

Cooling Systems in Injection Moulds

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Introduction

The main phases in an injection moulding process involve filling, cooling and ejection. The cooling phase is the most significant step amongst the three. It determines the rate at which the parts are produced. In the moment of the melted polymer injection, ideally, the mould's temperature should be like of the melted polymer's temperature and in the moment of the parts' removal the mould must to be to the temperature of the environment. Of this way, the polymer would be injected with the minimum of pressure and the difference between the surface temperature and the nucleus temperature of the injected parts would be a minimum leading a slow cooling and minimising the mouldings stresses. Notice that these technical advantages are not compatible with economical needs and the generalized rule is to produce parts with the biggest possible speed. According to this rule, the most important factor is the capacity of the cooling system removes heat of the cavities of the mould. Usually the time of cooling is around 50% of the total cycle. The injected material loses temperature in the contact with the mould surfaces', transferring itself heat through the mould. For speeding the heat transfer process, the mould designer design specific holes in the adjacent surfaces of the moulded part in the mould. These holes, known by "lines of water" (by the water is the more frequent fluid of cooling), constitute the cooling system of a mould.

The fundamental rules that should be had in count in the cooling system design are:

- i) The circuits of the water should be symmetrical and independent relatively to the filling zones and impression(s) of the mould;
- ii) Thermal variations in the walls of the impressions shouldn't be pronounced, so the lines of water should be designed in function of its distance to the impression walls';
- iii) The cooling fluid input and output should be placed for the mould backwards (opposite side to the operator), or alternative for the breaks lower;
- iv) It's important to guarantee that the cooling flow in the channels be turbulent. The index of turbulence is given by Reynolds number:

$$R_e = \frac{v \times d \times \rho}{\mu_m}$$

Where,

v – Flow's speed

d – Channel diameter

ρ – Fluid density

μ_m – Dynamic viscosity of the fluid

When it proceeds to the polymer injection for inside the impression of a mould the removal energy of the polymer in the melted state is transmitted by conduction through the mould material up to the channels of the cooling system and to the mould external surface. The heat exchange mechanisms (fig. 1) include the conduction for the structure of the injection moulding machine, the forced convection for the fluid that circulates into the cooling channels and the thermal radiation and natural convection for the air that surround the walls of the mould [1, 2].

Heat Transfer

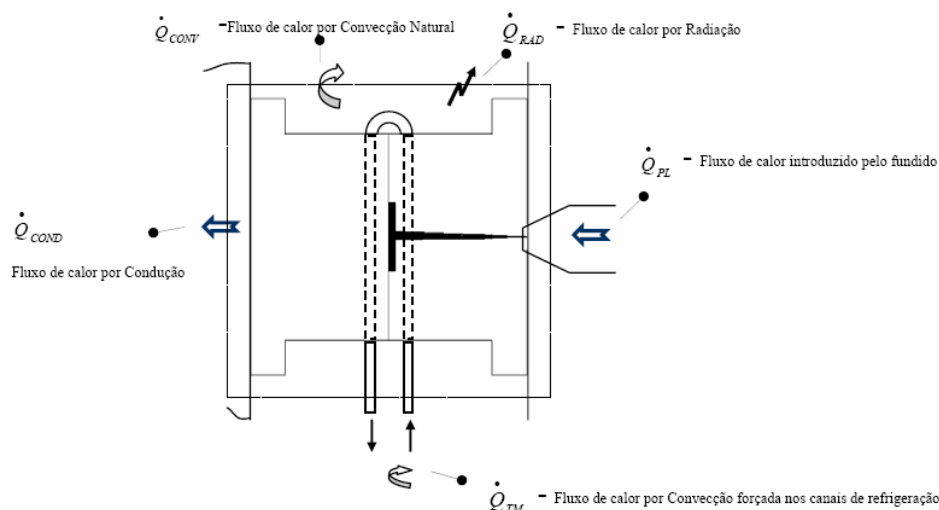


Figure 1 – Heat exchange in a mould of injection

In the injection moulding cycle, the heat corresponding to the enthalpy variation of the moulding material during the cycle, is exchanged for the moulding zone surface (or impression surface of the mould) and of this for his outside. To define the energy swing, is established an equilibrium between the heat powers that are introduced in the mould, the heat power accumulated in every single moment in their interior and the heat powers removed from the mould, being positive or negative those that respectively increase or diminish their internal energy [1, 3]. In a process analysis with accumulation of internal energy, the heat flow that is supplied to the mould and the heat flow that is removed from the mould should be in thermal equilibrium, in every single moment, with the heat accumulated in the structure of the mould:

Energy Balance

$$\dot{Q}_{PL} + \dot{Q}_{AMB} + \dot{Q}_{TM} = \dot{Q}_{ACCUM}$$

$\dot{Q}_{PL}$ – Heat flow supplied by the polymer

$\dot{Q}_{AMB}$ – Heat flow transferred for the environment

$\dot{Q}_{TM}$ – Heat flow transferred for the cooling fluid

$\dot{Q}_{ACCUM}$ – Accumulated energy in the mould material per time unit

Simplified hypotheses to obtain results

- i) Quasi - static process
- ii) During the cycles the temperatures and thermal flows fluctuations are despised
- iii) During the different periods medium values are considered

$$\dot{Q}_{PL} + \dot{Q}_{AMB} + \dot{Q}_{TM} = 0$$

Where,

$$\dot{Q}_{PL} = \frac{\Delta h \times m_{PL}}{t_{arref}} \quad \text{or,} \quad \dot{Q}_{PL} = \frac{\Delta h \times \rho_{PL} \times V}{t_{arref}}$$

Where,

$\Delta h = h_i - h_e$; h_i – Polymer enthalpy at the injection temperature; h_e – Polymer enthalpy at the ejection temperature; m_{PL} – Polymer mass injected in the mould; ρ_{PL} – Polymer medium density between the injection temperature and the ejection temperature; t_{arref} – Cooling time of the plastic part; V – Volume of the plastic part

$$\dot{Q}_{AMB} = \dot{Q}_{CONV} + \dot{Q}_{COND} + \dot{Q}_{RAD}$$

Where,

$\dot{Q}_{CONV}$ – Heat flow by convection on the mould lateral walls

$\dot{Q}_{COND}$ – Heat flow by conduction on the injection moulding walls

$\dot{Q}_{RAD}$ – Heat flow by conduction on the mould lateral walls

$$\dot{Q}_{CONV} = A_L \times h \times (T_{amb} - T_{mould})$$

Where,

A_L – Mould exposed area; h – Heat transfer coefficient, natural convection; T_{amb} – Environment Temperature; T_{mould} – Mould temperature.

$$\dot{Q}_{COND} = A_{fix} \times \beta \times (T_{amb} - T_{mould})$$

Where,

A_{fix} – Contact area Mould/Fixing system; β – Proportionality factor

$$\dot{Q}_{RAD} = A_L \times \varepsilon \times \sigma_{rad} \times \left(\left(\frac{T_{amb}}{100} \right)^4 - \left(\frac{T_{molde}}{100} \right)^4 \right)$$

Where,

σ_{rad} – Stefan-Boltzman constant; ε – Material emissivity

When the material is inside the mould cools supplying him heat, by that Q_{PL} is always positive. The heat changed with the environment, can be positive or negative depending on the temperature of the mould.

An efficient system of cooling, with optimal cooling conditions, leads to a part uniform distribution of temperatures, minimizing the undesired effects appeared during de cooling process, the cycle time and the rate of rejections. The conception of an efficient cooling system is not a simple trial, because there are different factors that can contribute for the final intended results. Some of the factors that influence the cooling process are: the geometry of the part, the temperature of the mould, the architecture of the cooling channels, the cooling fluid temperature and the speed of the flow.

It can be identified two reference terms for an iterative process of characterization of the mould cooling system [3]:

- i) The increase of the heat transfer rate
- ii) Uniform temperature distribution in the moulding surface

Whereas the increase of the heat removal rate between the plastic part and the mould is important in the economical point of view, the uniformization of the temperatures distribution on the parts' surfaces will provide the obtaining of parts with estates and quality improved.

The Wubken equation allow us to estimate the cooling time [3]

$$t_k = \frac{s^2}{\alpha \pi^2} \times \ln \left[\left(\frac{8}{\pi^2} \right) \times \left(\frac{T_w - T_a}{T_w - T_b} \right) \right]$$

Where α is the material thermal diffusivity; s is the part thickness'; T_a is the injection temperature; T_b is the ejection temperature and T_w is the medium mould temperature.

The medium mould temperature is considered one of the most significant variables in the cooling time determination [4, 5]. Some determinations use the temperature of the cooling fluid for calculating the medium mould temperature variable. However, such utilization ignores the temperature increases' of the melted plastic material in the molding zones, during the injection phase. During the molding cycle the mould temperature increase while the plastic material is injected, diminishing progressively up to the following injection. Also the flow regime of the cooling fluid, the temperature of the cooling fluid, the architecture of the channels, the kind of the cooling fluid, and the mould material properties (namely the mould material thermal conductivity), influence the mould temperature.

Table 1 – Properties of a typical resin, Aluminium and steel, used in the manufacture of injection moulds.

