PERFORMANCE EVALUATION OF COOLING SYSTEMS IN INJECTION MOULDS MADE OF STEEL AND ALUMINIUM THROUGH NUMERICAL SIMULATIONS

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Abstract. Among all techniques for manufacturing plastic parts, injection moulding stands as a process widely used by several industry sectors to produce items with complex geometry in large volumes. The demand for high-quality and low-cost parts that must quickly be available on the market is in constant growth and has great impact in the commercial and financial performance of companies. One of the most important factors, which directly affects the cost and efficiency of production, as it represents the longest stage of the process, is the cooling time of the injection cycles. In Brazil, the high-volume production of injection moulded parts is mainly done using alloy steel as the mould material. However, widely used for part prototyping and short series of production, aluminium alloys moulds have already demonstrated to be capable of producing high quality plastic parts with reduced cycle times. The design of the cooling system in steel moulds is already a well-known task, mainly due to the extensive experience about this type of tool. However, the guidelines for the definition of this system, when the moulds are made of aluminium, need information that is still little explored in the literature. Compared to steel, aluminium alloys have characteristics such as high thermal conductivity and high machinability rates, which, in addition to mechanical strength capable of withstanding the pressure and temperature of injection cycles, make them a very attractive option for mould making, even for high production. Therefore, the DEMALAP project (Demonstrador de Molde de Alumínio para Alta Produção), which aims to verify the feasibility of the use of aluminium moulds for high production, fits into this proposal. This article evaluates the consequences of a mould material change between steel and aluminium, in the cooling stage of the moulded part, based on numerical simulations. For each mould material, different cooling systems are evaluated based on the quality parameters and, when approved, the plastic part warpage is verified. The results presented comparatively reveal that the information obtained in these evaluations are fundamental to guide the design of cooling systems, especially in aluminium moulds. The results stand also as indicators of potential process optimization regarding manufacturing costs, cycle time and energy consumption.

Keywords: Aluminium mould; Cooling system; Thermoplastic; Injection moulding; Numerical simulation

1. INTRODUCTION

The plastics industry is increasingly driving manufacturers into highly competitive scenarios, which corroborate for devising strategies that offer lower prices, high-quality products and speed in the production process. Thermoplastic injection moulding is one of the processes that meet the high demand of the industry, as it enables high productivity in the production of plastic parts with highly complex geometries and high dimensional accuracy. However, to obtain parts with such accuracy and competitive characteristics on the market, it is necessary to master and control the process parameters, starting from the choice of the polymer to be injected to the characteristics of the mould selected.

According to Marques *et al*. (2015a), the AISI 420, AISI P20 and AISI H13 steels are the most used materials to produce injection moulds, because of their high mechanical strength, high wear resistance, good thermal stability, and

good weldability for possible repairs. However, steels have low thermal conductivity compared to other materials, such as aluminium alloys, whose conductivity is up to five times higher. The high thermal conductivity provides better heat distribution and dissipation in aluminium alloys than in steel moulds, reducing production cycle times by 20 to 40 %, as mentioned by Lammon (2013). On the other hand, Arieta Filho *et al.* (2006) report that aluminium alloys have inferior mechanical properties, which underpins the uncertainty of their use in robust injection moulding and high-volume production processes.

Marques *et al.* (2015b) describe that the cooling time accounts for 2/3 of the total cycle time, making it the parameter that most affects the total production time. In addition, Malloy (2010) points out that poor cooling systems promote quality problems due to uneven cooling of the cavity, which can lead to warpage and/or residual stresses in the part, resulting in differential shrinkage across the thickness.

Evaluating the behaviour and applications of steel and aluminium moulds is, therefore, of great value to the industry, as each proposal offers benefits and there are opportunities for process optimization that lead to cost reductions and productivity increases. In order to minimize the costs associated with defects in the manufacturing of moulds and increase the yield of the production cycle, Dihlmann (1993) and Peixoto (1999) point out that numerical analysis using Computer Aided Engineering (CAE) tools allow a careful evaluation of the influence of the part and mould's design characteristics. In addition, Garcia (2018) explains how the use of statistical tools such as DOE (Design of Experiments) allows the planning and execution of simulations aimed at reducing cycle time and minimizing distortion.

This paper aims to evaluate the performance of cooling systems in steel and aluminium moulds, mapping the constructive and operational differences of each material. The comparative evaluation provides direct guidance on what designers of steel and aluminium moulds should be considered in the design phase. The use of CAE tools in conjunction with statistical analysis underpins the accuracy of the parameters determined and the verification of the results. The study is thus expected to contribute to the standardization and simplification of circuit construction and evaluation process of mould cooling systems.

2. METHODOLOGY

In order to study the differences between steel and aluminium moulds, specifically in the cooling system, a methodology has been developed and applied to obtain cooling systems for each mould that can meet all the quality parameters of a good cooling process. This methodology consists on an experience-based initial cooling system, which can be improved or used as reference for completely new projects.

The first stage of the evaluation relates to the geometric spacing of the cooling circuits and its devices. Based on the references from literature, adjustments are made for each cooling system layout in each mould. Then, simulations of the cooling stage of the injection cycle are performed to verify the suitability of each cooling system (combination between geometrical layout and process parameters). For approved systems, simulations of the entire injection cycle are performed to verify plastic part quality results.

