OPTIMIZATION OF COOLING CHANNEL EFFICIENCY TO REDUCE WARPAGE IN MOLD DESIGN FOR TUBE-SHAPED PARTS

TỐI ƯU HÓA HIỆU SUẤT KÊNH LÀM MÁT ĐỂ GIẢM ĐỘ CONG VÊNH TRONG THIẾT KẾ KHUÔN CHI TIẾT DẠNG ỐNG

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Abstract - This study proposes a method for optimizing the cooling channel design in injection molding dies to improve the dimensional accuracy of tube-shaped products. By integrating simulation and analysis using Moldex3D software with the Taguchi method, the research predicts optimal design parameters. The results show that the optimization approach not only reduces product warpage but also ensures stable product quality. Furthermore, a mathematical model based on higher-order linear regression and the results of the Taguchi method has been developed to assist in predicting and adjusting cooling channel design parameters, thereby facilitating the design and manufacturing processes. These contributions open up new prospects for the development of intelligent injection molds in the industry.

Key words - Injection molding; cooling channel design; warpage; optimization; plastic mold

Tóm tắt - Nghiên cứu đề xuất một phương pháp nhằm tối ưu hóa hoá các thiết kế của thống làm mát trong khuôn đúc phun ép nhựa với mục đích cải thiện độ chính xác sản phẩm có dạng tương tự hình ống. Bằng cách kết hợp mô phỏng và phân tích trên phần mềm Moldex3D với phương pháp Taguchi để dự đoán các giá trị thiết kế tối ưu. Kết quả nghiên cứu cho thấy phương pháp tối ưu hóa không chỉ giúp giảm độ cong vênh cho sản phẩm mà còn đảm bảo tính ổn định về chất lượng. Hơn nữa, một mô hình toán học dựa trên hồi quy tuyến tính bậc cao và kết quả của phương pháp Taguchi đã được xây dựng để hỗ trợ dự đoán và điều chỉnh các giá trị thiết kế kênh làm mát giúp thuận tiện trong việc thiết kế và sản xuất. Những đóng góp này mở ra triển vọng mới trong việc phát triển khuôn ép nhựa thông minh trong công nghiệp.

Từ khóa - Ép phun; thiết kế kênh làm mát; cong vênh; tối ưu; khuôn nhựa

1. Introduction

Injection molding technology plays a crucial role in providing efficient, rapid, and sustainable manufacturing solutions for various industries such as aerospace, automotive, medical, and many others. Thanks to its ability to produce plastic products with high precision and diverse shapes that meet stringent technical requirements, injection molding has increasingly become an indispensable part of the global industrial supply chain [1] - [4]. The injection molding process consists of several main stages: mold filling, packing, holding, cooling, and part ejection. Among these, the cooling stage is considered the most critical component in ensuring product quality and stability [5] - [9].

The cooling phase not only helps reduce residual stresses but also determines the geometric accuracy and mechanical strength of plastic products. If this process is not optimized, defects such as warpage, shrinkage, or deformation may occur, adversely affecting product quality, especially for parts requiring high dimensional accuracy. It is essential to strictly control the temperature and cooling time to ensure that parts can be easily removed from the mold without damaging their structure, while maintaining uniformity and aesthetic appearance.

Designing an effective cooling channel system is a key issue that has attracted significant attention from researchers and engineers, aiming to enhance heat transfer efficiency and reduce cooling time, thereby improving production efficiency. The studies by Wang & Lee [10] and Park & Dang [11] indicate that the arrangement and dimensions of cooling channels play a vital role in effective heat transfer, particularly for parts with complex geometries. Properly designed cooling channels not only minimize operation time but also ensure uniform cooling, thus improving product quality and reducing scrap rates in manufacturing. The research by E. Farotti et al. [12] demonstrated that mold temperature and packing pressure are the main determinants of the mechanical properties of molded materials. However, if these values are too high, phenomena such as overpacking or product deformation, oversizing, and extended cycle times may occur. Therefore, controlling these parameters is crucial for ensuring the accuracy and durability of manufactured parts.

