Research Article

Pressure-Controlled Runner Optimization and Filling Balance Analysis in Multi-Cavity Injection Molds

Muhammet Furkan Çalık[1]*, Ceren Giray Karaeli[2]

[1]Escuturco, Orcid ID: https://orcid.org/0009-0006-1031-1672, e-mail: calik.mfc@gmail.com
[2] Escuturco, Orcid ID: https://orcid.org/0009-0008-3820-0960, e-mail: cereng22@gmail.com
* Correspondence: calik.mfc@gmail.com

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Abstract

In this study, the effects of runner-system design on filling balance and pressure distribution in multi-cavity injection molds were investigated through Moldex3D simulations. Four runner configurations—H-type, Symmetrical-type, Star-type, and Fishbone-type—were evaluated using the material SCHULAMID® 6 MV14 FR4 K1681. The simulation results revealed that runner geometry has a decisive influence on filling uniformity, and they further demonstrated the effectiveness of a pressure-controlled runner approach in improving overall product quality. The findings highlight the importance of rheology-based optimization in runner-system design. This study differentiates itself from previous research by providing a comparative analysis of multiple runner types and by demonstrating that balanced filling can be successfully achieved not only in molds with 2^n cavity counts but also in intermediate cavity numbers such as 12 and 14. The rheology-based pressure-controlled methodology presented here introduces a new optimization perspective for multi-cavity injection mold design.

Keywords: Injection molding, Runner design, Filling balance, Rheological analysis, Multi-cavity mold, Pressure distribution, Moldex3D

1. Introduction

Polymer materials are widely used in sectors such as automotive, aerospace, electronics, and consumer goods due to their favorable mechanical properties, ease of processing, and suitability for high-precision mass production (Bajracharya et al., 2016). Among polymer-processing technologies, injection molding stands out as one of the most efficient methods for producing parts with consistent quality and dimensional stability. In this context, mold design—particularly the design of the runner system—plays a decisive role in determining filling uniformity, product performance, and overall manufacturing efficiency. Achieving balanced filling in multi-cavity molds is essential to ensure that identical components are formed under equivalent pressure and thermal conditions.

The runner system governs the distribution of molten polymer into each cavity and strongly affects pressure drop, shear rate, and local thermal gradients along the flow path. An unbalanced runner system may lead to defects such as short shots, dimensional deviations, warpage, sink marks, and increased scrap rates. Pressure-controlled runner optimization aims to minimize these issues by ensuring that each cavity experiences similar pressure and flow characteristics. This approach enhances product quality, reduces cycle time and scrap rate, and contributes to more sustainable and cost-effective production.

Traditional multi-cavity molds frequently employ fishbone or family-type runner layouts. Although these designs can reduce mold size and simplify fabrication, they often exhibit filling imbalance due to unequal flow paths and shear-dependent viscosity variations (Strong, 1999; Beaumont, 2004). While geometric balancing—equalizing the distance from the melt entry point to each cavity—has been widely implemented, research has shown that geometric symmetry alone does not guarantee filling balance (Strong, 1999). Yang et al. (2008) demonstrated that even in geometrically balanced H-type runner systems, factors such as injection speed, melt temperature, and mold temperature influence filling behavior.

A major cause of imbalance arises from shear-induced temperature gradients within the runner. When molten polymer undergoes a 90° directional change from the gate into the first channel, high-shear regions experience greater viscous heating than low-shear regions, resulting in a non-linear temperature distribution along the runner (Yang et al., 2008). This temperature asymmetry reduces viscosity on the hotter side of the channel, promoting preferential flow and ultimately leading to cavity-to-cavity filling imbalance and quality inconsistencies (Abdullahi et al., 2016). These thermal and rheological effects are illustrated in Figure 1.

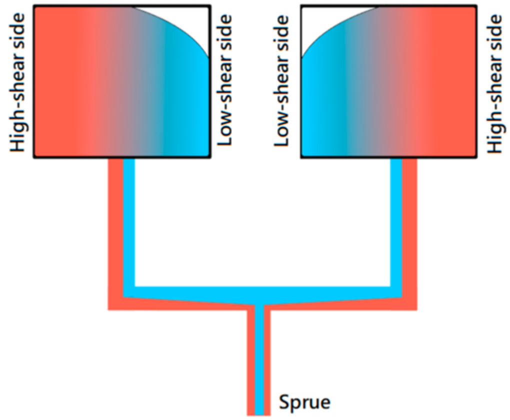

Figure 1: Effect of low shear rate and high shear rate within the runner.

