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INVESTIGATIONS ON THE FLUID FLOW INSIDE DEVICES DESIGNED FOR THE AUTOMOTIVE INDUSTRY. CASE STUDY: COOLING SYSTEMS DESIGNED FOR PLASTIC INJECTION TOOLS

BY

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Abstract. The paper presents a synthetic analysis of the main research directions regarding heat transfer and fluid flow processes in plastic injection molding, with a focus on the role of the cooling systems. Several works are analyzed. The literature review indicates that to investigate the complex phenomena occurring during the injection process, most topics refer to numerical methods such as CFD simulations, finite element methods, and finite volume approaches. Relevant results obtained by the scientific community show that the cooling performance is influenced both by the geometry of the cooling channels and by the flow parameters, especially by the Reynolds number. Additionally, it was established that inadequate cooling technologies can lead to a non-uniform temperature distribution inside the mold, which can generate significant defects, such as shrinkage and warpage of parts. The conclusions of this work emphasize the necessity to better control the cooling systems used in the plastic injection manufacturing, in order to improve both the performance of the process and the quality of the product obtained by plastic injection.

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Keywords: plastic injection moulding, cooling performance, pressure drop, fluid flow, Reynolds number, optimization.

1. Introduction

Injection moulding is one of the main manufacturing technologies, used to produce complex plastic devices and equipment. It has important benefits, such as the advantage to be able to achieve high precision at low cost. A key aspect of the technology is the cooling stage, which covers the largest period of the production cycle, having relevant impact on the quality of the final product. During the cooling process, the molten material is in contact with the cold walls of the mold, leading to progressive solidification as part of the process to create the designed shape of the product.

The major issues associated with this process are generated by the non-uniform shrinkage and by the local deformation, phenomena that occur due to the difference of temperature between the material and the mold. The scientific literature reveals that the undesirable effects are closely related to the non-uniform distribution of the heat inside the mold and also to the way the temperature decrease due to the cooling system. In this paper, some recent research works, regarding the cooling systems used within the injection molding technology are presented and discussed. The analysis is focusing especially on simulation and optimization methods to improve process performance and efficiency.

2. Methodology

To investigate the complex phenomena occurring during plastic injection molding, numerical methods and mathematical models are used.

H.H. Chiang et al. (1993) used a relevant approach, using a coupled simulation approach for flow dynamics and thermal behavior. In their work, the molten polymer is modeled as a viscous, compressible, and non-isothermal fluid, and the simulation combines finite element, finite difference and control volume methods, to identify the fields of temperature, pressure and velocity inside the mold. In Fig. 1, a schematic representation of a mold with polymer melt (Sp), cooling channels (Sc) and exterior surface (Se) is presented. The cavity geometry is defined based on the mid-surface representation of its surfaces.

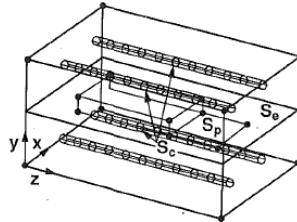


Fig. 1 – Schematic representation of a mold with polymer melt (S_p), cooling channels (S_c) and exterior surface (S_e) (Chiang *et al.*, 1993).

It is very important to identify the optimal Reynolds number for the cooling water circulating inside the mold through conformal cooling channels. The research developed by (Gao *et al.*, 2024) starts from the fact that a previous study elaborated proposed an optimal Reynolds number of 100,000. However, this value is high and by consequence it can generate large pressure drops in the cooling channels. Therefore, the authors repeated the numerical analysis using the same methods and assumptions as the previous study, in order to verify whether the value of 100,000 is realistic. More specifically, they built a hot stamping mold model with serpentine conformal cooling channels in CATIA, and then performed simulations in COMSOL Multiphysics 6.0. The mold was made of H13 steel, the channels had a diameter of 8 mm, the distance between the channel center and the cavity surface was 12 mm, and a heat flux of 190,000 W/m² was applied on the mold cavity walls. They analyzed the behaviour of the fluid flow for Reynolds numbers in the range 4,000 to 200,000, corresponding to water velocities in the range 0.51 m/s to 25.25 m/s.