2.1 Cooling channels design parameters

Regarding the geometrical configuration of the cooling circuits, the main parameters to be analysed are the distances between the cavity and the cooling channels (depth), and the distance between the centres of the cooling channels (pitch), as shown in Fig.1. These parameters, as well as the use of devices (e.g., baffles, bubblers, thermal pins), directly affect the manufacturing cost, the maintenance of the channels, the temperature uniformity, and the efficiency of heat removal from the mould surface. Therefore, the layouts proposed in this work were evaluated in comparison with the values reported in literature, most of which are derived from engineering experience with the injection moulding process.

Although there are small variations in the values reported in literature, Zöllner (1999), Goodship (2017), Jones (2008), and Shoemaker (2006) recommend similar ranges for the geometric parameters of cooling channel spacing in injection moulds. However, these authors focus their work on considerations for steel moulds, and recommendations for aluminium moulds are not as easily found in literature. Kazmer (2016) mentions special considerations when designing cooling systems for materials with high thermal conductivity, but only recommends a wider range of parameters for depth and pitch. A more direct reference is found in Bayer Corporation (2008), which focuses specifically on reaction injection moulding and recommends different spacing for cooling channels in steel and aluminium moulds, with spacing for aluminium about twice that for steel moulds. This variation in parameters is due to the high thermal conductivity of aluminium compared to steel and the effects of this thermal property on improving heat flow between the cavity and the cooling circuit. The range of values for the parameters in the present study followed the recommendations of Kazmer (2016), which are depth values from two to five times the channel diameter (2 ~ 5 x channel diameter) and pitch values from one to two times the depth value (1 ~ 2 x depth).

To ensure an uniform temperature distribution over the entire surface of the mould cavity, the use of devices, in addition to the appropriate values for pitch and depth, is required for geometries that have difficult-to-access areas and thus poorer cooling (e.g., areas with severe concavity). In the present study, baffles were chosen as cooling devices in the circuits. This choice is based on the possibility of using baffles in series, as well as cost savings and lower manufacturing

complexity compared to other devices. Baffles are devices that force coolant flow perpendicular to the lines of the cooling channels to reach regions inaccessible to conventional channels, as shown in Fig. 2. However, despite the increase in heat exchange in large hot regions of the mould, smaller hotspots can form at locations furthest from the baffle, depending on the part geometry, as seen in Fig. 2.b. This situation presents a challenge to the cooling process if the goal is to achieve temperature uniformity in the region where the device is used. To minimize the relevance of these hotspots, some strategies can be applied, such as changing the baffle diameters, adding baffles and reducing the distance between the baffle tip and the mould surface (dimensions Ba and Bb in Fig. 2.a).
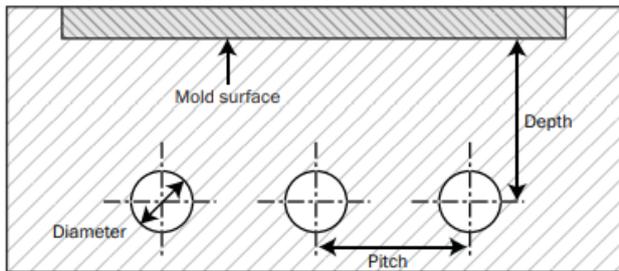

Figure 1 – Parameters of cooling channel spacing
(Shoemaker, 2006. Adapted)
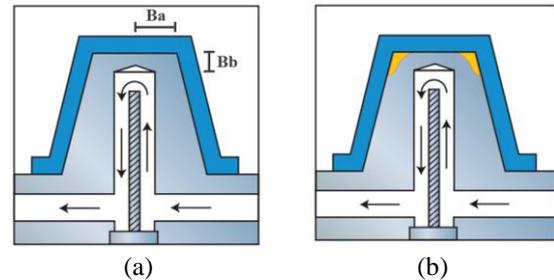

(a)   (b)

Figure 2 – (a) Baffle and dimensions representation
(b) Hotspots at the edges on the core
(Shoemaker, 2006. Adapted)

Mercado-Colmenero *et. al* (2018) mention, based on the experience and standardization of the industry, that the spacing of Ba and Bb should not be less than 10 mm to avoid structural problems in the mould. On this topic, Kazmer (2016) presents a study to ensure the integrity of the mould by investigating the stress concentration as a function of pitch and depth (see Fig. 3). This evaluation shows that holes very close to the surface of the cavity, as in the case of depth values less than one times the diameter, cause significant stress concentrations. For larger distances, the stress concentration behaves almost constant with increasing distance. Therefore, for the present study, it was determined that the minimum distances for Ba and Bb values are one times the baffle diameter (1 x baffle diameter).
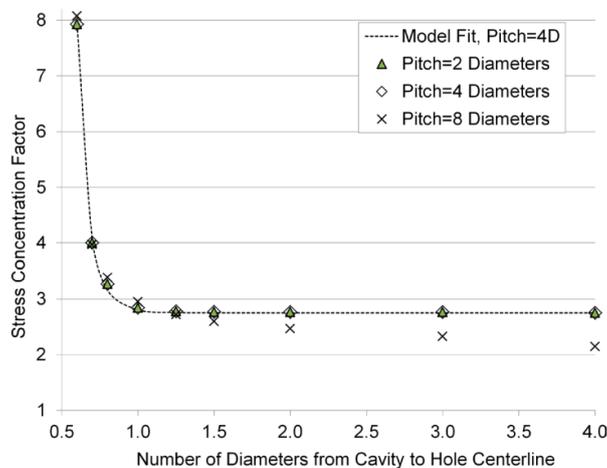

Figure 3 – Stress concentration as a function of distance (Kazmer, 2016)

2.2 Part geometry and cooling circuits

As part of the DEMALAP project, this study examined moulds for manufacturing an automobile cupholder, shown in Fig. 4. The average wall thickness of the part is 2 mm, the overall dimensions are approximately 100 mm x 235 mm x 100 mm, and the volume is about 120 mm³. The melt inlet is defined as a circle with a diameter of 3 mm and is located between the bottom sides of the geometry cups.