Advances in mold-flow simulation tools such as Moldex3D have made it possible to accurately predict filling behavior, pressure distribution, and shear-induced thermal variations during the early stages of mold development. Simulation-based runner optimization allows potential design flaws to be identified prior to mold fabrication, thereby reducing costly trial-and-error iterations and improving production reliability (Tsai et al., 2022). According to industrial guidelines, the pressure difference between cavities should generally not exceed approximately 13.7 MPa (2000 psi). Larger variations may lead to dimensional inaccuracies, surface defects, or incomplete filling (Protolabs, 2024). Among the factors affecting pressure distribution, including material rheology, mold temperature, and injection speed, the runner system remains the most difficult and expensive parameter to modify after tool manufacturing.

Although numerous studies have examined H-type or geometrically balanced runner configurations, there is limited research that compares multiple runner types within a unified rheological and pressure-controlled design framework (Wilczyński & Narowski, 2020; Zhu et al., 2021). Furthermore, while molds with cavity counts of 2^n are commonly used in industry, achieving balanced filling in intermediate cavity numbers such as 12 or 14 has not been extensively documented.

To address these gaps, this study investigates the effects of pressure-controlled runner optimization on filling balance and cavity-specific pressure distribution by comparatively analyzing four runner configurations: H-type, Symmetrical-type, Star-type, and Fishbone-type runners, using Moldex3D simulations. The objective is to evaluate the influence of runner geometry from a rheological perspective and to provide new insights into achieving balanced filling in multi-cavity molds, including those with non-standard cavity numbers. This research aims to contribute a comprehensive framework for runner-system optimization in multi-cavity injection molding.

2. Materials and Methods

2.1. Material Selection for the Study

In this study, the SCHULAMID® 6 MV14 FR4 K1681 Natural raw material, produced by LyondellBasell, was selected. This material is widely used in electronic components due to its high thermal resistance and suitable electrical insulation properties. Within the scope of this study, an electronic component, the insulator, was chosen, and this material was employed for analyses and part production. The main properties of the selected material are summarized in Table 1.

Table 1: Material Properties of SCHULAMID® 6 MV14 FR4 K1681.

Raw Material	SCHULAMID 6 MV14 FR4 K1681
Material Type	Polyamide 6 (PA6)
Density	1.26 g/cc
Melt Temperature	240 °C
Solidification Temperature	188 °C
Mold Temperature	75 °C

2.2. Part Design

The part selected for this study was an insulator with dimensions of 6 × 7 × 24 mm. The insulator is an electronic component that provides electrical insulation between circuit elements, preventing electrical conduction, while also facilitating mechanical assembly. The insulator used in this study is shown in Figure 2.

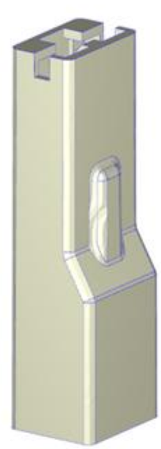

Figure 2: 3D model of the insulator used in the study.

2.3. Machine Selection and Injection Parameters

In this study, injection molding analyses were performed using Moldex3D software, and production simulations were conducted on a Fanuc S-2000i150B series machine. The technical specifications of the machine are presented in Table 2.

Table 2: Machine Specifications.

Machine	Fanuc
Serial No	S-2000i150B-STD-36
Screw Diameter (mm)	36
Clamping Force (tf)	180
Injection Pressure (bar)	2800

The general injection parameters used in the analysis studies are presented in Table 3.

Table 3: Injection molding process parameters used in the simulations.

