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Analysis of multi-cavity molding of parts with different geometries

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ABSTRACT

In the industrial processes of injection molding, one of the basic requirements is a uniform temperature filed within workpiece and the mold cavities. In the case of simple geometry of workpiece and mold with single cavity achieving a uniform temperature field is not a critical issue. However, if one deals with parts of complex geometries, multi-cavity molds and asymmetric layout of different forms in the mold additional analyses of the runner and cooling system are necessary in order to obtain the required quality and accuracy of end the products. Disposition and dimensions of both runners and cooling channels are directly related to the geometry of finished parts and material properties. In that sense, virtual models and numerical simulations of injection molding processes based on the finite element method are very effective tool which enable accurate prediction of potential problems and significant reduction of trial and error procedure. In this paper, FEM software package Moldex3D was employed for simulation and analyses of injection molding process in which pipe fittings Ø75/45^o and Ø75/90^o are produced using a mold with two asymmetric cavities.

Key words *Injection molding, viscosity, cooling system, mold design*

1. INTRODUCTION

The main phases in the injection molding process include filling, cooling and ejection. The cooling phase is the most significant step among the three. It determines the rate at which the parts are produced. In the moment when the melted polymer (resin) is injected, the mold's temperature should ideally be similar to that of the melted polymer, while in the moment of the removal of parts, the mold has to be at the temperature of the environment. This way, the polymer would be injected with the minimum of pressure and the difference between the surface temperature and the core temperature of the injected parts would be minimal leading to slow cooling rate, minimizing the molding stresses and increasing the quality of finished parts [1]. One should notice that these technical advantages are not compatible with economic needs, and the generalized rule is to produce parts with the highest production efficiency. According to this rule, the most important factor is the capacity of the cooling system which removes heat from the cavities of the mold [2, 3]. Usually the time of cooling is above 50% of the total cycle. The injected resin loses temperature in the contact with the mold surfaces, transferring its heat through the mold. To accelerate the heat transfer process, the mold designer creates specific holes in the adjacent surfaces of the molded part in the mold. These holes, known by lines of water (since water is frequently used as cooling fluid), constitute the cooling system of an injection molding mold.
In this study, influence of mold design on both viscosity and temperature field in case of injection molding of the pipe fitting arches Ø75/45 and Ø75/90 was investigated using a commercial software package Moldex3D with goal to prevent mold injection defects. The second Cross mathematical model was used in Finite Element Method (FEM) analysis of material viscosity.

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2. MATHEMATICAL MODELS OF THE VISCOSITY OF THERMOPLASTICS

In the process of injection molding, a thermoplastic resin has an intensive flow and heat exchange with the mold wall. As the plastic flows through different sections of the machine and the mold, there is a loss of the applied pressure at the flow front of the thermoplastic due to drag and frictional effects. Additionally, as the plastic hits the walls of the mold, it begins to cool, increasing the viscosity of the resin and requiring additional pressure to ensure complete filling of mod cavity (Fig. 1). The plastic skin that is formed at the walls decreases the cross-sectional area of the plastic flow, which also results in the pressure drop. The molding machine has a limited maximum amount of pressure available to push the screw at the set injection speed. The pressure required to push the screw at the set injection speed should never be higher than the maximum available pressure. In this case the process becomes pressure limited [3, 4]. During the process development, knowing the pressure loss in every section helps in determining the overall pressure loss and the sections where the pressure drops are high. All of the mold or running system can then be modified to reduce this pressure drop and achieve a better consistent flow.

