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Optimization Design of Injection Mold Conformal Cooling Channel for Improving Cooling Rate

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Abstract: Optimizing the design of the conformal cooling channel can increase the cooling rate of injection mold. The aim of this study was the problem of low cooling efficiency of injection mold for deep-cavity plastic parts under the conventional cooling channel. Based on the analysis of the heat transfer principle of the injection mold, a mathematical description of the cooling time of the conformal cooling channel was made. By designing orthogonal experiments and using simulation methods in the Autodesk Moldflow 2019 software, with the minimum cooling time of the mold as the optimization goal, experimental optimization was carried out for the three design variables of the channel, thereby obtaining the optimal combination of design variables for the conformal cooling channel. The conformal cooling channel layout was innovatively designed, and through computer simulation experiments, it was concluded that the conformal cooling channel adopted a series flat-head layout, which has the shortest cooling time and the fastest cooling rate. Metal additive manufacturing technology was used to complete the manufacturing of the mold insert with the conformal cooling channel. After the trial production of the conformal cooling injection mold, the molding cycle was obviously shortened, and the injection molding production efficiency was significantly improved.

Keywords: conformal cooling channel; cooling time; channel layout; deep cavity plastic part

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1. Introduction

The primary durations of the injection molding cycle consist of the mold closing, filling, holding pressure, cooling, and demolding times [1,2]. Figure 1 shows the time proportion distribution in each of the stages above. Among them, the cooling period is the most important, making up between 60% and 80% of the molding cycle for injection-molded products [3]. The molding cycle and plastic product yield are immediately impacted. Therefore, reducing the time that the injection molding production cycle needs to cool down is essential to increasing production efficiency.

The length of the cooling time depends on the cooling efficiency of the mold cooling system. Due to the limitations of mold processing technology, the mold cooling system channel is usually drilled into a linear structure in conventional mold manufacturing [4]. This structure makes the distance from the cooling channel to the mold cavity inconsistent, resulting in differences in cooling rates in different parts of the plastic part. The cooling rate of mold parts adjacent to the channel is faster, while the cooling rate of parts far away from the channel is relatively slow. Areas with slower cooling rates extend the cooling time of the entire plastic part, thereby prolonging the molding cycle and reducing production efficiency [5]. In order to improve the cooling efficiency of the mold, the conformal channel process using metal additive manufacturing was introduced into the field of injection mold manufacturing [6,7]. Using conformal cooling to change the heat distribution in the channel can quickly remove heat from the mold and shorten the cooling time, thereby improving production efficiency and ultimately improving the economic benefits of the enterprise.

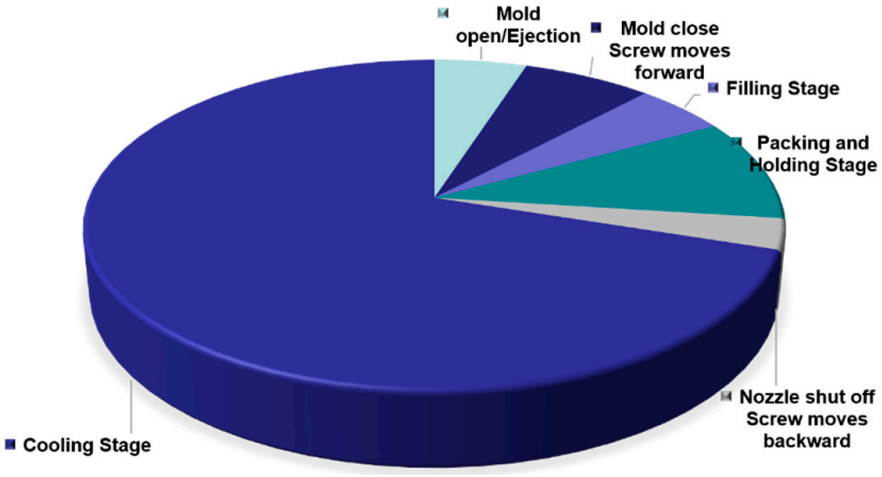


Figure 1. Proportion distribution chart of each stage of the injection mold cycle.

Since the concept of conformal cooling emerged, academic researchers and enterprise engineering designers have been exploring solutions to problems such as cooling channel design and manufacturing. In 2004, Sun et al. [8] explained that tool steel is the most commonly used mold material. However, due to its low thermal conductivity, there are better materials from the perspective of heat transfer efficiency. Although the cooling efficiency can be improved by increasing the coolant flow rate, if the mold cooling channel layout is unreasonable, the coolant flow pressure will increase, which may lead to higher coolant pumping costs. Dang et al. [9] of the University of Ulsan in South Korea introduced the U-shaped milling groove conformal cooling channel in 2011. Using this conformal cooling channel with a U-shaped milling groove can better achieve uniform mold cooling and improve cooling efficiency and part quality, but the processing process is complicated. In 2015, Marques et al. [10] of the SENAI Institute proposed parallel and serial conformal cooling channel design methods based on the analysis of mold heat transfer principles and concluded that the reasonable design of the conformal cooling channel layout is essential. However, the parallel and serial design forms are relatively simple. From 2016 to 2018, Jahan and his team members in the United States [11–13] used the experimental design method to study the optimal design parameters of conformal channels. The optimization objectives were cooling time and von Mises stress, but the product form of the research was relatively simple and did not involve simulation analysis. In 2017, Li et al. [14] of Dalian University of Technology used the topology optimization method to design a conformal cooling system. The results showed that the optimized conformal cooling improved the cooling efficiency. However, the disadvantage is that it still depends on the initial design to a certain extent and cannot achieve the goal of a completely free cooling system design. In 2020, Ma [5] of Qingdao University of Science and Technology used the NSGA-II multi-objective optimization algorithm to perform a multi-objective optimization design of conformal cooling channels and obtained the Pareto optimal solution of the conformal channel design parameters. However, the optimization analysis model was relatively simplified, and the analysis results had certain limitations. In 2021, Feng [15] introduced a rapid thermal cycle molding technology that used conformal cooling channels or additional resistors for heating in the mold. This technology improved the fluidity of the molten polymer during the injection filling stage, thereby improving part quality and shortening the cycle time. This expanded the application of conformal cooling channels in molds. In 2023, Arman et al. [16] summarized that shape, temperature distribution, and pressure drop are the critical parameters of conformal cooling channels in injection molds but did not mention the importance of the distance and layout.

