International Journal of Applied Science and Engineering

Reduce the displacement and the roundness of the round plastic product by the baffle cooling channel in the injection molding system

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ABSTRACT

Through numerical analysis, the impact of baffle cooling channels on the total displacement and circularity of plastic cup products has been investigated in this study. Case 1, with a single cooling channel on the cavity side, Case 2, with cooling channels on the cavity and core sides, and Case 3, with a baffle cooling channel on the core side, are the three cooling channel configurations that are considered. Our results highlight the need for core-side cooling channels to provide uniform heat transfer in deeply molded plastic parts. Consequently, the implementation of a baffle cooling channel in Case 3 reduces total displacement and circularity, two critical elements influencing product quality. In particular, the product's circularity significantly reduces from 0.29 mm in Case 1 to 0.01 mm in Case 3, and the overall warpage displacement drops from 0.42 mm in Case 1 to 0.09 mm in Case 3.

Keywords: Baffle cooling channel, Injection molding, Roundness, Total displacement

OPEN ACCESS

Received: October 12, 2023
Revised: April 18, 2024
Accepted: June 17, 2024

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Publisher:
Chaoyang University of Technology
ISSN: 1727-2394 (Print)
ISSN: 1727-7841 (Online)

1. INTRODUCTION

Molding by injection is the most used process right now in the high-demand plastic industry. One of the most serious defects that diminish the product's quality is the warpage inside the plastic product. Furthermore, the injection molding industry's primary goal is to decrease cooling time, which is recorded for more than 70% of the overall molding cycle.

There have been several types of studies on the impact of injection process conditions on plastic product quality. Chang and Yang (2001) used the finite volume method to create a 3D mold model for simulating the melting behavior during the filling stage. As a result, in the injection molding industry, finding the optimal process conditions of injection molding with low warpage inside the product and a short cooling time is a momentous challenge.

Park et al. (2010; 2019) used a baffle cooling channel to archive an advanced mold design with a uniform cooling rate and improved cooling efficiency. Their result indicated that the cooling time and the cycle time could be decreased by more than 50.00% in the baffle cooling channel compared to that in the traditional cooling channel. Hassan et al. (2009; 2010) developed a 3D injection molding model that is time-dependent in their papers. The inlet temperature, the temperature of injection, and the time for filling are among the procedure parameters that have been determined. The goal of this research is to see how these variables affect the cooling time. The time for filling had a significant impact on the plastification of the melt in the process of filling as well as the cooling time, according to the findings.

Ozcelik and Erzurumlu (2006) and Ozcelik et al. (2010) conducted some studies on injection molding parameters. In the Ozcelik and Erzurumlu (2006), the effect of the temperature of a melt, the pressure of packing, the time to pack, the cooling period, the type of runner, and the location of the gate on the warpage of plastic components was investigated. The impact of injection process parameters on mechanical characteristics, for example, the elastic module, the tensile resistance, and the tensile force were investigated by Ozcelik et al. (2010). To find the main effect parameter, the Taguchi method was used. The maximum tensile load of the samples was investigated by Ozcelik (2011) by looking into the injection pressure and melt temperature. Nian et al. (2015) discovered a way to reduce warpage inside the plastic part by adjusting the cooling system's local mold temperature setting. Dzukipli and Azuddin (2017) reported that different process conditions – temperature of a melt, material, and mold design – have a significant impact on the formation of the weldline. The result of parameters for cooling, for example, the temperature of a melt, the cooling period, or the cooling conditions on the warpage was considered by Sánchez et al. (2012). The review paper of Kanbur et al. (2020) showed the important effect of conformal cooling channels which could improve the cooling time, total injection time, temperature distribution, thermal stress, and warpage. Later in 2022, the paper of Kanbur et al. investigated the process of utilizing metal additive manufacturing to create conformal cooling channels (CCC). Three configurations of CCC were compared: circular CCC, serpentine CCC, and tapered CCC. The optimal diameter values of each type of CCC were determined and incorporated into the printing process.

Kuo and Xu (2018), Kuo et al. (2019a; 2021) studied a series of research on conformal cooling channels. Their results indicated that the cooling time of the plastic part is proportional to the distance between the part and the mold cavity. In the wax injection molding, the cooling efficiency could be increased to 82.92% with conformal cooling channels. Moreover, wax was found as the most proper material for making conformal cooling channels. The conformal cooling channel machining by rapid tooling technology could reduce the cooling time by about 89.00%. In the paper of Kuo et al. (2019b), the butt joint method was applied to produce long wax filaments to create molds with a smooth surface. The research has determined the best parameters to use in the butt joint method of producing long wax filaments, along with techniques to improve the wax cooling channels' surface quality. The study of Kuo and Chen (2021) found a method for increasing the thermal conductivity of a silicone rubber mold (SRM) by incorporating fillers into it. The investigation discovered a blended recipe for maximum cooling efficiency: 52.60 wt.% aluminum powder, 5.30 wt.% graphite powder, and 42.10 wt.% liquid silicon rubber. By including fillers into the SRM, thermal conductivity can be increased by more than 77.60%, while actual cooling time for the injection molded product can be lowered by up to 69.10%. Kuo and Qiu (2021) described the process for preventing coolant leakage in direct-metal-printed injection molds with CCC using injection mold fabrication combined with the solution of aging treatment (SAT). The results show that the injection mold's surface hardness increased from HV 189 to HV 546 as the Ni-Mo precipitates increased from 12.80% to 18.50%. Furthermore, the relative density of the injection mold increased from 99.18% to 99.72%, and the wax injection mold's total production time without coolant leakage during the cooling step decreased by 62.00% when compared to traditional methods. The research of Kuo and You (2022) provided a method for adjusting mold thickness to improve structural strength, which is lowered in wax injection molding, based on simulation and experiments. A trend equation is also predicted to determine the appropriate thickness value based on the cooling channel's diameter. To achieve a homogeneous vulcanization temperature for liquid silicone rubber (LSR) parts, Kuo et al. (2022a) used both a conformal heating channel (CHC) and a CCC concurrently. The results show that the CHC successfully maintains a consistent temperature within the cavity, while the CCC keeps the LSR in a liquid state, reducing runner waste. The study also discovered the best trend equation for estimating the solidification time of a convex lens, which could be lowered by 28.00% when utilizing an LSR injection mold with CHC and a water temperature of 70°C. The influence of different mold materials and coolant media on the cooling performance of CCC in rapid tooling technology (RTT) was investigated by Kuo et al. (2022b). The results indicate that cooling water with ultrafine bubbles is the most effective coolant, and mold material has a greater impact on cooling efficiency compared to coolant media.

