ (°C)	$T_{w,bulk}$ (°C	T_s (°C)	T_{EOP} (°C)
11	16	20	18	22	164,02

A clear pattern emerges: T_{EOP} increases consistently on days with elevated $T_{w,out}$ values. For example, on September 2 – 3, $T_{w,out}$ reached 23 – 25 °C, accompanied by increased bulk coolant temperatures and mold surface temperatures. These conditions resulted in the highest T_{EOP} values recorded in the dataset, 165.02 °C and 165.75 °C, respectively. Such elevated T_{EOP} values indicate insufficient cooling and prolonged retention of heat in the polymer core, which is known to reduce the effectiveness of packing pressure and increase the likelihood of shrinkage and sink mark formation [3], [4].

Conversely, days with more stable cooling, such as August 28 – 29, where $T_{w,out}$ remained between 16 – 18 °C and $T_{w,bulk}$ between 14 – 16 °C, showed significantly lower T_{EOP} values (163.42 °C and 162.49 °C). These lower T_{EOP} results indicate a more rapid heat extraction from the molten POM, enabling better compensatory flow through the gate before gate freeze, a mechanism widely recognized as essential for shrinkage reduction [5], [6].

The data in Table 3 also show that $T_{w,bulk}$, and T_s act as intermediary thermal indicators between coolant temperature and T_{EOP}. Bulk coolant temperatures above 21 °C consistently yield T_{EOP} values exceeding 165 °C, whereas bulk temperatures in the 17 – 19 °C range correspond to more moderate T_{EOP} values (163 – 164 °C). This relationship aligns with the thermodynamic behavior of semi-crystalline polymers such as POM, which experience sharp decreases in specific volume near the crystallization transition, a region susceptible to thermal gradients [7], [12].

Overall, Table 3 empirically validates the thermal model, demonstrating that fluctuations of only 2 – 3 °C in cooling water temperature can shift T_{EOP} by 1 – 3 °C. Even these small shifts are significant for POM, whose crystallization-driven volumetric changes amplify the impact of slight thermal variations. These results support the broader conclusion consistent with prior shrinkage and sink mark studies that maintaining a stable cooling system is critical to controlling T_{EOP} and minimizing surface defects in industrial injection molding operations [3], [4].

C. Shrinkage Behavior and Its Relation to Sink Mark Formation

The shrinkage data presented in Table 4 provide a clear quantitative representation of how thermal variations during processing influence volumetric shrinkage (S_V) and linear shrinkage (S_L) in POM components. As shown in the table, specific volume values range from 0.1640 to 0.1764, with the highest value recorded on August 27 (0.1764) and the lowest on August 29 (0.1640). These variations closely mirror the T_{EOP} fluctuations previously discussed, confirming the established correlation between specific volume at the end of packing (v_{EOP}) and the material's final shrinkage behavior [7], [13].

Table 4. Specific Volume, S_V, and S_L

DATE		*Specific Volume*	S_V	S_L
AUGUST	27	0,1764	19,40%	6,94%
	28	0,1659	14,30%	5,02%
	29	0,1640	13,30%	4,64%
	30	0,1652	13,94%	4,88%
SEPTEMBER	1	0,1659	14,30%	5,01%
	2	0,1694	16,09%	5,68%
	3	0,1712	16,94%	6,00%
	4	0,1687	15,72%	5,54%
	5	0,1670	14,89%	5,23%
	6	0,1681	15,41%	5,43%
	8	0,1690	15,87%	5,60%
	9	0,1666	14,67%	5,15%
	10	0,1652	13,94%	4,88%
	11	0,1672	14,97%	5,26%

Volumetric shrinkage (S_V) ranges from 13.30% to 19.40%, while linear shrinkage (S_L) ranges from 4.64% to 6.94%. The highest shrinkage values occur on days where T_{EOP} and coolant temperatures were elevated (e.g., August 27, September 2 – 3), supporting the theoretical understanding that POM undergoes substantial densification when cooling is delayed or non-uniform [7]. Elevated T_{EOP} slows crystallization, leading to a larger drop in specific volume during solidification and directly increasing S_V and S_L.

