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Analyzing the Flow of Injection Molding for Water Filter Handle: Filling, Packing, and Warpage

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ABSTRACT

Injection molding is a crucial manufacturing technology for producing complex, high-quality parts at scale, making it essential in various industries, including consumer electronics and automotive sectors. However, a lack of understanding about how injection parameters impact common defects like sink marks, short shots, and warpage often limits the widespread adoption of injection molding. This research aims to bridge this gap by providing a comprehensive digital simulation of the injection molding process within a complex mold cavity. Utilizing Moldex3D and the Finite Volume Method (FVM), this study characterizes essential material properties–viscosity, specific heat, density, and thermal conductivity–and examines the effects of gate location and part design on minimizing weld lines and warpage. The FVM involves dividing the computational domain into a finite number of small control volumes. This method is particularly well-suited for handling complex geometries and flow conditions, facilitating detailed and accurate simulations. This study employs Moldex3D, a leading simulation software in the field of injection molding, to demonstrate the use of CAE for design verification and process innovation. Moldex3D's advanced capabilities make it an ideal tool for simulating injection molding processes, helping improve the quality of parts and contributing to the overall advancement of molding skills in the industry. The simulations revealed optimal gate locations that significantly improved filling patterns, reduced warpage by 50%, and minimized weld lines, thereby enhancing overall part quality. Key contributions of this research include the identification of critical flow characteristics, the reduction of defect-prone regions, and the enhancement of plastic component rigidity. This study provides valuable insights into optimizing injection molding processes, offering a pathway to improved efficiency and part quality in advanced manufacturing.

1. Introduction

Injection molding is a cornerstone of modern manufacturing, especially in high-demand industries like consumer electronics and automotive, where complex, high-quality parts are produced on a large scale. The ability to create intricate shapes with high precision, consistency, and efficiency makes injection molding an indispensable technology in these sectors [1]. However, quality issues

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such as sink marks, short shots, weld lines, and warpage frequently pose challenges during the injection molding process, often leading to increased production costs and time due to required modifications or part rejection [2].

Simulation has become an essential tool for enhancing the injection molding process. By leveraging computer-aided engineering (CAE) software, such as Moldex3D, engineers can identify potential issues during the design phase, thus preventing costly changes later in production. Simulations provide insights into the flow of molten plastic within the mold, the effects of gate placement, and the packing and cooling dynamics–all of which are critical in minimizing defects. The role of simulation in reducing trial-and-error experimentation is particularly vital for optimizing gate locations and enhancing part quality while maintaining cost-effectiveness [2], [3].

Despite the advances in simulation tools, challenges persist in fully understanding the impact of gate location and design parameters on defect formation, particularly in parts with complex geometries. Existing literature has shown the importance of mold flow analysis for optimizing process parameters, but there remains a significant gap in systematically evaluating gate position's influence on critical defects like weld lines, warpage, and air traps. Most studies focus on specific aspects of defect minimization without fully integrating a comprehensive simulation-based approach that combines gate design, material properties, and cooling efficiency [4], [5].

This research aims to fill this gap by using Moldex3D to systematically simulate various gate locations for a complex mold design, specifically focusing on optimizing flow characteristics, reducing defect-prone regions, and improving part quality. This study is unique because it integrates multiple aspects of the injection molding process–from material characterization to gate location and defect analysis–into a holistic simulation framework. Unlike previous studies that have often treated these aspects separately, our approach provides a comprehensive methodology that bridges theoretical simulation and practical production outcomes [6], [7].

The main objectives of this research are threefold:

- To improve part quality by systematically simulating different gate locations on a complex mold and analyzing their influence on flow patterns and defect formation [8].
- To identify defect-prone areas, such as regions with air traps, weld lines, and warpage, by analyzing the results of multiple gate configurations [9].
- To enhance the structural rigidity and dimensional stability of the molded parts by optimizing both gate placement and cooling conditions [10].
- Before the stage of mass manufacturing starts, quality certification and small-scale production are used to increase the production yield [11].

The novelty of this research lies in the systematic evaluation of gate placement effects on defect minimization, incorporating both simulation and experimental validation in real-world scenarios. The study employs advanced numerical techniques, including the Finite Element Method (FEM) and Finite Volume Method (FVM), to simulate and analyze the mold flow, packing, and cooling phases. This combined approach ensures that each stage of the injection molding process is optimized for maximum efficiency and quality.

The contributions of this research are as follows:

- Comprehensive Gate Optimization: A detailed analysis of different gate locations has led to the identification of optimal configurations that significantly reduce common defects and enhance overall part quality [12].
- Integration of Material Properties in Simulation: The study characterizes key material properties–such as viscosity, specific heat, and density–and integrates these properties into simulations, enabling a more accurate prediction of flow and defect behavior [13].
- Practical Guidelines for Defect Reduction: The findings provide practical guidelines for mold

designers, including recommendations for gate placement, material selection, and cooling strategies, to improve product quality and reduce cycle times in industrial settings [14].

An illustrative example of the practical application of these findings can be seen in the optimization of gate placement for a complex automotive part. The results of this study showed that, by adjusting gate locations, air traps and weld lines could be minimized, leading to a 20% improvement in part rigidity and a significant reduction in the rate of defects compared to traditional trial-and-error approaches [15].

The remainder of this paper is structured as follows: Section 1 presents an introduction to the subject with a literature review background. Section 2 details the injection molding cycle, while Section 3 explores potential quality defects and their root causes. Section 4 discusses the fundamentals of molding simulation, and Section 5 presents the simulation results and analysis. Finally, Section 6 concludes the paper with key findings and future research directions.

2. Injection Molding Cycle

Injection molding is the process of creating a product by using injection molding equipment to inject liquid plastic material into a mold cavity. The plastic material is forced into a molten condition by the injection molding machine's screw, which causes a significant amount of heat to be produced through friction, as it enters through a hopper. To keep the plastic melted and injection-ready, it builds up in the front of the cylinder and is heated continuously [16].

The injection will then occur as the screw forces the melted plastic forward into the closed mold chamber. More melted plastic is injected under high pressure to make up for the plastic's volume loss from cooling and to ensure that the mold cavity is perfectly filled until the sprue solidifies. This process is known as packing. The initial injection of high molecular weight melted plastic is completed once the mold cavity is fully filled. To finally eject the trash, runner system, and molded product, the moveable side slides backward until the ejection pin touches the rear plate [17], [18]. The injection molding cycle is the name given to this cycle. You may find below the process of injection molding, as shown in Fig. 1.