Table 1

Reynolds number and the associated inlet normal velocity (Gao et al., 2024)

Reynolds number	Normal velocity at the inlet (m/s)
4,000	0.51
6,000	0.76
8,000	1.01
10,000	1.26
12,000	1.52
15,000	1.89
20,000	2.53
25,000	3.16
30,000	3.79
40,000	5.05
60,000	7.58
80,000	10.10
100,000	12.63
150,000	18.94
200,000	25.25

Hassan et al. (2009) carried out a transient 2D numerical analysis to study the cooling of a T-shaped polymer part produced by injection molding. They used the finite volume method to calculate temperature distribution in the mold and in the polymer, and they analyzed the solidification process of the polymer. The model includes heat transfer by conduction in the mold and in the polymer, forced convection toward the cooling fluid, and natural convection toward the surrounding air.

They also introduced a solidification model with a source term, which takes into account the latent heat of the polymer. The main parameters used were: injected polymer temperature of 220°C, cooling fluid temperature of 30°C, polymer fusion temperature of 110°C, latent heat of 115 kJ/kg, and heat transfer coefficient inside the cooling channel of 3650 W/m²K.

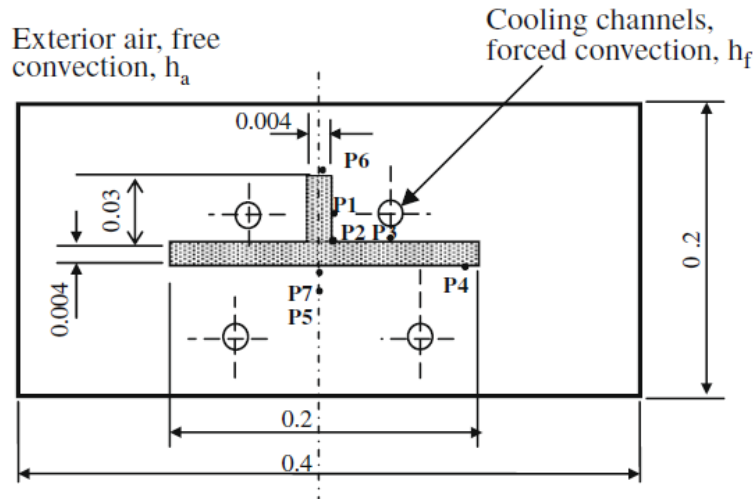


Fig. 2 – Mold structure with a T-shape product and four cooling channels [m] (Hassan et al., 2009).

Wagner G. et al. (2025) conducted a review on conformal cooling channels in plastic injection molding, focusing on how CFD/CAE simulations are used to analyze heat transfer. They examined parameters such as cooling time, temperature uniformity, pressure drop, shrinkage, and warpage, using software tools such as ANSYS-Fluent, Autodesk Moldflow Insight, COMSOL Multiphysics, and optimization tools such as MATLAB Optimization Toolbox.

St. Jacques (1982) analyzed flat polystyrene parts injected at 490°F, in order to observe how unbalanced cooling causes warpage after the part is removed from the mold. Three case studies identified by the value of the thicknesses were tested: 0.050 in, 0.100 in, and 0.150 in. The cooling periods were 7 s, 13 s, and 30 s; the cooling fluid temperature was modified in the range

60°F to 100°F, and the metal thickness between the cavity and the cooling channel was modified in the range 1.0 in to 2.5 in.

Dimla et al. (2005) carried out a design and optimization analysis of conformal cooling channels for an injection mold, starting from the construction of a 3D CAD model in I-DEAS / Model Master. Then, they used the Moldflow analysis option to choose the optimal injection point position, followed by FEA and thermal/heat transfer analysis to evaluate the positioning of the cooling channels. The analysis focused on quality, weld lines, air traps, sink marks, surface temperature, solidification time, and also on the cooling time reduction.

Coca-Gonzalez et al. (2025) conducted a review on the phenomenon of warpage, analyzing its causes, measurement methods, and deformation reduction strategies in three main processes: injection molding, compression molding, and 3D printing. The analysis focuses on the influence of the material, the mold, and key processing conditions, including the temperatures of the mold and melt, packing pressure, cooling time, coolant temperature, and 3D printing parameters.