In the research of Chung (2019), finite element analysis was obtained to determine the optimal layout of the cooling channel. The results indicated that conformal cooling channels with optimal process parameters could help to improve the mold temperature difference, the ejection time, and the warpage of the plastic lenses. The research of Muvunzi et al. (2021) aimed to propose a design method for hot stamping tools utilizing conformal cooling channels to reduce cycle time and increase product quality. Reggiani and Todaro (2019) proposed the selective laser melting (SLM) additive technology with CCC to control the uniform temperature in the extrusion process conditions of aluminum alloys. The research of Oh et al. (2022) proposed a strategy for improving uniform heat distribution in the mold by using micro-cellular cooling structures rather than traditional cooling channels. Various designs of triply periodic minimal surface (TPMS) in terms of structures, forms, and base coordinates were compared, leading to the conclusion that the TPMS design manufactured utilizing a powder-bed fusion (PBF)-type metal additive manufacturing (AM) process is the most optimal design. To cool the parts with complex or deep concave geometries, Torrest et al. (2021a) proposed fluted conformal cooling channels to enhance the turbulence in the coolant flow, hence improving the heat exchange within the fluid stream. According to the computational model, the novel cooling design can cut the injection molding cycle time by up to

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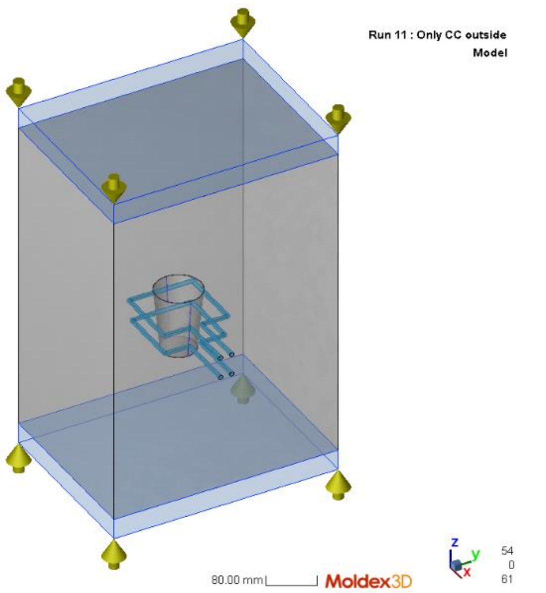
27.44% while, also improving a temperature uniformity by 51.67%. Torrest et al. (2021b) also used triple hook-shaped conformal cooling channels to produce a high-quality optical product in another paper. Simulation results reveal very favorable outcomes: an improvement in thermal efficiency by 267.1%, along with a reduction in overall maximum displacements by 36.34% and the Von-Mises maximum residual stress by 69.28% when compared to conventional cooling. The review article of Silva et al. (2022) emphasized the importance of CCC in improving parameters such as cooling time, total injection time, uniform temperature distribution, thermal stress, and warpage thickness by following molded geometry pathways, as opposed to conventional (straight-drilled) channels. The next section provides an overview of CCC production, design, simulation, and optimization. The physical model and geometrical variables of a conformal lattice element were dimensioned for parameter optimization in the paper of Mercado-Colmenero et al. (2019). The model was validated using four plastic parts of varying forms and sizes. Computational fluid dynamics (CFD)-type software was used to assess parameters such as coolant pressures and temperatures, temperature distribution on plastic parts, and time to attain the ejection temperature.

The most critical challenge encountered in injection molding processes is the occurrence of warpage, a defect that significantly degrades the manufactured plastic part. Historically, the predominant method for mitigating this concern has been iterative mold trials, a practice characterized by substantial consumption of time, energy, material, and other resources as successive adjustments are made until the requisite product standards are achieved. Consequently, the adoption of computer-aided engineering (CAE) software emerges as an imperative strategy in the contemporary solution, employing the predictive assessment of total warpage displacement within plastic injection molded parts. After a thorough analysis of relevant literature, it is clear that CCC have the potential for promoting a consistent temperature distribution and reducing warpage in injection molding plastic parts. However, due to the high cost of mold manufacturing, the implementation of CCC technology in mold fabrication requires a significant investment. Baffle cooling channels are a feasible option for dispersing heat in the core-side area of the mold and reducing warpage tendencies in the finished product with complex geometries with significant concavities or convexities.

Baffle cooling channels' impact on product quality—more especially, its warpage and roundness characteristics—is examined and scrutinized closely. Moreover, the result of various process parameters, such as coolant temperature, time to pack, and maximum packing pressure, on the warpage inside the product and the maximum cooling time of the cycle of injection molding, is numerically considered in this study. The goal of this project is to minimize the internal warpage and the maximum cooling time to preserve the optimal design and process conditions and improve the quality of the plastic part.

