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Resin molds for improving thermal management in the injection molding process

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Abstract

Effective thermal management within injection molds is crucial for improving the process energy efficiency. This study presents a novel hybrid mold design, combining steel inserts with polymeric base plates, to enhance thermal insulation and reduce energy consumption. Two mold configurations were experimentally tested on a micro-injection molding machine without active cooling: one made of conventional mold steel and the other using Formlabs White V05 resin. Thermal behavior was analyzed through experimental measurements and finite element simulations using Comsol Multiphysics, with numerical models calibrated using real process data. The results indicate that the hybrid mold retains heat more effectively, achieving higher steady-state temperatures and improved thermal stability during machine stops. At the steady-state regime, the thermal energy stored in the traditional mold insert is estimated at 1 J, while in the hybrid mold it is 2.1 J. The difference is lost by traditional molds since it is dispersed in the surrounding environment. On a limited transient of 164 cycles starting from ambient temperature, the overall advantage of hybrid versus traditional mold in terms of stored thermal energy is estimated at $\Delta E = 506$ J (+45%). This amount of thermal energy can be harvested and reused in other phases of the process, such as raw material pre-heating or drying. These results suggest that incorporating polymers as a strategic material in mold design can lead to more energy-efficient injection molding processes.

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Keywords: Injection molding; Resin mold; Energy efficiency; Sustainability; Thermal management.

1. Introduction

Injection molding stands as the preeminent manufacturing process for high-volume plastic products due to its versatility across diverse materials and complex geometries [1]. Within the process phases, thermal energy management is critical, directly impacting efficiency, product quality, sustainability, and cost-effectiveness. Studies on energy consumption in injection molding highlight total cycle time as the primary factor affecting overall energy usage, with the cooling phase representing the most significant contributor [2,3]. Therefore, effective cooling management (i.e., heat extraction) becomes crucial to reducing energy consumption, with optimizing the mold's thermal energy distribution being a key strategy for this purpose.

Traditional molds made of thermal conductive steels enable the heat extraction after the cavity filling by water circulation inside cooling channels in the mold core around the cavity. However, due to the mold's thermal conductivity, only a fraction of the molten polymer heat is extracted and harvested. A non-negligible fraction is transmitted to the entire mass of the mold and then dispersed into the surrounding environment. In addition, due to technological constraints of subtractive manufacturing, cooling channels are realized at variable distances from the mold cavity, resulting in non-uniform heat extraction and inefficient cooling.

To overcome this issue, additive manufacturing (AM) technologies offer a partial solution: uniform and localized cooling through mold inserts with conformal cooling channels, levelling out heat extraction [4,5]. Furthermore, AM can also be integrated as a "hybrid construction" approach; in this case, these technologies become more economically sustainable, combining conventionally pre-manufactured base workpieces as a build platform with additively generated functional geometries of minimal volume [6,7]. Two very recent papers deal with thermal management and energy efficiency with interesting findings, even if in different ways [8, 9]. Chalicheemalapalli Jayasankar et al. [8] used additive manufacturing for mold insert fabrication in vacuum-assisted resin transfer molding, proving the higher performance in thermal management enabled by conformal cooling and lattice structures, compared to traditional molds. Tang et al. addressed the optimization of the thermal performance of the energy management system of an injection molding machine. The main focus is on the recovery and utilization of the latent heat of solidification released by the molded part. The study proposes four energy management system configurations, which take into account all components of the cooling system [9].

The mold material's thermal conductivity significantly influences the thermal energy behaviour. The advent of AM has broadened material possibilities [10–12]. Current research explores the fast fabrication via AM of polymeric soft mold inserts with cavities having complex geometries, while retaining a conventional steel base mold for structural integrity [12–15]. In this case, the non-thermal conductivity of polymers sharply hinders the cooling effectiveness and increases the cooling time. This approach exploits the rapid manufacturing of molds and accepts the strong limitations of short mold life and long cycle times [12,15]. Therefore, there is no focus on sustainability and efficiency.