Gruber A. et al. (2026) performed a numerical thermal-fluid analysis in Autodesk Moldflow Insight 2023, using the Cool (FEM) module and 3D tetrahedral mesh models, to evaluate the effect of limescale deposits on coolant flow, heat transfer, cooling time, and part dimensional stability.

Kuo C-C et al. (2025) developed rapid molds made of aluminum-filled epoxy resin, integrated with a new cooling system called surface-cooled cooling channel (SCCC), and analyzed the cooling performance through Moldex3D simulations, later validated experimentally by injecting LDPE parts. For the simulation, they used a 1 mm mesh size, and the experiments were repeated 10 times using an injection molding machine with a 900 kN clamping force.

Sun et al. (2025) developed a topology optimization framework for conformal cooling channels in injection molds, using COMSOL Multiphysics v6.3, the Navier–Stokes equations, the convection–diffusion heat transfer equation, and a scaling strategy that approximates turbulent flow at $Re \approx 10,000$ through a reduced laminar model at $Re = 100$, later verified by comparison with RANS and Darcy models.

3. State of the art. Relevant case studies and analysis of results

The results obtained in the previous studies highlight the importance of integrated modeling of physical phenomena. In the work developed by (Chiang *et al.*, 1993), it was demonstrated that by coupling fluid flow and heat transfer simulations, accurate prediction of shrinkage and warpage can be achieved. The simulation model was successfully validated experimentally. The results show that non-uniform temperature distribution leads to differential shrinkage, which can be responsible of the deformation of the molded part.

The results in the article of (Gao *et al.*, 2024) show that when the Reynolds number (Re) is in the range 4,000 to 20,000, the cooling performance is very good; the maximum temperature inside the cavity surface decreases by 111.68 K, the maximum temperature drop decreases by 75.85 K, and the average temperature decreases by 80.27 K. However, for Re in the range 20,000 to 200,000, these values are lower; the maximum temperature decreases by only 40.39 K, and the maximum temperature drop by only 25.12 K.

On the other hand, the pressure drop increases strongly at high Reynolds numbers. Up to $Re = 20,000$, the pressure drop is low, approx. 0.047 MPa, but at $Re = 100,000$ it reaches 0.824 MPa. At $Re = 200,000$, the pressure drop becomes more severe.

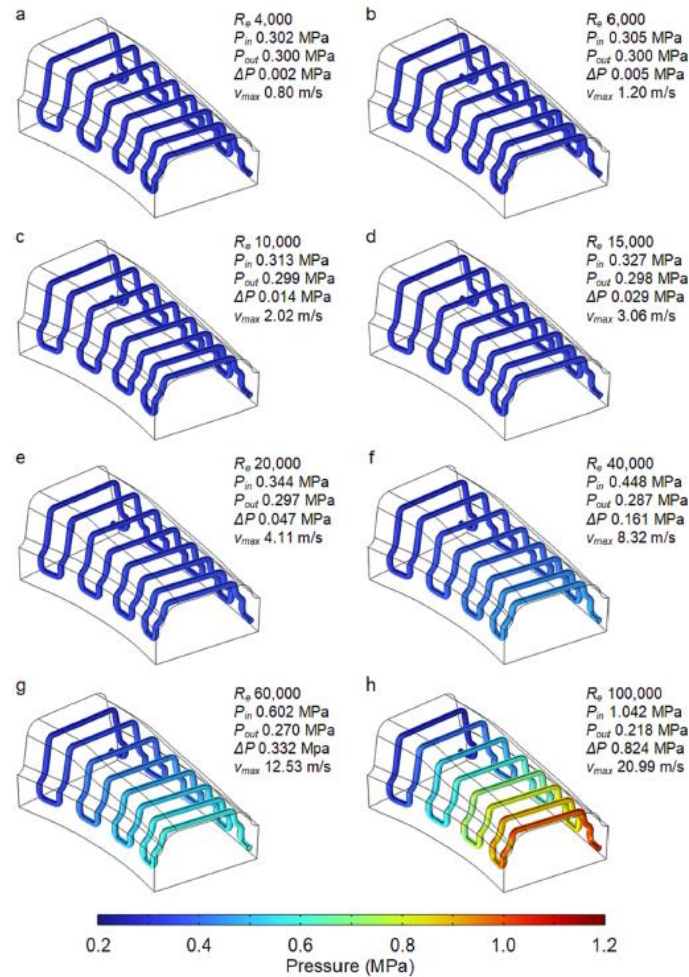


Fig. 3 – Pressure distribution of cooling water for $Re = 4,000 \dots 100,000$ (Gao *et al.*, 2024).