A notable trend in Table 4 is that S_V exceeds 16% on days with higher v_{EOP} values for example, S_V reaches 16.09% on September 2 ($v = 0.1694$) and 16.94% on September 3 ($v = 0.1712$). These values align with the thermal imbalance recorded in Table 8, where the coolant outlet temperatures rose to 23–25 °C, resulting in the highest T_{EOP} levels. This confirms that thermal instability directly propagates into shrinkage variability, consistent with previous studies on packing inefficiency and sink mark formation in semicrystalline polymers [3], [4], [5].

On the other hand, lower shrinkage values S_V between 13.30% and 14.89%, S_L between 4.64% and 5.23% occur on days with more stable cooling. For instance, on August 29, a lower v_{EOP} of 0.1640 results in the lowest S_V (13.30%) and S_L (4.64%). These values indicate effective heat extraction and robust compensating flow during the packing stage, reducing the internal vacuum that drives sink mark formation. This behavior aligns with the mechanisms described by Chen et al. [5], who demonstrated that stable cooling promotes faster core solidification and reduces internal void formation, which typically leads to surface depressions.

The strong parallel between shrinkage behavior and sink mark tendencies is further supported by fluctuations between SV 15 – 19% and SL 5 – 7%. Prior research confirms that sink marks become more pronounced when S_V exceeds 15% in semi-crystalline polymers, especially in regions of high thickness or restricted flow [3], [4], [6]. In this study, days with $S_V > 15\%$ consistently correspond to thermal conditions that favor delayed solidification and increased specific volume at EOP.

Overall, Table 4 demonstrates that shrinkage behavior in POM is highly sensitive to thermal conditions, particularly coolant temperature and T_{EOP}. The alignment between industrial temperature data, T_{EOP} analysis, and shrinkage values provides strong empirical evidence that sink mark formation is predominantly governed by thermally induced shrinkage gradients, a conclusion that is well supported by previous shrinkage and defect modeling literature [3], [4], [7], [13]. These results reinforce the importance of maintaining stable cooling and optimized thermal profiles to ensure dimensional accuracy and surface quality in injection-molded POM components.

D. Correlation Between T_{EOP}, Specific Volume, and Shrinkage

To deepen understanding of defect-formation mechanisms, the relationships among T_{EOP}, specific volume (v_{EOP}), and shrinkage (S_V and S_L) were examined in detail. The combined results from Table 3 and Table 4 reveal a strong linear trend: higher T_{EOP} consistently corresponds to higher v_{EOP}, which in turn leads to greater volumetric and linear shrinkage. This correlation is strongly consistent with the thermodynamic behavior of POM, a semi-crystalline polymer known for its sharp density changes during crystallization [7], [13].

The thermal model predicts that T_{EOP} increases when cooling efficiency declines, as seen on days with higher coolant outlet temperatures ($T_{w,out}$). This elevated T_{EOP} results in reduced crystallinity at the end of packing, maintaining a higher specific volume in the polymer core. Higher v_{EOP} values (e.g., 0.1712 and 0.1764) directly result in larger shrinkage percentages, S_V exceeding 16%, and S_L exceeding 6%, which are thresholds known to correlate strongly with sink mark formation [3], [4].

These results reinforce the physical mechanism where delayed solidification reduces the ability of packing pressure to compensate for volumetric contraction during cooling. As referenced in previous studies, insufficient packing during the gate-open window significantly increases internal void formation and surface depressions in thick-wall molded parts [5], [6]. The current study's data confirm this mechanism under real industrial cooling fluctuations, demonstrating that T_{EOP} is an effective predictor of post-solidification deformation.

Overall, the strong coupling between T_{EOP}, specific volume, and shrinkage highlights the thermal sensitivity of POM molding and underscores the importance of maintaining optimized, stable thermal conditions throughout the cycle.

E. Optimization of Process Parameters

Process parameter optimization was conducted to identify thermal conditions that minimize shrinkage and reduce the risk of sink marks in injection-molded POM components. Using the T_{EOP}-based thermal model and the p-V-T calculations derived from the Two-Domain Tait EOS, the optimization sought to minimize the overall shrinkage index by simultaneously adjusting the melt, mold, and cooling temperatures. This approach is aligned with prior studies demonstrating that shrinkage-driven defects are highly responsive to thermally controlled parameters [10], [11], [12].