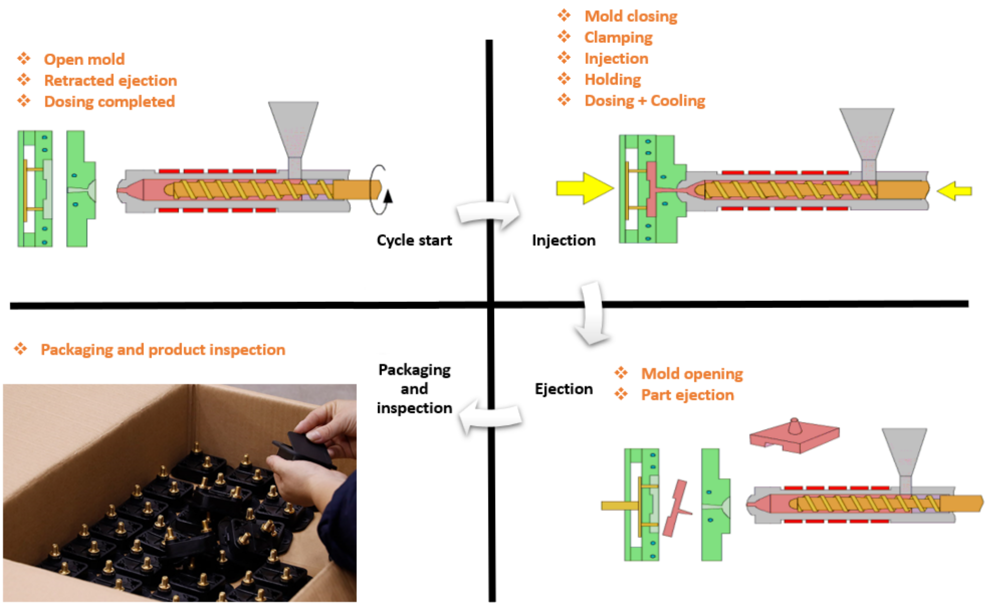

Fig. 1. Injection molding process

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3. Injection Molded Products Defects

When plastic is used to create the finished product using the molding process, product flaws become an additional worry. During the injection molding process, the plastic progressively takes on the shape of the cooling process, and when it comes out of the mold, it typically resembles a nearly finished object. Analyzing and comprehending the contributing components is essential if the plastic product has flaws [19]. The following is a basic description of typical injection molding defects:

3.1. Warpage

Warpage in injection molding refers to the deformation or distortion of a molded plastic part after it has been ejected from the mold. Warpage occurs when different sections of the part experience uneven shrinkage during the cooling process, leading to bending or twisting. Factors such as inconsistent cooling rates, material properties, part geometry, and non-uniform packing pressure can contribute to warpage. It is one of the most common defects in injection molding and can significantly affect the dimensional accuracy and structural integrity of the molded part. Preventing warpage typically involves optimizing mold design, cooling rates, material selection, and process parameters to ensure uniform shrinkage throughout the part [20].

Plastics can also expand and compress due to heat. As the melted plastic moves into the mold cavity, it begins to cool and solidify. During this time, the plastic contracts. Only shrinkage would occur if the contraction rate was spread equally across the product, eliminating the possibility of warp. However, it is very difficult for plastic finished products to contract evenly or with a low contraction rate due to the interaction between the external factors (such as molding conditions, mold cooling design, product appearance design), and the characteristics of the plastic (such as molecular chain and fiber orientation). Fig. 2 illustrates the warpage problem.

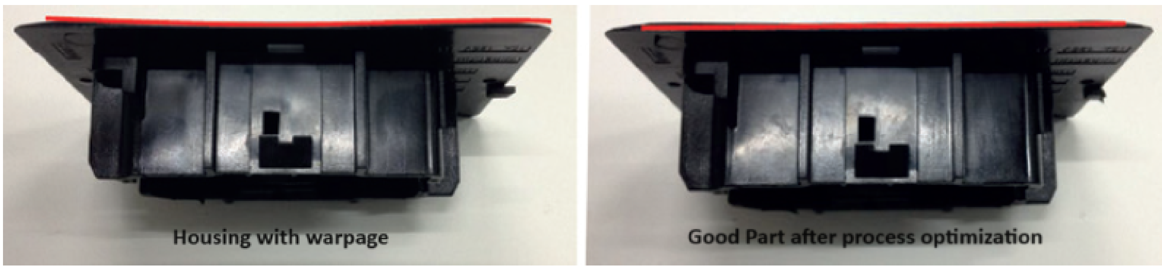

Fig. 2. Warpage

Geometric factors like component design, insert effect, process conditions like temperature and pressure, and material qualities like fibers and Pressure-Volume-Temperature (PVT) behavior are some of the causes of warpage. Finding the cause(s) of warpage is essential to resolving it. A fishbone diagram, like the one in Fig. 3, is typically used to identify every potential reason for warpage. The source can then be identified by comparing the list with the actual case.

3.2. Weld Line

Weld lines in injection molding are lines or weak spots that form when two or more flow fronts of molten plastic meet and fail to fully bond, often due to a cooler temperature at the point of convergence. This can lead to reduced structural integrity and visible surface defects. Techniques to minimize weld lines include optimizing gate placement to ensure that the melt fronts meet at a high enough temperature to fuse properly, increasing injection speed to maintain the melt temperature, and adjusting mold temperature to prevent premature cooling at the weld line location [21], [22].

An incomplete fusion may happen if two or more plastic flow fronts combine during the injection process because the melt front is colder and solidifies first. As a result, weld lines are produced as seen in Fig. 4. These flaws are typically observed in the areas surrounding the holes or limits where the finished items merge. Therefore, weld lines typically accompany race-tracking effects when they occur. Extreme caution should be exercised when it comes to circumstances like large thickness variations or several sprues in the mold in order to prevent the creation of weld lines [23].