Based on the analysis of the heat transfer principle during the cooling process of the injection mold, this study established a mathematical formula to describe the conformal cooling time of the mold, thereby finding the design variables that affect the cooling time.

The optimal design variable values were determined through orthogonal experiments and simulation methods, and the conformal cooling channel layout was innovatively designed. The optimal layout was obtained through simulation and comparative analysis. Finally, metal additive manufacturing and actual injection molding production were used to verify the conformal cooling channel design and manufacturing feasibility.

2. Research Methods

2.1. Mathematical Model of Heat Transfer in Conformal Cooling

The cooling of injection molds is a complex heat transfer process. Heat is transferred into the mold through the high-temperature viscous plastic melt, and then the mold transfers the heat outward. The heat transfer process mainly considers the heat conduction method, in which the high-temperature plastic melt in the mold cavity transfers heat to the mold and the injection molding machine, and the convection heat transfer method, in which the cooling medium carries away the heat. This study focused on the cooling process of injection molds, so it mainly considered the heat transfer between the mold and the cooling medium. The mold metal material transferred the melt heat to the cooling channel wall, then transferred the heat to the cooling medium, which was then carried out by the cooling medium in the form of convection heat transfer [17]. The heat Q_c carried away by the coolant is calculated as follows:

$$Q_c = hA(T_w - T_c) \tag{1}$$

In Formula (1), h represents the convection heat transfer coefficient, A represents the convection heat transfer area of the channel, T_w represents the average temperature of the mold cavity wall, and T_c represents the average temperature of the coolant. When the channel was a circular pipe, the water flow in the pipe was turbulent, and forced convection heat transfer was performed in the pipe. Formula (2) can approximately calculate the convection heat transfer coefficient h [18].

$$h = 2041 \times \frac{(1 + 0.015T_c)u^{0.87}}{d^{0.13}} \tag{2}$$

From Formula (2), it can be seen that the convection heat transfer coefficient is a complex function composed of the coolant fluid flow rate u, the mold cavity wall temperature T_w, the coolant temperature T_c, the fluid physical properties, and the cooling channel design variables, such as diameter and position arrangement. In order to improve the convection heat transfer capacity, it is often necessary to increase the heat transfer area, which requires the optimization design of the cooling channel. The more heat the cooling medium takes away, the faster the cooling rate and the shorter the cooling time.

The physical and thermal parameters are specific for a plastic part and mold. After the mold trial process was completed, specific injection molding process parameters were set. The temperature of the plastic melting entering the mold and the cooling water inlet temperature were also pre-set. By referring to relevant literature [19], the cooling time of flat plastic parts can be expressed by Formula (3):

$$t = \left(\frac{\delta}{\pi}\right)^2 \times \frac{1}{e} \times ln\left[\frac{4}{\pi} \times \left(\frac{T_m - T_w}{T_d - T_w}\right)\right] \tag{3}$$

From the analysis of Formula (3), we can see that the factors affecting the cooling time of plastic parts are the following process parameters: δ, representing plastic part thickness, e, representing the plastic part melt thermal conductivity coefficient, T_m, representing the melt temperature injected into the mold cavity, and T_d, the plastic part demolding temperature. Among them, e is defined as:

$$e = \frac{\lambda_p}{\rho_p c_p} \tag{4}$$

In Formula (4), λ_p represents the thermal conductivity coefficient of plastic, ρ_p represents the density of plastic, and c_p represents the specific heat capacity of plastic. It can be concluded that when plastic's thermal conductivity coefficient is larger, plastic melt's thermal conductivity coefficient is larger, and the cooling time of plastic is shorter.

Although there is no direct correlation between the cooling time and the design variables of the cooling channel from Formula (3), since the design variables of the cooling channel affect the cavity temperature of the mold, they indirectly affect the cooling time.

Through model assumptions and simplification, the model included the heat conduction model inside the product, the heat transfer model of channel convection, and the heat transfer model of the mold. After research and analysis, it was concluded that the cooling time at a certain point of the plastic part can be expressed by Formula (5) [20].

$$t_c = \frac{[c_p(T_m - T_d)]\rho_s \frac{\delta}{2} l}{T_w - T_c} \cdot \left\{ \frac{1}{2\pi\mu_m} ln\left[\frac{2lsin(2\pi\frac{s}{l})}{\pi d}\right] + \frac{1}{0.031395\pi {R_e}^{0.8}} \right\} \quad (5)$$

It can be seen from Formula (5) that the design variables of the cooling channel will affect the cooling time of the plastic part. Among them, ρ_s represents the coolant density, d represents the channel diameter, l represents the spacing between adjacent channels, s represents the distance from the channel center to the mold wall, δ represents the wall thickness of the plastic part, μ_m represents the thermal conductivity coefficient of the mold steel, and R_e represents the Reynolds number.

2.2. Experimental Design

From the previous mathematical analysis of heat transfer, it can be seen that the conduction of heat in the cooling channel is related to the channel design variables d, l, and s. Therefore, for conformal cooling channels, the design variables of the channel are the main factors affecting the cooling of plastic parts [21]. In order to shorten the cooling time, it is necessary to determine the optimal conformal cooling channel design variables.

2.2.1. Simplify Model Setting Up

Since the wall thickness and structure of various products vary greatly in actual applications, it is not conducive to analyzing the impact of design variables. In order to eliminate other interference factors, the product model was summarized and simplified. This study is mainly aimed at deep-cavity, thin shell products. Therefore, it can be assumed that the product was simplified to a cylindrical, thin-walled shell, with a wall thickness of 1.5 mm, a diameter of 50 mm, and a height of 120 mm. The material was ABS.