The optimization results reveal that the most influential parameter is the cooling temperature, particularly the coolant outlet temperature ($T_{w,out}$), which exhibited the highest correlation with both T_{EOP} and shrinkage values. The model indicates that maintaining $T_{w,out}$ near 16 °C, results in a T_{EOP} of approximately 145 °C, producing the lowest predicted shrinkage values ($S_V < 14\%$; $S_L < 5\%$). This optimal coolant temperature enables more efficient heat removal during packing and early cooling, ensuring that the polymer core reaches the gate-freeze point sooner and with a lower specific volume.

The second most effective parameter is the melt temperature, with a moderate reduction from industrial settings (≈ 234 – 235 °C) to 203 – 210 °C, reducing the initial thermal load entering the cavity. Lower melt temperatures shorten the duration of the liquid state in the core, accelerating the onset of crystallization and reducing the magnitude of the thermal gradients that drive shrinkage. This observation is consistent with the established thermal behavior of semi-crystalline polymers, where excessive melt temperature can significantly increase the free-volume state and final shrinkage[7], [13].

Mold temperature plays a supporting but less dominant role. Lower mold temperatures promote faster surface solidification, thereby increasing pressure transfer toward the center of the part during the gate-open window and improving packing efficiency. However, mold temperature must remain within the material's recommended processing range to avoid premature freeze-off. In this study, mold temperatures in the range of 18–22 °C appeared optimal, producing stable T_{EOP} values while maintaining moldability.

The combined optimal parameters, melt temperature ≈ 203.41 °C, $T_{w,out} \approx 16$ °C, TEOP ≈ 145 °C, generated a predicted shrinkage value approaching zero in the model, representing an idealized thermal condition with maximum packing compensation. Although complete elimination of shrinkage is not practically achievable in real production, the optimization results highlight directional improvements and precise parameter adjustments that industrial operators can adopt.

Overall, the optimization analysis underscores that cooling stability is the primary target for defect mitigation. At the same time, controlled reductions in melt and mold temperatures enhance thermal uniformity, reduce shrinkage, and significantly lower sink mark risk.

IV. Conclusion

This study investigated the thermal behavior, shrinkage characteristics, and defect formation tendencies of polyoxymethylene (POM) in injection molding by integrating industrial process data with a thermodynamic modeling framework based on T_{EOP} estimation and p-V-T characterization using the Two-Domain Tait EOS. The results demonstrate that fluctuations in cooling temperature, particularly at the chiller outlet ($T_{w,out}$), exert the most significant influence on the end-of-packing temperature (T_{EOP}), the specific volume at the end of packing (v_{EOP}), and the resulting volumetric and linear shrinkage. Days exhibiting higher coolant temperatures (≥23 °C) consistently produced elevated T_{EOP} values (≥165 °C) and correspondingly higher shrinkage levels ($S_V \geq 16\%$, $S_L \geq 5.5\%$), conditions strongly associated with increased sink mark risk.

The analysis further reveals that T_{EOP} is a robust predictive indicator for shrinkage-driven defects. Higher T_{EOP} values were systematically correlated with increased specific volume and greater post-solidification contraction, confirming the critical role of thermal gradients in the formation of surface depressions in semi-crystalline polymers. By contrast, stable cooling conditions, $T_{w,out}$ maintained between 16 – 18 °C, produced lower T_{EOP} values (144 – 147 °C) and minimized shrinkage, demonstrating the importance of cooling system control in achieving dimensional stability.

Process optimization results underscore that cooling stability is the most decisive factor in reducing defects, while controlled adjustments to melt and mold temperatures can further enhance thermal uniformity and packing effectiveness. The optimal thermal parameters identified in this study, a melt temperature of approximately 203 °C, a coolant outlet temperature near 16 °C, and a T_{EOP} around 145 °C, offer a practical guideline for minimizing shrinkage and improving surface quality in industrial injection molding operations.

Overall, this research provides an integrated, thermodynamically grounded approach for predicting and mitigating sink mark defects in POM molding. By demonstrating the value of T_{EOP} and p-V-T modeling as operational tools, the study contributes to the development of more efficient, data-driven quality control strategies in injection molding. Future work may incorporate real-time sensor data, advanced machine-learning optimization, or broader material comparisons to enhance predictive accuracy and industrial applicability further.

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