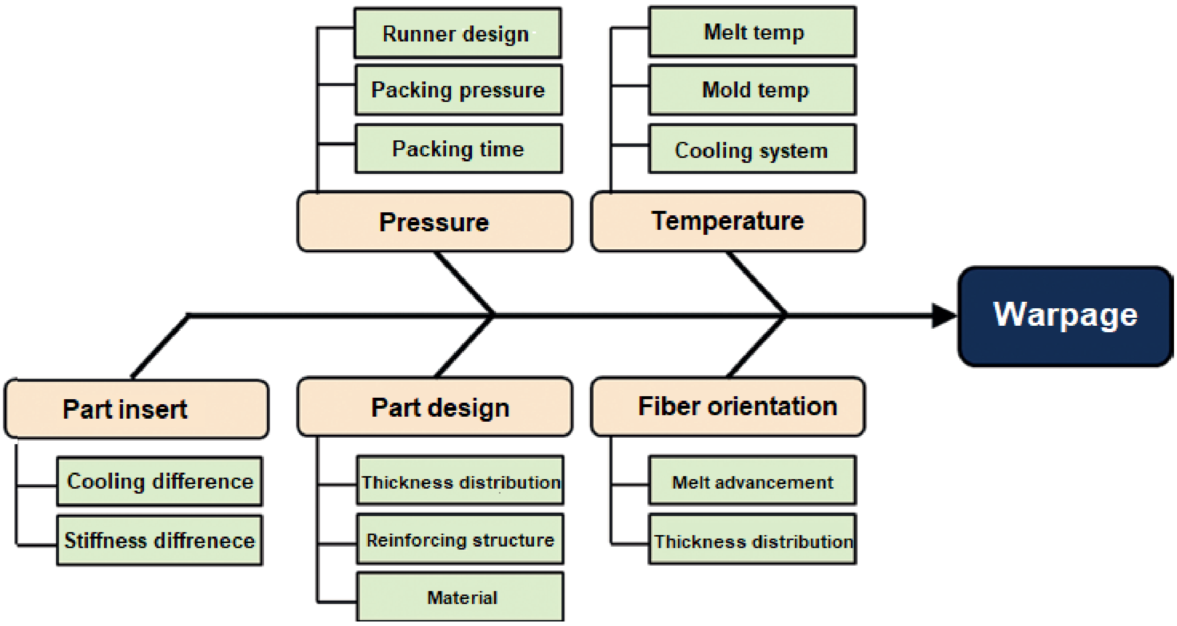

Fig. 3. Warpage root cause analysis

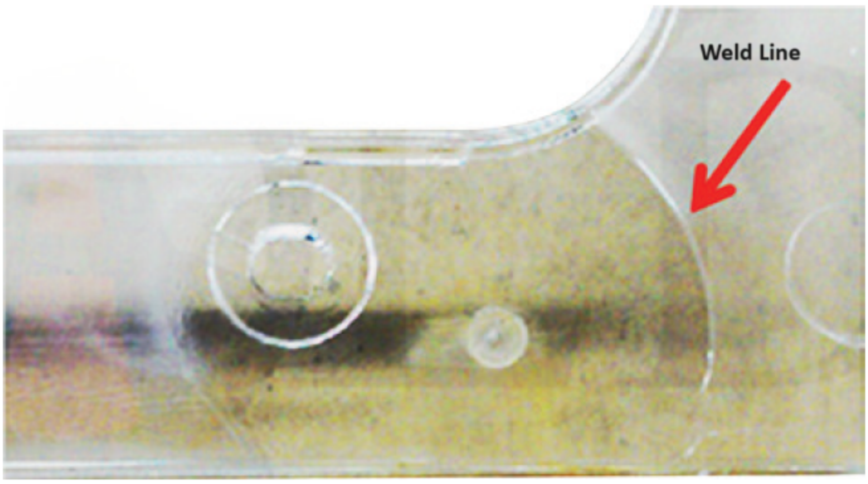

Fig. 4. Weld line

4. Molding Simulation

A molded plastic product's quality is mostly determined by the characteristics of the plastic material, the design of the component mold, and the process parameters, as was demonstrated in the paragraph before. A well-managed molding process yields high-quality products when used in injection molding. But the process itself is a mystery, so you never know what might go wrong until it's time to demold, let alone what's causing these issues [24].

The goal of simulations for molded products is to potentially realize the designed product's manufacturability. Every day, thousands of ideas are generated; only a small percentage of these may be successfully produced. The goal of molding analysis is to make sure that a good production quality may be attained by designing goods or molds appropriately in the design stage.

To answer computer-based problems, we must explain the governing equations for the physical system and present numerical techniques. From a technical perspective, computational analytical engineering (CAE) is a numerical application that solves the theoretical model of a physical system. As a result, the degree of theoretical model emulation, the accuracy and convergence of the numerical approach, and the mesh model employed for analysis are all strongly correlated with the analysis's correctness and dependability [25].

4.1. Governing Equations in Injection Molding

The conservation laws–that is, the conservation of mass, momentum, and energy–are the fundamental governing equations of a molding system. These laws can be obtained by applying the conservation of the control volume, which is the system's smallest unit. As demonstrated in Fig. 5, the rate of change of the physical measurement over time is obtained by taking into account the sum of a physical quantity that enters, exits, and is formed in an infinitesimal element. The total measurement of a macroscopic system can be found by summing the values of all these microscopic spaces [26].

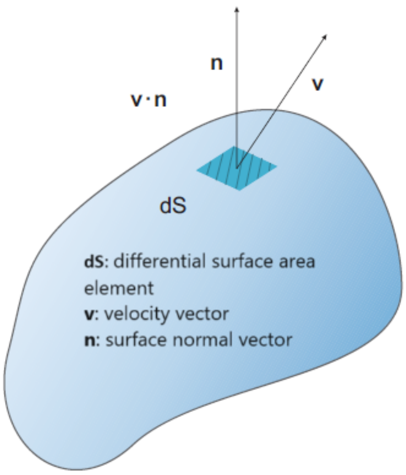

Fig. 5. Control volume

A shaded region within a fluid and velocity vector field v represents a universal control volume. The differential surface area element, denoted as dS, is displayed alongside the corresponding unit outward surface normal vector, n.

4.2. Continuity Equation

Expression (1) is the standard continuity equation, where ρ is the density, t is the time, and v is the velocity vector.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho v) = 0 \tag{1}$$

4.3. Momentum Equation

Expression (2) is the momentum equation, where g is the gravity and τ is the shear stress.

$$\frac{\partial}{\partial t}(\rho v) + \nabla(\rho v v) = -\nabla p + \rho g + \nabla \tau \tag{2}$$

The shear stress τ is defined as the force per unit area that acts parallel to the plane of interest in a material. It arises when forces are applied tangentially to a surface, causing deformation by sliding layers of the material relative to each other.