Machine	Fanuc
Serial No	S-2000i150B-STD-36
Melt Temperature	240 °C
Mold Temperature	75 °C
Injection Speed	40-50-60 (3 step)
Injection Pressure	1300 bar
Injection Time	0.2 s
Transfer Point	98%
Holding Pressure	60%-45%-25% (3 Step)
Holding Time	3 s
Cooling Time	10 s

2.4. Analysis Studies

The same part was filled using four different types of runner configurations. The designed runner diameters were 3 mm. A round runner cross-section type was used, as this geometry minimizes pressure loss and offers lower flow resistance. Only the Fishbone-type runner (d) had a trapezoidal cross-section. The mold concept was designed such that the hot runner system extends inside the mold up to the cold runner gate. The runner configurations analyzed in this study include commonly used designs such as (a) H-type runner, (c) Star-type runner, and the newly developed (b) Symmetrical-type runner, as well as the (d) Fishbone-type runner. The comparative weights and cavity numbers of the runners are presented in Table 4.

Table 4: Cavity count and runner weight comparison for the four runner configurations.

Runner Type	Runner Weights (grams)	Number of Cavities (units)
H-type runner	5.79	16
Symmetrical-type runner	4.64	12
Star-type runner	5.04	14
Fishbone-type runner	9	48

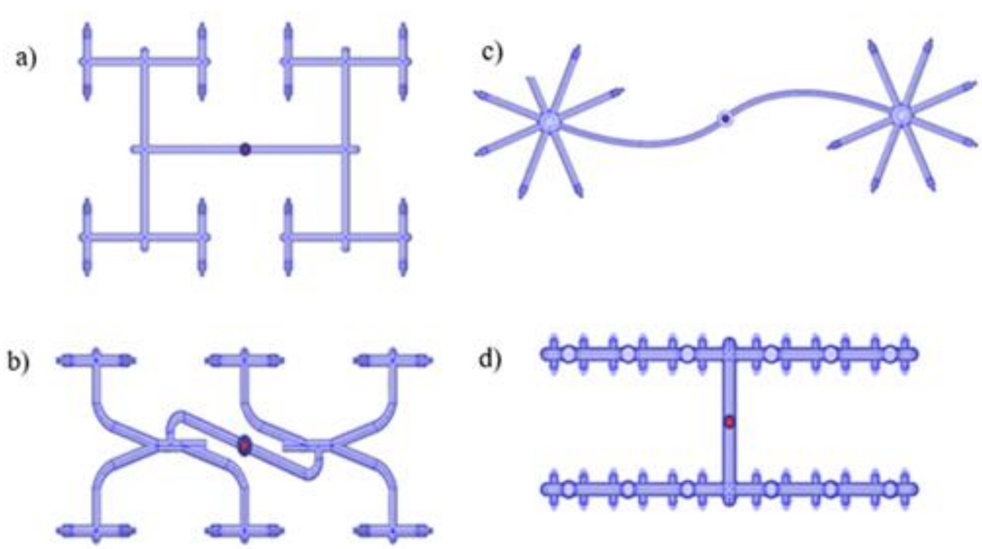

Figure 3: Mold layout and cavity arrangement for multi-cavity runner evaluation.

Separate analyses were conducted for each runner type, and the filling amounts in each cavity were examined in detail. In this study, the Taguchi optimization method was employed to determine the optimum processing parameters, and the evaluations were carried out under conditions in which the filling pressure values among all cavities were as close to each other as possible. The Taguchi optimization method is an effective approach for designing and optimizing production processes under varying conditions and is widely used in injection molding to achieve high product quality and low production costs (Zhu et al., 2021). The combination of Taguchi methods and simulation techniques can effectively address filling imbalance issues in injection molds (Wilczyński & Narowski, 2020). Altan (2010) reported that the Taguchi method serves as an efficient predictive tool for determining the effects of process parameters on the shrinkage of injection-molded parts, thereby contributing to improved product quality. The quality of injection-molded products is evaluated based on filling behavior, volumetric shrinkage, warpage, and sink marks, all of which are influenced by mold temperature, melt temperature, flow rate, and injection pressure (Yang et al., 2008; Wu et al., 2021). These four parameters play a critical role in selecting the most optimal filling conditions. In this study, melt temperature, flow rate, mold temperature, and filling pressure were designed and evaluated using the Taguchi L9 orthogonal array, which is well known for its efficiency and effectiveness in experimental design (Alafaghani & Qattawi, 2018). Table 5 presents the parameters used in the Taguchi L9 orthogonal array for the Symmetrical-type runner distribution (b).