Starting from the definition of the part geometry, a layout of a conventional cooling system for injection moulds was created based on experience. This is shown in Fig. 5 and consists of four circuits with 20 baffles on the cavity side and two circuits with 6 baffles on the core side. The regular section of the channels has a diameter of 10 mm and the baffles have a diameter of 16 mm. This layout was used as a starting point for the study of circuits for steel and aluminium moulds.
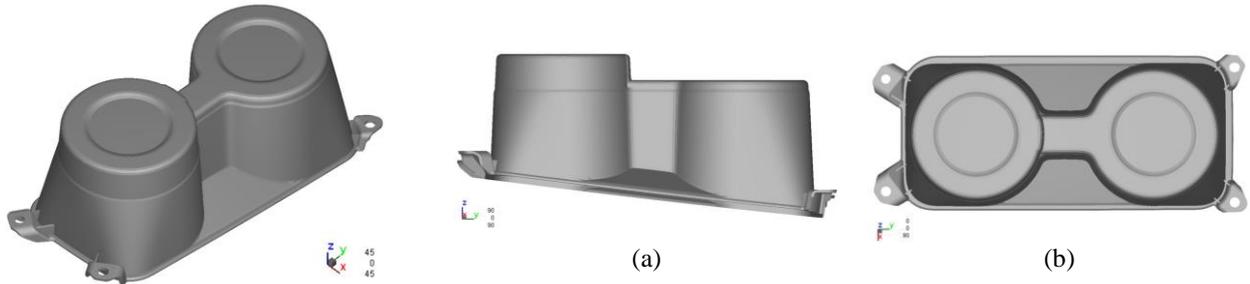
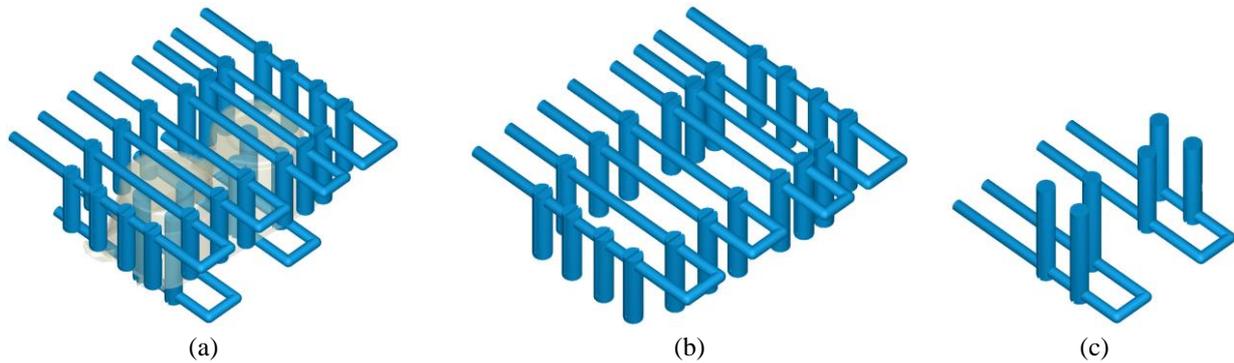Figure 4 – Part geometry (cupholder) (a) Side view (b) Top view