Current optimization studies often focus on specific conditions, making it challenging to find widely applicable solutions. This study aims to optimize the cooling channel design for tube-shaped products, develop an approximate formula to reduce warpage, and expand applicability to similar products. The results offer numerous benefits, such as cost savings, reduced machining time, improved efficiency and quality, and flexible mold design suitable for various cases.

This research utilizes Moldex3D simulation software to evaluate product warpage. The Taguchi method is then applied to identify optimal ranges for channel design parameters; finally, based on the results obtained from the combination of Moldex3D numerical simulation and the

Taguchi method, an optimal equation for the size and position of the cooling channels is proposed. Numerous studies have demonstrated the reliability and high effectiveness of the Taguchi method alongside computational simulation using Moldex3D. For example, Tsai H et al. [13] introduced a method to overcome unbalanced filling in multi-cavity molds during PVC injection molding by developing a multi-stage injection speed strategy during the filling phase, utilizing Moldex3D and the Taguchi method. Similarly, Lin C and Chen W [14] devised a systematic approach to minimize optical aberrations in injection-molded double-convex Fresnel lenses and their retardation characteristics, leveraging the synergy of the Taguchi method and Moldex3D. Wang M et al. [15] explored the influence of inserts on shrinkage in multi-shot injection molding, particularly in the production process of Blu-ray objective lenses. Their approach involved Moldex3D simulation and optimization using the Taguchi method. Additionally, Lin C and Chen Y [16] discussed the combined use of Moldex3D simulation and the Taguchi method to optimize injection molding parameters for the core of bi-telecentric lens devices. These examples collectively highlight the robustness of combining Moldex3D simulation and the Taguchi method in various injection molding applications.

This study demonstrates that optimizing cooling channels helps reduce product warpage and shrinkage rates, ensuring stable quality for tube-shaped parts. The optimal parameters developed through mathematical formulations enable the prediction and adjustment of cooling channel designs in industrial mold design processes. The research process utilizes Moldex3D numerical simulation and the Taguchi method to determine optimal values and establish a predictive model for warpage based on cooling channel design parameters. The results of this study have contributed to substantial enhancements in both manufacturing quality and operational performance. Moreover, the study provides valuable tools and data to support engineers and manufacturers in designing more effective cooling systems.

This scientific article provides a solid foundation for applying numerical simulation methods to predict warpage in molded products. The research opens new prospects for the development of intelligent injection molds in the industry.

2. Research content and investigation

2.1. Research model

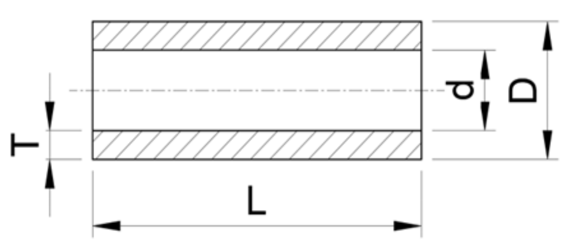


Figure 1. *Basic dimensions of the tube-shaped part*

Figure 1 presents the basic geometric structure of the tube-shaped part, including the main parameters: outer diameter D = 42 mm, inner diameter d = 38 mm, and length L = 42 mm. From these values, the average diameter is determined to be Da = 40 mm, while the calculated wall thickness is T = 2 mm. These values serve as the initial basis for simulation and subsequent analysis, which are used to optimize the cooling channel system in order to minimize the warpage of the tube product. The part and mold structure selected in this study not only reflects high practical relevance but also represents common mold configurations in large-scale industrial production. The obtained results demonstrate broad application potential, allowing for flexible expansion and adjustment for similar mold designs in practice.

The cooling system model in this study is designed with two main components: an internal cooling channel using a Bubbler structure and an external cooling channel with a circular structure. This division aims to optimize heat transfer efficiency and ensure uniformity during the cooling process.