2.2.2. Orthogonal Test

When the channel layout was fixed, the design variables that affected the cooling time of the conformal cooling channel were mainly: d, the channel diameter; l, the spacing between adjacent channels; and s, the distance from the channel center to the mold wall [11]. The positional relationship of the design variables can be seen from schematic in Figure 2 of the conformal cooling channel model unit.

The range of values of the design variables of the experimental model was based on the design criteria proposed by Mayer [22] in the EOS white paper, as shown in Table 1.

Table 1. Range of channel design variables with different wall thicknesses.

δ (mm)	d (mm)	l (mm)	s (mm)
0–2	4–8	(2–3) d	(1.5–2) d
2–4	8–12	(2–3) d	(1.5–2) d
4–6	12–14	(2–3) d	(1.5–2) d

Variables d, l, and s were set as factors, and two basic level values for each factor were set. Using the orthogonal test method [23,24], the best conformal cooling design variable combination was obtained by changing the three conformal cooling design variable factors d, l, and s. According to the actual size and wall thickness of the experimental model, the conformal cooling channel design variable factor level was formulated, as shown in Table 2.

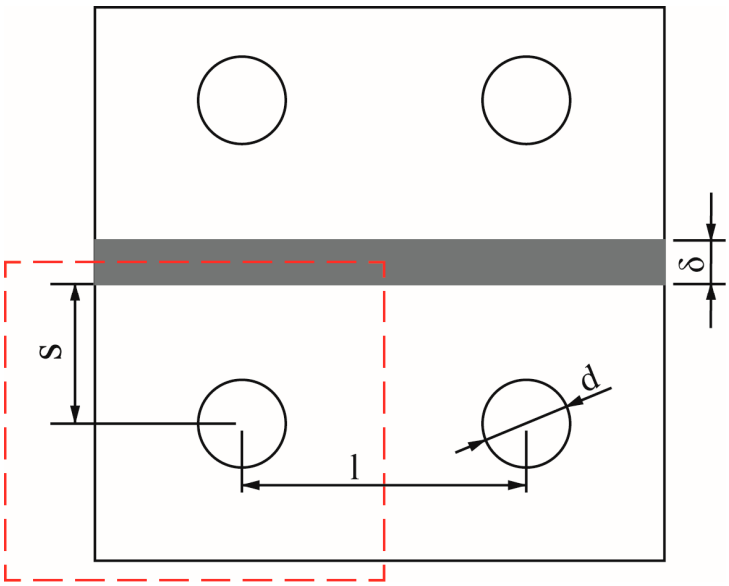


Figure 2. Conformal cooling channel model unit.

Table 2. Cooling variables factor levels.

Levels	Factors		
	d (mm)	l (mm)	s (mm)
1	4	12	8
2	6	18	12

According to the level of design variable factors, eight groups of conformal cooling channel orthogonal experiments can be arranged (see Table 3). In order to make the experimental results of design variables more objective, the conformal cooling channel design uniformly adopted the same layout form and only changed three design variables. According to the design variables specified in each group of orthogonal experiments, eight conformal cooling channel design models, as shown in Figure 3, were drawn using Unigraphics NX 12 software.

Table 3. Orthogonal test of conformal cooling channels.

Test Number	d (mm)	l (mm)	s (mm)
1	4	12	8
2	4	12	12
3	4	18	12
4	4	18	8
5	6	12	8
6	6	12	12
7	6	18	8
8	6	18	12

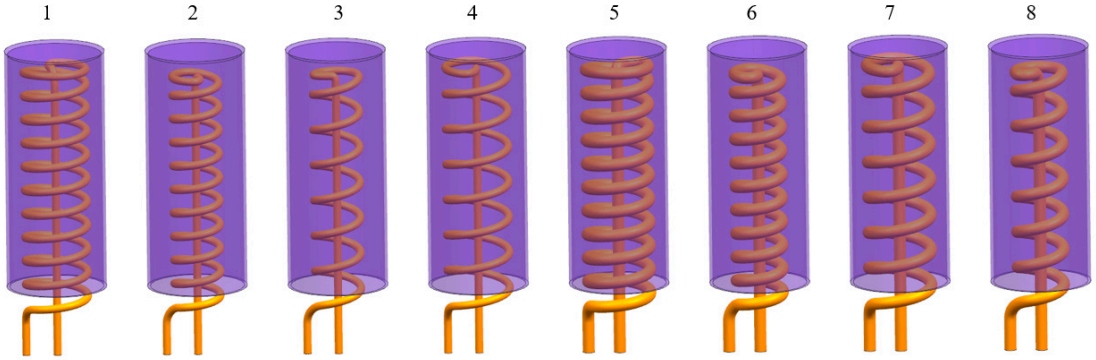


Figure 3. Cooling channel experimental design model.

2.2.3. Computer Simulation

The cooling time required for the plastic part to reach the ejection temperature was taken as the test result, and the design variable was optimized with the minimum cooling time. The cylindrical plastic part's ejection temperature was set to 88 °C. According to the number of orthogonal experiments, the cooling time for the plastic part to reach the ejection temperature was simulated by a computer using the Autodesk Moldflow 2019 software. Figure 4 shows the cooling time diagram output by the software.

The results of each group of simulation tests are summarized in Table 4. In the fifth group of experiments, d was 6 mm, l was 12 mm, and s was 8 mm. The cooling time under this group of design variables had the smallest optimization target value in each group of experiments, which was 2.873 s. From the combination relationship of the design variable settings, it can be analyzed that in the design variable combination, the larger the d, the smaller the l, and the smaller the s is, the less time required for plastic part cooling and the faster the cooling rate.