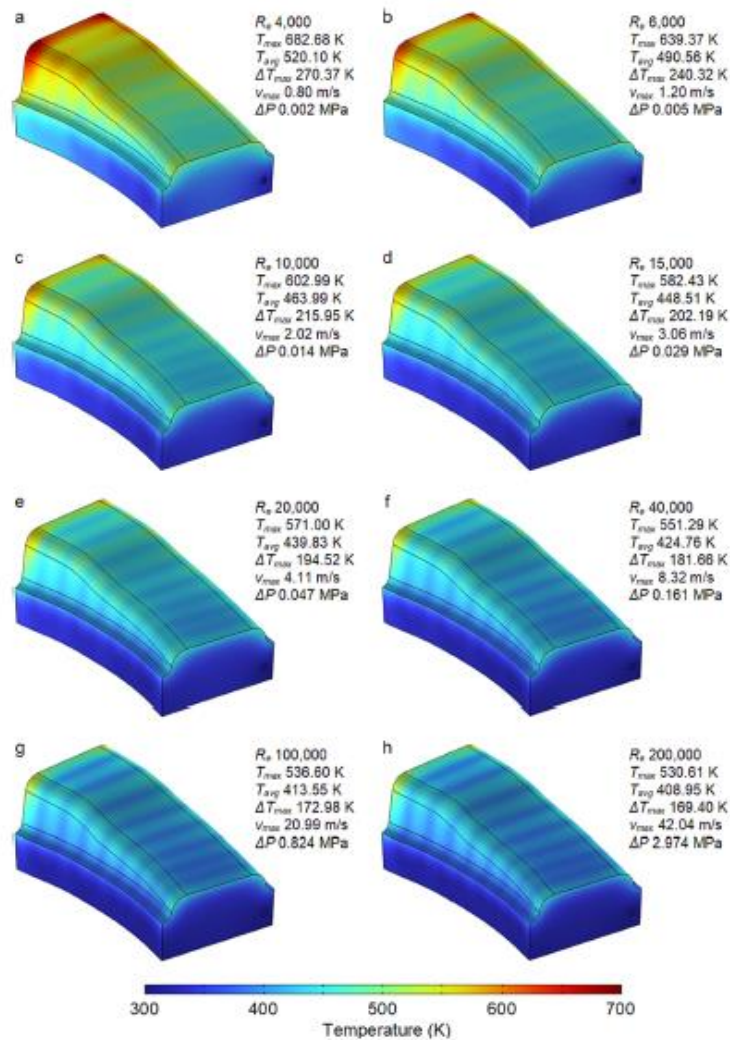


Fig. 4 – Temperature distribution of cooling water for $Re= 4,000....200,000$ (Gao *et al.*, 2024).

The study of (Hassan *et al.*, 2009) proposes a mold for a T-shaped polymer part, with four cooling channels. Four types of channel cross-sections were investigated: circular, square, rectangular 1, and rectangular 2 — as well as several channel positions relative to the product. The shape of rectangular 2 channel showed the best results when the comparison was made for the same cross-sectional area and cooling period of 24 s. It indicated approximately 0.91–0.92 solidification degree, comparing with 0.90 for the square channel, 0.88–0.89 for rectangular 1 channel, and 0.87–0.88 for the circular channel.

The conclusion is that cooling improves when the channel shape follows the product geometry more closely and when the channels are positioned closer to the polymer. However, the authors emphasize that the solution which provides the shortest cooling time or the highest solidification percentage does not automatically ensure a uniform temperature distribution, so the cooling system must be optimized for both productivity and final part quality.