This study changes that approach. Indeed, it is possible to conceive a new mold structure: high-strength steel mold inserts with cavities and conformal cooling combined with polymeric/composite mold base components (i.e., support plates). This "hybrid mold" concept mitigates potential thermal and mechanical weaknesses of soft molds by leveraging the advantages of polymers and composites as lightweight and thermal insulation capabilities. This unique approach is since no prior work in literature has explored this configuration. Maintaining a steel mold core with AM-fabricated cavities allows achieving the benefits of conformal cooling, high-quality molded parts, and reduced cycle times without limitations compared to conventional steel molds. Simultaneously, the polymeric/composite mold base components change the thermal behaviour of the mold and the process by acting as an insulator rather than a heat conductor. Furthermore, using polymers and composites for mold components enables the design of lightweight molds, offering additional benefits in terms of reduced mechanical energy consumption for mold movement (opening/closing) during production and production turnover phases. Ultimately, this innovative approach contributes to the conception of a more sustainable injection molding process.

This research aims to demonstrate the feasibility of this new mold design and to evaluate the use of unconventional materials to optimize thermal energy utilization. An experimental campaign was conducted using a micro-injection molding press by designing and testing hybrid molds with polymeric bases and steel inserts with cavities. A comparative analysis with the conventional all-steel mold allowed for a preliminary investigation of heat transfer regimes, thermal transients' evolution, and the advantages of the proposed hybrid solution. For the transient numerical analysis, Comsol Multiphysics simulation software, based on the finite element method (FEM), was employed. It is a well-established tool for analyzing complex multi-physics processes [16,17] and models the heat exchanges throughout the injection molding process, assessing the mold's internal thermal behaviour. The experimental-numerical comparison calibrated the numerical model, thereby validating its effectiveness as a powerful tool for optimizing and accelerating the design phase of mold systems and the entire injection molding process.

2. Experimental procedure

The experimental activity aims to acquire thermal transient data on the molds (traditional and innovative), such as mold thermal transients during the injection molding cycles, the steady state regime, and air cooling after shutdown. The tested specimen (Fig. 1) was a mini dogbone tensile test sample with a part thickness of 1 mm, length of 12 mm, and width of 1.5 mm in the narrow region and 3 mm in the larger one [18]. The molded mass is about 78 mg, including sprue, cold runner channels, and molded parts. The mold insert is made of X33CrS16 steel fabricated with conventional subtractive technologies (Fig. 1). This insert was used in two different molds: a traditional steel mold (TM) and a hybrid mold (HM) (Figure 2).

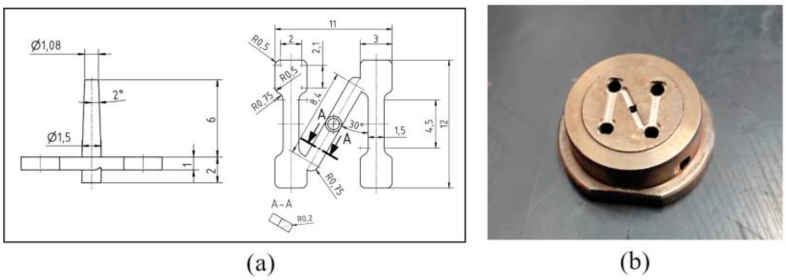

Fig. 1. Specimen design (a) [18] and mold insert, ejection side (b)

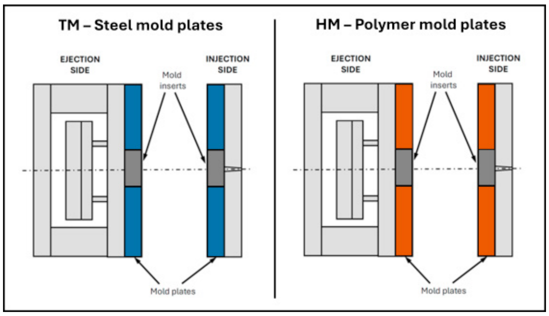

Fig. 2. Schematic section of two setups: TM with steel mold plates; HM with polymer mold plates.