Table 5: Taguchi L9 orthogonal array for the Symmetrical-type runner distribution (b)

Control Factor	Melt Temperature [°C]	Mold Temperature [°C]	Max. Flow Rate Profile Value [%]	Max. Injection Pressure Profile Value [%]
Level	3	3	3	3
Max	250	78	20	65
Min	230	70	10	45
L1	230	70	10	45
L2	230	75	15	55
L3	230	78	20	65
L4	240	70	15	65
L5	240	75	20	45
L6	240	78	10	55
L7	250	70	20	55
L8	250	75	10	65
L9	250	78	15	45

L9*	250	78	15	45

3. Results

According to the analysis results obtained using the optimum parameters determined by the Taguchi method for each runner design, when approximately 75% of the filling process was completed, it was observed that the H-type (a), Symmetrical-type (b), and Star-type (c) runner layouts exhibited similar filling ratios among all cavities.
In contrast, in the Fishbone-type (d) runner layout, the cavities located closer to the mold gate were found to have higher filling volumes compared to those positioned farther away.
Figure 4 illustrates the 75% filling stage within the mold.

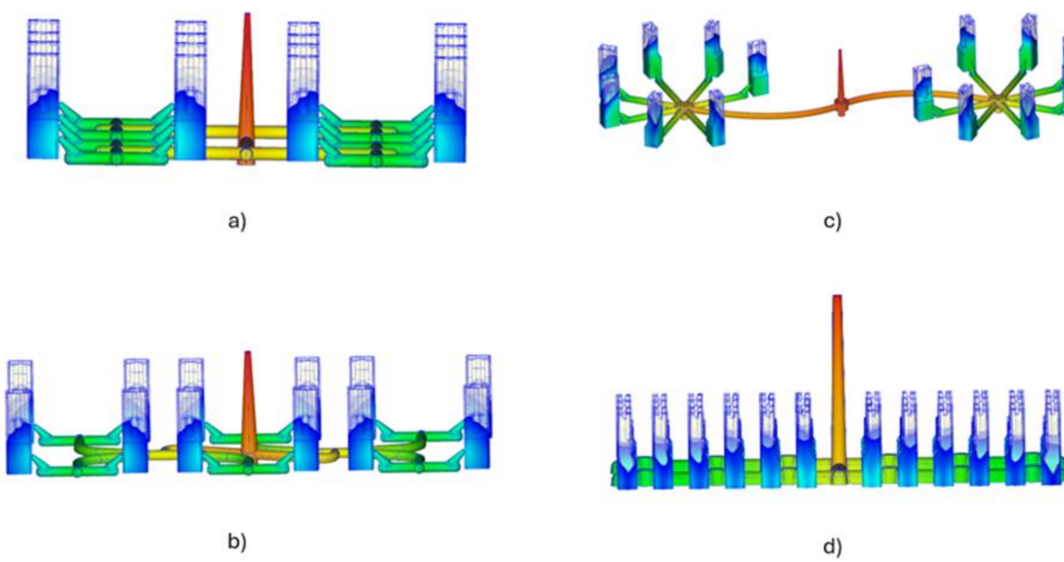

Figure 4: Filling behavior at 75% of the injection stage for the four runner designs.

When the filling level reached 90%, the variations became more pronounced. In the H-type (a) and Symmetrical-type (b) runner layouts, the filling balance was maintained for all cavities. However, in the Star-type (c) runner layout, the filling volume of the four cavities located near the runner gate increased compared to the others. In the Fishbone-type (d) runner layout, the cavities close to the gate completed filling, while the remaining cavities had not yet been fully filled. Figure 5 shows the 90% filling level within the mold.