2. MATHEMATICAL MODEL

The heat transfer mechanism inside the mold, as well as the plastic melt and cooling channel's flow motion, are represented in 3D, as illustrated in Fig. 1. At the bottom of the product, there is a melt inlet. The item is the 40 mm^R × 30 mm^r × 115 mm^H × 0.8 mm^T plastic cup. R is the diameter of the cup's top; r is the diameter of the cups' bottom; H is the height of the cup; T is the thickness of the cup. ABS_CAE-321 plastic was used. There are a total of 3 cases considered. The heat generated by the melting of plastic is removed by the coolant that circulates. The current model takes into account the heat conduction by the cooling channel and the moldbase, as well as heat removal from the moldbase by convection. The process condition is also listed. The filling time is 1.2 s, the packing time is 3.3 s, and the cooling time is 10.6 s. the mold temperature is 225°C, while the mold temperature is 60°C.



[Filling]	
Filling time (sec)	1.22
Melt Temperature (oC)	225
Mold Temperature (oC)	60
Maximum injection pressure (MPa)	250
Injection volume (cm^3)	24.3376
[Packing]	
Packing time (sec)	3.3
Maximum packing pressure (MPa)	250
[Cooling]	
Cooling Time (sec)	10.6
Mold-Open Time (sec)	5
Eject Temperature (oC)	96.95
Air Temperature (oC)	25
[Miscellaneous]	
Cycle time (sec)	20.12
Mesh file	Design 4_CC outside and Baffle inside....
Material file	ABS_CAE-321(GB002-20A05)_1.mtr

Fig. 1. The injection molding model with process conditions in this study

The equations that govern 3D, unsteady, incompressible fluids are as follows:

$$\frac{\partial\rho}{\partial t}(\rho u) + \nabla \cdot (\rho u u + \tau) = -\nabla p + \rho g \quad (1)$$

$$\frac{\partial\rho}{\partial t} + \nabla \cdot \rho u = 0 \quad (2)$$

$$\rho c_p\left(\frac{\partial T}{\partial t} + u \cdot \nabla T\right) = \nabla(k\nabla T) + \eta\dot{\gamma}^2 \quad (3)$$

where ρ is the volumetric density, t is the time, u is the velocity vector, T is the temperature, p is the pressure, τ is the stress tensor, η is the viscosity, k is the thermal conductivity, C_p is the specific heat and $\dot{\gamma}$ is the shear rate.

Moldex3D is used to solve the equations and the boundary conditions in this model. The governing equations were derived using the control volume conservation principle. The authors make use of a boundary layer mesh (BLM). BLM mesh is made up of two types: five layers of prism mesh on the surface and the tetra mesh inside the product. The shear heating effect in the plastic was precisely captured by the BLM mesh. This model has a total of 852,084 solid mesh elements.

3. RESULTS AND DISCUSSION

The injection molding system's thermal and flow fields are investigated. As shown in Fig. 2, three different channel layout designs are investigated: Case 1 with the only cooling channel of 8 mm diameter at the cavity side, Case 2 with 2 cooling channels of 8 mm diameter at both cavity side and core side and Case 3 with 2 cooling channels: 8 mm diameter at the cavity side and 12 mm diameter with baffle cooling channel at the core side.