The former has all components made of steel, while the latter has components of the base mold (i.e., support plates) made of polymeric material. Thus, the TM plates are fabricated with the same material and manufacturing technologies as the mold inserts, which are assumed to be the technology baseline. HM plates, particularly support plates, are fabricated of photosensitive polymer Formlabs White V05 (code RS-C2-GPWH-05). The polymer mold plates were optimized in the topology. They have a bulk structure near bushes and columns where higher stresses are expected, and then connected to the center of the mold where the steel mold insert with cavity is placed. These guarantee the effectiveness of the guiding and alignment of the mold parts. A lattice structure was adopted in regions where the stress is not transmitted or limited. This structure allowed a further weight reduction of the mold. The support plates of the HM were manufactured with a Formlabs Form4 machine, which implements the so-called Low-Force Display (LFD) technology, a Formlabs proprietary version of stereolithography (SLA). The process parameters were set as follows: layer thickness (LT) 25µm; the part lies on the build platform with edges oriented along the two (X, Y) axes and without base and supports. After the processing, the part is detached from the build platform and washed for 20 minutes in Tripropylene glycol monomethyl ether (TPM) with a Formlabs Wash Machine. After the washing, the part is gently blown with air compression to dry the solvent and remove solid residues. The last post-processing phase is the UV-curing, which was executed according to the material supplier's prescriptions: 5 minutes at 60°C with a Formlabs Cure machine. A DesmaTec Formica Plast 1K injection molding machine was used for the experimental tests. The machine can have a maximum injected volume of 150 mm^3, a maximum injection pressure of 300 MPa, and a maximum injection rate of 3.5 cm^3/s. The injection molding material was a Polyoxymethylene (POM) BASF Ultraform N2320 003. No coolant circulation was adopted during the cooling step; therefore, the cooling was obtained by heat transmission with the mold kept below the glass transition temperature, but defined by the injection molding thermal transient starting from the ambient temperature of about 32°C. The process parameters are shown in Table 1.

Table 1. Injection molding process parameters in experimental tests.

Parameter	**Symbol**	**Unit**	**Value**
Melt Temperature	T_{melt}	°C	230
Initial mold temperature	T_{mold}	°C	20
Injection speed	V_{inj}	mm/s	150
Filling time	t_{fill}	s	0.4
Holding time	t_{hold}	s	4
Holding pressure	P_{hold}	bar	500
Piston stroke/Dosing	S	mm	10
Cycle time	t_{cycle}	s	12
Number of injection runs	n	-	470

The mold temperatures were acquired with a custom data acquisition (DAQ) system. Four k-types thermocouples were placed on the molds. The thermocouples were connected to four Max6675 digital modules to interface the thermocouples with an Arduino Uno. A custom firmware was developed to acquire data with a sampling period of 0.4 s. The thermocouples T1 and T2 were put inside the ejection and injection inserts, respectively, using holes to reach the mold cavity. The other thermocouples, T3 and T4, were fixed on the support plates, ejection and injection sides, respectively. Figure 3 and 4 show, respectively, the thermocouples position onside the mold, and the overall experimental setup.

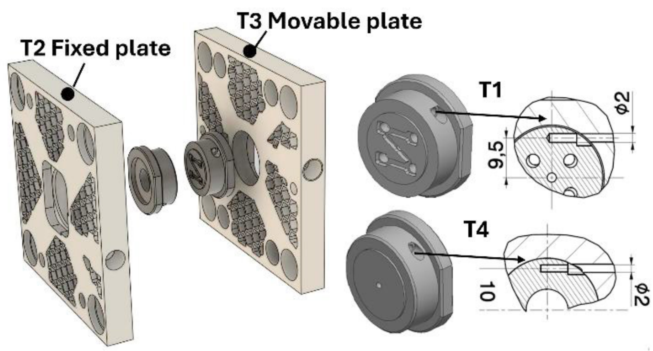

Figure 3. Thermocouples placement on plates and inserts

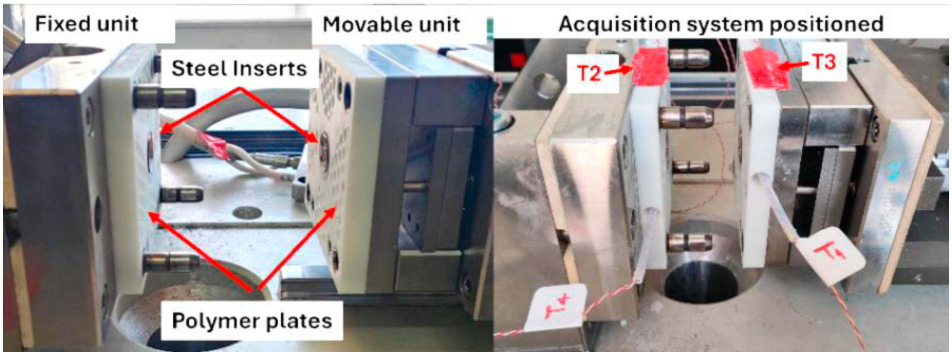

Figure 4. Experimental setup of HM solution.