	SL Vantico 5260	Aluminium AlZn5Mg3Cu	Steel – P20
Young modulus	600 - 800 MPa	72 MPa	2500 GPa
Tensile strength	40 - 65 MPa	540 MPa	965-300 MPa
Thermal conductivity	0.2 W.m ⁻¹ K ⁻¹	120-150 W.m ⁻¹ K ⁻¹	29-34 W.m ⁻¹ K ⁻¹
Coefficient of thermal expansion (at 20°C)	105×10 ⁻⁶ K ⁻¹	23,6×10 ⁻⁶ K ⁻¹	12,8×10 ⁻⁶ K ⁻¹

Cooling Conditions

Cooling Time

If the cooling channels aren't correctly designed (fig. 2), the core and cavity mould wall temperature can be different. If there is a strong gradient in the cavity between the two halves the part may warp and distort its shape [6-8].

So the targets that a correct cooling system has to follow are the uniformity of the wall temperature and a gradual reduction of the polymer temperature, in order to find a compromise between the necessity of reducing cycle time and allowing for the crystallization.

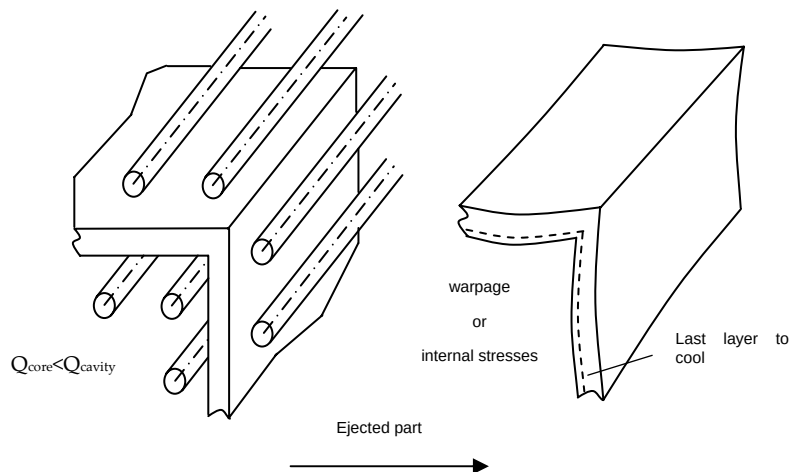


Figure 2 – Cooling through the part thickness.

The differences showed in figure 2 that are able to must itself, by ex., the differences in the cavity and core geometry. After part's ejection, the more shrinkage on the hotter side of the molding (core side) promote the warpage or internal stresses [6, 9].

Generally, convex areas need high cooling because in these parts there is a concentration of heat. On the contrary concave areas need less cooling because the presence of more material helps the diffusion of heat in the mould. Thus, attention must be paid to designing corners and the cooling system in these areas [10].

The diameter and the arrangement of the cooling channels is limited by constructive aspects of the mould. However, a cooling system balanced and uniform provides improvement in the quality of the mouldings. Also it should not be forgetful that to bigger efficiency of the cooling fluid is obtained when his flow regime is turbulent.

According to the literature [eg., 11, 12], the localization of the cooling channels has a great importance for having an uniform cooling, because it decides the moulding surfaces temperature distribution and evolution during the period of cooling.

In this context, the distance between the cooling channels and the moulding surface (h) and the distance between cooling channels (e) are the main parameters to be considered, as shown in the scheme of the figure 3.

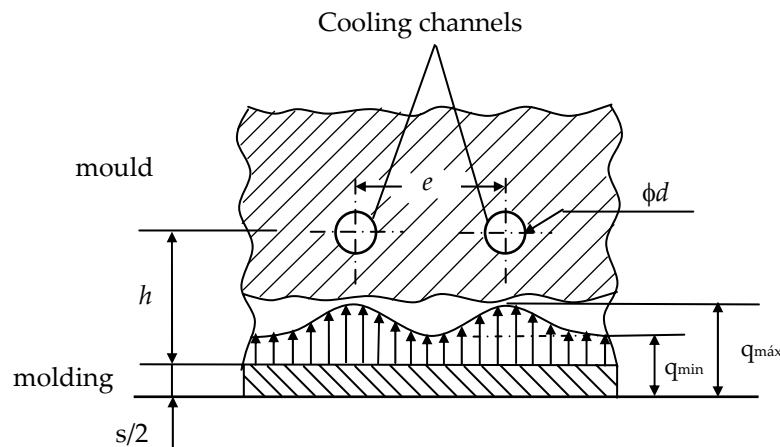


Figure 3 – Heat flow profile [13].

In the practical one, is common to consider: $e = 2,5 \text{ a } 3,5 d$ e $h = 0,8 \text{ a } 1,5 e$

On the issue of dimensional criteria in designing cooling channels, three dimensions have to be considered: the diameter of the cross-section (or the cross-section area if not circular), the distance between channels and the distance between channel and wall of the mould. The main problems that arise when choosing these dimensions concerns the pressure losses derived from the choice of the diameter and the design of the channel. A heating/cooling relationship reported in Zollner [14] gives a guideline on the channels positioning. This states that the value resulting from the solution of the relationship should stay between 2.5 and 5% for semi crystalline thermoplastics and between 5 and 10% for amorphous thermoplastics.