4.4. Energy Equation

Expression (3) is the energy equation, where T is the temperature field, C_p is the heat capacity, k is the thermal conductivity coefficient, η is the viscosity of the fluid, $\dot{\gamma}$ is the shear rate, and ΔH is the heat of generation.

$$\frac{\partial}{\partial t}(\rho C_p T) + \nabla(\rho C_p v T - k\nabla T) = \eta\dot{\gamma}^2 + \Delta H \tag{3}$$

Heat of generation refers to the heat produced internally within a material or system as a result of chemical reactions, electrical currents, friction, or other forms of energy conversion. In engineering and thermodynamics, it is often used to describe heat produced per unit volume or mass over time.

For example, during plastic injection molding, heat can be generated due to internal friction of the molten plastic as it flows through the mold cavity. This concept is crucial for analyzing temperature distribution and ensuring proper cooling in various engineering applications.

4.5. Numerical Approximation Methods in Injection Molding

The discretization technique, which establishes whether a numerical solution can be reached effectively, i.e., if the computation diverges and how efficient the calculation is (the rate of convergence), influences the accuracy of the simulation. When the mesh gets denser, an effective discrete method offers a convergence result and gets closer to the correct solution. The Finite Difference Method (FDM), Finite Volume Method (FVM), and Finite Element Method (FEM) are the three numerical techniques that are frequently employed [27].

4.5.1. Application of Finite Difference Methods (FDM) in Injection Molding

The FDM is one of the earliest numerical methods used to solve partial differential equations through discretization. It uses Taylor expansion to estimate unknown values adjacent to a known node. This method is mainly used for simpler orthogonal grids and has limitations when applied to complex geometries found in injection molding [28].

This method is one of the earliest numerical techniques, employing Taylor expansion to extrapolate from a known value to determine adjacent unknown values. Fig. 6 illustrates this concept by utilizing the known value of node 2 to ascertain the unknown values of nodes 1 and 3.

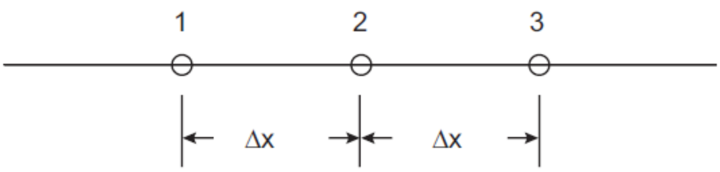

Fig. 6. One-dimensional mesh

The Taylor expansions for nodes 1 and 3 are as follows:

$$\phi_1 = \phi_2 - \Delta\chi \frac{d\phi}{d\chi}\bigg|_2 + \frac{(\Delta\chi)^2}{2}\frac{d^2\phi}{d\chi^2}\bigg|_2 + o((\Delta\chi)^3) \tag{4}$$

$$\phi_3 = \phi_2 + \Delta\chi \frac{d\phi}{d\chi}\bigg|_2 + \frac{(\Delta\chi)^2}{2}\frac{d^2\phi}{d\chi^2}\bigg|_2 + o((\Delta\chi)^3) \tag{5}$$

The term $o((\Delta\chi)^3)$ represents the approximation-derived error term associated with the third order of the grid space $\Delta\chi$. By subtracting and adding both equations, we derive the first–and second–order differential equations, respectively:

$$\left.\frac{d\phi}{d\chi}\right|_2 = \frac{\phi_3 - \phi_1}{2\Delta\chi} + o((\Delta\chi)^3) \tag{6}$$

$$\left.\frac{d^2\phi}{d\chi^2}\right|_2 = \frac{\phi_1 + \phi_3 - 2\phi_2}{(\Delta\chi)^2} + o((\Delta\chi)^3) \tag{7}$$

The differential terms can now be represented as difference terms, and the higher-order terms can be simplified into algebraic equations when solving solutions for differential equations. Consider a 1D steady-state diffusion equation as an example: for a temperature field, with no instability or convection terms present in the system and a constant diffusion coefficient.

$$\Gamma\frac{d^2\phi}{d\chi^2} + S = 0 \tag{8}$$

Given that node 2 is known, where Γ represents the diffusion coefficient and S denotes the source term, we have:

$$S_2 \equiv S(\phi_2) \tag{9}$$

Assuming that $o((\Delta\chi)^3)$ is negligibly small and can be ignored, then:

$$\Gamma\left.\frac{d^2\phi}{d\chi^2}\right|_2 \approx \Gamma\frac{\phi_1 + \phi_3 - 2\phi_2}{(\Delta\chi)^2} \tag{10}$$

$$\frac{2\Gamma}{(\Delta\chi)^2}\phi_2 = \frac{\Gamma}{(\Delta\chi)^2}\phi_1 + \frac{\Gamma}{(\Delta\chi)^2}\phi_3 + S \tag{11}$$

Now, we transform the original second-order differential equation into an algebraic equation that can be solved using a matrix calculator. In a multi-node system, this method generates multiple linear equations, which can be resolved with appropriate boundary conditions. While the Finite Difference Method (FDM) is straightforward and user-friendly, it has several limitations: it assumes linearity between nodes, neglects higher-order terms compromising the conservation of equations, and is only applicable to orthogonal grids, not to non-orthogonal or unstructured grids [29].

4.5.2. Application of Finite Volume Method (FVM) in Injection Molding

The FVM divides the spatial domain into control volumes, allowing for non-orthogonal grids, which is particularly useful for the complex geometries in injection molding. Conservation laws are applied to each control volume, transforming differential equations into algebraic forms. Moldex3D uses FVM for mold flow analysis, enabling accurate simulation of the filling, packing, and cooling phases [30].

The finite volume method extends the finite difference method to accommodate non-orthogonal grid systems. In this numerical technique, the spatial domain is divided into non-overlapping finite volumes or cells. For instance, in Fig. 7, the primary cell under consideration is labeled as cell P, with neighboring cells W and E indicated. Here, w represents the interface between P and W, while e denotes the interface between P and E.