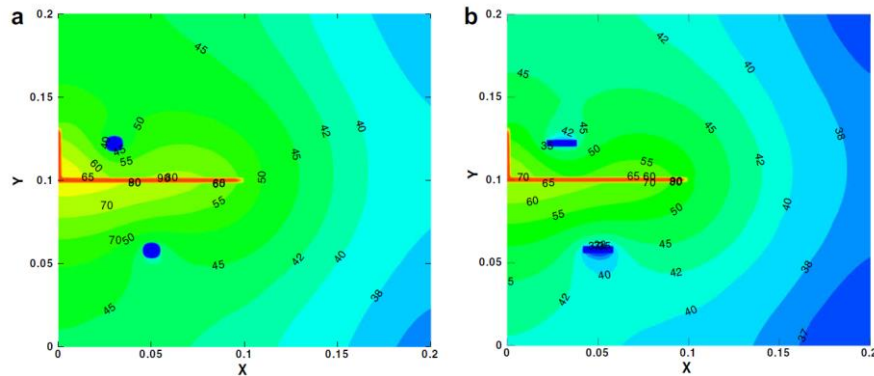


Fig. 5 – Temperature distribution through the mould for different cooling channels shapes having the same cross sectional area: (a) circular, (b) rectangular 2 (Hassan *et al.*, 2009).

One example presented in the article is the study of (Wagner *et al.*, 2025). Four types of cooling channel configurations were studied: normal channel, conformal channel with baffle, conventional channel with conformal channel, and totally conformal channel. The diameter was 10 mm for all channels and the only difference between case studies was the architecture of the channels inside the mold. The main result was that the fully conformal cooling channels configuration had the best performance, because it allowed the mold to reach the ejection temperature faster, reduced volumetric shrinkage could be observed and the deformation was not significant due to the uniform cooling. The conclusion is that conformal cooling is more efficient than conventional cooling because it follows closely the geometry of the mold and allows a more uniform temperature distribution, leading to a shorter cycle time and to high quality of the final product.

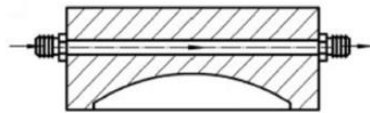


Fig. 6 – Straight-drilled cooling channel (Wagner *et al.*, 2025; Feng *et al.*, 2021).

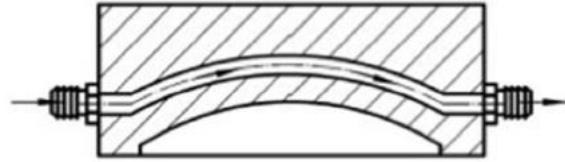


Fig. 7 – Conformal cooling channel (Wagner *et al.*, 2025; Feng *et al.*, 2021).

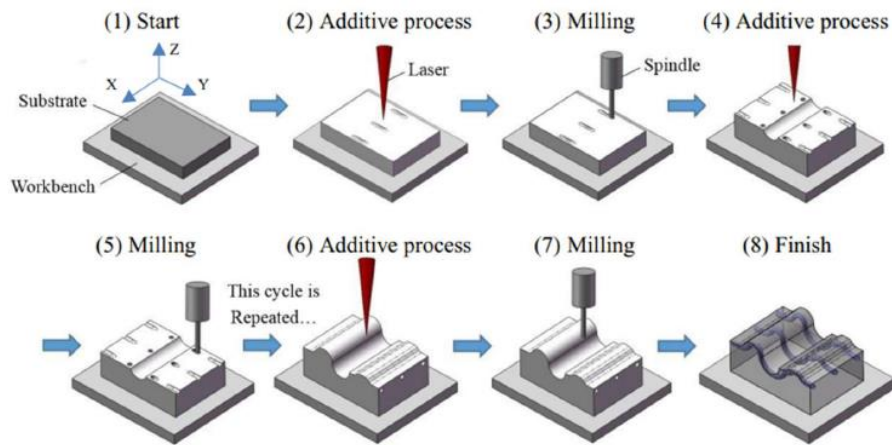


Fig. 8 – Schematic of a hybrid process (Wagner *et al.*, 2025; Du *et al.*, 2016).