Figure 5 – (a) Initial cooling circuits layout (b) Cavity side (c) Core side

2.3 Numerical procedure

The flowchart in Fig. 6 shows a process proposed to specifically study the cooling stage of the injection cycle and its effects on the quality of the manufactured parts in steel and aluminium moulds. The simulations and analyses were splitter into two parts. First, simulations of the cooling analysis (Ct) were performed in order to evaluate the quality of the cooling system and the sensitivity of the parameters of the cooling stage. Then, for the systems approved in the evaluation of the cooling quality parameters, simulations of the whole injection cycle were performed to evaluate the influence of these cooling systems on the quality parameters of the plastic parts.
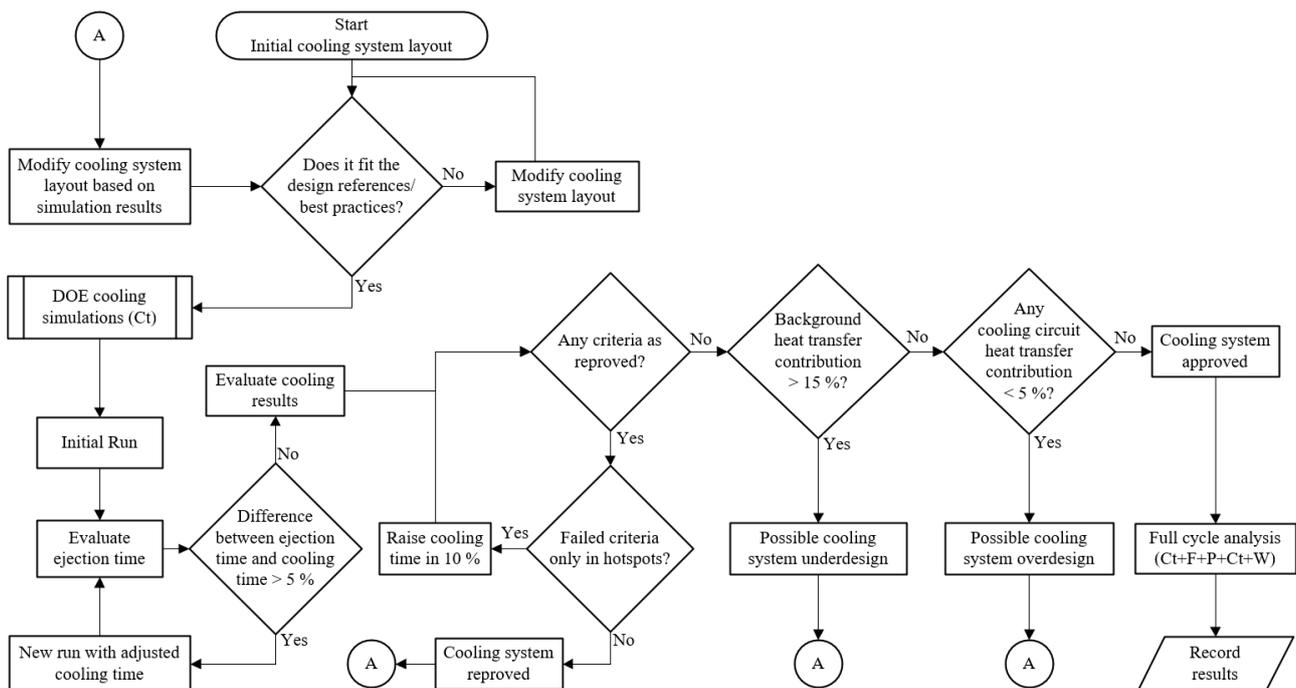

Figure 6 – Cooling system evaluation flowchart

Simulations where the mould cavity is kept at constant temperature were executed and a set of process parameters for the filling and packing stages of injection cycle was defined. These parameters are shown in Tab. 1 and were kept constant in all cases of this study. The software used to perform all the numerical simulations of the injection process in this work was Mouldex3D™ 2020.1.

Table 1 – Parameters previously defined for part injection

Filling time: 2.3 s	Packing time: 8 s	Melt temperature: 200 °C
Filling pressure: 25 MPa	Packing pressure: 30 MPa	Mould temperature: 45 °C

For the simulations of the cooling stage, a DOE (Design of Experiments) procedure was used via the Taguchi method to define the matrix of combinations between the factors to be changed in each simulation. The parameters considered to be exclusively related to the cooling stage of the injection moulding cycle, and therefore to be evaluated in this work, were the coolant inlet temperature (T), which was changed in a range of 10 °C – 40 °C; and the coolant flow rate (Q), which was changed in a range of 100 – 400 cm³/s. A Taguchi array with two factors, four levels, and 16 runs, L16(4^2), was created and is shown in Tab. 2. The DOE array was created and the results analysed using Minitab™ statistical software.

Table 2 – Taguchi array created for cooling simulations

	T (°C)	Q (cm³/s)		T (°C)	Q (cm³/s)		T (°C)	Q (cm³/s)		T (°C)	Q (cm³/s)
Run01	10	100	Run05	10	200	Run09	10	300	Run13	10	400
Run02	20	100	Run06	20	200	Run10	20	300	Run14	20	400
Run03	30	100	Run07	30	200	Run11	30	300	Run15	30	400
Run04	40	100	Run08	40	200	Run12	40	300	Run16	40	400

Menges *et. al* (2001) and Kazmer (2016) propose methods to estimate the cooling time for thermoplastics. Both authors consider the plastic and mould material characteristics, the moulded part thickness and the process parameters as variables on their methods, and propose simplified equations for standard geometries. The simulation software, based on data of the used geometry, chosen material and defined process parameters, is also able to estimate the cooling time for the part. This resource was used for the initial estimation of the cooling time for the simulations carried out in the study. The coolant for all simulations was water. All simulations are run until a steady state is reached or the calculation stopping criteria is met. The stopping criteria used for the cooling simulations were 20 cycles or a maximum mould temperature deviation of 0.5 °C.

The first evaluation and loop of adjustments to be made for the cooling simulations concerns the cooling time, which is considered, in this study, the amount of time after the packing stage that the part needs to remain inside the mould to be cooled until it reaches the ejection temperature. This time is estimated by the software based on the average temperature across the thickness of the part. If the result of this estimation differs less than 5 % from the cooling time set as input to the simulation, the cooling quality parameters are evaluated, otherwise a new run is simulated with the same T and Q parameters but with adjusted cooling time. These initial adjustments are to ensure that the quality parameters are evaluated in the cooling phase when the part is ready to be ejected, that is, there is no idle time for the part in the mould. Once the cooling time is set, the cooling quality parameters shown in Tab. 3 are evaluated.