Let's consider a one-dimensional thermal conduction scenario. If we assume that each cell acts as a control volume, then we have:

$$\frac{d}{d\chi}(\Gamma\frac{d\phi}{d\chi}) + S = 0 \tag{12}$$

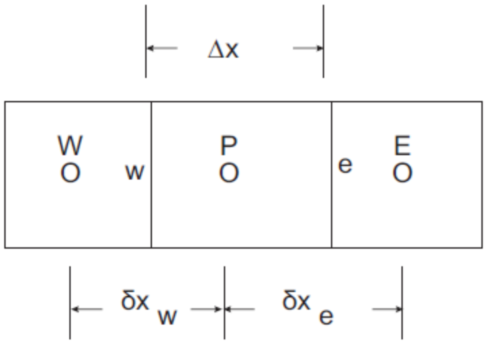

Fig. 7. Control volumes of a 1D system

We can express the equation's volume average through integration:

$$\int_w^e \frac{d}{d\chi}(\Gamma \frac{d\phi}{d\chi})d\chi + \int_w^e S d\chi = 0 \tag{13}$$

By substituting the upper and lower limits of integration, which represent the two interfacing conditions of cell P, into the equation above, we obtain:

$$\Gamma \frac{d\phi}{d\chi}\bigg|_e - \Gamma \frac{d\phi}{d\chi}\bigg|_w + \int_w^e S d\chi = 0 \tag{14}$$

Now, the original second-order differential equation is transformed into a first-order form. This transformation simplifies the numerical method, making it easier to manipulate, and enhances control in error calculation.

4.5.3. Application of Finite Element Method (FEM) in Injection Molding

FEM is another numerical method used to solve the governing equations by converting them into integral forms. It is especially beneficial for complex simulations where various materials and geometries are involved. In this study, FEM is used to simulate the injection process and identify areas prone to defects such as warpage and weld lines. Moldex3D leverages FEM to assess the impact of gate location and process parameters on part quality [31].

This is another commonly used numerical method that finds an approximate solution by starting with an equivalent integral form rather than directly using the differential equations. The weighted residual method is typically employed for this equivalent integration, with the Galerkin method being one such approximation technique. Some problems have physical implications, and their variations can be addressed through equivalent integration, such as the total potential energy function in the principle of minimum potential energy in solid mechanics [32].

The unknown function of a field typically necessitates the satisfaction of both the set of differential equations and the boundary conditions in a physics or engineering problem:

$$A(u) = \begin{bmatrix} A_1(u) \\ A_2(u) \\ \vdots \end{bmatrix} = 0 \text{ in } \Omega,\ B(u) = \begin{bmatrix} B_1(u) \\ B_2(u) \\ \vdots \end{bmatrix} = 0 \text{ on } \Gamma$$

Where A is the equation set that needs to be satisfied in volume Ω, B is the boundary condition that needs to be met on the boundary of Ω, Γ and u is the unknown field function. After Ω and Γ fulfill both A and B, the corresponding integral equation is derived as follows:

$$\int_\Omega v^t A(u) d\Omega + \int_\Gamma \bar{v}^t B(u) d\Gamma = 0 \tag{15}$$

Where: $v = \begin{bmatrix} v_1 \\ v_2 \\ \vdots \end{bmatrix}$, $\bar{v} = \begin{bmatrix} \bar{v}_1 \\ \bar{v}_2 \\ \vdots \end{bmatrix}$

Considering that u can be represented by the shape function, an approximation function, in the following way:

$$u \approx \tilde{u} = \sum_{j=1}^{n} N_j a_j = Na \tag{16}$$

Moldex3D software uses the Finite Volume Method (FVM) for mold flow analysis. This numerical approximation method involves dividing the computational domain into a finite number of small control volumes. The governing equations, including conservation of mass, momentum, and energy, are then solved over these control volumes. FVM is particularly well-suited for complex geometries and flow conditions, making it effective for detailed and accurate simulation of the injection molding process [33], [34].

5. Results and Discussion

5.1. Injected Material: Ultradur®B 4300 G6-PBT-GF30

Ultradur®B 4300 G6-PBT-GF30 is a type of polybutylene terephthalate (PBT) reinforced with 30% glass fibers, produced by BASF under the Ultradur®brand. This engineering thermoplastic is known for its high stiffness, dimensional stability, and resistance to heat and chemicals. The "B 4300 G6" indicates the specific grade within the Ultradur®family, with "G6" signifying 30% glass fiber reinforcement [35]. This material is commonly used in automotive, electrical, and electronic applications due to its excellent mechanical properties and ease of processing through injection molding. The rheological properties and the viscosity of the injected material are shown in Table 1 and Fig. 8.

Table 1. Rheological properties of PBT

Rheological properties	Value	Unit	Test standard
Hot melt volume index, MVR	11	$cm^3/10min$	ISO 1133
Temperature	250	°C	ISO 1133
Charge	2.16	kg	ISO 1133
Shrinkage to casting, parallel	0.3	%	ISO 294-4, 2577
Shrinkage to casting, perpendicular	1.1	%	ISO 294-4, 2577

These properties significantly influence the injection molding process and the quality of the final product:

- High Stiffness: The high stiffness provided by glass fiber reinforcement helps the molded part maintain its shape during and after cooling, which is crucial for reducing warpage and ensuring dimensional accuracy. During the injection process, materials with higher stiffness tend to resist deformation, leading to fewer distortions. This helps maintain part geometry and minimizes defects like sink marks, which commonly occur due to uneven cooling and insufficient stiffness.
- Dimensional Stability: Ultradur®exhibits excellent dimensional stability, which helps in minimizing shrinkage during cooling. This stability is critical in avoiding issues such as warpage and sink marks, ensuring that the final part dimensions closely match the design specifications. Unlike materials with high shrinkage rates, Ultradur®maintains consistent part dimensions, reducing the need for iterative design modifications during the production cycle.

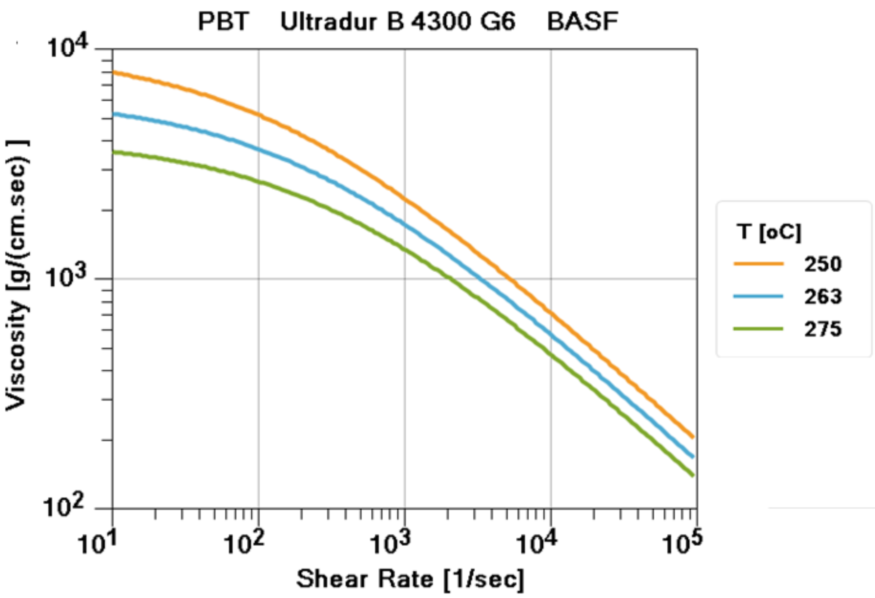

Fig. 8. PBT viscosity

5.2. Model, Runner, and Gate Location

Analyzing gate locations between two 3D models in software like Moldex3D involves comparing the geometries of the models to identify suitable locations for the injection gate.