Each test run consisted of 470 molding cycles starting from room temperature. When the steady-state temperature was reached after 470 cycles, the cooling at room temperature of the open mold was acquired to simulate a machine stop, for example, for technical issues. For the same purpose, two machine-controlled stops at cycles 164 and 336 were done, respectively for 60s and 150s.

3. Numerical Modeling

The experimental data served as the foundation for calibrating the boundary conditions employed in the numerical simulations of both the TM and HM processes. All process parameters were kept constant across both configurations, with the only variation being the mold material properties.

The simulations were performed using COMSOL Multiphysics 6.1. To optimize computational efficiency, the original 3D model of the mold block was geometrically simplified. Specifically, the injection and extraction units were represented as planar surfaces to account for heat exchange phenomena with the respective systems. Figure 5 shows the complete simulation model, as implemented in COMSOL Multiphysics.

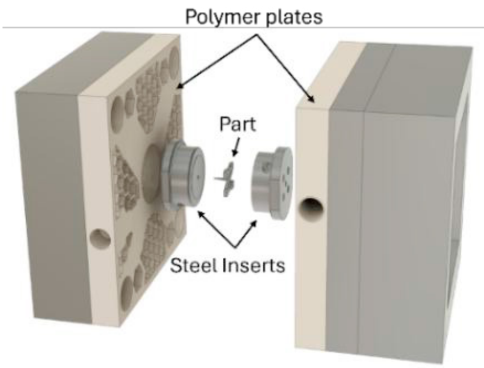

Figure 5. Model (polymer plates) used in COMSOL Multiphysics, with simplified clamping plates

Following the import of the modified 3D geometry into the software, boundary conditions were defined as illustrated in Figure 6, considering the dynamics of the injection molding process.

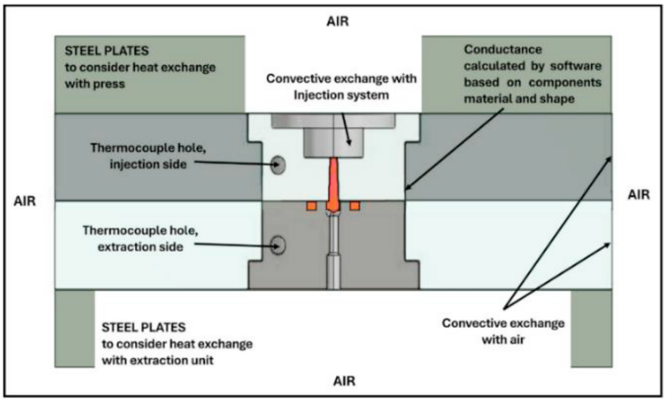

Figure 6. Boundaries set in COMSOL Multiphysics

Given that the model's primary objective was to predict the thermal field evolution during the process, the fluid dynamics of the injection phase were simplified. A variable heat source was introduced to simulate the temperature rise of the POM within the cavity during the filling stage. In addition to convective heat exchange with ambient air, two key boundary conditions were calibrated: heat transfer with the injector and with the extractor systems. This approach enabled accurate thermal predictions while significantly reducing computational demands, eliminating the need to model the entire press assembly.

Process timing parameters, such as filling, holding, and cooling durations, were managed using the Events Interface Module in Comsol to replicate the actual experimental sequence. Following the experimental procedure, two machine stops were implemented in the numerical simulation. The thermal behaviour after complete shutdown of the system was considered, modelling the cooling of both inserts and plates as convective exchange with static air at room temperature. The 3D mesh consisted of 406,670 tetrahedral elements, with a maximum element size of 1 mm for the cavity and insert regions, and 5 mm for the remaining components, ensuring a high-fidelity representation of the geometry.

The process parameters and the boundary conditions implemented in the numerical model are summarized in Table 2, while Table 3 reports the material properties sourced from technical datasheets.

Table 2. Process parameters and boundary conditions set within the numerical model.