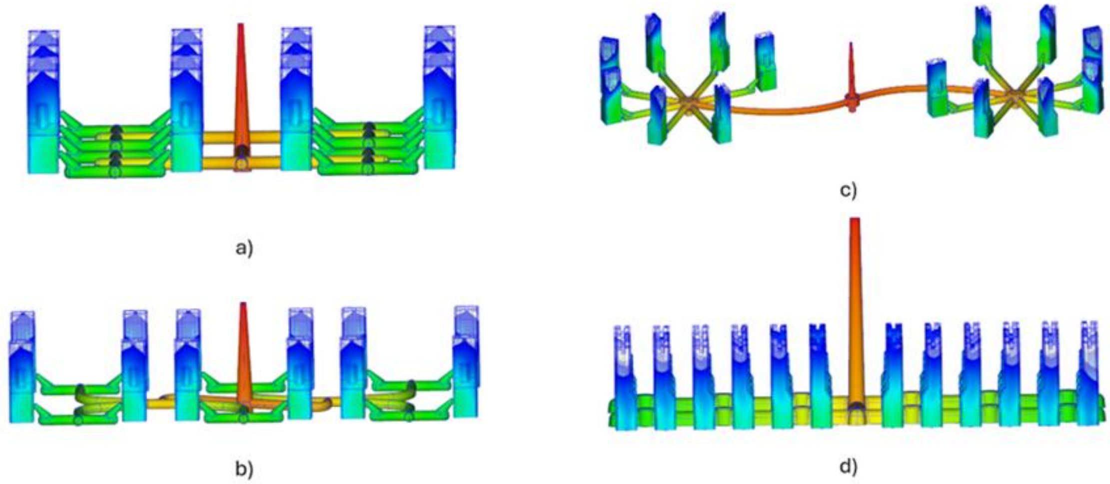

Figure 5: Filling behavior at 90% of the injection stage for the four runner designs.

At the 100% filling level obtained from the rheological analysis (Figure 6), measurements were taken from the final filling points of each cavity.

These measurements reveal the influence of runner design on product performance. Since the measurements taken along the symmetry axes of each runner design yielded nearly identical values, the probe measurements were conducted at the regions where the differences were most significant.

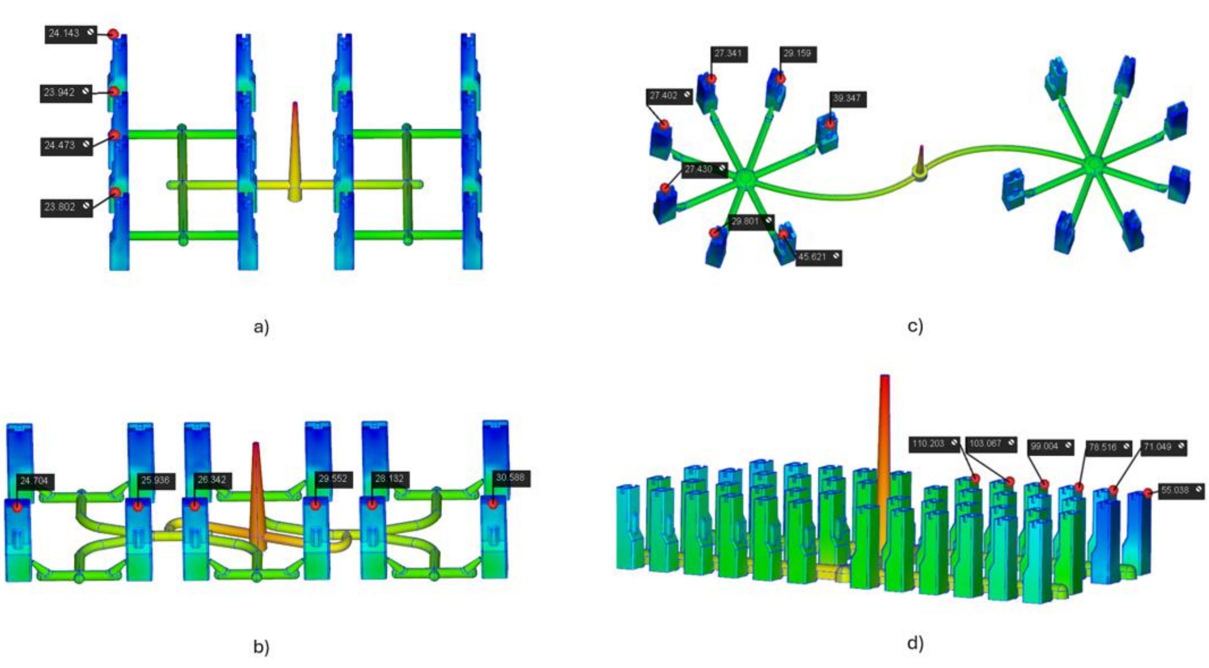

Figure 6: Filling behavior at 100% of the injection stage for the four runner designs.