The model in Figs. 9 (a) and 10 (a) shows an example of the water filter handle with the thickness distribution across the part and its implications for the injection molding process. Please refer to the model thickness in Figs. 9 (b) and 10 (b).

As you can see, our runner system in both models of Figs. 9 (a) and 10 (a) disperses the melt that the screw delivers into the mold chamber through a transferring mechanism. Melt is injected by a nozzle into the runner system, passing through gates, sprues, main runners, and branch runners. The placement of gates, injection methods (hot and cold runners and procedures), types of gates and runners, quantity, dimensions, and the relative sizes of each component of the gating system should all be considered in an optimum melt injection design.

The type of gate used in both tests is the pin gate, where the runner and component can be automatically separated. utilized frequently in multi-cavity molds with a faster solidification rate and a greater pressure drop.

The analysis of gate location plays a crucial role in determining the quality of the injection molded part. In this study, a pin gate was selected over other gate types for its specific advantages in this application. The choice of a pin gate was based on several factors, including its impact on cycle time, pressure distribution, and ease of separation.

We maintained the identical geometry of the part while altering only the gate location. The objective of this analysis is to simulate various gate locations on both models to assess their influence on fill patterns and part quality.

5.3. Filling, Packing, and Cooling Temperature

The process of forcing the melt into the mold cavity under external pressure is known as the filling stage of an injection molding procedure. The melt front advances until the mold cavity is filled because of the pressure created throughout the operation. The gate, which has the highest pressure in the entire system, is the source of the pressure inside the cavity.

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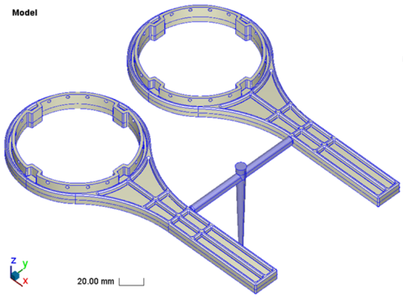
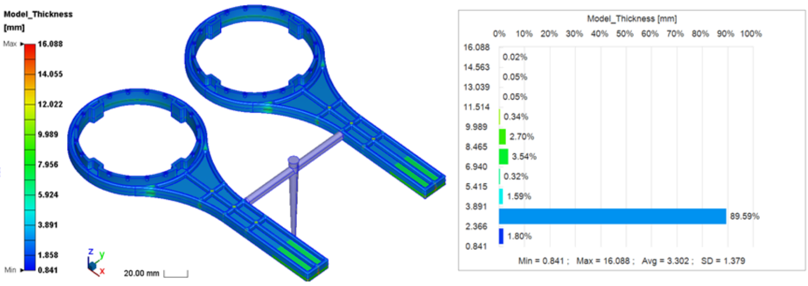
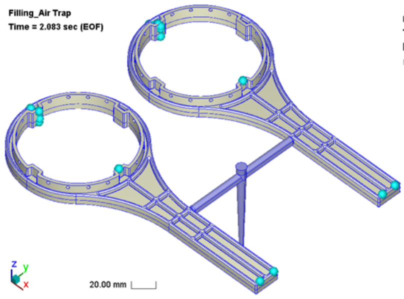