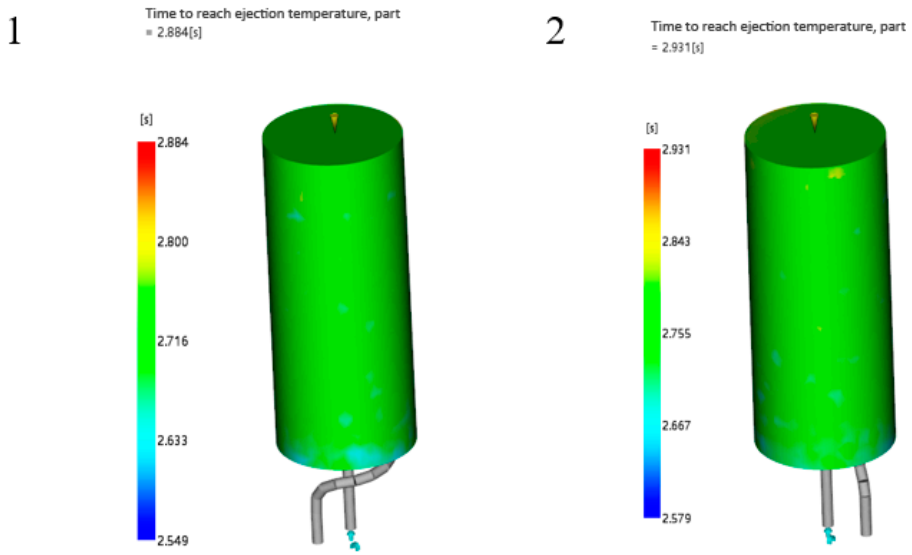


Figure 4. *Cont.*

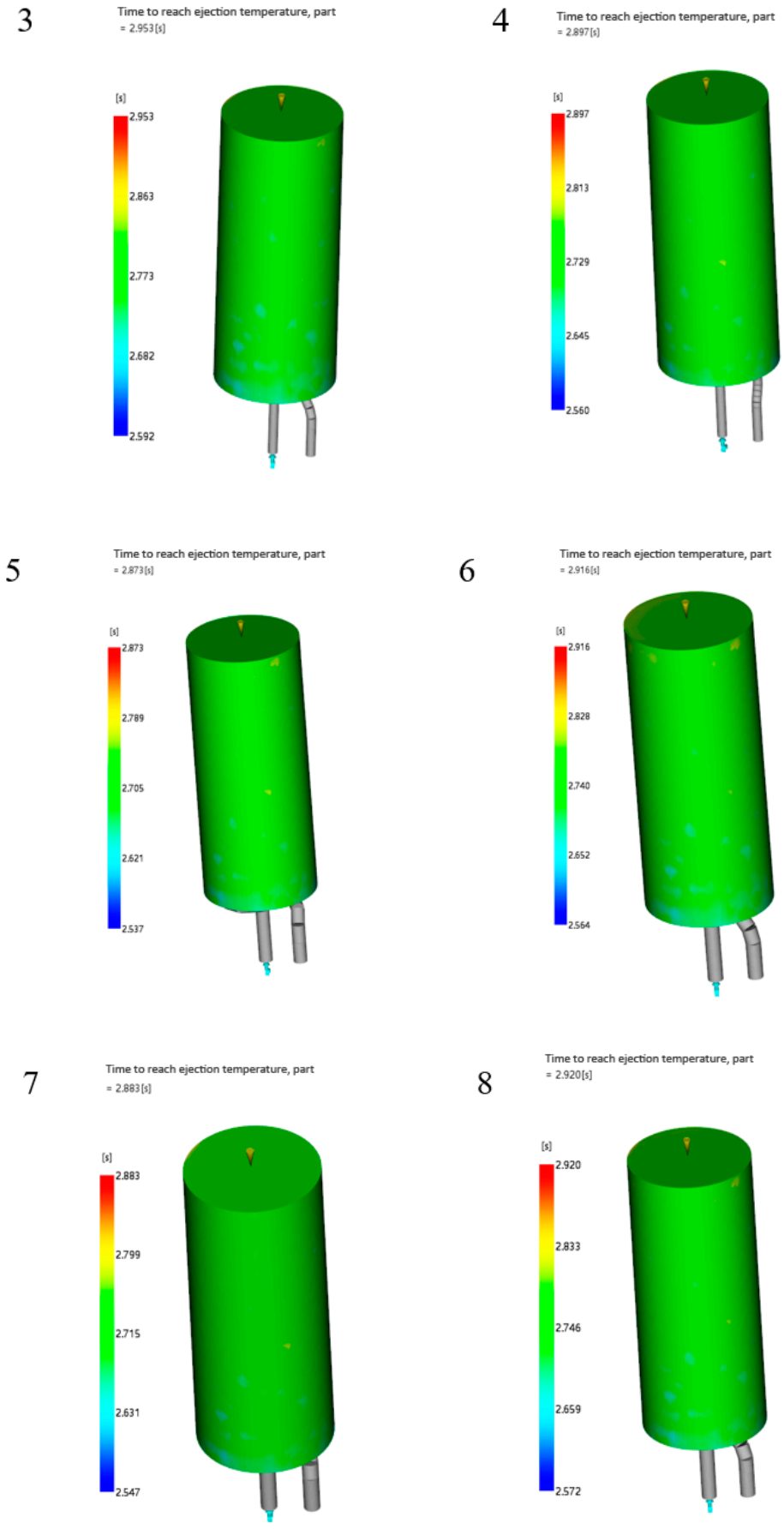


Figure 4. Cooling time of experimental models.

Table 4. Orthogonal test of cooling time results.