In the injection molding process the main part of the cycle time is determined by the cooling process. Therefore, it is important to optimize the cooling cycle in order to reduce the cooling time. Conformal cooling channels (i.e. channels that follow the geometric shape of the part) have been used for this purpose allowing a significant cooling time reduction. According to Wohlers [15] it is possible to reduce the cooling cycle by 20% using conformal cooling channel. Similarly, Dimla et al. [10] considers that cycle time can be significantly reduced with cooling taking place uniformly in all zones if the cooling channels are made to conform to the part's shape as much as possible. Some investigations have related the moulds' cycle time reduction with conformal cooling; the most relevant result associated to its use is the mould surface temperature uniformity. Furthermore, if the part is ejected with the same temperature in every point the subsequent shrinkage outside the mould is also uniform, which avoids post-injection warpage of parts. This was also pointed out by Voet et al. [16], which mentioned that the goal of cooling a mould is to obtain a uniform temperature at the mould surface and within the final injected product to avoid internal stresses.

Conformal Cooling

A method that utilises a contour-like channel (fig. 4), constructed as close as possible to the surface of the mould to increase the heat absorption away from the molten plastic, ensures that the part is cooled uniformly as well as more efficiently.

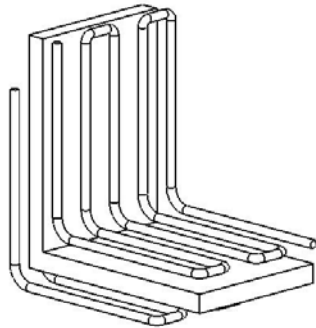


Figure 4 – Conformal cooling channels

When molten plastic is injected in the mould it must be solidified to form the object. The mould temperature is regulated by circulation of a liquid cooler, usually water or oil that flows inside channels inside the mould parts.

Table 2 – Heat convection coefficient of the air, water and oil.

	Air	Water	Oil
Heat convection coefficient $Wm^{-2} K^{-1}$	50	900	400

When the part is sufficiently cooled it can be ejected. Most (95%) of the shrinkage happens in the mould and it is compensated by the incoming material; the remainder of the shrinkage takes place sometime following the production of the part [17].

If the channels carrying the water could be conformed to the shape of the part and their cross section changed to increase the heat conducting area then a more efficient means of heat removal could be realised. This may also help to reduce warpage when the part is ejected, as the plastic would be cooled more uniformly.

Another advantage is that a mould equipped with conformal channels reaches the operation temperature quicker than a normal one equipped with standard (or drilled) cooling channels [18, 19].

The analysis tools utilization for the cooling systems conception that assures the uniformity of the cooling along the part, drive the significant improvements in the mould production and definition of the process conditions to the specifications of the product demanded.

The main resistance to the transference of heat in the cooling happen of the own material due to the low thermal diffusivity of the plastic material. So, it's essential to consider the dependence of the material with the temperature in the modulation of the heat conduction.

Modelling

In the cooling process it's essential to consider the thermal properties of the mould material and appropriate border conditions (e.g. the heat transfer by forced convection in the cooling channels).

In isotropic domain the heat transfer is described by the energy conservation equation [20]:

$$\rho C_p \frac{\partial T}{\partial t} = \nabla(K \nabla T) + \dot{Q}$$

Where ρ , C_p and k represent the density, the specific heat and the thermal conductivity of the material, respectively. T represents the local temperature in each instant moment t and in each spatial coordinate, whereas $\dot{Q}$ represents the energy generated/dissipated by unit of time and by unit of volume in the material. This differential equation with derived partial for bi-dimensional heat conduction, not stationary, in Cartesians' coordinates and in a simplified form, takes the form:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(K \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left(K \frac{\partial T}{\partial y} \right) + \dot{Q}$$

The temperature profile in a given zone of the material and his variation with the time are able to be obtained resolving this equation. However, it is necessary specify the temperature profile in the initial instant and the border conditions.

To optimise the design and construction of the mould, with attention on refining the tool design through application of finite element and thermal flow analyses, specific commercial software for injection moulding have been used. In the next section it will be made a brief description about the heat transfer process analysis using some commercial software.

The latest commercial software of CAE allows three dimensional simulation of the injection molding process. This software has modules for conception efficient cooling systems. The cooling analysis is based in the method of the border elements approach.

