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Design of conformal cooling for plastic injection moulding by heat transfer simulation

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Abstract

The cooling channels of a mold for plastic injection have to be as close as possible to the part geometry in order to ensure fast and homogeneous cooling. However, conventional methods to manufacture cooling channels (drilling) can only produce linear holes. Selective laser melting (SLM) is an additive manufacturing technique capable to manufacture complex cooling channels (known as conformal cooling). Nevertheless, because of the high costs of SLM the benefits of conformal collings are still not clear. The current work investigates two designs of conformal coolings: i) parallel circuit; ii) serial circuit. Both coolings are evaluated against to traditional cooling circuits (linear channels) by CAE simulation to produce parts of polypropylene. The results show that if the conformal cooling is not properly designed it cannot provide reasonable results. The deformation of the product can be reduced significantly after injection but the cycle time reduced not more than 6%.

Keywords: *plastic injection moulding process, conformal cooling, additive manufacturing.*

1. Introduction

The industries of plastic parts are a driving force for the current market. Such manufacturing process requires tooling known as moulds to manufacturing plastic parts and products. The mould is the most important component in the process of manufacturing a plastic part because it influences the cycle time and the quality of the product.

Optimal properties of plastics parts can be achieved only when the correct mould temperature is used and maintained during the manufacturing process. The mould temperature influences the: mechanical properties; shrinkage; warpage; surface quality; cycle time and the flow length for thin walled parts^[1,2]. The cooling time during an injection moulding process usually represents about 2/3 of the total cycle time^[3]. Therefore, any reduction on the cooling time will have a great repercussion on the complete production time.

The efficiency of the cooling circuit directly influences the quality and the cooling time of the part. At least 60% of visible defects such as wrapping recorded in the injected component may be related to the inefficiency of the cooling system^[4].

The cooling system inside the mould cavity is manufactured by drilling machining. It means only linear channels are possible to manufacture. Then, in most of the cases a uniform heat transfer is not obtained. Researches can be found in literature about linear cooling circuits^[5-7].

New technologies to manufacture metal parts have been developed during the past decades known as Addictive

Manufacturing techniques (AM). Among them the selective laser melting (SLM) is unique powder-based technologies that produce objects from metal powders with complex geometries. The mechanical properties are comparable to that one of tool steel^[8].

Using SLM techniques the cooling channels can be manufactured following the product topography. These complex channels are kwon as conformal cooling. An expressive reduction of the production time of a plastic part together to a better product property is expected with the conformal cooling channels^[9,10]. However, the cost of this technology is still very high. Thus, the benefits of the conformal cooling for a plastic injection mould should be determined before the mould manufacture using SLM. According to Hamdy et al.^[11] to achieves an optimum thermal reduction and shrinkage rate distribution throughout the product, the conformal cooling system layout must be optimized.

According to Dalgarno and Stewart^[12] the use of conformal cooling channels in an injection mould can result in a significant reduction in the cycle time. Ilyas et al.^[13] stated an improvement of the productivity and energy saving due to the high efficiency of the heat transfer by the conformal cooling channels. Hsu et al.^[14] identify the efficiency of conformal cooling by three-dimensional simulation to reducing the cooling time displacement. However, none of these have investigated the design of conformal cooling and options of the cooling channels.

Focusing this issue, the current works aims to understand the behavior of different conformal cooling designs. Using the geometry of a plastic part as a workpiece, two designs of conformal cooling are proposed: parallel circuit (manifold) and serial circuit. Both conformal cooling circuits are evaluated against the traditional cooling circuits (linear channels) by CAE simulation to produce parts of polypropylene.

1.1 Thermal analysis

After the injection phase, the heat transferred to the mould cavity by the molten material needs to be extracted, ensuring the solidification of the polymer melt. After the polymer is solidified, it is ejected from the mould cavities.

Generally, the recommended moulding conditions for injecting polypropylene (based on the standard ISO 1873-2:2007^[15]) suggests the mould temperature about 40°C and the melt temperature was 200°C^[16]. Heat exchange occurs between the mould and the molten material, causing a constant temperature increase of the mould up to a temperature where it is stabilized.

According to Park and Dang^[17], when the heat balance is established the heat flux supplied to the mould and the heat flux removed from the mould are in equilibrium. The heat balance is expressed by Equation 1.

$$Q_m + Q_c + Q_e = 0 \quad (1)$$

where Q_m , Q_c and Q_e (W/m²) are respectively: the heat flux the melt, the heat flux exchange with coolant and environment.

1.2 Cooling time

The cooling time is proportional to the square of the thickest wall of the part and the largest runner diameter powered of 1.6, and inversely proportional to the thermal diffusivity of the polymer melt. These relationships are given by the Equation 2^[1,2].

$$T_c \propto (Th_w^2 + D_r^{1.6}) \propto \frac{1}{a} \quad (2)$$

where T_c (s) is the cooling time, Th_w (m) is the thickness at the thickest part of the part wall, D_r (m) is the diameter of the largest runner, and a is the thermal diffusivity (m²/s). Thus, doubling the wall thickness quadruples the cooling time.

The thermal diffusivity of polymer melt is defined according to the Equation 3^[18].

$$a = \frac{K}{\rho C_v} \quad (3)$$

where ρ is the thermal conductivity (W/m.K), $\rho\rho$ is the density (kg/m³), and C_v is the specific heat constant volume (J/kg.K).

The Reynolds number is described according to the Equation 4^[1,2].

$$Re = \frac{\rho U d}{\eta} \quad (4)$$

where ρ is the density of the coolant (kg/m³), U is the averaged velocity of the coolant (m/s), d is the diameter of the cooling channel (m), and η is the dynamic viscosity of the coolant (kg m⁻¹s⁻²). The type of coolant flow can be determined by the Reynolds number Re , as listed in Table 1.