Test Number	*d* (mm)	*l* (mm)	*s* (mm)	Cooling Time/y_t (s)
1	4	12	8	2.884
2	4	12	12	2.931
3	4	18	12	2.953
4	4	18	8	2.897
5	6	12	8	2.873
6	6	12	12	2.916
7	6	18	8	2.883
8	6	18	12	2.920

2.3. Design Schemes

2.3.1. Injection Molded Part Analysis

This study selected a lamp housing part. The injection molding process requires good surface gloss and no filling dissatisfaction. The plastic parts were free of process defects such as burrs, flash, scratches, shrinkage holes, etc. The product had good dimensional stability, insulation, and bending strength, was unaffected by humidity or environment, and had a long service life. According to the above requirements, the material selected was ABS PA-757, which has a density of 1.05 g/cm^3 and a shrinkage rate of 0.5%. A single plastic part weighs about 12.86 g. The main performance parameters of ABS PA-757 are detailed in Table 5.

Table 5. ABS PA-757 performance parameters.

Performance	Test Method	Test Condition	Unit	Parameter
Melt flow rate	ASTM D1238 [25]	220 °C, 10 kg	g/10 min	22
Tensile strength	ASTM D638 [26]	3 mm, 6 mm/min	kg/cm^2	460
Bending strength	ASTM D790 [27]	6 mm, 2.8 mm/min	kg/cm^2	790
Impact strength	ASTM D256 [28]	3 mm, 23 °C	kg-cm/cm	21
Heat distortion temperature	ASTM D648 [29]	Annea	°C	95
Vicat softening temperature	ASTM D1525 [30]	3 mm, 50 °C/h	°C	105

The structural analysis of the three-dimensional model of the part showed that the part was a deep-cavity thin shell, with a uniform wall thickness of 1.5 mm. There were holes and grooves in the cavity. The overall shape was a combination of cones and cylinders with medium complexity. The overall dimensions are shown in Figure 5.

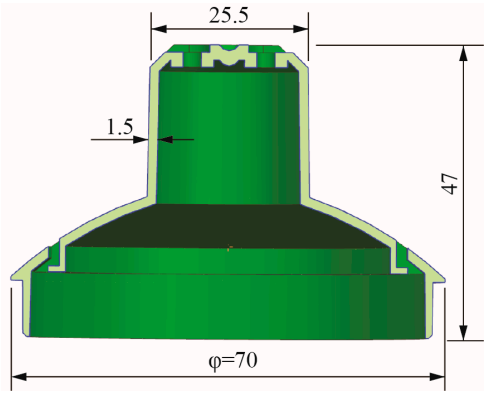


Figure 5. Part dimension drawing.

2.3.2. Injection Molding Filling

Autodesk Moldflow 2019 software can simulate and analyze the injection molding filling of plastic parts. As can be seen from Figure 6, there was no short shot in the filling, and the product filling was balanced. The filling volume at the speed/pressure conversion point was 98.76%, and the maximum nozzle pressure was 43.57 MPa (as shown in Figure 7), so the V/P conversion point met the requirements. The holding time was 10 s, the nozzle pressure curve is shown in Figure 8, and the holding pressure control curve is shown in Figure 9. During the holding process, the maximum clamping force was 10.24 tons (see Figure 10), 50 tons less than the selected injection molding machine, so it met the injection molding requirements.

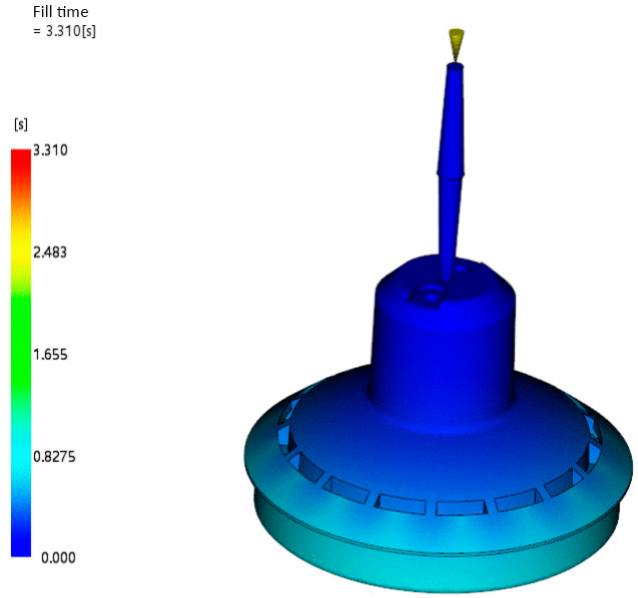


Figure 6. Dynamic filling diagram.

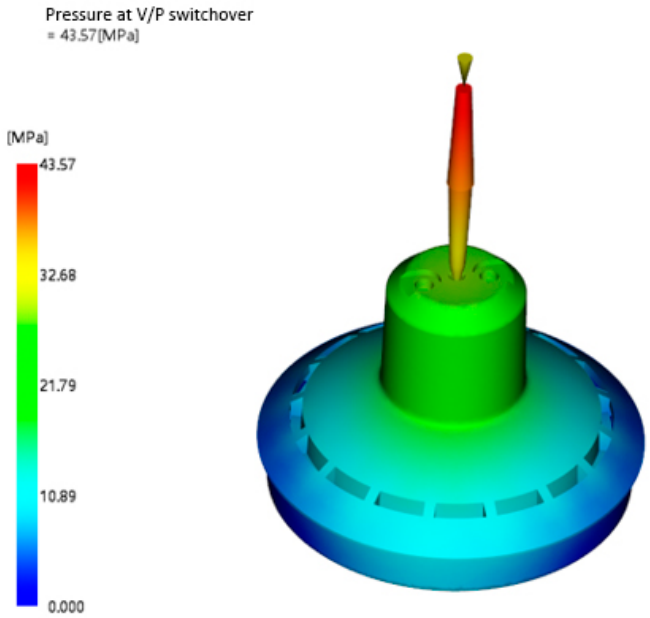


Figure 7. V/P conversion and pressure distribution.