In the cooling module of the commercial CAE software, the transference of heat in the polymer is treated as one-dimensional conduction located in transient regime. The heat exchange between the surface of the cooling channels and the cooling fluid are considered in stationary regime, considering the correlation for the heat transference coefficient by convection. To solve simultaneously the prominent equations of transference of heat in this process, the program utilizes a hybrid scheme where the transference of heat is calculated by the approach modified analyzes of the element of three dimensional border for the region of the mould, and one-dimensional heat transference analysis, along the part thickness for the region of melted plastic. These two analyses are conjugated of form it equal the temperature and the heat flow in the interface polymer/mould.

Cooling system simulation

The equations for the flow of the fluid in a circuit of cooling are resolved through the iterative approach of Newton-Raphson, to obtain the torrent and the fall of pressure in each channel of the cooling system. Then, the heat transference coefficients between the surfaces of the channels and the cooling fluid are calculated.

The change of heat by natural convection between the environment and the walls of the mould are also calculated. For this calculation, commercial software considers the exterior surface of the mould as a sphere with an area equivalent to the surface of a box, in that the channels of cooling will be included, the feeding system and the molding zones.

The process simulation starts in the phase of the mould filling. When the cooling module of cooling is used, the polymer injection temperature is assumed as constant. This assumption has some associated errors; therefore the injection temperature can be a superior due to the heating by viscous dissipation of the material in the sprue. That temperature would be able to go up until 30°C depending on the speed of injection and of the material properties [21].

The thermal resistance in the interface polymer/mould defines the heat transmission coefficient (h_{int}) in the interface between the polymer and the molding surfaces. This coefficient is used for simulate the resistance to the existing heat in the contact between the two materials by the following equations:

$$h_{\text{int}}(T_{\text{int}} - T_M^-)_{x=-b} = -k \left(\frac{\partial T}{\partial n} \right)_{x=-b}$$

$$h_{\text{int}}(T_{\text{int}} - T_M^+)_{x=+b} = -k \left(\frac{\partial T}{\partial n} \right)_{x=+b}$$

where, T_{int} is the melt temperature in the interface of the two materials; T_M^- and T_M^+ are the molding zones temperatures, on the cavity side (negative side) and on the core side (positive side), respectively. The indices $-b$ and $+b$ – indicate the positive and negative side of the distance relatively to the center of the part (equivalent the half of its thickness).

If the thermal conductivity assumes the zero value, (thermal isolated border), the changes between the two materials do not exist. If it assumes an elevated value, exist a perfect thermal contact between the materials and the interface temperature is considered equivalent at the mould wall temperature. Many times, and by defect, this value is of 25000 w/m² °C, in commercial software.

The case study presented shows some important aspects when different cooling systems are considered.

Case Study

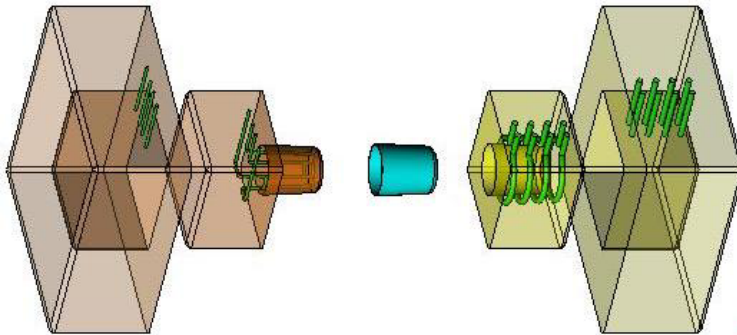


Figure 5 – Cooling system case study.