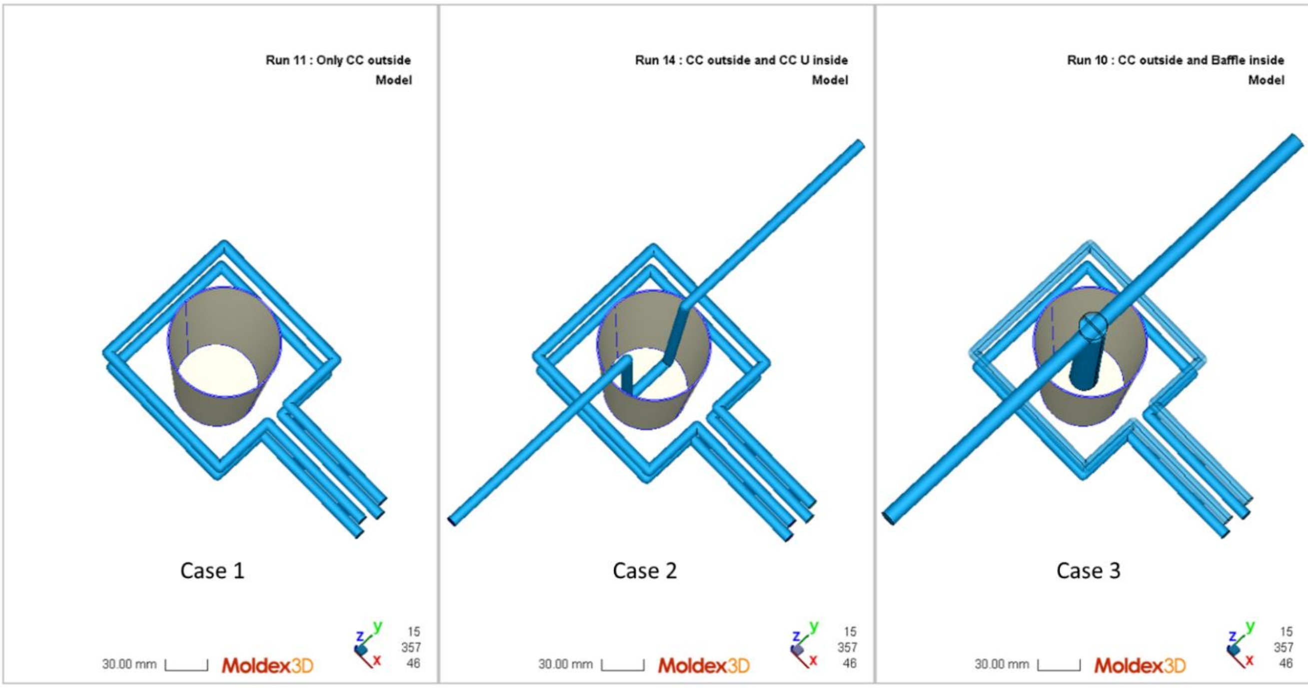


Fig. 2. Three different cooling channel designs

The channel centers are separated by 40 mm. Water is the coolant, and the time for cooling is 10.6 s. The temperature of the coolant has been set to the same temperature as the mold (35°C). The current cooling channel has a flow rate of 120 cm^3/s. The cooling channel's Reynold number is 26,273, indicating that the fluid flow is turbulent.

In the filling process, melt front time is defined as the movement of the melt front boundary over a period of time. Controlling the filling stage is essential for the plastic product with thin wall thickness because the high resistance inside the mold cavity makes the filling stage more difficult and increases the risk of short shots. The filling process is depicted in Fig. 3 at various stages: 25%, 50%, 75%, and 100%. The part has been 100% filled at 1.25 s, and there are no issues with short shots or weld lines visible. This may be due to the model's low flow length ratio (L/T, where L represents flow length and T represents thickness). The flow length ratio in this model is within ABS's reference range.

Based on the data from the previous three sets of parameters, the optimal process parameter was predicted. The total product displacement and the maximum cooling time are quality factors. The results show that in the optimal run, the total displacement of the product and the maximum cooling time is significantly lower than in the basic run.

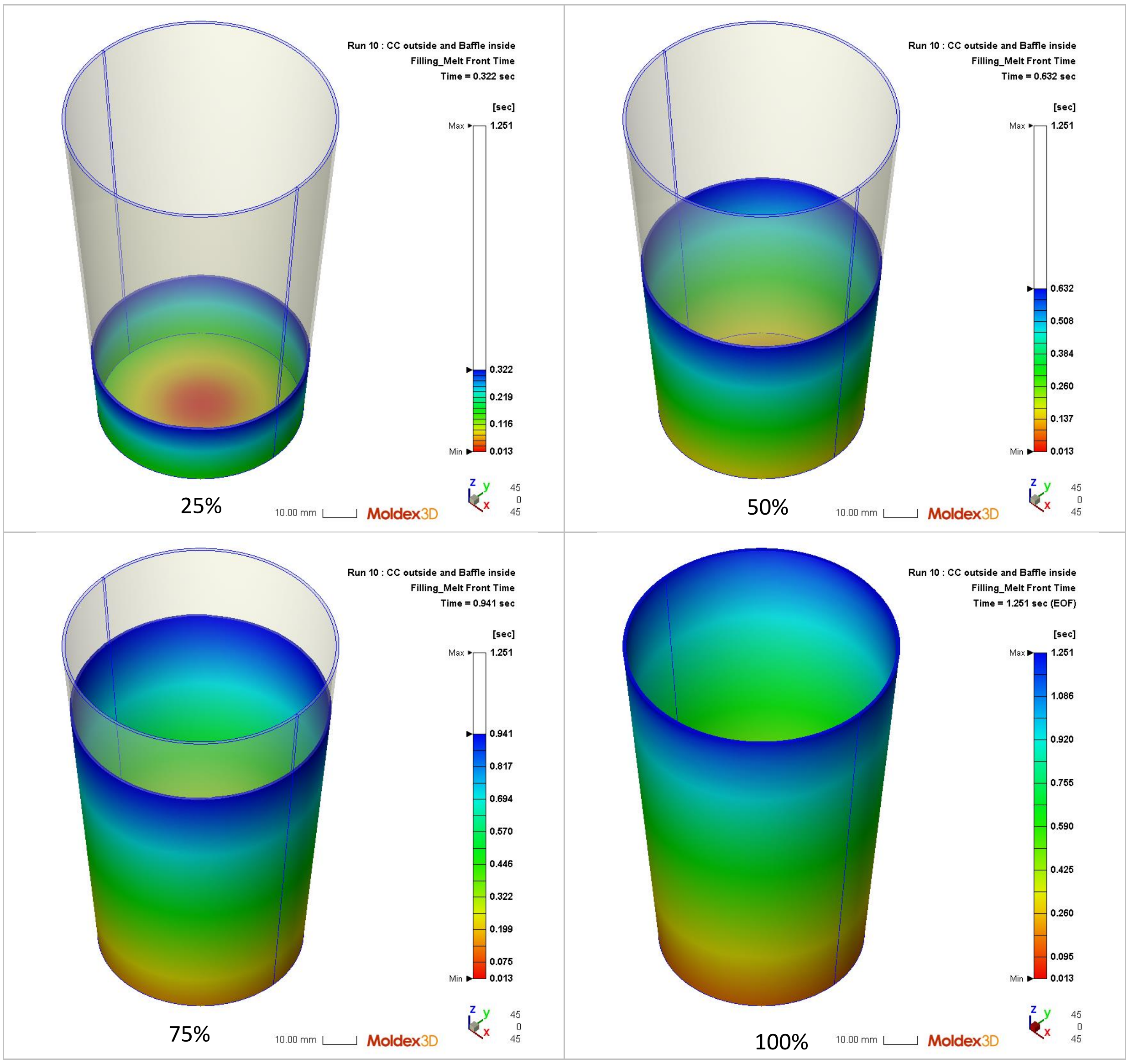


Fig. 3. Melt front time for the filling process at different stages: 25%, 50%, 75%, and 100%