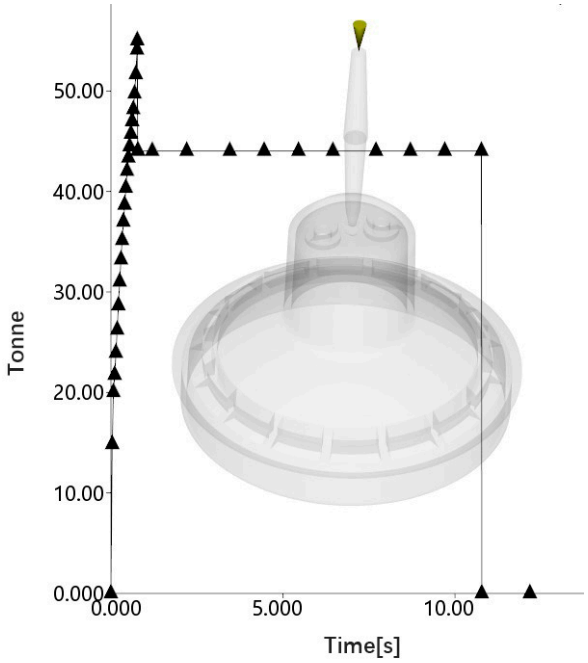


Figure 8. Nozzle pressure curve.

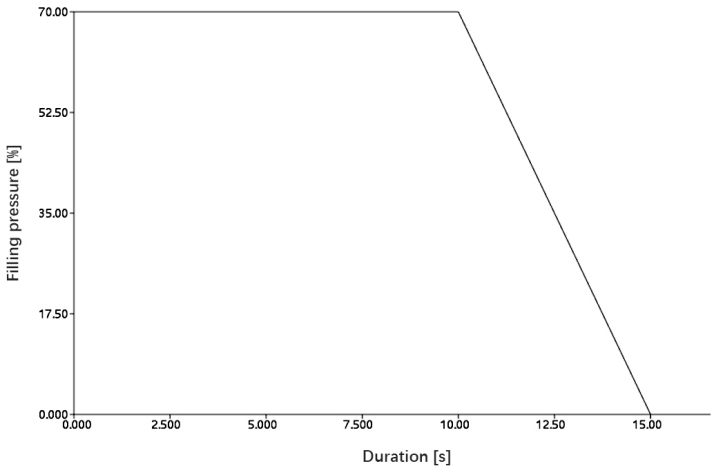


Figure 9. Pressure holding control curve.

The lamp housing parts were manufactured using the injection molding process. Combined with the previous simulation results, the molding process parameters can be set as follows, the details of which can be seen in Table 6.

Table 6. Injection molding process parameters.

Process Parameter Items	Unit	Parameter
Mold surface temperature	°C	50
Melt temperature	°C	230
Ejection temperature	°C	88
Cooling water temperature	°C	25
Maximum shear stress	MPa	0.28
Maximum shear speed	1/s	12,000
Compress time	s	10
Holding pressure	MPa	70
Nozzle pressure maximum	MPa	43.57

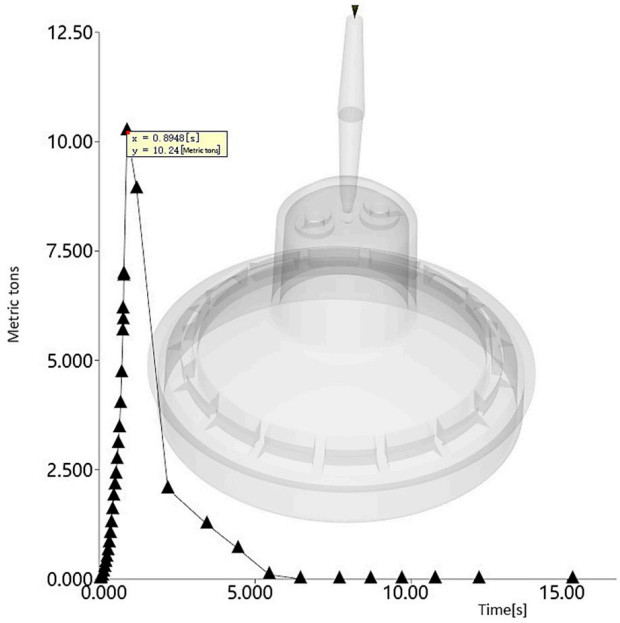


Figure 10. Change diagram of clamping force and holding time.

2.3.3. Channel Optimization Design

When conventional manufacturing processes make the mold, the cooling channel is generally designed to be straight and processed by a drilling machine, which is simple and efficient [4]. The internal space structure changes greatly because the ribs and deep cavity structures are inside the plastic part. Due to the limitations of the manufacturing process, the cooling of the deep cavity can only be performed by using a water well structure to penetrate the cavity (as shown in Figure 11). However, it is still difficult for the channel to fit closely to the mold cavity wall and penetrate the gate position, which can easily lead to an inconsistent mold cooling rate and prolonged cooling time [20]. Therefore, the cavity part that cannot be penetrated by the straight drilling channel can be cooled by the conformal channel.

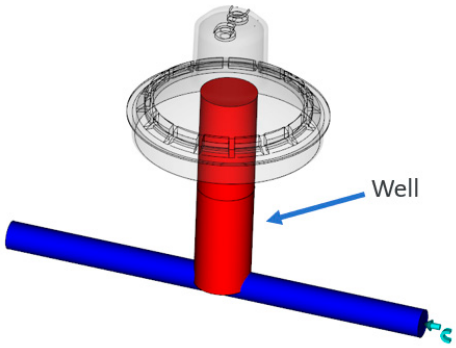


Figure 11. Conventional cooling channel design.

According to the design variable setting conclusions obtained from the experimental design, in order to improve the cooling rate, combined with the analysis of the size and internal structure of the part, due to the limitation of the diameter of the cylindrical part of the lamp shell, the maximum value of the channel diameter is 4 mm, so it can be determined that the optimal combination of design variables for the mold conformal cooling channel of this part are: d at 4 mm, l at 8 mm, and s at 6 mm. According to this group of values, three conformal cooling channel models are designed at the core position of the injection mold, as shown in Figure 12a–c. The cooling channel layout adopts series and parallel types [10,31]. In the series channel layout, two structures, a flat head and a pointed head,

are designed near the gate position. According to the order of the design drawing, they are referred to as conformal cooling channels 1, 2, and 3. The conformal cooling channels established are all close to the mold cavity.