According to the analysis results, the filling end pressure values measured by the probes for each runner type are presented in Table 6. It was observed that the pressure differences in the Star-type runner (c) and Fishbone-type runner (d) configurations exceeded 13.7 MPa (Protolabs, 2024).

Table 6: End-of-Fill Pressures for Each Cavity.

	Fill Pressures at Marked Probes (MPa)			
Number of Cavities	a)	b)	c)	d)
1	24.143	30.588	39.347	110.203
2	23.942	28.132	29.159	103.067
3	24.473	29.552	27.341	99.004
4	23.802	26.342	27.402	78.516
5	-	25.936	27.430	71.049
6	-	24.704	29.801	55.038
7	-	-	45.621	-
Difference	0.671	5.884	18.280	55.165

Note. "–" indicates that the corresponding cavity does not exist for that runner configuration.

The equality of filling end pressures between cavities is a critical parameter for maintaining filling balance and ensuring part quality.

In the graphical analysis of the results, under ideal conditions, the pressure curves corresponding to each runner type are expected to exhibit a horizontal distribution.

Increasing variations in filling pressures cause the curves to become steeper, which makes the imbalance within the runner system more apparent. This is illustrated in Figure 7.

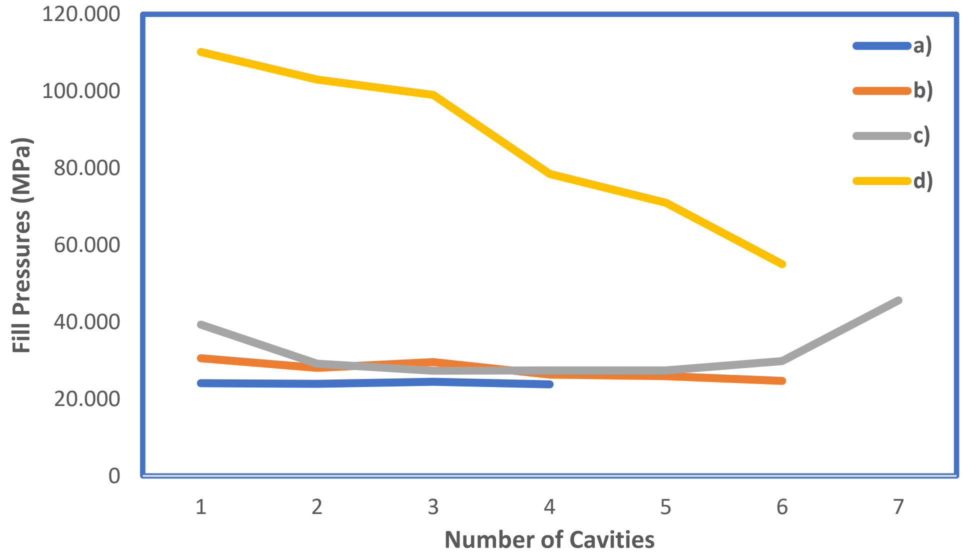

Figure 7: Fill-end pressure distribution for the four runner designs.

When the filling process was completed at 100% cavity fill, the pressure difference between the cavities in the Star-type runner (c) was found to be 18 MPa. The cavities causing this pressure difference were those located near the runner gate. To balance the filling pressure, the runner lengths of the two cavities closest to the gate were extended by 20 mm, and the analysis was repeated. As a result of the new analysis, it was observed that the pressure difference between the cavities decreased to 11 MPa.