Table 1. Type of coolant flow^[1,2].

Reynolds number, (Re)	Type of flow
4 000 < (Re)	Turbulent
2 300 < (Re) < 4 000	Transition
100 < (Re) < 2 300	Laminar
(Re) < 100	Stagnated

1.3 Temperature variation of polymer melt

All flow problems involve solving the equations of conservation of mass, momentum and energy, these equations are described as Kennedy^[19] and Li and Shen^[20]:

$$\text{Mass equation: } \frac{\partial \rho}{\partial t} + (\nabla \cdot \rho \mathbf{v}) = 0 \quad (5)$$

$$\text{Momentum equation: } \rho \frac{\partial \mathbf{v}}{\partial t} = -\nabla \cdot \mathbf{p} + [\nabla \cdot \underline{\eta \dot{\gamma}}] - \rho [\mathbf{v} \cdot \nabla \mathbf{v}] \quad (6)$$

$$\text{Energy equation: } \rho C_p \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) = \beta T \left(\frac{\partial p}{\partial t} + \mathbf{v} \cdot \nabla p \right) + \eta \dot{\gamma}^2 + \nabla \cdot (k \nabla T) \quad (7)$$

where ρ is the material density (kg/m³), t is the time (s), \mathbf{v} is the melt velocity (m/s), η is the viscosity (Pa.s), $\dot{\gamma}$ is the shear rate (s⁻¹), C_p is the specific heat (J/K), β is the coefficient of thermal expansion (K⁻¹), k is the thermal conductivity (W/m.K), and T is the temperature (K).

Adopting a system of Cartesian plane and assuming the thin thickness of the cavity compared with other dimensions, the mass and momentum equations can be reduced to Equations 8 and 9^[19,20].

$$\frac{\partial}{\partial x} \left(S \frac{\partial p}{\partial x} \right) + \frac{\partial}{\partial y} \left(S \frac{\partial p}{\partial y} \right) = \quad (8)$$

$$\frac{1}{2} \int_{-H}^H \left\{ K \frac{\partial p}{\partial t} - \frac{\beta}{\rho C_p} \left[\eta \dot{\gamma}^2 \frac{\partial}{\partial z} \left(K \frac{\partial T}{\partial z} \right) \right] \right\} dz$$

$$S = \frac{1}{2} \int_{h^-}^{h^+} \frac{z^2}{\eta} dz - \left[\frac{\left(\int_{h^-}^{h^+} \frac{z}{\eta} dz \right)^2}{\int_{h^-}^{h^+} \frac{1}{\eta} dz} \right] \quad (9)$$

$$S = \frac{1}{2} \int_{h^-}^{h^+} \frac{z^2}{\eta} dz - \left[\frac{\left(\int_{h^-}^{h^+} \frac{z}{\eta} dz \right)^2}{\int_{h^-}^{h^+} \frac{1}{\eta} dz} \right]$$

where h^+ and h^- are respectively the highest and lowest z coordinate of the frozen layer's position, K is the coefficient of expansion (K⁻¹), and represents half the wall thickness (m).

Assuming that convection in the z direction can be ignored, the energy equation is described according to Equation 10^[19,20].

$$\rho C_p \begin{pmatrix} \frac{\partial T}{\partial t} + v_x \frac{\partial T}{\partial x} + v_y \frac{\partial T}{\partial y} \end{pmatrix} = \beta T \frac{\partial T}{\partial y} + \eta \dot{\gamma}^2 + \frac{\partial}{\partial z} \left(k \frac{\partial T}{\partial z} \right) \quad (10)$$

The left side of the energy equation represents the rate of temperature change and convection, while the term on the right describes the expansion/compression by heating, viscous dissipation and heat conduction to the mould

However, the Hele-Shaw model, neglects the velocity and pressure variation in the thickness direction, resulting in a two-dimensional flow with a heat flow problem in the plane of flow and an additional problem of thermal conduction in the thickness direction^[4]. Consequently, this technique is not recommended for models with high wall thickness and complex geometries, such as used in this study. For these cases a simulation analysis using full 3D technology is required. By matching Equations 11 and 12 the variation of the viscosity (η , Pa.s) as a function of the shearing rate ($\dot{\gamma}$, s⁻¹), temperature (T, K) and pressure (p, Pa) is obtained.

$$\eta(\dot{\gamma}, T, p) = \frac{\eta_0}{1 + \left(\frac{\eta_0 \dot{\gamma}}{\tau^*}\right)} \quad (11)$$

$$\eta_0(T, p) = D_1 \cdot \exp\left(\frac{-A_1 \cdot (T - D_2 - D_3 \cdot P)}{A_2 + T - D_2}\right) \quad (12)$$

The coefficients τ^* , η , D1, D2, D3, A1 and A2 are adjusted data. τ^* is the tension (Pa) on the transition of the shearing behavior, D2 temperature, (K) glass transition (Tg).

2. Materials and Methods

This work investigates the designs of the conformal cooling circuits of a plastic injection mould. A plastic tray of eggs-holder for refrigerators was used as the work piece. Table 2 shows the work piece, inserts and the injection mould used in this study.

The work piece geometry has five equidistant cavities interconnected by a thickness of 2 mm and 140 mm overall diameter. The supply channel dimensions are: 60 mm in length, 6.5 mm diameter at the entrance and draft angle of 2°. The dimensions of top insert are

190mm (L) × 155mm (W) × 65mm (H). The dimensions of bottom insert are 190mm (L) × 155mm (W) × 61mm (H).

Braskem H201 polypropylene was used as the plastic material for injection moulding simulation according to Table 3.