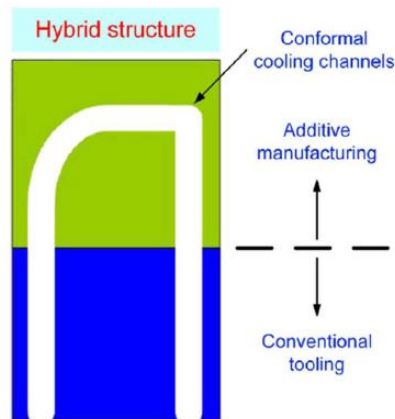


Fig. 9 – Hybrid subtractively (blue) and additively (green) manufactured CC mold (Wagner *et al.*, 2025; Feng *et al.*, 2021).

The research performed by (St Jacuques, 1982) showed that warpage increases almost linearly as the temperature difference of the cooling fluid between the two mold sides increases, while the thinnest part, 0.050 in, showed

the highest deformation because of its lower bending stiffness. Also, differences in metal thickness between the two mold sides caused asymmetric cooling and increased warpage, and when both casualties occurred at the same time, their effects were additive.

The case study analyzed by (Dilma *et al.*, 2005) was a 3D-modeled injection-molded part with an 8° draft angle and an internal rib for increased stiffness, for which different injection point positions and two cooling solutions — straight-drilled channels and conformal channels — were analyzed. The results indicated that the solution with a single injection point was preferred, because increasing the number of injection points did not improve cooling time or part quality and may favor the formation of weld lines, since several molten material fronts meet inside the mold at different temperatures. For the optimized solution, the estimated injection period was approximately 1.18 s. Results indicate that the weld lines were reduced, the quality prediction improved. Concluding, the conformal channels were considered more efficient because they can reduce cooling time and ensure a more uniform temperature than conventional channels.

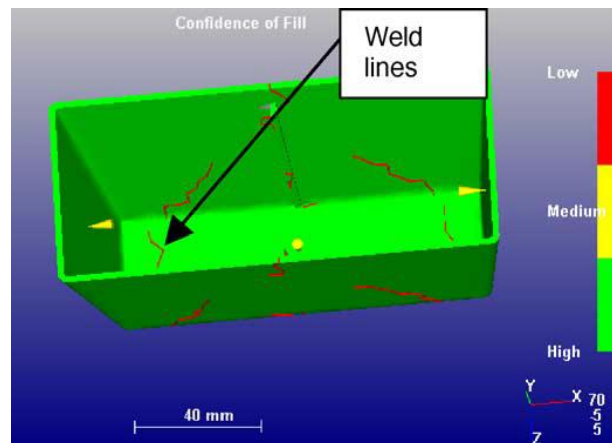


Fig. 10 – Weld lines on the model surface (Dilma *et al.*, 2005).

Coca-Gonzalez *et al.* (2025) concluded that in the area of injection molding, the article shows that the warpage occurs mainly due to the non-uniform shrinkage, uneven temperatures, and residual stresses. The authors mention that changing the cooling water temperature in the mold can reduce warpage by approximately 80% in compression molding, an AI algorithm can achieve more than 95% accuracy in warpage prediction, and cooling systems are recommended to operate in turbulent flow, with a Reynolds number higher than 5000, because heat transfer becomes more efficient and helps reduce part deformation.

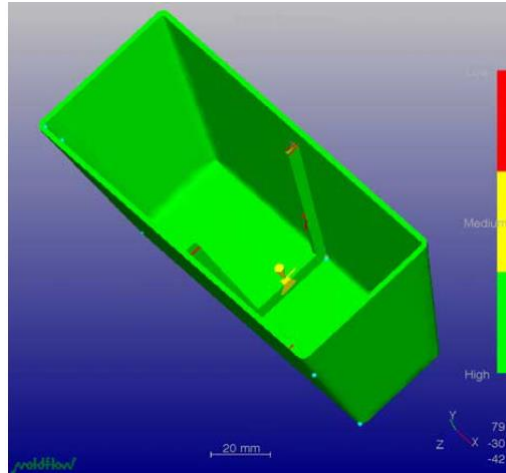


Fig. 11 – Single gate position: quality prediction. (Dilma *et al.*, 2005).