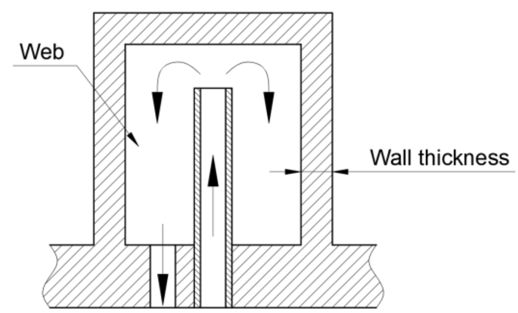


Figure 2. *Bubbler cooling channel*

The Bubbler cooling channel, a common solution in plastic injection molds, is applied to control mold temperature. The study by Eiamsa-ard et al. [17] demonstrated that the effectiveness of this system significantly reduces production cycle time and increases cooling rates. With its ability to evenly distribute temperature across the contact surface between the mold and the molten plastic flow, the Bubbler channel plays a key role in limiting warpage, which is especially important for products requiring high precision and surface quality.

Figure 3(a) describes the positional parameters of the cooling channels, including four main parameters: x – the distance between the centers of the conventional cooling channels; y – the distance from the center of the outer conventional cooling channel to the outer wall of the part; do – the diameter of the conventional cooling channel; and l – the distance from the outer wall of the Bubbler cooling channel to the inner wall of the part. Figure 3(b) provides an intuitive and clear view of the structure, illustrating in detail the correlation between the tube, Bubbler cooling channel, gate, and runner. This helps readers easily visualize how these components interact with each other.

The edge gate is a type of gate placed at the edge of the product, allowing the molten plastic flow to easily fill the mold cavity. Advantages of the edge gate include simple manufacturing and maintenance, as well as effective control over the plastic flow, making it suitable for various part geometries [18].

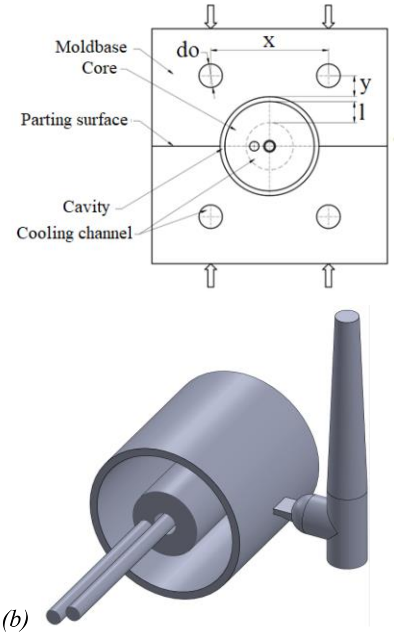


Figure 3. *(a) Schematic diagram of the cooling system positions and dimensions; (b) 3D models used in numerical simulation*

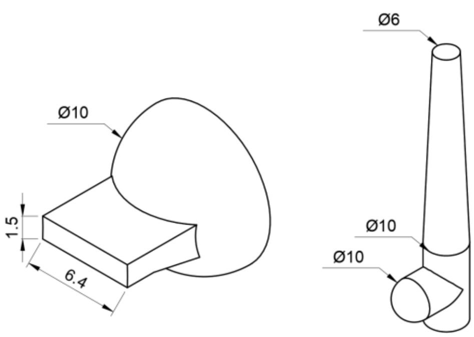


Figure 4. *Dimensions of the injection gate and sprue*

The cold runner system is a type of runner that is not heated, maintaining the plastic at a lower temperature compared to hot runner systems. This system is low-cost, allows for easy material changes, and is commonly used in the production of electronic components, aerospace, medical, and automotive parts.

2.2. Methodology

2.2.1. Simulation model

Table 1. *Technical specifications of PVC material*

Item name	Item data
Polymer	PVC
Grade Name	LACOVYL BB 9010
Producer	Arkema
Comment	D = 0.61
Melt temperature (minimum)	170°C
Melt temperature (normal)	190°C
Melt temperature (maximum)	210°C
Mold temperature (minimum)	40°C
Mold temperature (normal)	60°C
Mold temperature (maximum)	80°C
Ejection temperature	128.85°C
Freeze temperature	148.85°C

Table 2. *Mesh size parameters for simulation*

Item	Value
Cavity mesh node count	82.756
Cavity mesh element count	196.505
Cavity mesh volume	10.55 (cc)
Runner mesh node count	14.61
Runner mesh element count	45.228
Runner mesh volume	4.86 (cc)

Table 1 provides the main technical specifications of the PVC material LACOVYL BB 9010 used for the injection molding simulation in this study. Table 2 details the mesh partitioning for both the mold and runner system, with mesh parameters such as the number of nodes and elements influencing computation time and system resource requirements. These parameters serve as necessary inputs for numerical simulation using Moldex3D.