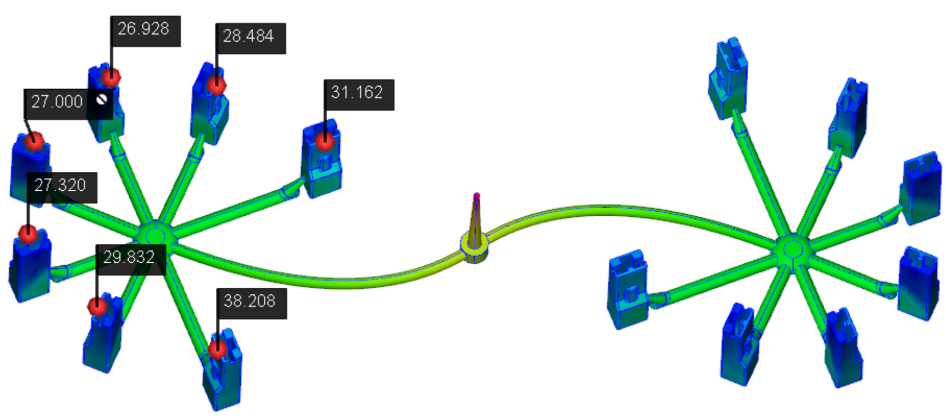

Figure 8: Star-type Runner Extended by 20 mm and Measured Pressures at Probes.

Based on the analyses performed, the amount of runner material consumed for filling each cavity was determined by considering the filling balance (Table 7).

According to the analysis results, it was found that the runner consumption per part was equal in the H-type (a) and Star-type (c) runner layouts.
In the Fishbone-type runner (d) layout, the lowest runner consumption per part was obtained; however, due to the unbalanced filling behavior observed in this design, its use was deemed unsuitable.
On the other hand, the runner consumptions in the H-type (a), Symmetrical-type (b), and Star-type (c) runner layouts were found to be very close to each other.
Therefore, the selection among these runner designs can be made based on criteria such as part geometry, mold structure, and production requirements.

Table 7: Runner Material Consumption.

Runner Type	Runner Weights (grams)	Number of Cavities (units)	Runner Weight per Cavity (grams)
(a) H-type runner	5.79	16	0.362
(b) Symmetrical-type runner	4.64	12	0.387
(c) Star-type runner	5.04	14	0.360
(d) Fishbone-type runner	9	48	0.188

4. Discussion and Conclusion

In this study, the effects of different runner designs on filling balance in multi-cavity injection molds were investigated. The analysis results showed that the H-type runner and Symmetrical-type runner configurations distributed the filling pressure more evenly across all cavities, and the inter-cavity pressure differences at 100% filling remained below the 13.7 MPa limit recommended in the literature (Protolabs, 2024). In particular, in the Star-type runner, the increased pressure applied to the cavities near the gate intensified the filling imbalance, which is consistent with the “critical effect of runner geometry on filling balance” reported in previous studies (Yang et al., 2008; Abdullahi et al., 2016). In the Fishbone-type runner, the high filling differences among the cavities resulted in early filling of the cavities near the gate and delayed filling in the distant cavities, further emphasizing the importance of pressure-controlled runner optimization. The Taguchi optimization method proved effective in enhancing filling balance across all cavities by optimizing filling pressure, melt temperature, mold temperature, and injection speed (Zhu et al., 2021; Altan, 2010). In the Star-type runner, extending the runners near the gate by 20 mm reduced the inter-cavity pressure difference from 18 MPa to 11 MPa, demonstrating the significant influence of small geometric modifications on filling balance.

The pressure differences obtained for each runner layout were evaluated within acceptable limits considering the part requirements, and it was demonstrated that production could be performed using molds with different numbers of cavities. Considering the optimal runner consumption per part and the filling pressure balance, it was found that mold manufacturing is feasible not only for 2^n numbers of parts in the H-type runner layout but also for molds with 12, 14, and their multiple cavity counts. From an economic perspective, although the Fishbone-type runner design exhibits lower runner consumption per part, its usability is limited due to filling imbalance. The H-type runner and Symmetrical-type runner designs maintain filling balance while keeping runner consumption at an optimal level, thereby achieving a balance between product quality and production cost. This highlights the importance of producing high-quality parts at sustainable manufacturing costs.

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