Table 3 – Quality factors for cooling simulations

Quality factor	Description	Units	Range	Classification
Q1	Max difference between part surface average temperature and mould reference temperature defined in isothermal simulations	°C	00 – 10	Approved
			over 10	Reproved
Q2	Max difference between mould cavity and core sides temperatures	°C	00 – 20	Approved
			over 20	Reproved
Q3	Max difference between coolant inlet and outlet temperatures	°C	00 – 05	Approved
			over 05	Reproved

If the criteria are not met solely due to hotspots, the cooling time is readjusted. A hotspot is a zone that has a high temperature and cannot be cooled as uniformly as the adjacent area, due to the geometry of the part or limitations in the manufacture of the mould. If a zone of the mould has high temperatures but can be improved by changing the cooling circuits, this geometric change should be made in the layout and all parameters should be re-evaluated from the beginning.

If, after the time adjustments, any of the quality parameters is classified as reproved, the combination between geometrical cooling system layout, coolant inlet temperature, and coolant flow rate is reproved. When all quality

parameters are classified as approved, the heat transfer contributions of the mould and each cooling circuit are evaluated individually. This phase of the evaluation aims to identify possible under – or over – design in the cooling system. Assuming that the cooling channels are the main source of heat extraction from the system, the total contribution of the mould-air surfaces to the total heat transfer should be equal to or less than 15 %. Values above this range are indicators of possible under-design of the cooling system and will not be approved. Conversely, a cooling circuit with a heat transfer contribution of less than 5 % is considered ineffective and indicates possible oversizing of the cooling system. Systems that result in low values of the heat exchange contribution of their cooling circuits could be considered approved, though with reservations, since they can meet the quality factors but have potential for optimization. In this study, due to time constraints, the systems that fell under this possible to optimization category were considered as reproved. In the cases where the system was not accepted, the layout of the cooling circuits was changed and the evaluation process was run again. Once the cooling system is approved, a complete injection moulding cycle (an analysis sequence of cooling, filling, packing, cooling, and warpage) is simulated and the results recorded for comparison. The polymer used in this study was polypropylene (PP) due to its good mechanical properties and its wide use in the automotive industry. For the moulds, according to the recommendations of Arieta Filho (2006), the steel used was AISI P20 due to its wide use in injection moulds and the aluminium alloy 7075-T651 due to its mechanical properties, which is therefore an option for moulds with high production capacity. The properties of the materials used for the moulds are described in the Tab. 4.

Table 4 – Properties of the metal materials used in moulds

Properties	Units	P20 Steel	Aluminium 7075-T651
Density	kg/m³	7750	2795.6
Thermal Conductivity	W/(m.K)	29	137
Elastic modulus	GPa	207	70
Poisson's ratio	-	0.3	0.34
Coefficient of thermal elasticity (CLTE)	1/K	1.29×10^{-5}	2.35×10^{-5}
Heat capacity	J/(kg.K)	462	931.5

The part initial shell mesh, used as a reference for the construction of the internal 3D mesh, was created in Altair HyperMesh™ 2019 with an aspect ratio lower than 5 (-) in all elements. The 3D meshes for the part, cooling circuits, and mould base were created directly in the injection simulation software. A boundary layer mesh (BLM) was created for the part with five layers of hexahedral elements on each side and a connecting layer of tetrahedral elements in between, for a total of about 540 thousand elements. A circular profile with hexahedral elements was used for the cooling circuits in the regular cylindrical sections, and a BLM similar to that of the part was created for the baffles. Only tetrahedral elements were used for the mould base.

3. RESULTS

This section contains the results obtained for the geometrical modifications of the cooling circuits and the numerical simulations for aluminium and steel moulds.

3.1 Geometrical layout

As Shoemaker (2006) reports, as thermal conductivity of the mould material increases, the spacing of depth and pitch become less important. This is justified because materials with high thermal conductivity allow greater uniformity of mould surface temperature by allowing smaller temperature differences between the cooling fluid and the mould surface. On this basis, and in attempt to achieve greater consistency between the spacing parameters presented by Kazmer (2016), the values of depth of 2.5d and pitch of 2.5d for steel moulds, and depth 2.5d and pitch of 5d for aluminium moulds were first established, where d is the nominal diameter of the channel hole. For the baffles, the spacing values were initially set to 2.5d for both parameters Ba and Bb in steel and aluminium moulds, keeping the depth value. Figure 7 shows the circuit configuration after the initial layout adjustments to the spacing parameters for the steel and aluminium moulds.

The changes in the circuits' geometry follow the nomenclature M|cavity(NB)DXPX|core(NB)BaXBbX , where M stands for the material of the mould, followed by the indication of the number of baffles, and the distance used in the cavity and core sides of the mould. The value NB in brackets stands for the number of baffles on each side (cavity and core) and X for the channels spacing, related to the nominal value of the hole diameter for the parameters depth (D), pitch (P), centreline of baffles and cavity (Ba), and end of baffles and cavity (Bb) as show in Fig. 1 and 2. The diameters of the regular channels and baffles remained constant and corresponded to the initial layout. In this work, only the spacing between holes was assessed. The change in the holes' diameter was not considered.