Cooling system in the cavity side

a) Conventional cooling system

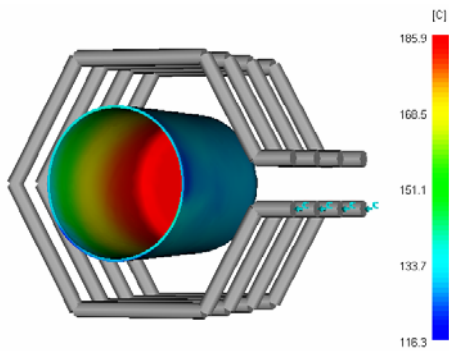


Figure 6 - Temperature distribution on the part's surfaces

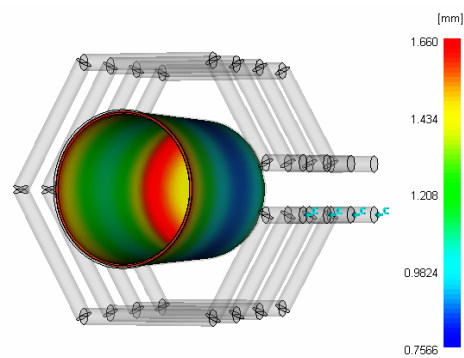


Figure 7 - Part's deflection

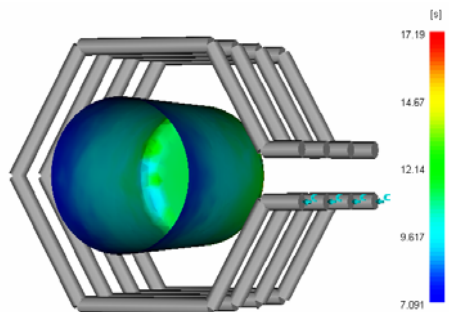


Figure 8 - Part's cooling time

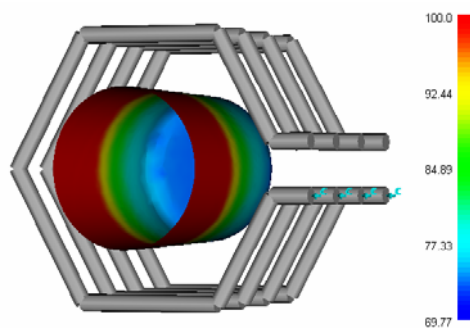


Figure 9 - Percentage frozen layer

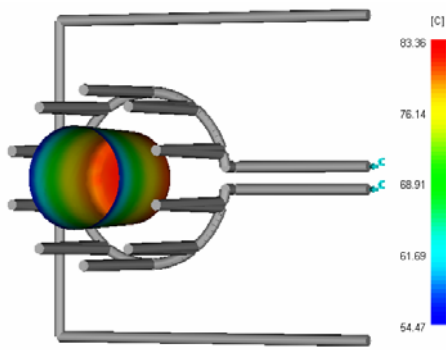
b) Baffle cooling system

Figure 10 - Temperature distribution on the part's surfaces

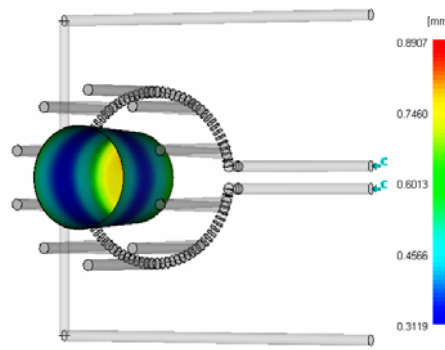


Figure 11 - Part's deflection

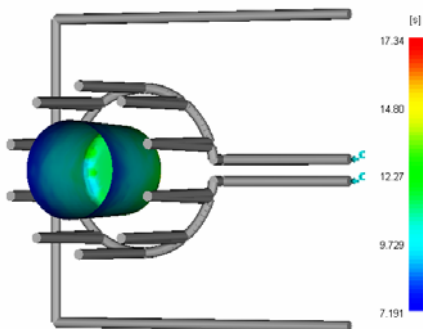


Figure 12 - Part's cooling time

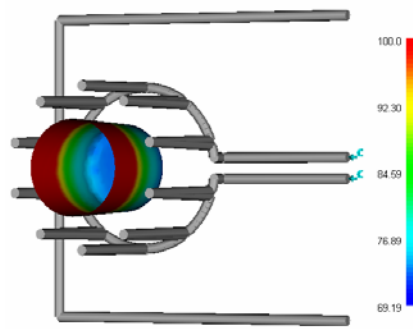


Figure 13 - Percentage frozen layer

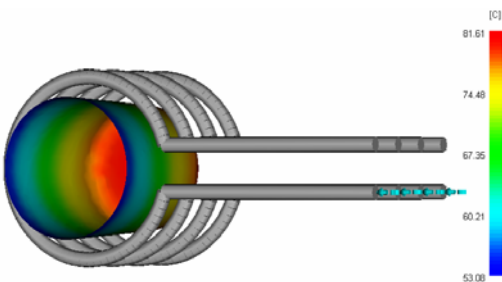
c) Conformal cooling system

Figure 14 - Temperature distribution on the part's surfaces

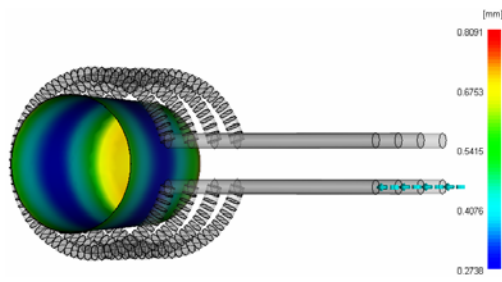


Figure 15 - Part's deflection

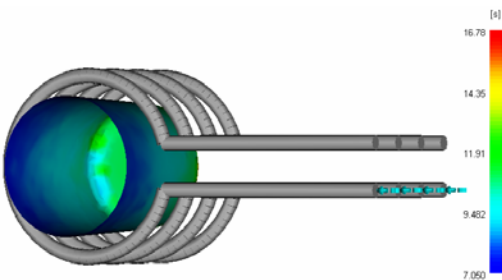