Fig. 4 shows the part's temperature distribution at the end of the cooling process (EOC). The highest temperature is found in the part's corner, where heat accumulation is hard to dissipate. With the constant coolant temperature in 3 Cases, the temperature at EOC drops considerably compared to Case 1. The maximum temperature reduces from 98.88°C in Case 1 to 65.43°C in Case 2 and increases to 69.85°C in Case 3. In Case 2 cooling temperatures on the part are uneven compared to Case 3. With the symmetric axial design of the baffle cooling channels in Case 3, the distance from the cooling line to the product wall, especially the core-side portion, is consistently maintained. Consequently, although the heat dissipation process in Case 2 is superior, as evidenced by the lowest maximum temperature, the uniformity of heat distribution in Case 3 holds a comparative advantage. These results were a good match with the previous study of Kuo et al. (2021), in which the optimal conformal cooling channel design has a lower distance from the cooling channel to the mold cavity, then has a lower mold temperature difference, as well as the cooling time. The uniformity of heat distribution significantly influences the warpage of the product. For the considered plastic product, balancing heat along the y-axis is a factor crucial to enhancing the product's roundness.

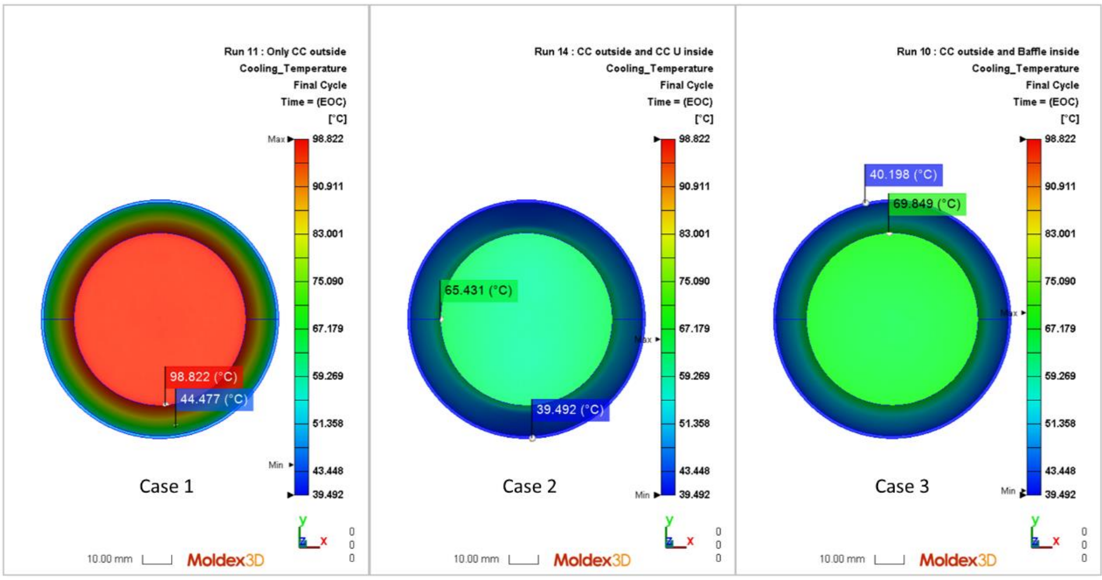


Fig. 4. Temperature distribution of the part after cooling in each of the three cases

In Fig. 5, the part's temperature cooling (slicing) also distributed the same tendency as in Fig. 4. The maximum temperature decreases from 104.94°C in Case 1 to 70.94°C in Case 2 and increases to 75.18°C in Case 3. Although the maximum cooling temperature value (slicing) is higher than that in Case 2, the temperature distribution inside the cup in Case 3 is more uniform compared to that in Case 3. The reason may be due to the cooling channel design of 3 Cases. In Case 1, there is no cooling channel on the core side, so the heat inside the cup cannot be released and the temperature at EOC is still very high. With the cooling channel in the core side in Case 2, the temperature at EOC drops significantly. However, the channel layout makes the heat dissipation not even through the x-direction. With the axisymmetric design of the baffle cooling channel in Case 3, the distance between the cooling channel and the wall of the cup is uniform. As mentioned in the study of Wang et al. (2018), a baffle cooling channel obtains the maximum cross-sectional area of the water and forces it to the area that normally lacks cooling which is the core side in the present research. Therefore, the heat is released evenly and the temperature distribution inside the cup in Case 3 is more uniform. The uniform heat distribution, along with low-temperature differentials within the mold, is one of the crucial factors influencing the warpage process of plastic products manufactured by injection molding. Employing baffle cooling channels is a viable option to achieve uniform heat distribution within the mold, with a reasonable cost compared to conformal cooling channels.