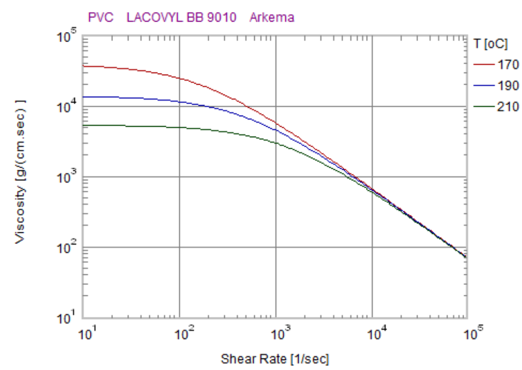


Figure 5. *Thermal properties of PVC material*

Figure 5 illustrates the variation in the viscosity of PVC LACOVYL BB 9010 as a function of temperature and shear rate. An increase in temperature leads to a decrease in viscosity, thereby more easily facilitating the filling of the mold cavity by the molten plastic.

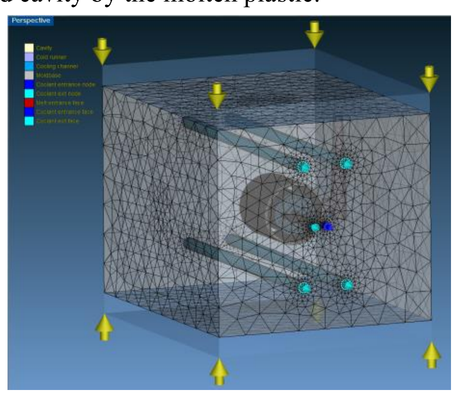


Figure 6. *Basic mold mesh structure*

Figure 6 describes the mesh model used in the injection molding simulation with Moldex3D software. The model incorporates mesh structures for the mold cavity, runner system, and cooling channels, enabling accurate simulation of physical phenomena such as flow, thermal distribution, and part warpage. Mesh quality is a critical factor that directly affects the reliability and accuracy of simulation results. Coarse meshes can produce distorted or overly stretched elements, leading to poor numerical convergence and inaccurate predictions of stress or deformation, particularly in geometrically complex regions. In contrast, high-quality meshes offer better geometric fidelity and more precise field variable distributions, contributing to stable and reliable simulation outcomes. Nevertheless, overly fine meshes significantly increase computational time and resource consumption. Striking a balance between accuracy and computational efficiency remains a fundamental challenge in finite element analysis. As such, evaluating the influence of mesh resolution on simulation outputs is essential in this study.

Figure 7 shows the variation of warpage with mesh size, with a decreasing trend as the mesh is refined. From 0.8 mm to 0.6 mm, the difference in warpage is negligible (0.004 mm), indicating stable results. In contrast, mesh sizes coarser than 3 mm result in a significant increase in warpage, unsuitable for high-precision applications.

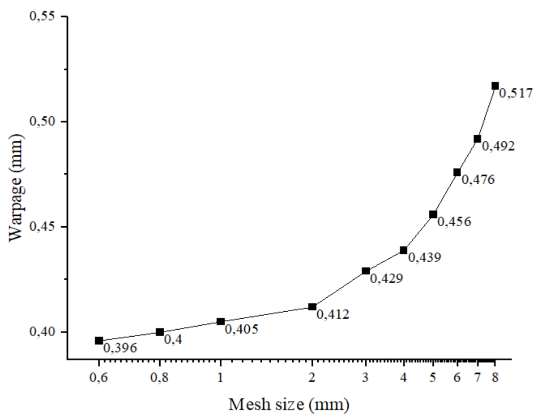


Figure 7. *Effect of mesh convergence on product warpage*

To ensure simulation reliability, this study conducts a grid convergence check based on the Grid Convergence Index (GCI) method proposed by Roache [19] and Celik et al. [20]:

$$\varepsilon = \frac{\left|W_{coarse} - W_{fine}\right|}{W_{fine}} \times 100\% \tag{1}$$

$$GCI_{fine} = \frac{F_S . |\varepsilon|}{r^p - 1} \tag{2}$$

$$r = \frac{h_{coarse}}{h_{fine}} \tag{3}$$

Where:

ε Relative error, GCI_{fine}: Grid Convergence Index, W_{coarse} and W_{fine}: Warpage simulation results for coarse and fine meshes (mm), F_s: Safety coefficient ($F_s = 1.25$ for three or more mesh sizes), r: Mesh size ratio (h_{coarse} and h_{fine} are coarse and fine mesh sizes), p: Order of convergence (p = 2 is commonly used in simulations).

Table 3 presents the calculated GCI values for successive mesh pairs. The 0.6 mm and 0.8 mm mesh pair achieves a GCI of 1.623%, meeting the good convergence criterion (GCI < 2%) according to Roache [19]. The 1.0 mm and 2.0 mm mesh pair achieves an even lower GCI of 0.72% (GCI < 1%). However, in terms of absolute warpage, the 2.0 mm mesh (0.412 mm) shows a larger deviation compared to the 0.6 mm mesh (0.396 mm), with a difference of up to 4%, which exceeds acceptable limits for high-precision applications. Conversely, the 0.8 mm mesh yields results nearly identical to the 0.6 mm mesh (only 1% error), indicating stable convergence.

Table 1. *Calculation results of relative error and GCI between grid sizes*

Mesh size (mm)	Relative error (%)	GCI (%)
0.6 mm & 0.8 mm	1.01	1.623
0.8 mm & 1 mm	1.25	2.778
1 mm & 2 mm	1.728	0.72
2 mm & 3 mm	4.126	4.126
3 mm & 4 mm	2.331	3.746
4 mm & 5 mm	3.872	8.605
5 mm & 6 mm	4.386	12.46
6 mm & 7 mm	3.361	11.635
7 mm & 8 mm	5.081	20.749

Considering both accuracy and computational efficiency, the 0.8mm mesh size is selected as optimal for subsequent simulations. This size ensures a good GCI (1.623%) while keeping computation time reasonable. Furthermore, the difference between the 0.8mm and 0.6mm mesh is only 1%, confirming that the convergence state is maintained steadily. Therefore, the 0.8mm mesh size is recommended to balance accuracy, reliability, and computational cost in warpage simulations for tube-shaped parts.

2.2.2. Taguchi method

The Taguchi method was applied to determine the necessary parameter ranges for optimizing and minimizing part deformation. In this study, four cooling channel factors were considered and evaluated for their impact on warpage. The results were assessed using the signal-to-noise (S/N) ratio, with the "smaller-is-better" criterion to identify values for deformation control [21]:

$$\frac{S}{N} = -10 \log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{4}$$

Where: y_i: Warpage value, n: Number of simulation trials.

Table 4. *Factors and levels used in the study*

Factors	lv1	lv2	lv3
	-1	**0**	**+1**
x (mm)	40	45	50
y (mm)	5	10	15
do (mm)	6	8	10
l (mm)	5	7.5	10

Four factors, representing the positional and dimensional components of the cooling channels. Each factor was evaluated at three levels, as described in the Taguchi experimental design shown in Table 4.