For this cupholder geometry, the results of cooling simulations for the cavity side were found to be acceptable once the geometric parameters were adjusted to achieve a uniform temperature distribution on the cavity surface. On the core side, the temperature values in the mould surface varied over a wider range, so the presence and spacing of baffles on the core side was a critical point of the study. Therefore, the spacing of the first adjustment was kept for the cavity side and

further geometrical changes were made in the layouts directly on the core side. Five cooling circuit layouts were created for the steel mould and three cooling circuit layouts were created for the aluminium mould.
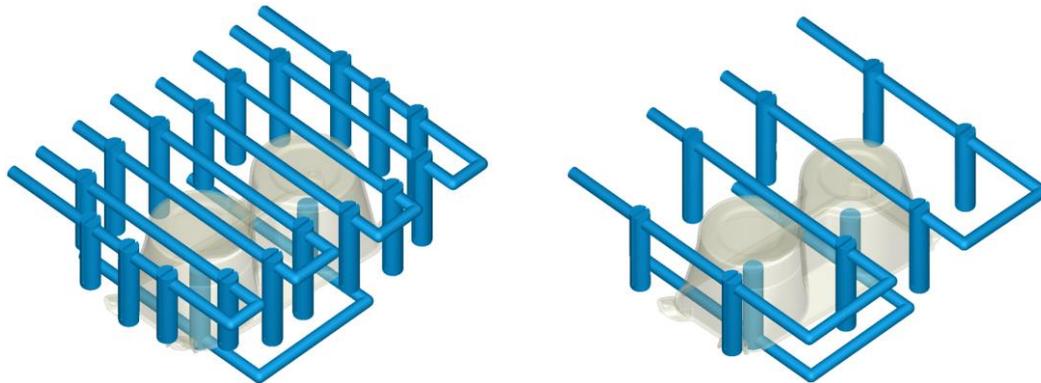
(a) ST|cavity(18)D2.5P2.5|core(2)Ba2.5Bb2.5   (b) AL|cavity(8)D2.5P5|core(2)Ba2.5Bb2.5

Figure 7 – Cooling circuits adjusted based on initial geometry spacing parameters (a) Steel mould (b) Aluminium mould

3.2 Cooling analysis

The first stage of evaluation for the simulations refers to the time it takes for the part to reach the ejection time or, if hotspots are detected, the time it takes for the mould to cool down to a temperature that is considered acceptable, so it does not affect the results of the next cycle. After all the times were adjusted, the cooling quality criteria were evaluated and the results for the systems that were accepted for each mould material are presented. The quality criteria regarding the coolant difference between inlet and outlet (Q3) was accepted for all the simulations, therefore is not presented.

In the case of aluminium moulds, two geometrical configurations for the cooling circuits were made until a layout that met all the quality parameters was achieved. The first layout, using the initial layout spacing for the baffles of 2.5d for both Ba and Bb, showed very high values of difference between the temperatures of the mould cavity and the core sides (Q2) for all process parameters simulated and was therefore discarded. The AL|cavity(8)D2.5P5|core(2)Ba2.5Bb1 layout was approved with coolant at 40 °C and flow rates of 200 cm³/s – 400 cm³/s. No hotspots were identified in the simulations for aluminium mould, therefore the cooling time is defined by the ejection time of the part and varied between 4.5 and 6 seconds. Figure 8 shows the result of the simulations performed with this layout. The maximum acceptance range for each quality parameter is highlighted by a red dashed line. Some combinations between coolant temperature and coolant flow rate for this layout were reproved due to the low contribution to heat exchange in the circuits.

It was verified that, for aluminium moulds, the coolant temperature has the greatest influence on the results of the cooling time and the difference between the average surface temperature of the part and the reference temperature of the mould (Q1). The coolant flow rate has greatest influence on the difference between the temperatures of the mould cavity and the core sides (Q2).
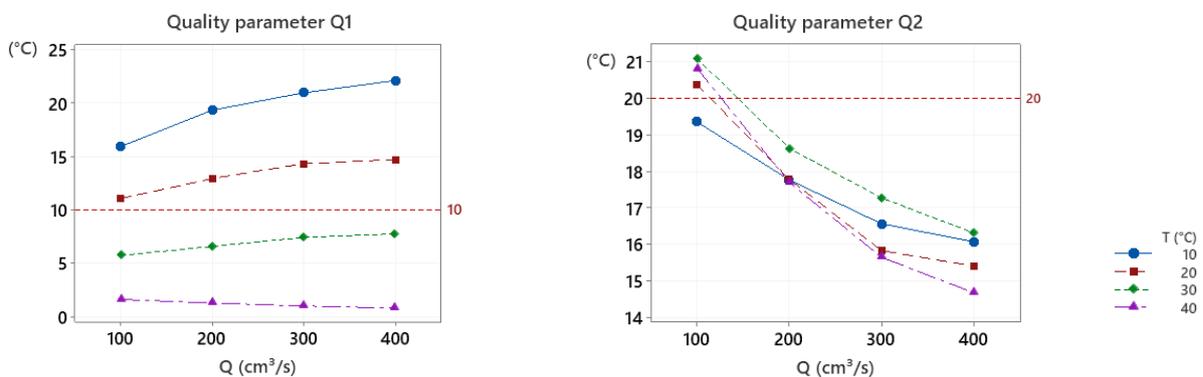

Figure 8 – Results of cooling quality parameters for AL|cavity(8)D2.5P5|core(2)Ba2.5Bb1