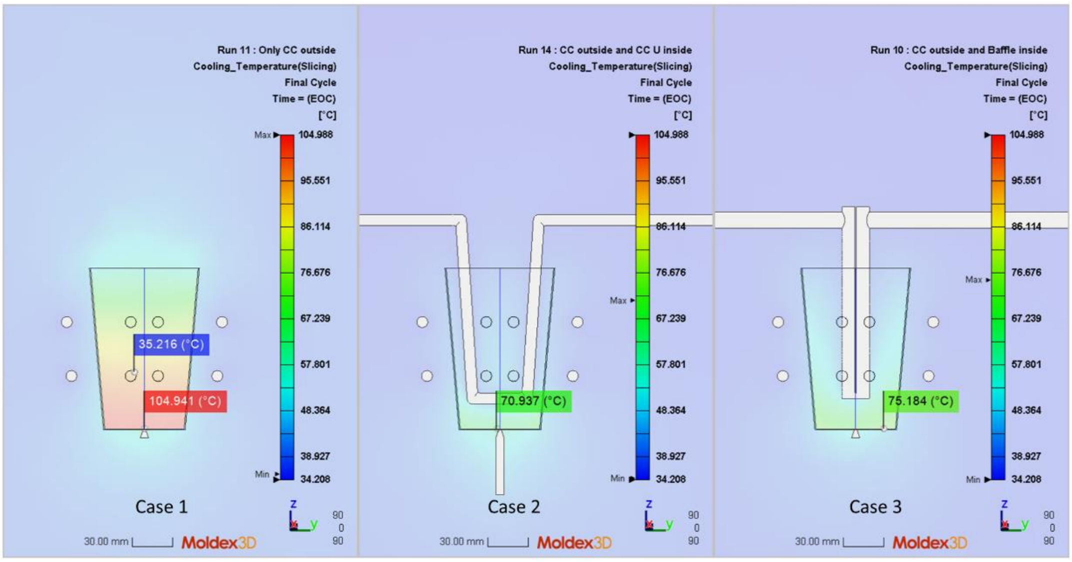


Fig. 5. Maximum cooling temperature (slicing) of the three cases

Fig. 6 illustrates the part's overall displacement warpage distribution. It could be seen that plastic product has the tendency of shrinkage. The top and bottom of the part have the most total displacement warpage. The reason may be due to the product's thin wall. In Case 1, the maximum total displacement warpage occurs at the bottom of the product. This can be explained by the fact that there is no cooling line design on the core side of the product, which prevents heat buildup from dissipating at the bottom. On the other hand, in Cases 2 and 3, the maximum total displacement warpage moves to the top of the product instead of the bottom because cooling lines are positioned at the core side of the mold. The greatest overall displacement warpage decreases significantly from 0.423 mm in Case 1 to 0.130 mm in Case 2 and continues to reduce to 0.086 mm in Case 3. The drop of warpage displacement is the result of the advanced design of the cooling channel through 3 cases. In Case 1, the maximum warpage is at the bottom of the cup where heat concentration is highest. With the cooling channel inside the cup in Case 2, the temperature inside the cup is lower. Therefore, the maximum warpage in Case 2 is at the top of the cup where the packing effect is lowest due to the longest flow length. The same tendency of maximum warpage at the top of the cup occurs in Case 3, and the maximum warpage displacement is even lower due to the strong effect of the baffle cooling channel in Case 3 which is shown in Fig. 4 and Fig. 5. The significant reduction of the total displacement of the warpage in the current model was also shown in the report of Kuo et al. (2021). The minimal overall displacement warpage of the thin-wall plastic product contributes significantly to the product's quality.

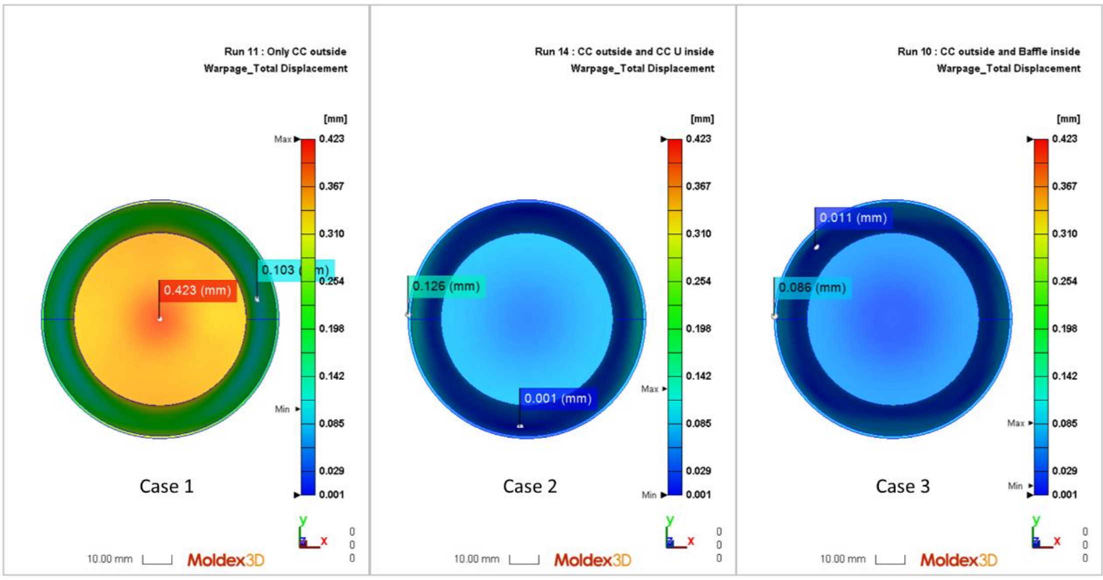


Fig. 6. Total displacement warpage of the part for the three cases with a scale factor of 10

Fig. 7 indicates the effect of cooling on the volumetric shrinkage warpage significantly drops, from 5.716% in Case 1 to 1.476% in Case 2 and increases to 1.480% in Case 3. The volumetric shrinkage percentage indicates the change in the volume when the product is cooled down to the ambient temperature conditions. The value of volumetric shrinkage is positive means that the part will tend to shrink. The volumetric shrinkage in Case 1 is the highest since there is the largest temperature gradient when plastic drops from the hot melt temperature to the ambient temperature. This is an important indicator to predict the warpage inside the injection molding product.