Figure 16 - Part's cooling time

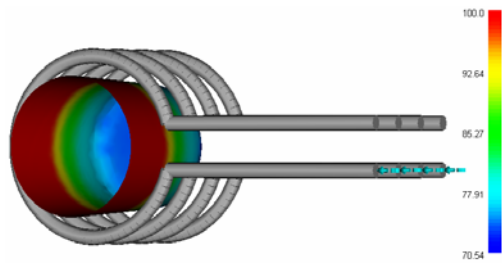


Figure 17 - Percentage frozen layer

Cooling system in the cavity and core sides

a) Conventional cooling systems in the cavity and core sides

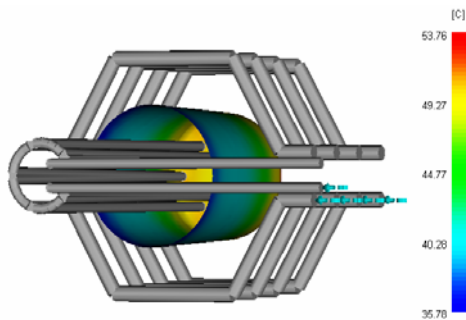


Figure 18 - Temperature distribution on the part's surfaces

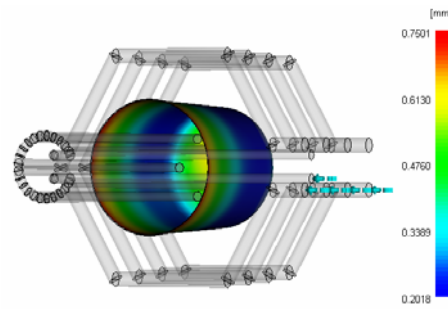


Figure 19 - Part's deflection

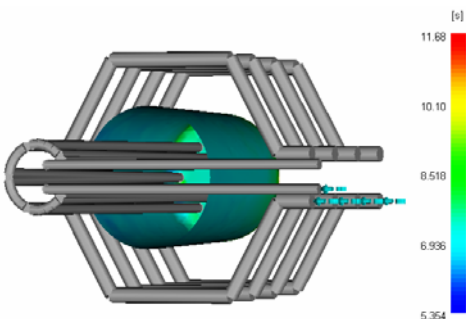


Figure 20 - Part's cooling time

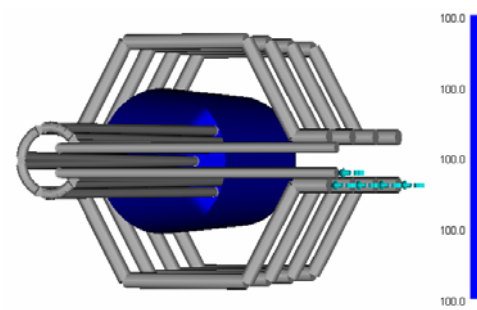


Figure 21 - Percentage frozen layer

b) Baffle cooling systems in the cavity and core sides

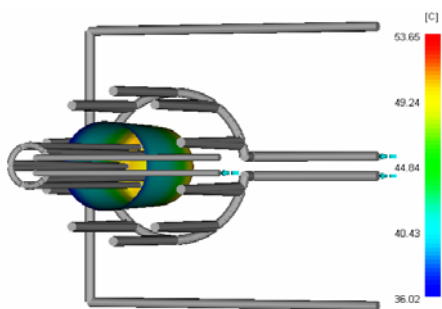


Figure 22 - Temperature distribution on the part's surfaces

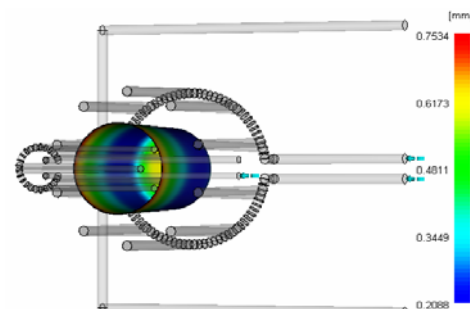


Figure 23 - Part's deflection

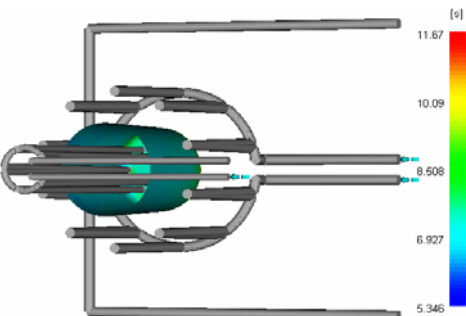


Figure 24 - Part's cooling time

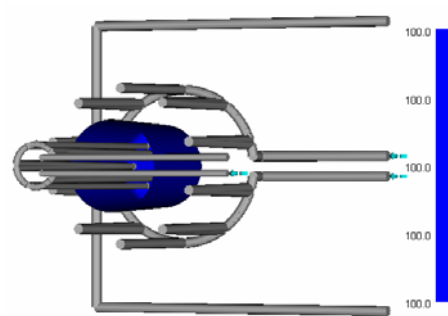


Figure 25 - Percentage frozen layer

c) Conformal and baffle cooling systems in the cavity and core sides, respectively