Process parameters	**Units**	**Value**
Melt temperature	°C	230
Filling time	s	0.4
Holding time	s	4
Cooling time (no coolant)	s	4
Mold open/close time	s	3.6
Initial mold temperature	°C	30
Air (ambient) temperature	°C	30
Injector temperature	°C	230
Extractor temperature	°C	30
HTC with air	$W/(m^2 K)$	30
HTC with injector	$W/(m^2 K)$	260 (filling + holding), 130 (cooling), 0 (shutdown)
HTC with extractors	$W/(m^2 K)$	Linear decrease from 500 to 25 in 1000s

Table 3. Material properties implemented within the numerical model

Material property	Units	POM	X33CrS16 Stainless steel	White Resin V5
Density	g/cm^3	1.4	7.8	1.11
Thermal conductivity	W/ (m K)	0.14	17	0.28
Heat capacity at constant pressure	J / (kg K)	f(T), 2137 at 230°C	460	2160

4. Results and Discussion

4.1. Experimental Results

The first remarkable result is that the polymer molds resisted during the whole campaign (over 600 cycles, also considering the preliminary tests not reported in the paper) without visible damage and loss of performance, confirming its reliability in terms of mechanical resistance. Experimental thermal data collected during the molding campaigns are shown in Figure 7. Internal temperature measurements revealed that the initial thermal gradient for the HM configuration was consistently higher than the TM one, confirming the beneficial insulating effect of polymer molds. In detail, the HM configuration reached the temperature of 70°C in T4 (fixed insert) after 1000 s, while the TM only after 3000 s. In addition, before the system shutdown (after 470 cycles), an average difference of approximately 10°C was still present between HM and TM on the injection side, evidencing again the possibility of storing more thermal energy with polymer molds. Similar results were obtained on the ejection side, but generally a lower temperature was reached. In detail, the temperature differential between the injection and ejection sides was around 15°C for HM and 12°C for TM. During the prefixed stops, the temperature drop was more pronounced in the TM due to the high thermal conductivity of the steel compared to the polymer. More in detail, during the first stop (60 s at cycle 164), the temperature drop within the insert was approximately 8°C for TM and 4°C for HM. In the second stop (150 s at cycle 336), the temperature decreased by 12°C for TM and 6°C for HM.

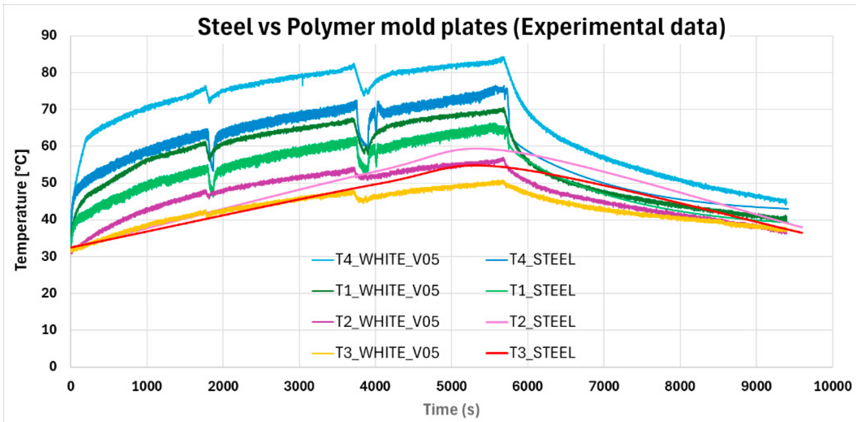

Figure 7. Experimental comparison of experimental data

These results indicate that the HM configuration provides improved thermal stability during process interruptions, which may contribute to a reduction in defect rates in molded parts. This aspect became more apparent after the final system shutdown, during which the TM system exhibited a temperature decrease of approximately 4 °C/min over the first 300 seconds, compared to the 2.8 °C/min observed in the HM system. The greater heat dissipation in the TM system was also evidenced by the higher temperatures recorded on the external surfaces of the mold, with a difference of approximately 3 °C at both T2 and T3 compared to the HM system. It is important to note that temperature measurements at T2 and T3 during the TM tests were taken only at the beginning of the test and during predefined stops to prevent short circuit issues with the thermocouples—an issue not encountered when using polymer plates. In summary, the HM acted as a thermal insulator for the steel insert, resulting in higher core temperatures, reduced heat dissipation, and increased thermal sensitivity.