3. Results and discussion

3.1. Influence of cooling channel design parameters on warpage

Table 5 presents the simulation results and signal-to-noise (S/N) ratios for warpage corresponding to nine experiments with different cooling channel designs. Warpage is measured in millimeters (mm). To analyze the influence of each design factor, the mean S/N ratio at each level was calculated and is shown in Table 6, which allows identification of the impact trends of the design parameters on warpage. The Delta (Δ) parameter, as defined in Eq. (5), represents the difference between the maximum and minimum S/N values for each factor. This value reflects the degree of influence each factor has on the optimal outcome, thereby prioritizing which design parameters should be adjusted.

$$Delta\ (\Delta) = max(S/N) - min\ (S/N) \quad (5)$$

Table 5. *Taguchi L9 orthogonal array and simulation results for warpage*

Test no	Parameter				Warpage (mm)	S/N (dB) η_{STB}
	x	y	do	l		
1	40	5	6	5	0.397	4.01209
2	40	10	8	7.5	0.402	3.95774
3	40	15	10	10	0.41	3.87216
4	45	5	8	10	0.404	3.93619
5	45	10	10	5	0.397	4.01209
6	45	15	6	7.5	0.403	3.94695
7	50	5	10	7.5	0.399	3.99027
8	50	10	6	10	0.408	3.8934
9	50	15	8	5	0.398	4.00117

Table 6. *Response table for S/N Ratios, STB for warpage*

Level	x	y	do	l
1	7.895	7.959	7.902	8.017
2	7.93	7.909	7.93	7.93
3	7.923	7.88	7.916	7.801
Delta (Δ)	0.035	0.079	0.028	0.216
Rank	3	2	4	1

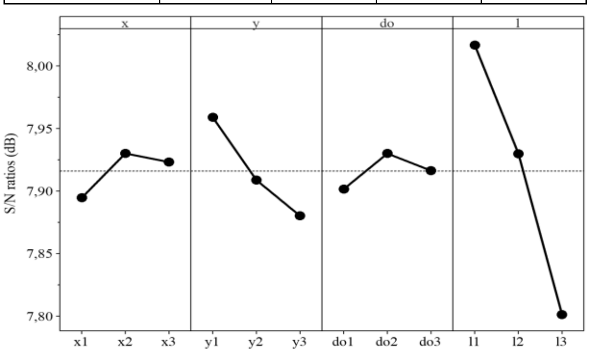


Figure 8. *S/N ratio plot of the simulation results for warpage*

Analysis of Table 6 and Figure 8 shows that the parameter **l** distance from the Bubbler channel to the inner wall) has the greatest impact on warpage, while **do** (outer cooling channel diameter) has the least effect. The optimal parameter combination, **x2y1 do2 l1** (**x=45mm, y=5mm, do=8mm**, and l=5mm), reduces warpage to W=0.396mm.

The optimal combination is achieved by effectively balancing the core cooling system (Bubbler) and the outer cooling channels, ensuring uniform heat transfer and shrinkage between the inner and outer regions of the tube part. Reducing the distance l between the Bubbler channel and the inner wall enhances local core cooling efficiency, while optimizing the distances x and y synchronizes the outer wall cooling rate without causing thermal imbalance. Additionally, the diameter of the outer cooling channel contributes to improving heat transfer performance.

Table 7 presents the ANOVA results, indicating that the parameter l plays a decisive role, accounting for 83.3% of the total variation (SS = 0.000150mm²). This confirms the critical importance of adjusting the core cooling channel position in controlling part warpage. The regression model achieves an R^2 value of 1 and an adjusted R^2 of 1, demonstrating an excellent fit with no indication of overfitting.

Table 7. *ANOVA for parameters affecting warpage*

Source	DF	SS	MS	F-Value	P-Value
Model	8	0.000180	0.000022	*	*
Linear	4	0.000174	0.000043	*	*
x	1	0.000003	0.000003	*	*
y	1	0.000020	0.000020	*	*
do	1	0.000001	0.000001	*	*
l	1	0.000150	0.000150	*	*
Square	4	0.000006	0.000002	*	*
x^2	1	0.000002	0.000002	*	*
y^2	1	0.000000	0.000000	*	*
do^2	1	0.000002	0.000002	*	*
l^2	1	0.000002	0.000002	*	*
Error	0	*	*		
Total	8	0.000180			

The proposed second-order regression model is primarily applicable within the investigated design parameter ranges: x = 40÷50mm, y = 5÷15mm, do = 8÷12mm, and l = 5÷15mm. The model is suitable for tubular plastic parts featuring an outer circular cooling channel and a central Bubbler system. Beyond this range, the model may be extended to other parts if the geometric ratios are maintained. For designs outside the studied parameter space, additional simulations or validations are required to ensure the accuracy of warpage predictions.