To understand the influence of the arrangement in the aluminium mould cooling systems, an additional layout with four (4) baffles on the core side was created and simulated. The results for Q1 and Q2 for all layouts with a coolant temperature of 40 °C were compared and are shown in Fig. 9. The layout with more baffles results in values within the acceptance range for the cooling quality parameters, however the presence of more baffles could have an impact on the complexity and cost of manufacturing the mould.
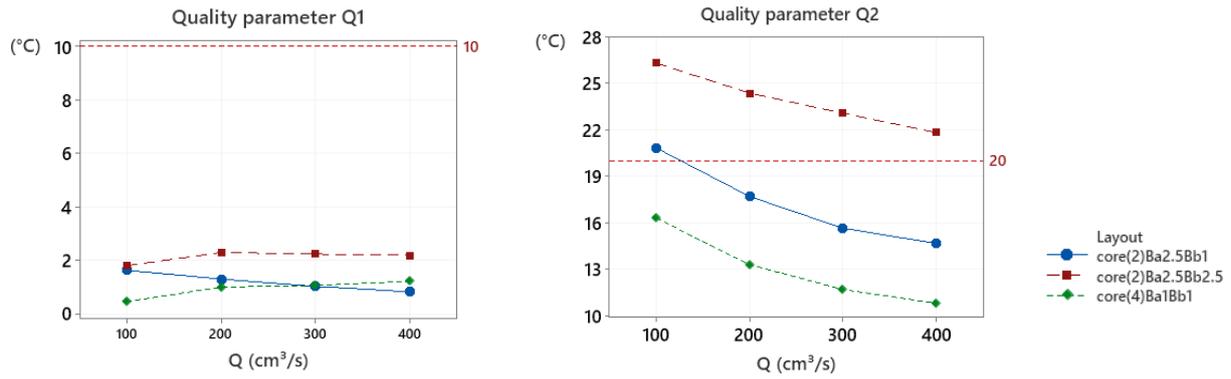
Figure 9 – Results of cooling quality parameters for different layouts in aluminium moulds

In the case of steel moulds, four geometrical configurations for the cooling circuits were made until a layout that met all the quality parameters was achieved. The first three layouts that had two (2) and four (4) baffles in the core side, varying the spacing of Ba and Bb between 1d and 2.5d, resulted in very high values for Q1 and Q2 and, therefore, were discarded. The ST|cavity(18)D2.5P2.5|core(6)Ba1Bb1 layout was approved with coolant at 30 °C and a flow rate of 300 cm³/s, and with coolant at 40 °C and flow rates of 100 cm³/s and 200 cm³/s. Hotspots were identified in the simulations with six (6) and eight (8) baffles on the core side. Therefore, the cooling time for these simulations was defined by the time required for the mould to cool to the maximum temperature difference between core and cavity surfaces accepted in the quality criteria (Q2) and varied between 12 and 15 seconds. Figure 10 shows the result of Q1 for the simulations performed with this layout and the maximum acceptance range is highlighted with a red dash line. Some combinations between the coolant temperature and the coolant flow rate for this layout were reproved due to the low heat exchange contribution in the circuits.
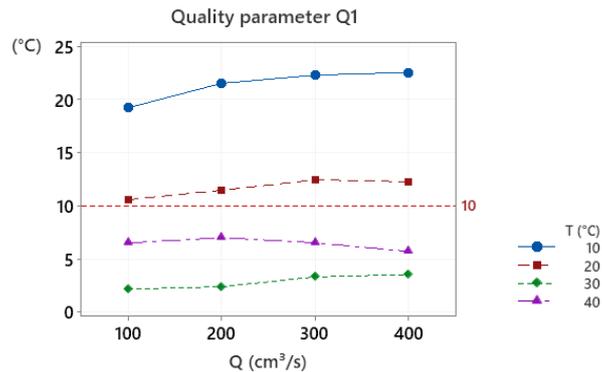

Figure 10 – Results of Q1 quality parameters for ST|cavity(18)D2.5P2.5|core(6)Ba1Bb1

For steel moulds, the coolant temperature has the greatest influence on the cooling time and the parameters Q1 and Q2. To understand the influence of the layout in the cooling systems, an additional layout with eight (8) baffles on the core side was created and simulated. The results for Q1 and Q2 for all layouts with a coolant temperature of 40 °C were compared and are shown in Fig. 11. The layout with more baffles results in values that are within the acceptable range for the cooling quality parameters. However, due to the small difference to the aforementioned system, its implementation would not justify the complexity and cost of the tool design.
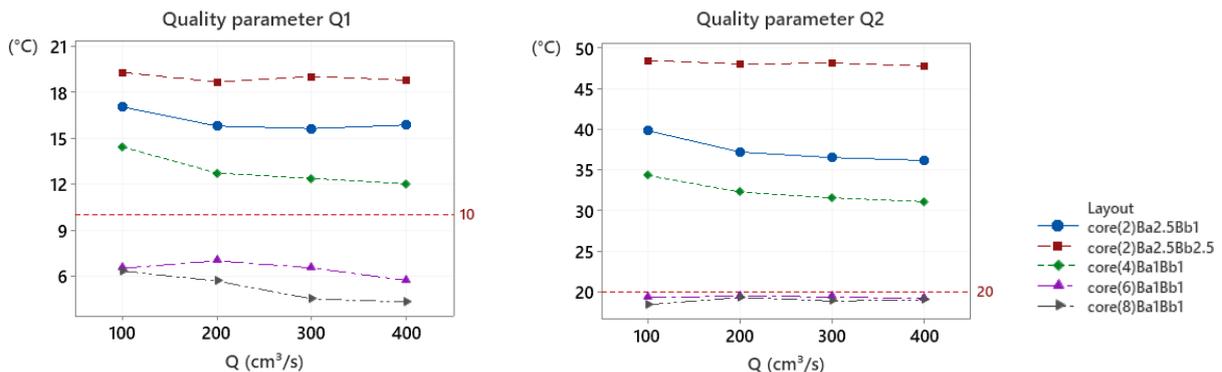