The Mouldflow V10[®] CAE software was used for the simulation and the specific parameters were assumed to be:

- Material of the inserts: AISI P20.
- Injection temperature: 230°C.
- Injection time: 1 sec.
- Coolant fluid: water.
- Maximum pressure injection machine: 180 MPa.
- Maximum force closure machine: 7000 ton.

Three designs of the cooling channels are proposed: i) series conformal cooling; ii) parallel conformal cooling; iii) linear cooling channels (ordinary) as presented ahead.


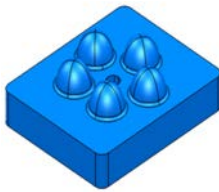
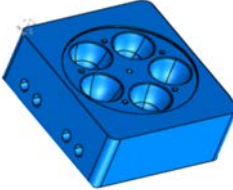
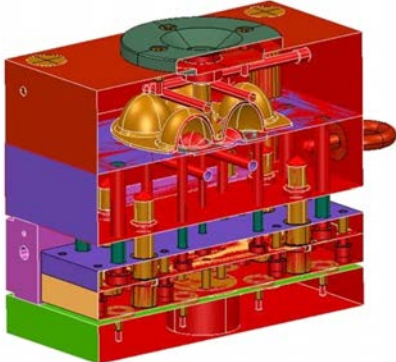
2.1 Conformal cooling design

Identifying the requirements for conformal cooling designing was the first task in this phase. The position of the channels, the pitch distance, its diameter and its length must be considered^[3,22]. Based on this information, these dimensions were obtained from^[23], as presented by Table 4 and Figure 1.

Considering the moulded product (work piece) is 2mm thickness, the dimensions of the cooling channels is assumed to be: b = 5mm. Thus: a = 2.5 × 5 = 12.5mm and c = 1.7 × 5 = 8.5mm.

But besides dimensions of the circuits, the topology of the conformal cooling must be designed. Because this is a new approach to design cooling circuits, a guide about its geometry was not found in literature. Therefore this work investigates the conformal cooling topography. It is proposed and evaluated by FEA-CAE simulation the design of conformal cooling in series channels and conformal cooling in parallel channels, as detailed ahead.

Table 2. Work piece, inserts and mould design^[21].

Product	Inserts	Sketch of the Mould
	<p>Top</p>  <p>Bottom</p> 	

2.1.1 Conformal cooling in series channels

In this case the conformal cooling channels were designed so that the cooling liquid passes through each cavity one at a time, in series. Series cooling channels are connected in a single loop from the coolant inlet to its outlet (Table 5). This type of cooling channel network is the most commonly used in practice (for linear channels). By design, if the cooling channels are uniform in size, the

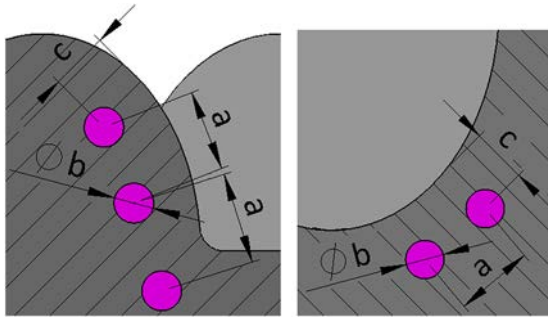


Figure 1. Optimal design of a ‘three dimensional channel system’^[23].

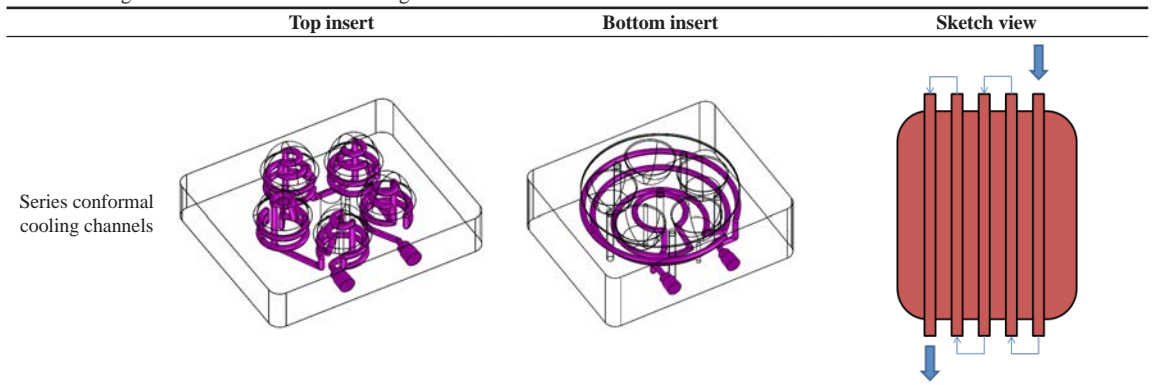
Table 3. Physical and mechanical properties typical of polypropylene.

Properties	PP H 201
Fluidity index (g/10min)	20
Density (g/cm ³)	0.905
Secant flexural modulus 1% (GPa)	1.5
Tensile strength in the flow (MPa)	34
Stretching in the flow (%)	12
Rockwell Hardness (R scale)	102
Izod impact strength 23°C (J/m)	23
Heat deflection temperature 0,455 MPa (°C)	97
Heat deflection temperature 1,820 MPa (°C)	57
Vicat softening temperature 10 N (°C)	154

Table 4. Optimal design of a three dimensional channel system^[23].

Wall thickness of moulded product (mm)	Hole diameter, b (mm)	Centreline distance between holes, a (mm)	Distance between centre of holes and cavity, c (mm)
0-2	4-8	2-3×b	1.5-2×b
>2-4	>8-12	2-3×b	1.5-2×b
>4-6	>12-14	2-3×b	1.5-2×b

Table 5. Design of the series conformal cooling channels.



coolant can maintain its turbulent flow rate through its entire length. Turbulent flow enables the heat to be transferred more effectively. According to Park and Dang^[17], for linear channels it is not appropriate use channels in series circuits in the following situations:

- If the length of the series circuit requires a higher pressure than the pump capacity can support.
- The physical constraints in the mould design means that the mould cannot be effectively cooled with a series circuit.