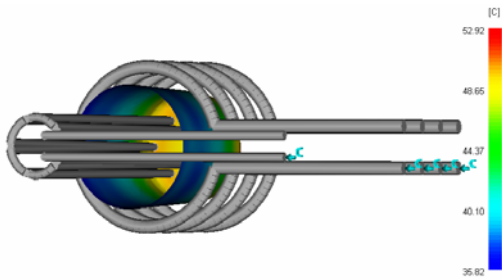


Figure 26 - Temperature distribution on the part's surfaces

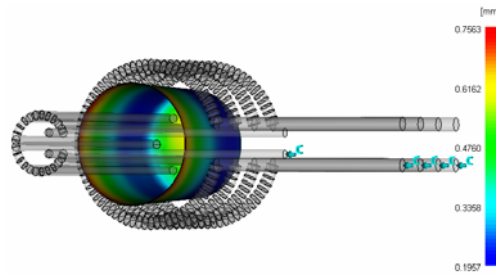


Figure 27 - Part's deflection

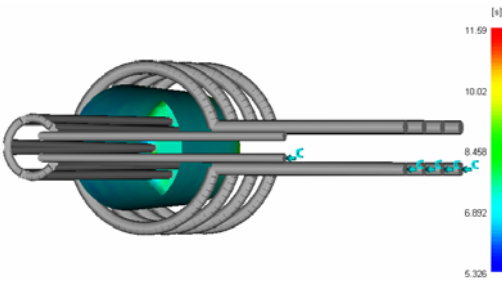


Figure 28 - Part's cooling time

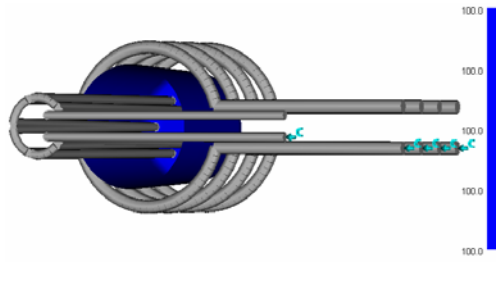


Figure 29 - Percentage frozen layer

d) Conformal cooling system in the cavity and core sides

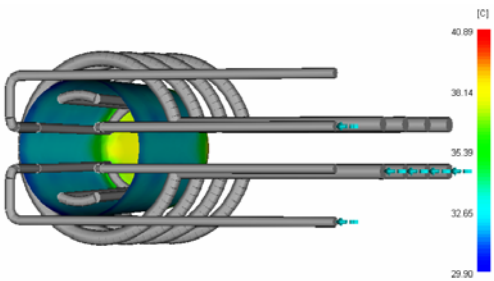


Figure 30 - Temperature distribution on the part's surfaces

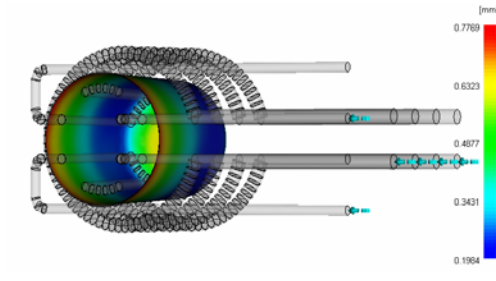


Figure 31 - Part's deflection

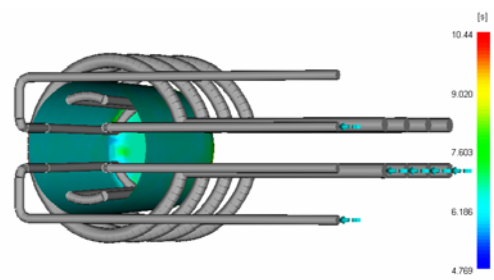


Figure 32 - Part's cooling time

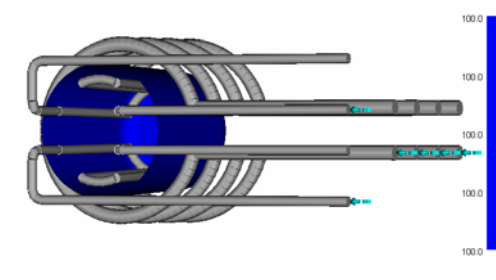


Figure 33 - Percentage frozen layer

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