Figure 11 – Results of Q1 and Q2 for different layouts in steel moulds

3.3 Full cycle analysis

The last stage of verification of the cooling systems effect is to determine its influence on the moulded part quality. For this evaluation, all the cooling systems approved in the cooling analysis were used for the execution of full cycle analysis, and the warpage values obtained for comparisons. For other simulations, values of warpage total displacement and differential temperature effect for a simulation of filling, packing and warping stages with the mould cavity kept at constant temperature (isothermal simulation) are used as reference. The results are presented in Tab. 5.

Table 5 – Warping results of full cycle analysis

Cooling system				Variation from isothermal simulations	
Layout	T (°C)	Q (cm³/s)	Cooling time (s)	Total warpage displacement	Differential Temperature Effect
AL|cavity(8)D2.5P5|core(2)Ba2.5Bb1	40	200	5.5	0.93 %	0.413 mm
	40	300	5.8	0.93 %	0.370 mm
	40	400	5.8	1.21 %	0.348 mm
ST|cavity(18)D2.5P2.5|core(6)Ba1Bb1	40	100	14.5	1.31 %	0.172 mm
	40	200	12	2.89 %	0.170 mm
	30	300	13	0.22 %	0.170 mm

According to Moldex3D (2020) the thermal displacement result shows the distribution of total displacement considering only the cooling effect. A large value of thermal displacement indicates the need of a cooling system review, since this result is an indicator of cooling balance and, as also mentioned by Malloy (2010), unbalanced cooling may lead to non-uniform volumetric shrinkage and possibly cause further warpage. The results from the approved cooling systems show a small variation, below 3 %, in comparison to the reference warping value from isothermal analysis. Within this result, the differential temperature effect results also remained within an acceptable range. It should be noticed that the cooling systems in aluminium mould present higher differential temperature effect values, which is directly related to the smaller the cooling time. Therefore, these results corroborate the acceptance of the systems and verify that the part quality was not compromised by the cooling system.

4. CONCLUSIONS

The evaluation of the cooling system is an essential step in the analysis of the production cycle performance of injection moulding. In this context, the lack of knowledge about the behaviour of aluminium moulds is an obstacle to overcome for its implementation in large-scale production in the national scenario.

In order to achieve satisfactory cooling systems, this study was developed based on a method that takes into account the main parameters for injection moulds' cooling systems and numerical simulations to verify the influence of each parameter. The achievement of cooling systems with adequate geometrical layout and cooling time that results in uniform temperature profile in the mould cavity promotes an injection process that allows dimensional quality of the part and lower costs.

According to the results showed in Fig. 8, aluminium offers a good heat dissipation capacity due to its excellent thermal properties and allows not only a larger pitch value (5d) as it is also able to fulfil all cooling quality parameters with the use of only two baffles in the core side of the mould. Since steel is a material with lower thermal conductivity, it cannot as easily uniformize the temperature profile in the mould cavity compared to aluminium. This lack of heat dissipation favours the formation of hotspots, which is always a concern in injection mould designs and leads to longer cycle times. The results showed in Fig. 10 illustrate that a smaller pitch (2.5d) must be used for the steel mould to meet the cooling quality parameters, resulting in a higher number of channels and baffles, and a longer cooling time. For the core area, six baffles were used in the steel mould, three times more than in the aluminium mould. As for the isolated cooling analyses on the layouts, the results in Fig. 9 and Fig. 11 showed that for both steel and aluminium moulds geometrical configurations with more baffles leads to values within the acceptance range for the cooling quality parameters. However, the implementation of a higher number of devices could have an impact on the complexity and cost of manufacturing the mould.

In terms of cycle time, (not regarding the time for mould opening and closing) the one approved for aluminium mould (AL\|cavity(8)D2.5P5\|core(2)Ba2.5Bb1) ranges from 14.8 to 16.3 s, while for the approved systems for steel (ST\|cavity(18)D2.5P2.5\|core(6)Ba1Bb1) ranges from 22.3 to 25.3 s, which represents a 26.9 to 41.5 % reduction in cycle time when using aluminium moulds instead of steel moulds. The result supports the studies of Lammon (2013) and Bryce (1998), that mentions that the use of a 7075 aluminium alloy can lead to a reduction of the injection moulding cycle time up to 40 %. Regarding the quality of the moulded part, the results of Tab. 5 showed that the layouts approved in the prediction methodology have a small deviation compared to the reference value for the isothermal analysis (less than 3 %). This result endorses that the cooling system is satisfactory and guarantees that the dimensional quality of the part is not affected by the system.

Due to the different thermal capacities of each mould material, a critical point for the approval or non-approval of the cooling systems is the influence of the geometrical placement of the circuits and devices. In this scenario, the use of numerical simulations to verify the quality of the systems is proved to be essential, as it allows the evaluation of several criteria on a wider basis and serve as a fundamental tool for the design and optimization of cooling systems.

5. ACKNOWLEDGEMENTS

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