2.1.2 Conformal cooling in parallel channels

Parallel cooling channels are straight drilled channels in which the coolant flows from a supply manifold to a collection manifold. The collection manifold is designed with a larger diameter than the cavity’s channels (Ø12 mm). Due to the flow characteristics of the parallel cooling channels, the flow rate along various cooling channels may be different, depending on the flow resistance of each individual cooling channel. The varying of the flow rate, cause the heat transfer efficiency of the cooling channels to vary from one to another. As a result, cooling of the mould may not be uniform with a parallel cooling channel configuration, but a balanced parallel circuit provides uniform heat extraction. However, it is suggested only to use a parallel circuit if the model has one of the following circumstances^[17]:

- The pressure drop over a series circuit is too high to be realistic.
- An area of the mould cannot be effectively cooled with a series circuit.

Table 6 shows the proposed design of the parallel conformal cooling circuit.

2.2 Design of the ordinary cooling system with linear channels

The linear cooling system manufactured by drilling usually requires plugs to connect the channels and to close the circuit. Because of the constraints of this process, the circuits developed normally do not follow the geometry of the product, as they are linear channels. Table 7 shows the design of the linear cooling channels proposed in this work.

3. Results and Discussions

The simulation results are presented by graphics comparing the three cooling systems investigated. Some graphics had to be presented in an individual scales, in order to have a good representation of the cooling phenomenon.

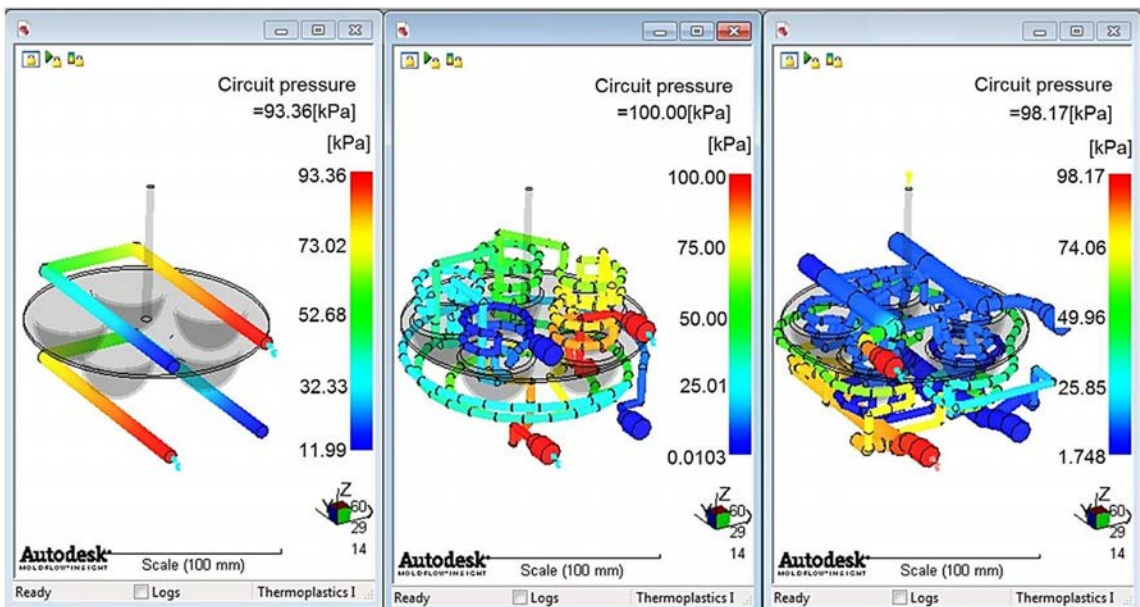
Figure 2 shows the circuit pressure inside the cooling circuit generated from a cooling analysis to show the

Table 6. Design of the parallel conformal cooling channels.

Descriptions	Top insert	Bottom insert	Sketch view
Parallel conformal cooling channels			

Table 7. Design of the series cooling channels.

Descriptions	Top insert	Bottom insert
Linear cooling channels		



(a) Linear channels

(b) Series channels

(c) Parallel channels

Figure 2. Circuit pressure results

distribution of pressure along the cooling circuits. The circuit pressure is responsible for making the refrigerant fluid circular in the channels. The value of the circuit pressure is directly dependent on the geometry of the circuit. It is one of the important factors to evaluate whether a cooling system is viable, since high pressures are not preferred^[24].

The linear circuit operates with a lower pressure flow, because it is a simple geometry with little restriction to flow. It is observed that both conformal cooling circuits

required higher pressures to operate and have larger pressure drops along the circuit because of the high level of flow restriction (complex geometry).

Figure 3 and 4 shows the flow rate of the coolant and Reynolds number inside the cooling circuit.