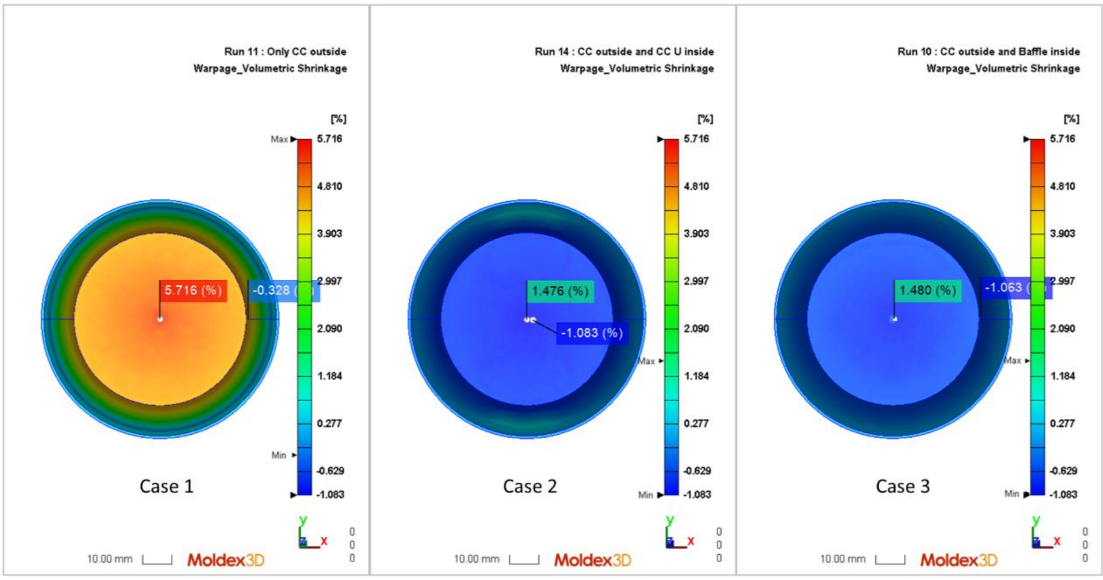


Fig. 7. The effect of cooling design on the volumetric shrinkage

The roundness of the part is one of the most important quality factors for a product with a round shape. Therefore, the deformation at the round boundary needs to be controlled well. Figure 8 shows the roundness of the cup for three cases. It could be seen that the roundness of the product is significantly reduced from 0.29 mm in Case 1 to 0.14 mm in Case 2 and 0.01 in Case 3. The extremely low roundness in Case 3 could be explained by the baffle cooling channel at the core side which helps to release the heat inside the cup uniformly in every direction. It is clearly observable that different designs of cooling channels will have varying effects on the roundness of the product. Case 1, despite featuring the simplest design, exhibits the highest deviation in roundness, negatively impacting the product quality. Conversely, Case 3 demonstrates the optimal design among the three cases, resulting in the lowest roundness deviation, as well as facilitating easier machining compared to Case 2.

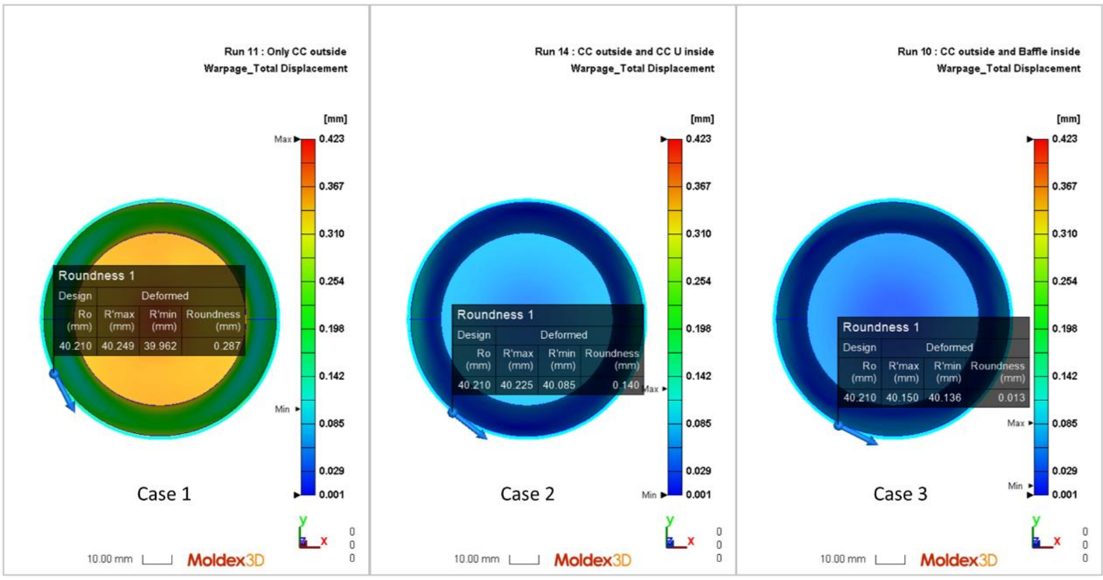
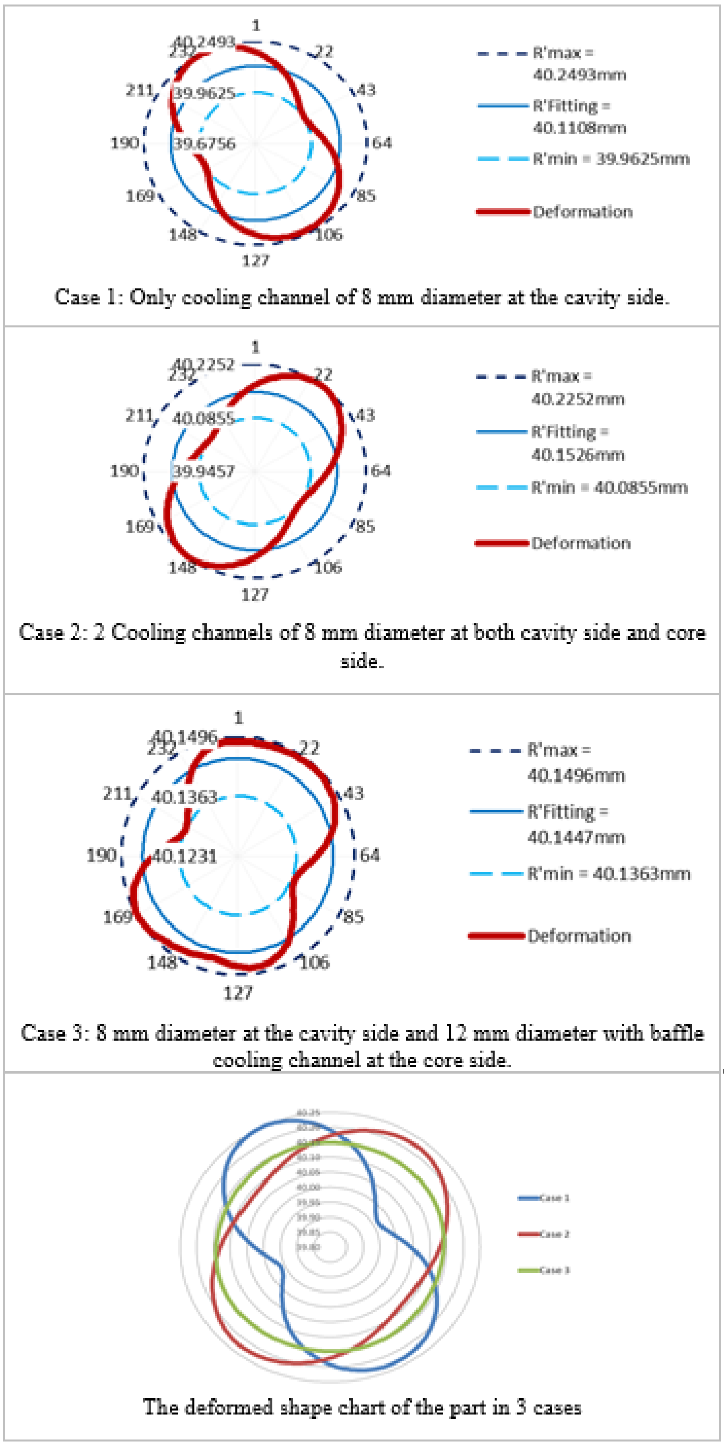