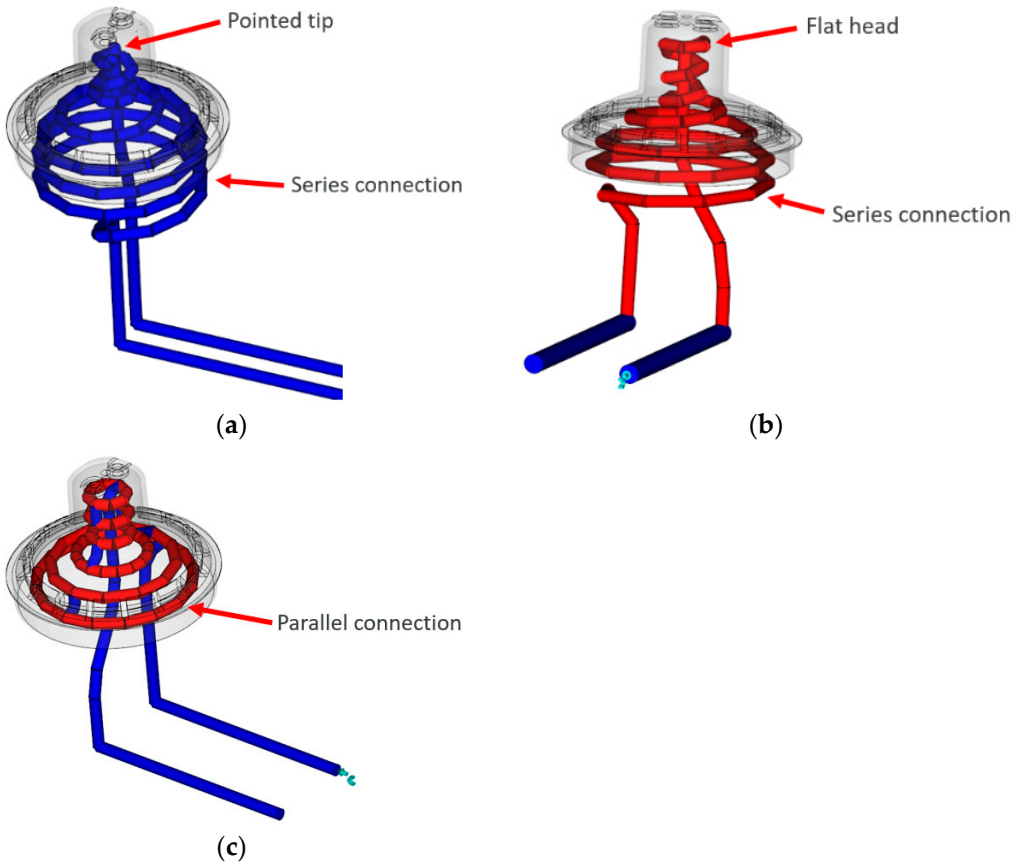


Figure 12. (**a**) Conformal cooling channel 1: series pointed conformal cooling channel; (**b**) conformal cooling channel 2: series flat-head conformal cooling channel; (**c**) conformal cooling channel 3: parallel conformal cooling channel.

3. Analysis and Results

3.1. Cooling Time Analysis

In order to verify whether the cooling time of plastic parts can be shortened after optimizing the design of conformal cooling channels, simulation experiments were carried out in Autodesk Moldflow 2019 software to calculate the cooling time under different design models of conventional cooling channels and conformal cooling channels. After a comparative analysis, the optimal design model was obtained.

After setting the injection molding process parameters according to the injection molding filling analysis results, Figure 13 shows the times required for the plastic part to cool to the ejection temperature (this time was calculated from the end of the pressure holding) under the four channel design models.

The cooling time statistics of the conventional cooling channel and the conformal cooling channel are shown in Table 7. It can be seen that the cooling rate of the conformal cooling channel was significantly higher than that of the conventional cooling channel. Among the conformal cooling optimization design models, the series flat-head conformal cooling channel had the shortest cooling time, the highest cooling efficiency, and the most reasonable design. The design model has practical application value.