The circuit's flow rate and the circuit's Reynolds number are used to determine the flow rate required to achieve a turbulent coolant flow. The flow rate itself is not the dominant factor in heat extraction, but it should

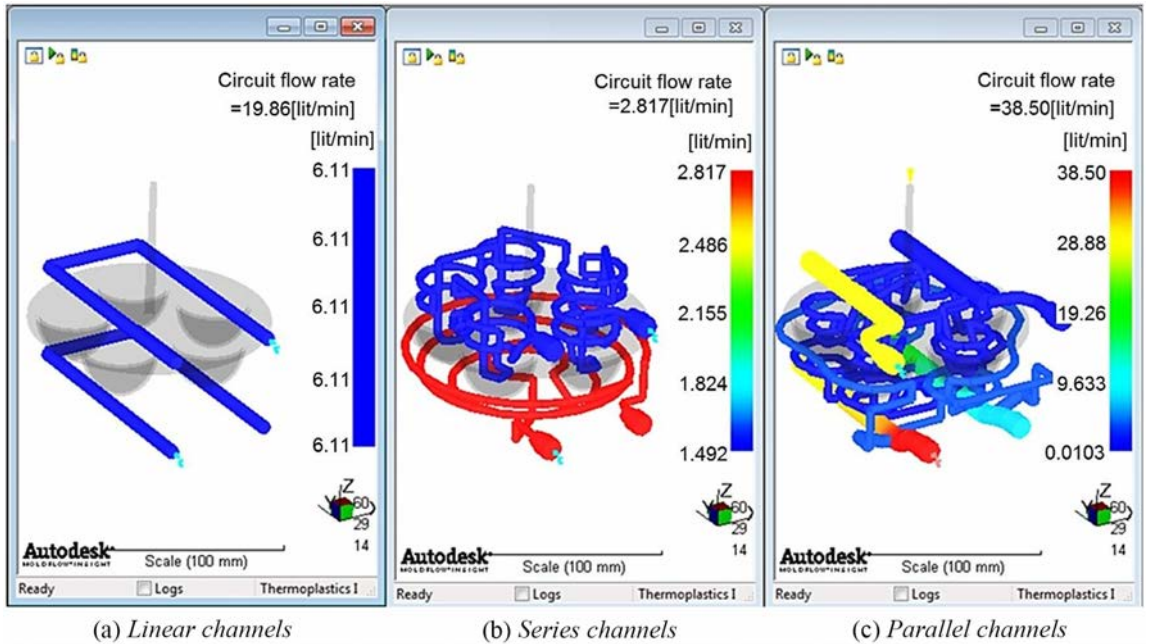


Figure 3. Circuit flow rate result.

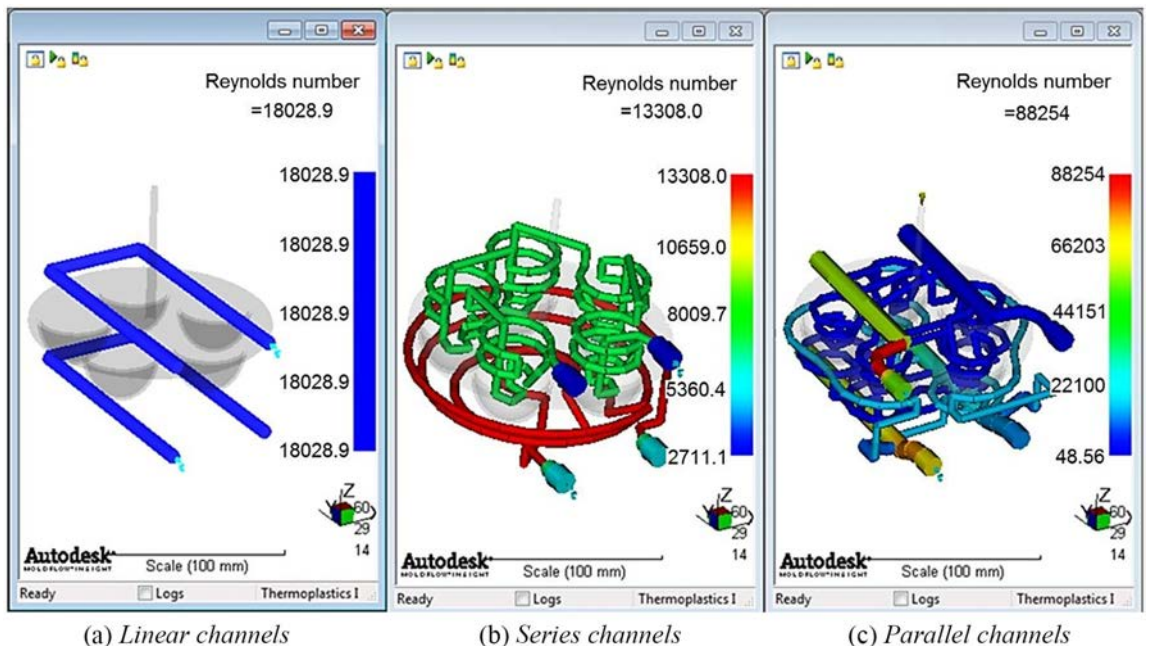


Figure 4. Reynolds number result.

be the minimum requirement to achieve the necessary Reynolds number. The flow rate is constant for a series circuit, but not for a parallel circuit.

A Reynolds number of 4,000 or higher represents a more turbulent flow, which is preferred for cooling applications. However, the higher the Reynolds number in the circuit, the more energy is required to pump it through the circuit. Hence, the ideal Reynolds number for cooling circuits is 10,000. The pumping losses associated with a Reynolds number higher than 10,000 outweigh the heat transfer gains that can be achieved with higher Reynolds numbers^[1,2].

The simulations shown in Figure 3a, b and Figure 4a, b shows that for linear and for series circuits the flow rate and the Reynolds number are constant. Whereas for the parallel circuit the flow rate and the Reynolds number varies (Figure 3c and Figure 4c).

The flow rate for linear circuit and for series circuit is sufficient to achieve turbulent coolant flow and their values are close to 10,000, which is the optimal value for the Reynolds number. Whereas in most regions along the parallel circuit the flow rates are insufficient to achieve turbulent coolant flow. And in the regions where the flow rates are sufficient to achieve turbulent coolant flow, the values are very high compared to the optimal value of Reynolds number.

Figure 5 shows the coolant temperature results inside the cooling circuit. The temperature of the coolant is related to the flow rate and pressure applied in the circuit.