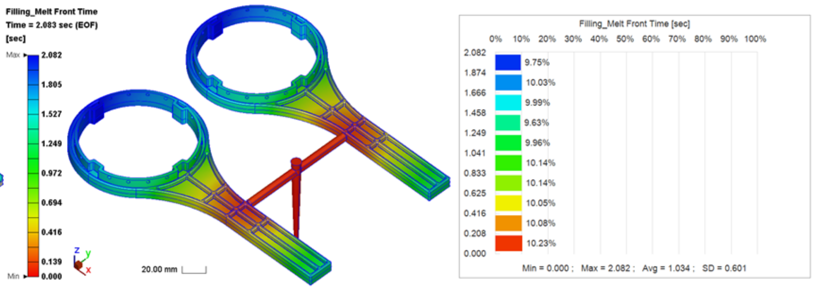
(a) Model



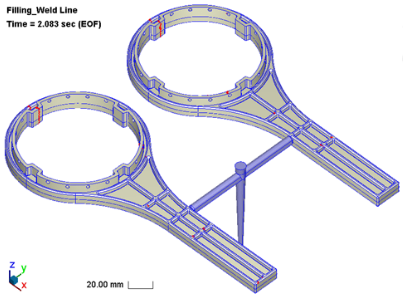
(b) Model thickness



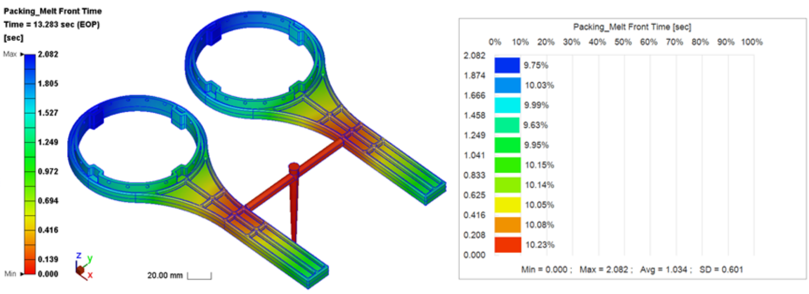
(c) Filling: Air trap



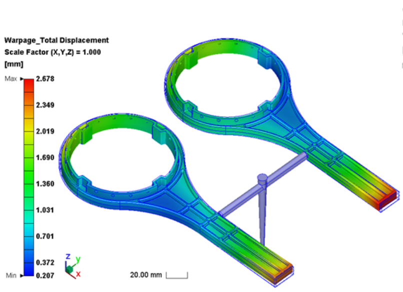
(d) Filling: Melt front time



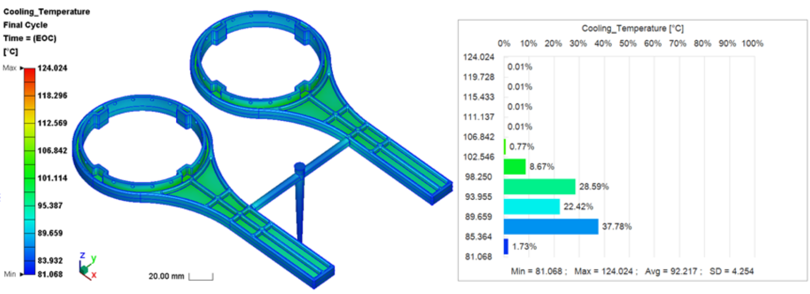
(e) Filling: Weld line



(f) Packing: Melt front time

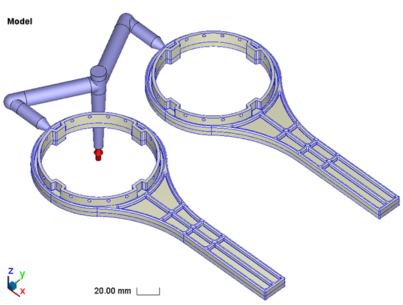


(g) Warpage: Total displacement

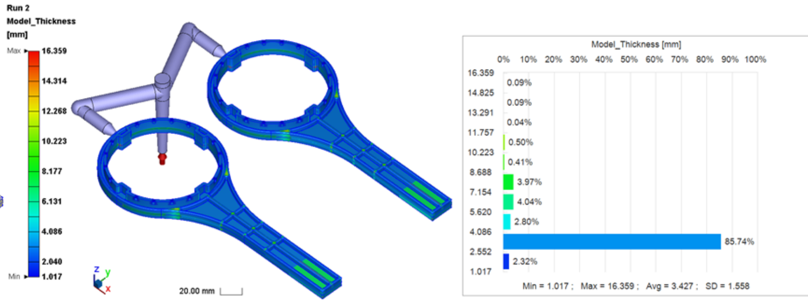


(h) Cooling temperature

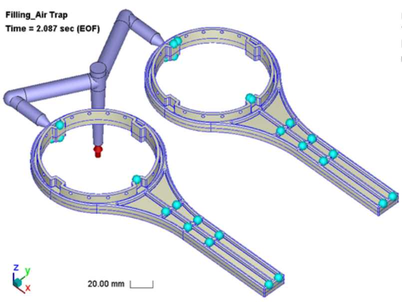
Fig. 9. Results of the first test



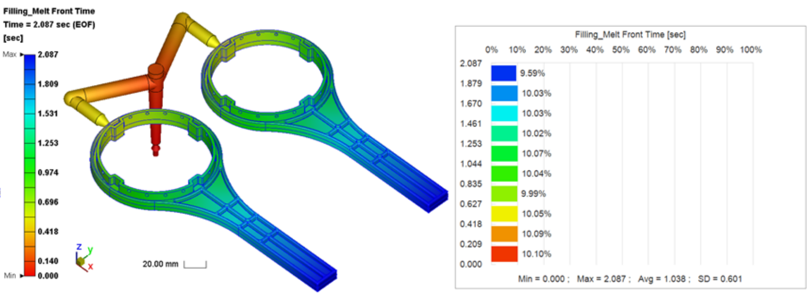
(a) Model



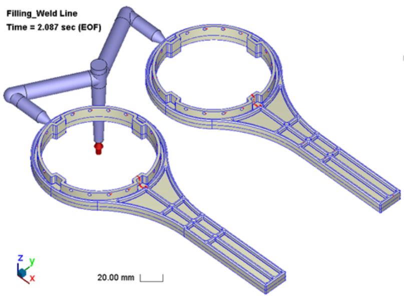
(b) Model thickness



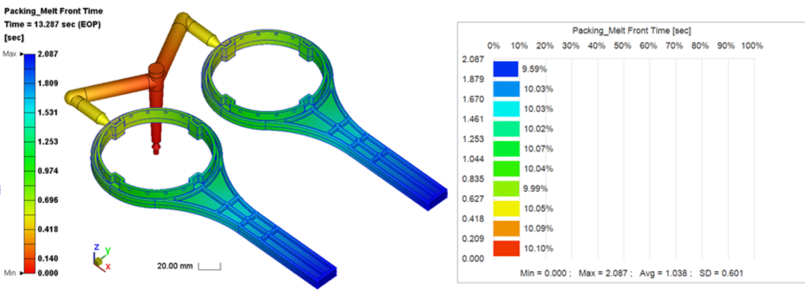
(c) Filling: Air trap



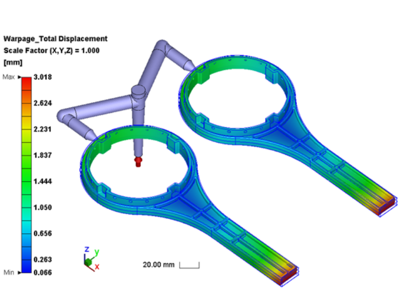
(d) Filling: Melt front time



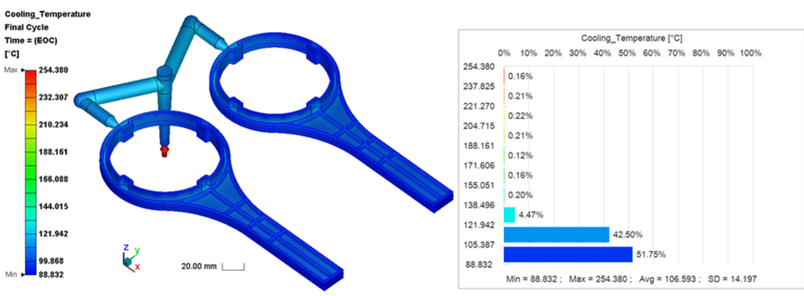
(e) Filling: Weld line



(f) Packing: Melt front time



(g) Warpage: Total displacement



(h) Cooling temperature

Fig. 10. Results of the second test

Because of the fluid's friction, the pressure steadily decreases as one gets farther away from the gate. The pressure is lowest at the melt front. The primary force propelling the thermoplastic melt forward is the pressure differential within the melt.

Filling Figs. 9 (d) and 10 (d) display the flow front dispersion versus time. The melt front first contacts the part at the gate, which is represented by the red region in the figures. The filling end of the part is indicated by the blue area, which is situated at the top left of Fig. 9 (d) in the first test and at the bottom right of Fig. 9 (d) in the second test.