The case study of (Gruber *et al.*, 2026) was a well plate, with wells of approximately 6 mm diameter and 10 mm depth, cooled by a system of 96 bubblers; the analyzed material was polystyrene, with a melt temperature of 200°C, a P20 mold, water as coolant, a coolant pressure of 250 kPa, a mold temperature of 45°C, and an ejection temperature of 108°C. The results showed that a limescale layer of only 0.1 mm can increase the time to touch ejection temperature by 29% when it is assessed only as an additional thermal resistance, and by 51% when the associated flow limitation is also taken into account.. For the complete model, the least efficient setup, including limescale deposits and long bubblers, produced an average mold temperature that was 11% higher and a cooling time increased by 17% compared with the optimized limescale-free configuration.

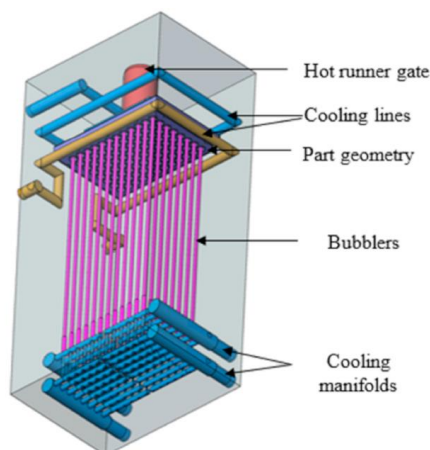


Fig. 12 – Simplified mold block configuration used for the simulations (Gruber *et al.*, 2026).

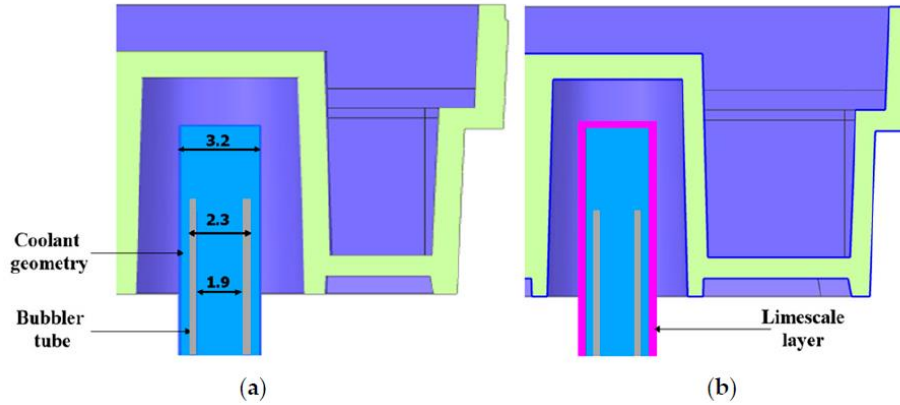


Fig. 13 – Two-dimensional section of the mold: (a) cooling system layout and single bubbler measurements (mm); (b) modeled position of the limescale deposit. (Gruber *et al.*, 2026).

Kuo C.-C. *et al.* (2025) investigated four mold cooling approaches for a 2 mm-thick LDPE cup-shaped component: a mold without cooling channels, a conventional cooling layout, a conformal cooling design, and an SCCC system. The cooling passages had a diameter of 6 mm, while the processing conditions were set to a melt temperature of 160°C, a mold temperature of 30°C, an injection pressure of 10 MPa, and a cooling duration of 20 s. The experimental data indicated that cooling from 180°C to 30°C required 4801 s in the absence of cooling channels, 1105 s for the conventional cooling solution, 971 s for the conformal cooling design, and only 401 s when using SCCC. Therefore, the SCCC configuration achieved approximately 58.7% improvement in cooling efficiency compared with the conformal cooling channel.

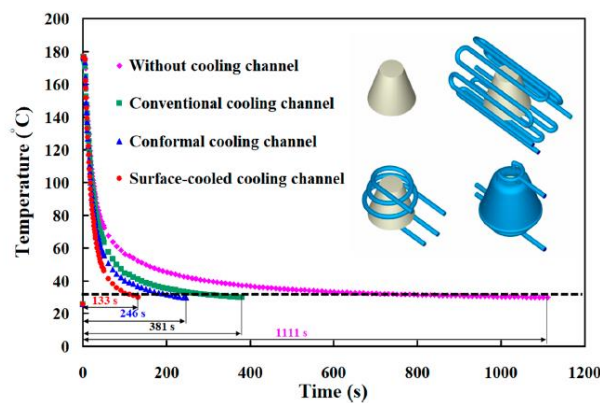


Fig. 14 – Numerical assessment of molded part cooling under four different cooling channel designs. (Kuo *et al.*, 2025).