Fig. 8. The roundness of the part in three cases

Fig. 9 illustrates the roundness radar chart along the top boundary of the part in three cases. R'max and R'min indicate the maximum and minimum diameter of the cup, respectively. The higher the difference between R'max and R'min is, the more deformation of the cup at the top boundary is. In Case 1, the significant circular deformation is notable due to the absence of cooling channel arrangements on the core side. In Case 2, cooling channels are present on the core side, but there is also significant circular distortion. This is because the cooling channels on the core side in Case 2 are not symmetric with respect to the z-axis. It can be seen the deformed shape chart of the part in 3 cases in Fig. 9 that Case 3 with the baffle cooling channel on the core side has the lowest deformation and most uniform shape. This result indicates that with the plastic part with a deep shape like the cup, the cooling channel in the core side is necessary to release the heat accommodation inside the part, then reduce the warpage and improve the quality of the product. Furthermore, the utilization of baffle cooling channels represents a suitable heat dissipation solution for the core side, particularly applicable to products with a circular form, while maintaining an affordable tooling cost.



Case 1: Only cooling channel of 8 mm diameter at the cavity side.

Case 2: 2 Cooling channels of 8 mm diameter at both cavity side and core side.

Case 3: 8 mm diameter at the cavity side and 12 mm diameter with baffle cooling channel at the core side.

The deformed shape chart of the part in 3 cases

Fig. 9. The roundness radar chart of the part in three cases

In this paper, the results regarding temperature distribution within the mold, total displacement warpage, and volumetric shrinkage for various cooling design configurations have been investigated. The findings have highlighted the significance of baffle cooling channels in cooling the core side of the mold, thereby enhancing the roundness of products such as injection-molded plastic parts. Baffle cooling channels present a feasible mold design solution for circular-shaped injection-molded products, aiming to improve product quality with significantly lower costs compared to the utilization of conformal cooling channels.

4. CONCLUSION

Conformal cooling channels represent a solution aimed at improving cooling time, total injection time, temperature distribution, and warpage during the injection molding process of plastic parts. Nevertheless, this method has the disadvantage of being expensive to mold and difficult to manufacture. This paper has investigated the influence of various cooling channel designs on quality factors of plastic parts, including total displacement and roundness. Simulation results have highlighted the feasibility of using baffle cooling channels in manufacturing injection-molded products with round shapes while maintaining reasonable manufacturing costs. Several inferences can be drawn from the paper:

1. The integration of baffle cooling channels on the core side is necessary for plastic products characterized by intricate geometries or deep cavities.
2. For circular-shaped injection-molded products, baffle cooling channels offer an economically viable mold design approach that aims to improve product quality at a much lower cost than conformal cooling channels.
3. With the advanced design of the baffle cooling channel, improvements in both the total displacement and the roundness of the product could contribute to enhancing the product's quality.

ACKNOWLEDGMENT

This research is supported by Ho Chi Minh City University of Technology and Education (HCMUTE), Vietnam (Project No. T2023-01).

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