These results provide important guidance for optimizing cooling channel design, enabling effective deformation control and improving product quality. By analyzing and adjusting the appropriate parameters, the cooling system can be improved to ensure geometric stability and high accuracy for tubular parts after injection molding.

3.2. Proposed predictive model

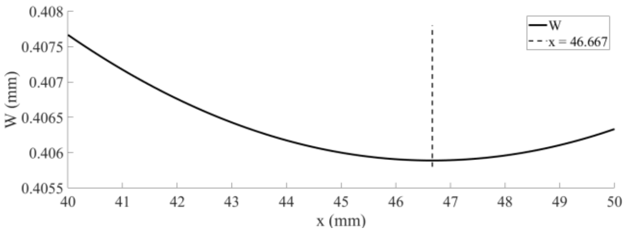
$$\begin{aligned} W = {} & 0.493 - 0.003733x + 0.000767y \\ & -0.004167do - 0.0004l + 0.00004x^2 \\ & -0.00002y^2 + 0.00025do^2 + 0.00016l^2 \end{aligned} \quad (6)$$

The Eq. (6) was developed using polynomial regression, a robust method for modeling complex relationships between dependent and multiple independent variables. The combination of the Taguchi analysis and regression modeling provides high accuracy in identifying optimal parameters for effective deformation control. This approach, as demonstrated in studies by Montgomery & Runger [22] and Myers et al. [23], is a useful method for analyzing and optimizing multivariable systems, particularly in this case, the relationship between the input variables (x, y, do, l) and the warpage (W).

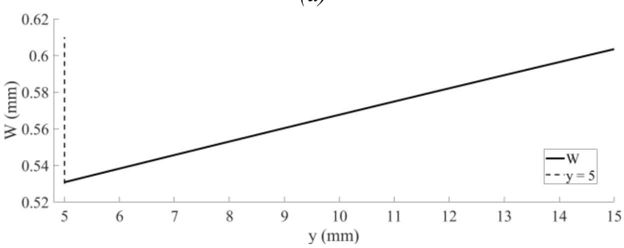
The proposed second-order regression model in Eq. (6) is not strictly constrained by specific mold dimensions but primarily depends on the design parameters x, y, do, and l.

These parameters reflect the layout of the cooling channel system and possess a relative nature, allowing the model to be extended to new mold designs featuring an outer circular cooling channel combined with an internal Bubbler system.

In traditional mold design processes, changing mold dimensions often requires rebuilding the simulation model and repeating the entire experimental process, including parameter analysis, multiple simulations, and physical trials, significantly increasing cost and development time. However, with the current model, mold engineers can predict warpage trends (W) in response to changes in x, y, do, and l, quickly identifying near-optimal parameter combinations. This reduces the number of physical trials needed to finalize the mold, saving design costs and significantly shortening the new product development cycle.



(a)



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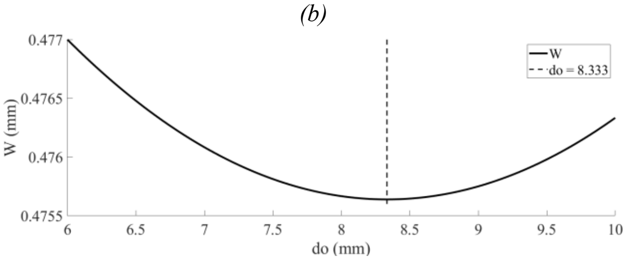

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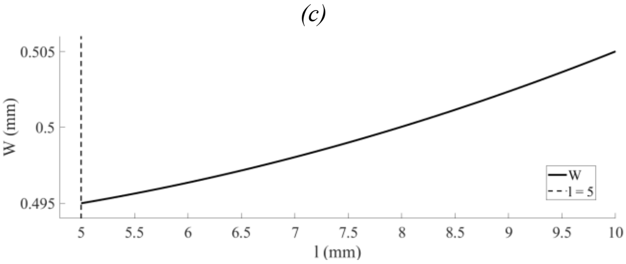