The coolant temperature varies along the circuit. It can be noticed that on the serial circuits, this variation occurred linearly and the temperature at the output channel is higher than the temperature along the circuit, unlike a

parallel circuit, where the highest temperature occurs at the centre of the circuit. The difference between the in and outlet coolant temperatures should be no more than 3°C. Higher values may indicate a high mould surface temperature, and should be avoided in order to get a good product quality^[1,2].

The difference of temperature observed on Figure 5 is according to the specified threshold, but the conformal cooling circuits presented higher temperature variations due to the higher heat transfer, because the channels are closer to the mould cavity, compared with conventional circuits. The lowest variation of the temperature along the circuit between the conformal cooling circuits was achieved by the series conformal cooling circuit (Figure 5b).

Figure 6 identifies that the regions with the highest temperature is the interior of the cavities of the top insert and the centre of the bottom insert. This helps the further analysis of the heat removal of the mould.

Focusing the investigation on the regions with a greater concentration of heat (Figure 6), Figure 7 shows the efficiency of the heat extraction according to the regions of the mould for each cooling system designed. Value close to 1 indicates a more efficient region of the circuits.

Figure 7b shows that the series circuit had the highest efficiency (up to 1) in the warm regions of the mould cavities. Compared to some regions, where the efficiency is zero in regions with a high heat load. The most appropriate cooling design the heat removal efficiency must be high in the regions of the product and also be homogeneous to keep the residual stress as uniform as possible.

Figure 8 indicate the mould surface temperature inside the mould, during the cycle.

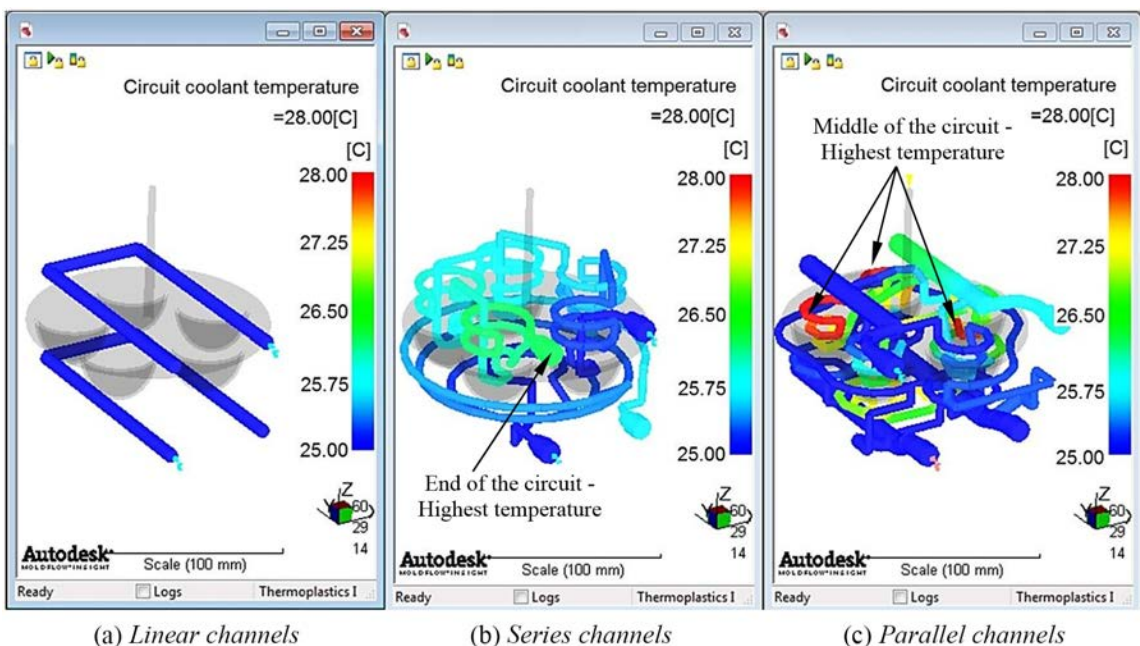


Figure 5. Circuit coolant temperature result.

Figure 8b shows the series cooling circuit had the greatest efficiency and propitiated a homogeneous cooling around the mould. The most regions of the part kept temperatures around 28°C (blue colour in the graph). Satisfactory performance of the cooling system requires a homogeneous temperature in this interface without any hot spots, which is the great cause of tensions and warpages in parts. When the interface is cooled homogeneously with small temperature differences, the chance of defect is less and the quality of the part will be better^[1,2].

Figure 9 shows the time required to reach the part ejection temperature. The series conformal cooling channels have the shortest cycle time (Figure 9b). The difference in cycle time (ejection temperature) between the series

circuit and the conventional circuit was 1.33 sec., which means a 6% reduction.

The simulation indicates there is not a significant reduction in the cycle time when using conformal cooling. Probably it happens because either the product geometry is not so complex with deeper regions more difficult the cool down, or because the injection channel is extracted together with the product. Therefore, the geometry of the product and a hot runner injection must be taken into account to design a conformal cooling and identify the worth case.

The deflection of the product after the injection was also simulated according to the cooling design as illustrated by Figure 10.

According to simulation, the linear cooling system caused a deflection about 0.29 mm inside the product cavities and in its centre. A relative large area of the product was significantly deformed. The best results can be found on the series cooling system (Figure 10b). Only small area inside the product's cavities suffered small deformations. The mould with parallel cooling channels propitiates deformations inside the product's cavities, similar to the serial channels case, but further deformation can be observed on the product border, about 0.1mm.

As previously stated by Figure 8b the mould with a series cooling circuits results in a homogeneous cooling around the mould. Now, Figure 10b shows that this homogeneous cooling of the mould propitiates the lowest deflection compared with its counterparts.

Table 8 presents the summary of the simulations results of the three different cooling systems.