4.2. Experimental-Numerical Comparison

Figures 8 and 9 show the experimental-numerical comparison for TM and HM systems, respectively. As previously mentioned, the numerical simulation covered the entire campaign, also including the two machine stops and the final shutdown. For TM system, the numerical prediction within the inserts showed a general underestimation in terms of temperature, with an almost constant deviation of 6°C in T4 (actual value of 76°C vs predicted one of 70°C) and of 4°C in T1 (actual value of 65°C vs predicted one of 61°C). The temperature drops during the predefined stops were accurately captured, and the numerical errors generally decreased during the cooling phase following the system shutdown. The results can be considered highly satisfactory, as a maximum error of only 10% was observed during a complex transient thermal evolution process spanning 470 cycles and including three predefined stops. Similar considerations can be made regarding the external surfaces of the mold. However, as previously mentioned, experimental data acquisition was performed at only four discrete time steps, which limited the accuracy of the transient thermal evolution analysis.

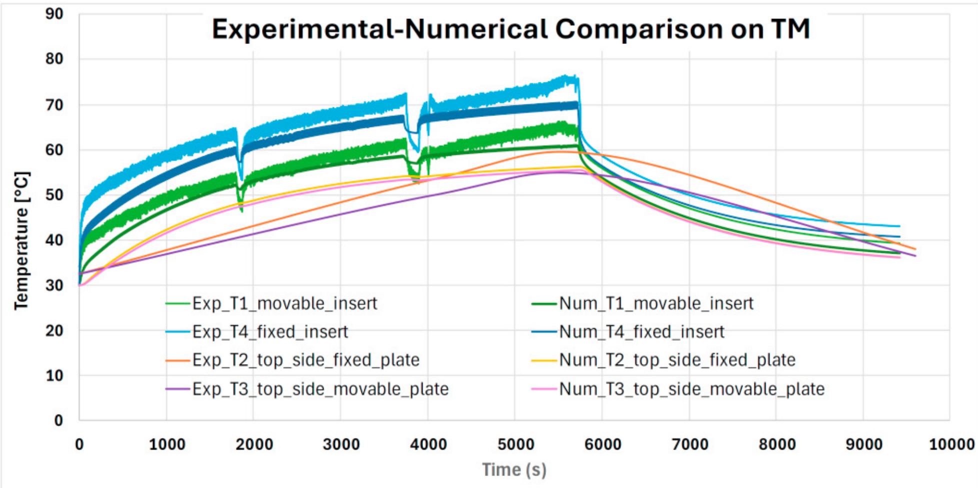

Figure 8. Experimental-numerical comparison of temperature transients acquired by the thermocouples (TM system).

It can be seen from figure 9 that the calibration of the boundary conditions was good, since the temperature evolution trend within the inserts was well captured as the cycles progressed with a general overestimation at the steady-state regime of about 6°C in T4 (actual value of 82°C vs predicted one of 88°C), while an underestimation of 5°C in T1 (actual value of 70°C vs predicted one of 65°C). In addition, temperature peaks resulting from the two controlled machine stops are immediately noticeable at cycles 164 and 336, as well as the decreasing trend after machine switch off, at $t = 5640\ s$, which was well described by the numerical prediction, confirming its accuracy despite simplifications in the model geometry and boundary conditions. The numerical discrepancy on the mold external surfaces is very low, with a good overlap between experimental and numerical curves.

In summary, despite the simplifications adopted in the model, the simulation calibration yielded highly satisfactory results. This demonstrates the potential of numerical tools for accurately predicting thermal fields, thereby providing valuable support during the design phase.

Moreover, the numerical simulation enabled the estimation of the energy stored by the inserts and the evaluation of the energy consumption in the two different configurations. Considering the last cycle before machine shut down, where a quasi-stationary regime condition is reached, the energy stored by the insert with the TM system is estimated at 1 J, while with the HM system it is 2.10 J. Operating at full capacity, the inserts correctly stop accumulating heat significantly in both solutions. Considering the first heating up phase, from the start point at ambient temperature until the first machine stop occurred at cycle 164, the energy stored by the insert with the TM system is 1121.7 J, while with the HM system it is 1627.6 J (+45%). With the same amount of energy input into the system, compared to the HM configuration, the TM shows a loss of 505.9 J on 164 molding cycles. Although energy assessments are preliminary estimations of actual consumption in the process, it is clear that the insulating capacity of the polymer can improve the energy efficiency of the process.