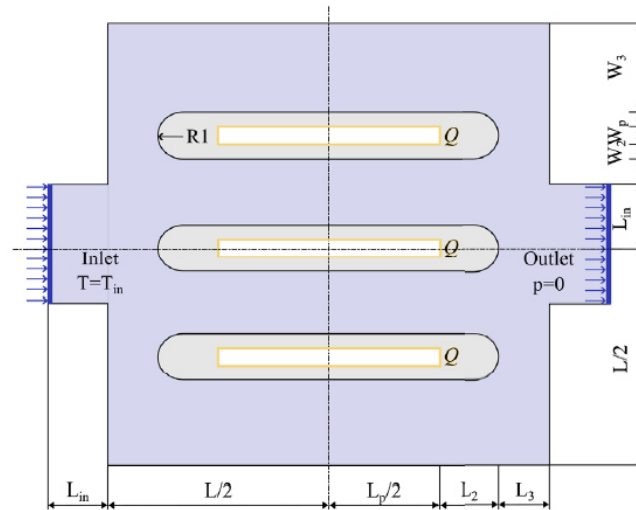


Fig. 15 – Dimensions and boundary conditions of the verification case: Verification case where inertial effects are. Influential (Sun *et al.*, 2025).

Sun *et al.* (2025) applied their optimization framework to a 2D injection mold model composed of a polymer part, the mold, and conformal cooling channels, using a mold length of 0.3 m, a part thickness of 0.15 m, a coolant inlet velocity 1.35 m/s, an inlet temperature 323.15 K, and a heat source of 1000 kW/m³. They optimized the cooling channel layout to reduce the average part temperature, improve surface temperature uniformity, limit pressure drop, and maintain manufacturable channel dimensions. They showed that the scaling model reproduced inertial effects and flow distribution in branched channels better than the Darcy model, while temperature uniformity constraints reduced thermal variations in sensitive areas, including corners and protruding features. In the examples with length-scale constraints, the RANS-validated average part temperature remained around 371.84–372.20 K, showing that manufacturable cooling channels can be obtained with acceptable trade-offs between thermal performance and pressure drop.

4. Conclusions

The review of the investigated studies indicates that the performance of injection molding is highly dependent on the configuration of the cooling system. Among the process stages, cooling has a decisive role, since insufficient thermal control can generate defects such as shrinkage and warpage.

The analyzed research also emphasizes that advanced numerical simulations support a better evaluation of the thermal behavior and fluid flow

phenomena occurring during the process. Through these methods, the process can be improved from the design stage.

Furthermore, current solutions, including conformal cooling channels, can significantly enhance cooling efficiency and the quality of the final product. Therefore, further work focusing on numerical simulation methods with advanced cooling design has innovative potential for the identification of optimized injection molding processes.

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INVESTIGAȚII ASUPRA CURGERII FLUIDULUI ÎN INTERIORUL
DISPOZITIVELOR PROIECTATE PENTRU INDUSTRIA AUTO. STUDIU DE
CAZ: SISTEME DE RĂCIRE PROIECTATE PENTRU MATRIȚE DE INECȚIE A
MATERIALELOR PLASTICE

(Rezumat)

Acest articol prezintă o analiză sintetică a principalelor direcții de cercetare privind procesele de transfer termic și curgere a fluidelor în inecția maselor plastice, cu accent pe rolul sistemelor de răcire în determinarea calității produselor finale. Studiile analizate evidențiază utilizarea metodelor numerice, precum simulările CFD, metoda elementelor finite și metoda volumelor finite, pentru investigarea fenomenelor complexe care apar în timpul procesului de inecție. Rezultatele arată că performanța răcirii este influențată atât de geometria canalelor de răcire, cât și de parametrii de curgere, în special numărul Reynolds, pentru care există valori optime. De asemenea, distribuția neuniformă a temperaturii conduce la apariția unor defecte precum contracția și deformarea pieselor. Concluziile subliniază necesitatea optimizării sistemelor de răcire pentru a îmbunătăți atât eficiența procesului, cât și calitatea produselor.