(d)

Figure 9. *Graphs of the proposed computational model showing the influence of variables x, y, do, and l on W, corresponding to subfigures a, b, c, and d, respectively*

Figures 9a–9d illustrate the relationships between each design parameter (x, y, do, l) of the cooling system and the warpage (W) of the tube part, based on the second-order regression model derived from simulation data.

Figure 9a shows the effect of the distance between outer cooling channels (x) on warpage. If x is too large, the region between channels is insufficiently cooled, increasing heat transfer through the part wall and causing warpage. If x is too small, the cooling regions overlap, some areas cool too quickly while others cool slowly, leading to local temperature differences and increased warpage. The relationship between warpage (W) and x is parabolic, with a minimum at x = 46.667 mm, where heat exchange between channels is optimally balanced.

Figure 9b illustrates the influence of the distance (y) on warpage. When y is small, heat transfer is more efficient, leading to faster cooling and reduced warpage. However, if y values are too small, they may cause the outer wall to cool too quickly while the core remains hot, resulting in uneven shrinkage and increased warpage. Similarly, overly large y values reduce heat transfer efficiency and prolong cooling time, which also contributes to greater warpage.

Figure 9c analyzes the effect of the outer cooling channel diameter (do) on warpage. Reducing do initially improves heat transfer due to higher flow velocity and heat transfer coefficient. However, if do is too small, pressure losses become significant, reducing actual flow under constant pump conditions, and increasing the risk of clogging. The surface area for heat transfer also decreases, and thermal gradients along the channel increase, leading to uneven temperature distribution and internal thermal stresses, which cause warpage. Thus, do should be optimized for balance between heat transfer efficiency and flow stability.

Figure 9d illustrates the effect of the distance (l) on warpage. When l is small, the Bubbler channel is near to the inner wall, facilitating faster core cooling and balancing the shrinkage between the inner and outer regions of the part, thereby reducing warpage. As l increases, the heat transfer efficiency from the Bubbler channel decreases, resulting in slower core cooling compared to the outer wall. This thermal gradient causes a greater temperature difference within the part, leading to increased warpage.

These results confirm that the optimal combination is achieved by effectively balancing inner and outer cooling systems, ensuring uniform shrinkage and minimizing thermal deformation.

Table 8. *Comparison of results between predictive model and simulation validation*

Methods	x	y	do	l	W
Proposed model	46.67	5	8.33	5	0.39388
Numerical	46.67	5	8.33	5	0.394

Table 8 compares the optimal warpage predicted by the second-order regression model with the simulation validation at the optimum case. The model prediction is 0.39388 mm, while the actual simulation result is 0.394 mm, with a difference of only 0.00012 mm. This error is extremely small, well within the acceptable tolerance for precision plastic manufacturing, confirming the high reliability of the proposed model.

The strong correlation between the proposed model and simulation results demonstrates that the model is well suited for predicting warpage based on design parameters. This allows mold engineers to efficiently determine optimal parameter combinations without having to repeat the simulation multiple times. This shortens design time, reduces production costs, and increases efficiency in developing new molds for tubular plastic parts with similar structures.

4. Conclusion

This study successfully developed a highly accurate predictive model for optimizing cooling channel design, aimed at controlling and minimizing warpage during the injection molding process of plastic tube components. By combining the Taguchi method with numerical simulation using Moldex3D software, four key parameters (x, y, do, l) were investigated, and a second-order regression model was highly compatible. With its flexibility, high accuracy, and broad applicability, the proposed optimization model is not only suitable for mold production of tubular plastic parts but also holds great potential for application in other engineering plastic products.

The practical application of this model enables mold engineers to quickly predict warpage trends and optimize designs from the outset, thereby significantly reducing the number of experimental trials, shortening mold development time, and saving production costs.

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