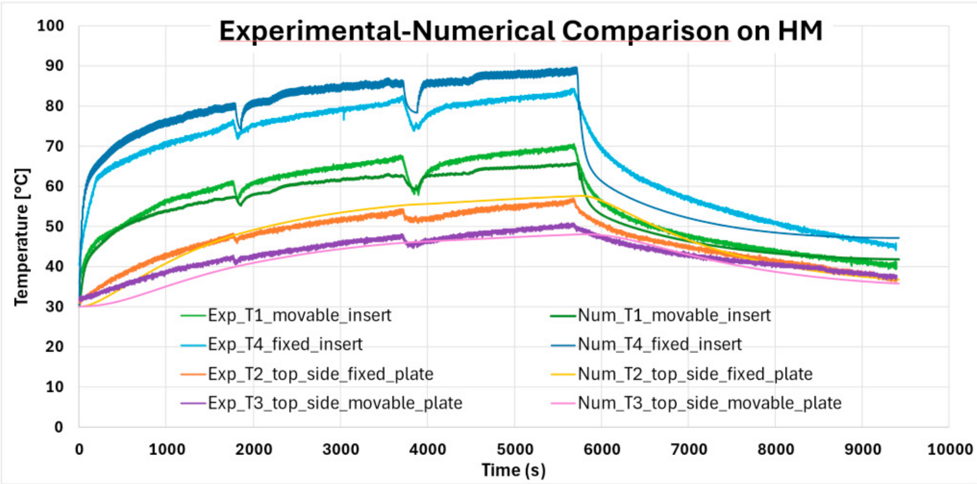

Figure 9. Experimental-numerical comparison of temperature transients acquired by the thermocouples (HM system)

5. Summary

This study explored an innovative hybrid mold (HM) design for injection molding, combining steel inserts with polymeric support plates, and compared its thermal performance to that of a traditional all-steel mold (TM). The experimental campaign, supported by numerical simulations using COMSOL Multiphysics, demonstrated the feasibility and advantages of the proposed solution. The HM configuration showed enhanced thermal insulation, resulting in higher internal temperatures and slower heat dissipation than the TM setup. These characteristics were particularly evident during transient phases such as controlled stops and final system shutdown, where the HM mold maintained thermal stability more effectively.

The polymeric components also contributed to reduced temperature gradients and energy loss, suggesting potential energy efficiency and process consistency benefits. Despite geometric and boundary simplifications, the numerical model accurately captured the thermal behaviour of both mold types, with a maximum deviation of 10%, confirming its reliability as a predictive tool. Overall, the results validate the hybrid mold concept as a promising approach for improving thermal energy management in injection molding and highlight the value of simulation tools in supporting design optimization and sustainable design and manufacturing practices.

This work preliminarily demonstrates the feasibility of a new roadmap to increase the sustainability of the injection molding process. Following this initial validation of the HM design, further experimental campaigns are necessary to improve the statistical rigour of the results and the numerical model forecast confidence. Furthermore, an in-depth and accurate analysis of energy consumption must be carried out, also considering conformal cooling system activation and a scale-up to macro injection molding. Finally, crucial industrial metrics such as cycle time, cost benefits analysis, molds' lifespan and strength, and productivity impacts will be investigated to support the adoption of this innovative and more sustainable solution. Future work will follow this line to make HM design an innovative solution for the industrial world.

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References

[1] H. Fu, H. Xu, Y. Liu, Z. Yang, S. Kormakov, D. Wu, J. Sun, Overview of Injection Molding Technology for Processing Polymers and Their Composites, ES Materials & Manufacturing Volume 8 (June 2020) (2020) 3–23.

[2] G. Lucchetta, D. Masato, M. Sorgato, Optimization of mold thermal control for minimum energy consumption in injection molding of polypropylene parts, Journal of Cleaner Production 182 (2018) 217–226. https://doi.org/10.1016/j.jclepro.2018.01.258.