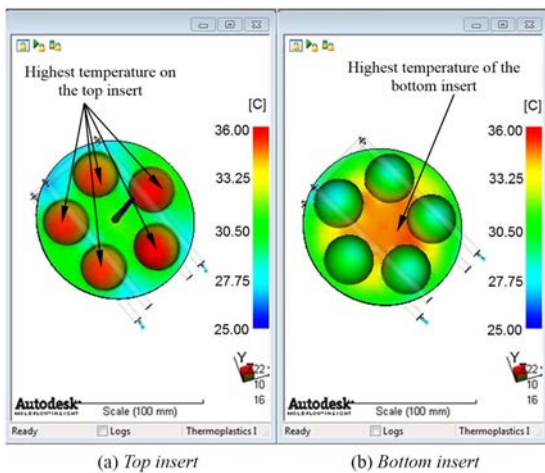


Figure 6. Regions of the mould with a greater concentration of heat.

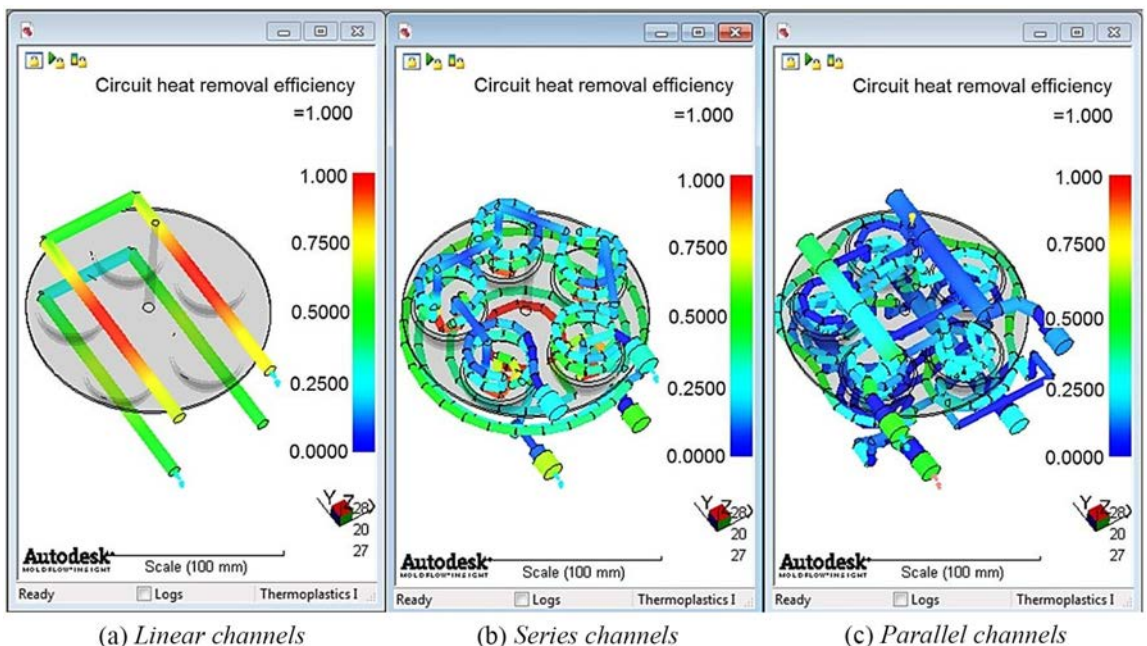


Figure 7. Circuit heat removal efficiency result.

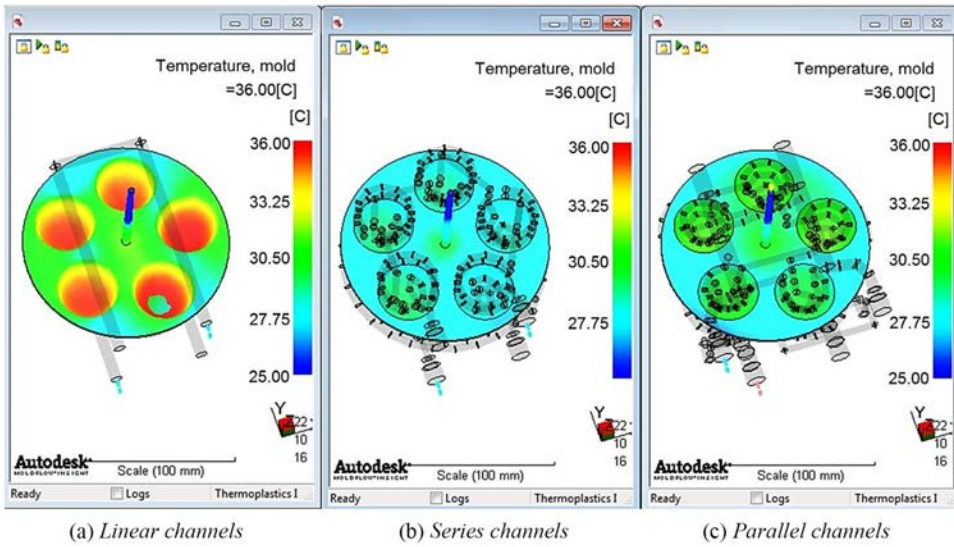


Figure 8. Mould temperature result.