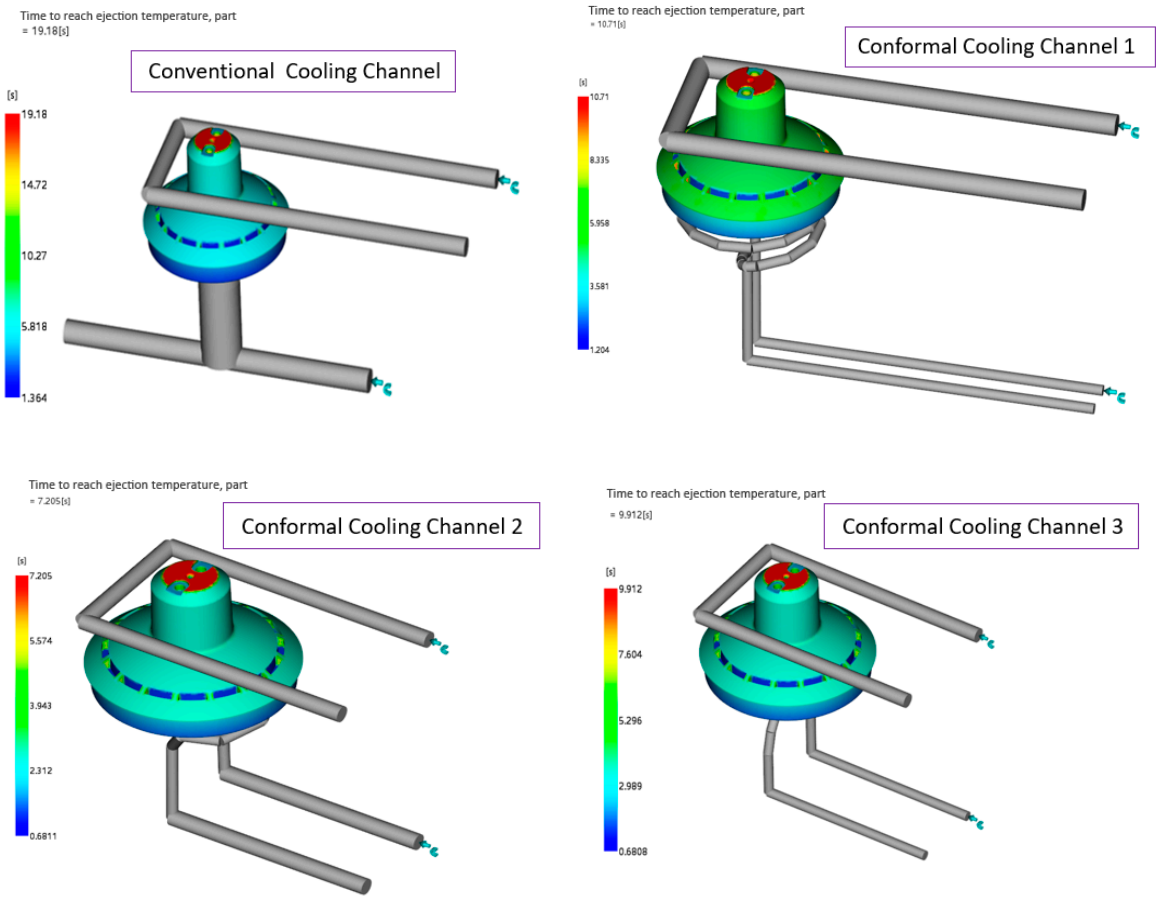


Figure 13. Comparison of cooling times.

Table 7. Comparison of cooling time.

Comparative Items	Cooling Time
Conventional cooling channel	19.18 s
Conformal cooling channel 1	10.71 s
Conformal cooling channel 2	7.205 s
Conformal cooling channel 3	9.912 s

3.2. Test Verification

According to the analysis results, the most optimized conformal cooling channel 2 was selected for mold manufacturing. First, the core model of the injection mold was created using the Unigraphics NX 12 software. The internal structure of the core was composed of the optimized series flat-head conformal cooling channel, as shown in Figure 14. Then, the core insert with a conformal cooling channel was manufactured by selective laser melting (SLM), as shown in Figure 15. The insert made of metal additive manufacturing was assembled into the mold base to complete the mold manufacturing of the product (see Figure 16). Finally, the mold was used for actual injection molding production (see Figure 17). After testing, the cooling time was 6.9 s, and the molding cycle was shortened to 23.2 s. This result is 0.3 s different from the cooling time value of the computer simulation experiment, which is basically in line with the expected result. The plastic part after injection molding is shown in Figure 18, with a smooth surface, stable size, and no flaws and process defects, meeting the use requirements.



Figure 14. Core model with conformal cooling channel.



Figure 15. Metal additive manufacturing core insert.

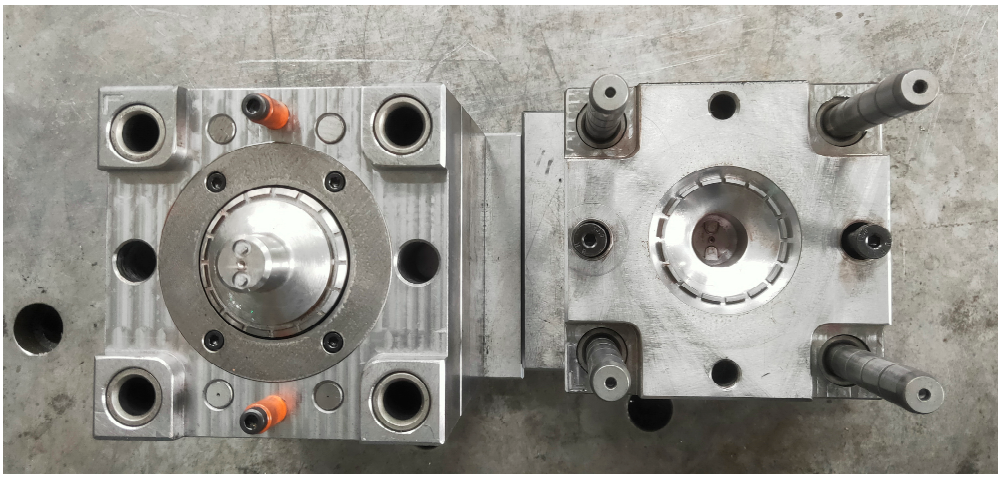


Figure 16. Conformal cooling injection mold.



Figure 17. Injection molding production.



Figure 18. Injection molding plastic part.

4. Conclusions

The following conclusions were drawn from this study: Through orthogonal tests and simulations, the design variable values of the three conformal cooling channels that affect the cooling time of the mold were determined, which were d = 4 mm, l = 8 mm, and s = 6 mm. Three conformal cooling channel layouts were innovatively designed using the minimum cooling time as the optimization goal. Through simulation experiments, it was found that the cooling time of the series flat-head conformal cooling channel was the shortest. The change values of cooling time between the conventional cooling channel and the optimized series flat-head conformal cooling channel were compared and analyzed. After conformal cooling optimization, the injection molding cycle was shortened by 62.43%.

In summary, the design of the injection-molded products' cooling system greatly impacts the injection molding cycle of deep cavity shells. Using metal additive manufacturing technology to achieve reasonable conformal cooling optimization can significantly improve the cooling rate of the mold and the injection molding production efficiency.

Author Contributions: Methodology, software, experimental analysis, and writing the manuscript: J.L.; review and editing: Y.C.O.; supervision: W.M.W.M. All authors have read and agreed to the published version of the manuscript.

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Data Availability Statement: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest: The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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