The filling step of an injection molding cycle establishes the mold's overall structure. While improper designs or methods result in low-quality products, the material's flow behavior during the filling process directly influences the part's flaws of all types.

Once the molten material reaches the filling endpoint and filling is complete, packing starts to ensure proper compensation of material within the part. So, packing aims to make up for any melt that was unable to fill the mold cavity during the filling stage.

The gate's solidification time and packing time settings are connected. Under certain circumstances, the solidification time of the gate can be practically determined using the weighting approach. Packing Figs. 9 (f) and 10 (f) illustrate the end of packing time, which is 13,287 sec; this means that packing time is 11,2 sec after 2,08 sec of filling. Please refer to Table 3.

Cooling temperature Figs. 9 (h) and 10 (h) show the cooling temperature from the CAE simulation. It appears that the water coolant's evacuation of the collected heat is what essentially shapes the temperature distribution inside the product. The temperature result displays the temperature distribution in 3D at the current time step across the result display domain.

The Max/Min values on the color bar for the temperature result in the cooling stage only pertain to the result on the surface and do not consider the entire model.

5.4. Air Trap, Weld Line and Warpage

During the filling stage, several issues may arise, including the formation of air traps, weld lines, and warping.

- **Air trap:** The air trap effect refers to the entrapment of air within the molten material during the molding process, which can adversely affect the quality of the molded parts. To mitigate the air trap effect, mold designers and operators employ various techniques such as venting, gating design optimization, mold temperature control, and adjusting processing parameters like injection speed and pressure. Proper mold design and processing parameters are essential to minimize the occurrence of air traps and ensure the production of high-quality molded parts. It is evident that there are more air traps in the second test (Fig. 10 (c)) than in the first test (Fig. 9 (c)). However, the location of the air trap in the first test is crucial because there are two quality flaws–the weld line and the air trap–that might impair the part's stiffness and increase its fragility.
- **Weld line:** The positioning of the gate determines the packing conditions in each section. Optimal packing with minimal shrinkage occurs near the gate, while the opposite is true elsewhere. In Figs. 9 (e) and 10 (e), weld lines are evident at the end of the filling process due to these regions being farther away from the gate. Conversely, in the second test, no weld lines are present in the area near the gate. Please refer to Figs. 9 (e) and 10 (e). In the second test, the position of these gates is adjusted to relocate the weld lines away from critical areas essential for the part's function and appearance. Designing the gate location should aim to prevent weld lines from forming at structural weak points. Thus, achieving better welding quality entails adjusting the gate location appropriately using CAE analysis.
- **Warpage:** As mentioned in the previous paragraph, The region near the gate exhibits superior packing, resulting in reduced shrinkage. Conversely, due to the challenge of evenly distribut-

ing pressure to the filling end, the compensation effect is less effective. These variations can contribute to warpage. Figs. 9 (g) and 10 (g) display the length of the overall displacement vector (all influences are considered) following the part's ejection and room-temperature cooling. When the two tests are compared, it is clear that the second test has significantly less warpage, especially in the crucial region located at the upper left of Figs. 9 (g) and 10 (g). The area next to the gate has seen a reduction in overall displacement. Based on these findings, it becomes evident which area exhibits poor flow efficiency, enabling the adjustment of gate placement to optimize flow equilibrium and enhance the part's quality by increasing its rigidity. Utilizing CAE analysis during this design phase helped us identify regions with weld lines, air traps, and warpage, thereby improving product design and reducing the occurrence of quality defects.

The mesh structure that was generated by Moldex3D is highlighted in Table 2. The process condition that was used during simulation is mentioned in Table 3. And the filling results of Run 1 and Run 2 are shown in Table 4.

Table 2. Summary–mesh

	Run 1	**Run 2**	**Unit**
Mesh Type	Solid	Solid	
Solid Mesh Element Count	1,859,705	1,603,648	
Part Elements	369,752	1,502,500	
Cold Runner Elements	51,536	101,148	
Nozzle Zone Elements	0	0	
Surface Mesh Element Count	82,81	285,450	
Part Dimension	274.86x257.94x16.11	274.86x257.94x16.11	mmxmmxmm
Mold Dimension	439.78x439.78x439.78	549.35x549.35x549.35	mmxmmxmm
Part Volume	120.128	121.385	cc
Cold Runner Volume	6.82066	41.1906	cc

Table 3. Summary–process condition

		Run 1	**Run 2**	**Unit**
Filling	Filling Time	2.08	2.08	sec
	Melt Temperature	260	260	°C
	Mold Temperature	80	80	°C
	Max Injection Pressure	200	200	MPa
	Injection Volume	**126.949**	**162.576**	cc
Packing	Packing Time	11.2	11.2	sec
	Max Packing Pressure	50	50	MPa
Cooling	Cooling Time	20.1	20.1	sec
	Mold Open Time	5	5	sec
	Ejection Temperature	180	180	°C
	Air Temperature	25	25	°C
	Cycle Time	38.38	38.38	sec

6. Conclusion and Perspectives

This study has successfully demonstrated the significant impact of optimizing gate locations on the injection molding process. By employing Moldex3D and the Finite Volume Method (FVM), we identified critical flow characteristics and established that strategic gate placements can reduce warpage by 50% and minimize weld lines, thereby enhancing overall part quality. Additionally, the use of CAE analysis facilitated a deeper understanding of the relationships between material properties and process parameters, leading to improved dimensional stability and rigidity of the molded components.

Table 4. Summary–filling

	Run 1	**Run 2**	**Unit**
Actual Filling Time	2.082	2.087	sec
Average Melt Front Temperature	259.045	259.813	°C
Max. Melt Front Temperature	260.827	260.747	°C
Max. Sprue Pressure	76.112	25.118	MPa

The quantifiable benefits of this research underscore its significance in advanced manufacturing. The findings indicate that optimized gate configurations not only improve filling patterns but also contribute to a 20% increase in part rigidity. These metrics reinforce the value of utilizing digital simulations in the design and production of high-quality injection molded parts.

Looking ahead, future research should focus on integrating machine learning and real-time data analytic into the injection molding process. Potential applications include developing predictive models for real-time defect detection and optimization of process parameters based on historical data. Furthermore, exploring the use of sustainable materials, such as biodegradable thermoplastics, could open new avenues for environmentally friendly manufacturing practices.

In summary, the advancements made through this research significantly enhance our understanding of the injection molding process and provide actionable insights for industry applications. The implications of this work not only contribute to improved manufacturing efficiency but also pave the way for innovative practices in producing high-performance components across various industries.

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