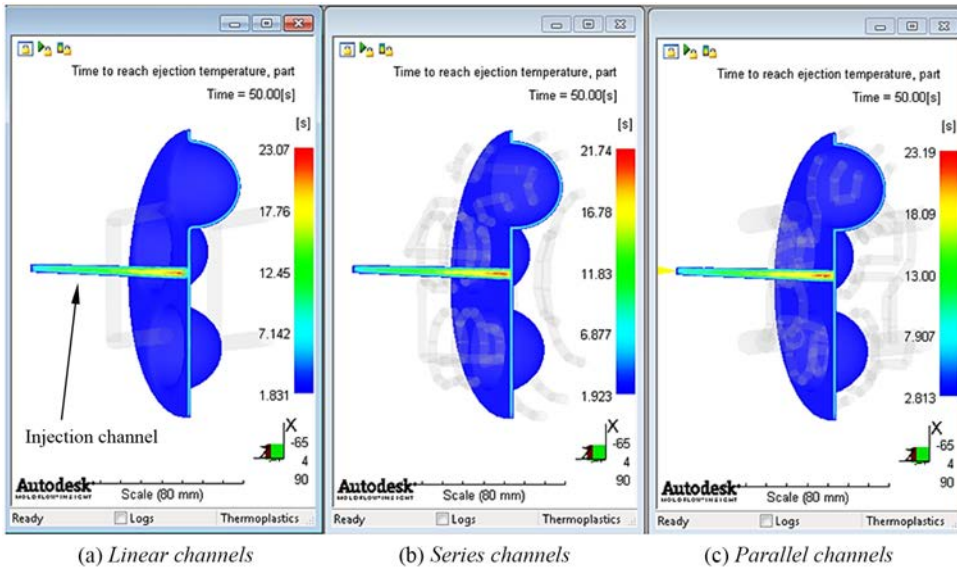


Figure 9. Time to reach ejection temperature result.

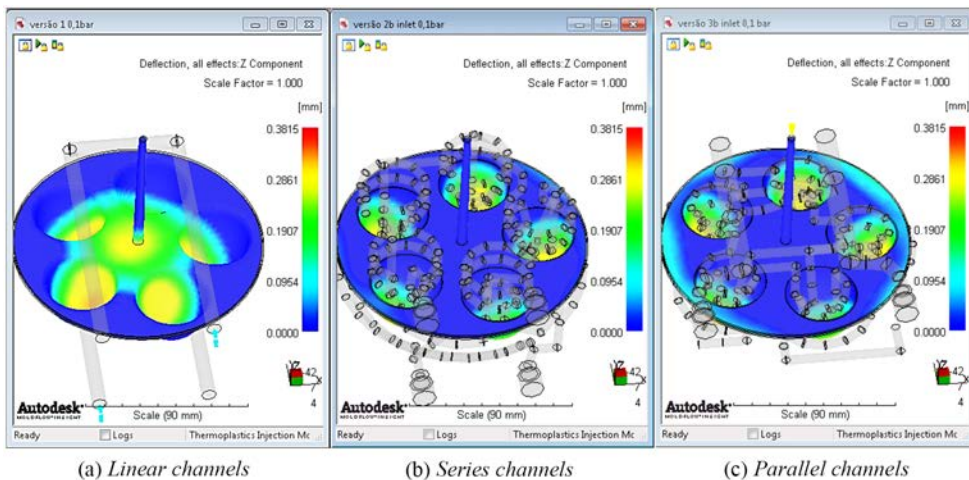


Figure 10. Deflection of the injected part.

Table 8. Summary results.

Cooling channels	Ordinary (a)	Series (b)	Parallel (c)
<i>Circuit pressure (psi)</i>			
Top insert	1.36-0.16	14.5-0.0014	14.24-1.46
Bottom insert	1.36-0.16	14.5-0.0072	14.06-0.62
<i>Circuit flow rate (l/min)</i>			
Top insert	6.11	1.49	29.89-0.01
Bottom insert	6.11	2.82	38.5-0.03
<i>Circuit Reynolds number</i>			
Top insert	18029	7049	88254-49
Bottom insert	18029	13308	75776-146
<i>Circuit coolant temperature (°C)</i>			
Top insert	25-25	25-26	25-28
Bottom insert	25-25	25-27	25-27
<i>Circuit heat removal efficiency</i>			
Top insert	0.96-0.45	0.98-0.0	0.5-0.0
Bottom insert	0.64-0.31	0.98-0.0	0.5-0.0
<i>Mould temperature (°C)</i>	25.0-36.2	28.0-30.0	25.0-33.0
<i>Time to reach ejection (s)</i>	23.07	21.74	23.19
<i>Part deflection</i>	Higher	Smaller	Intermediate

4. Conclusions

Conformal cooling designed for plastic injection moulding could be an attractive alternative to improve the plastic product quality, reducing cycle time and energy consumption. However due to the high costs to manufacture such cooling channels (additive manufactures techniques must be applied) together to the lack of knowledge about its quantitative benefits, this application is still insipient. Concerning this issue the current work proposed two designs for conformal cooling. By CAE simulation (Moldflow V10[®]) both designs were evaluated against ordinary cooling channels (linear ones) in a case study. The performance of these 3 cooling designs were accessed by the simulation and discussed. The remarkable points are:

1. The proposed conformal cooling design in series channels proved to be the best option for the case investigated. The reduction of the product deformations was significant if compared with the liner channels and parallel conformal cooling. However the reduction of the cycle time was not as expected. It propitiates 6% reduction to produce a part. Probably it happens because either the geometry used as work piece didn't have a high degree of complexity or because the injection channel is extracted with the product.
2. Conformal cooling tends to be worthy when the product has deep regions which linear cooling channels cannot archive reasonable hot transfer. Identify this point is the challenge for the mould designers. Current commercial CAD/CAE software does not offer a wizard routine to add this identification.
3. The flow rates for the series circuit are sufficient to achieve turbulent coolant flow and their values are close to 10,000, which is the optimal value for the

Reynolds number. It propitiates a very homogeneous mould temperature and then an injected product with the smaller deformation.

4. The parallel conformal cooling propitiates an insufficient flow rate to achieve turbulent coolant flow in most area of the circuit. In the regions where the turbulent coolant flow was possible to be archived, the values are very high compared to the optimal value of Reynolds number.

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