[3] A.G. Smith, L.C. Wrobel, B.A. McCalla, P.S. Allan, P.R. Hornsby, A computational model for the cooling phase of injection moulding, Journal of Materials Processing Technology 195 (2008) 305–313. https://doi.org/10.1016/j.jmatprotec.2007.05.018.

[4] K. Altaf, A. Majdi Abdul Rani, V.R. Raghavan, Prototype production and experimental analysis for circular and profiled conformal cooling channels in aluminium filled epoxy injection mould tools, Rapid Prototyping Journal 19 (2013) 220–229. https://doi.org/10.1108/13552541311323236.

[5] K.M. Au, K.M. Yu, A scaffolding architecture for conformal cooling design in rapid plastic injection moulding, Int J Adv Manuf Technol 34 (2007) 496–515. https://doi.org/10.1007/s00170-006-0628-x.

[6] C. Kolbe, Strahlschmelzen - LaserCUSING® - Integration im Werkzeug- und Formenbau, RTe Journal (2010). https://rtejournal.de/rte/article/view/2010_3 (accessed March 7, 2025).

[7] G.R. Berger, D. Zorn, W. Friesenbichler, F. Bevc, C.J. Bodor, Efficient cooling of hot spots in injection molding. A biomimetic cooling channel versus a heat-conductive mold material and a heat conductive plastics, Polymer Engineering & Science 59 (2019) E180–E188. https://doi.org/10.1002/pen.25024.

[8] D. Chalicheemalapalli Jayasankar, T. Tröster, T. Marten, Optimizing Injection Molding Tool Design with Additive Manufacturing: A Focus on Thermal Performance and Process Efficiency, Materials 18 (2025) 571. https://doi.org/10.3390/ma18030571.

[9] Y. Tang, H. Hu, Y. Ding, T. Wang, P. Xie, W. Yang, Thermal Performance Analysis of Integrated Energy Management System for Mold Cooling/Heat Pump/Material Preheating of Injection-Molding Machine, Symmetry 17 (2025) 637. https://doi.org/10.3390/sym17050637.

[10] H.M. Silva, A review of the design optimization of conformal cooling channels in injection molds, Int J Adv Manuf Technol (2025). https://doi.org/10.1007/s00170-025-15234-2.

[11] S. Arman, I. Lazoglu, A comprehensive review of injection mold cooling by using conformal cooling channels and thermally enhanced molds, Int J Adv Manuf Technol 127 (2023) 2035–2106. https://doi.org/10.1007/s00170-023-11593-w.

[12] V. Basile, F. Modica, R. Surace, I. Fassi, Micro-texturing of molds via Stereolithography for the fabrication of medical components, Procedia CIRP 110 (2022) 93–98. https://doi.org/10.1016/j.procir.2022.06.019.

[13] V.F. Moritz, G.S.N. Bezerra, M. Hopkins Jnr, E. Fuenmayor, S. Günbay, C. Hayes, J.G. Lyons, D.M. Devine, Heat Dissipation Plays Critical Role for Longevity of Polymer-Based 3D-Printed Inserts for Plastics Injection Moulding, Journal of Manufacturing and Materials Processing 6 (2022) 117. https://doi.org/10.3390/jmmp6050117.

[14] H.S. Ong, C.K. Chua, C.M. Cheah, Rapid Moulding Using Epoxy Tooling Resin, Int J Adv Manuf Technol 20 (2002) 368–374. https://doi.org/10.1007/s001700200165.

[15] Surace, Rossella, et al. "Micro injection molding of thin cavities using stereolithography for mold fabrication." *Polymers* 13.11 (2021): 1848. https://doi.org/10.3390/polym13111848.

[16] B. Burlaga, A. Kroma, P. Poszwa, R. Kłosowiak, P. Popielarski, T. Stręk, Heat Transfer Analysis of 3D Printed Wax Injection Mold Used in Investment Casting, Materials 15 (2022) 6545. https://doi.org/10.3390/ma15196545.

[17] T. Lodygowski, J. Rakowski, P. Litewka, Recent Advances in Computational Mechanics, CRC Press, 2014.

[18] V. Bellantone, R. Surace, G. Trotta, I. Fassi, Replication capability of micro injection moulding process for polymeric parts manufacturing, Int J Adv Manuf Technol 67 (2013) 1407–1421. https://doi.org/10.1007/s00170-012-4577-2.