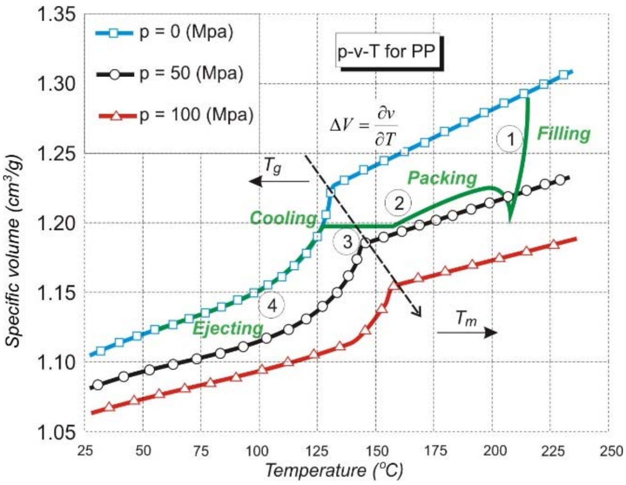

Fig. 1 *Pressure change during an injection molding cycle*

The viscosity of thermoplastics depends on its chemical composition and processing conditions, especially temperature. Various mathematical models are used to describe viscosity of thermoplastics and many of them are incorporated into software for numerical simulation of mold injection processes [5, 6, 7].
Newtonian fluid is assumed to be independent of temperature viscosity and shear rate. It has the simplest mathematical formulation and does not take into consideration the non-linear characteristics of thermoplastics. This model is not recommended to simulate the behavior of thermoplastics and is used mainly in order to check quickly the mesh generated and validity of the FE model (Fig.2). In this case, analysis and mathematical calculation are significantly simplified because of the constant viscosity:

$$\eta = \eta_0 \tag{1}$$

where η is the viscosity and η_0 is the Newtonian viscosity.

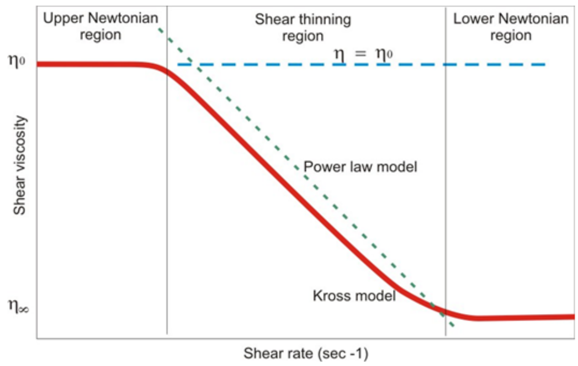

Fig. 2 *Viscosity models of thermoplastics*

The dependence of the viscosity on the shear rate can be expressed by the "power-law" equation [7]. The "power-law" model ignores the upper Newtonian regions. When this model is used to simulate thermoplastics, the results of the evaluation of viscosity can be in the region of lower rates of shear:

$$\eta = \eta_0 \left(\dot{\gamma}\right)^{n-1} \tag{2}$$

$$\eta_0 = B \exp\left(\frac{T_b}{T}\right) \tag{3}$$

where n is the "power-law" index with a value between 0 and 1; T_b shows the temperature sensitivity of the material; T is the melt temperature (K); η_0 is the viscosity at zero shear rate and, B is the material specific parameter.
A three-parameter model reflects the observation that the function of medium - high shear rate is almost a straight line in the log-log coordinate system. Many analytical equations for transformation of the polymer are derived from this model. The first Cross mathematical model describes the dependence of the shear rate in the "upper Newton regions" and "shear thinning region" [6, 7]:

$$\eta = \frac{\eta_0}{1 + C\left(\eta_0 \cdot \dot{\gamma}\right)^{1-n}} \tag{4}$$

$$\eta_0 = B \cdot \exp\left(\frac{T_b}{T} + DP\right) \tag{5}$$

where D is the parameter of the pressure corrected for the effect of pressure on viscosity and C is the shear rate parameter.
The second Cross mathematical model is similar to the first Cross model and it also shows the dependence of the shear rate in the "upper Newtonian region" and "shear thinning region". It is usually applied for thermoplastics with a wide distribution of molecular weight (BMWD). Products with the BMWD data are commonly available on the market, so that this model is widely present in the standard database of software for numerical simulation such as Moldex3D.

This model has an exponential temperature dependence and is also known as the "Cross-Exponential" model [6, 7]:

$$\eta = \frac{\eta_0}{1+\left(\frac{\eta_0 \cdot \dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{6}$$

where τ* is the shear stress relaxation. In the case of thermoplastics, the viscosity index shows a large temperature dependence. The most common viscosity rapidly decreases with increasing temperature. Most often, the manufacturer provides physical and chemical characteristics of the chosen material for the operating temperature range. For the material chosen in this paper, PP Moplen HP548R, the FEM analysis of the viscosity fields was performed by the "modified Cross model-2" in the Moldex3D program [8, 9].
The FEM analysis of the investigated injection molding process was performed using the Moldex3D Project module. Mathematical models and assumptions in the field of fluid mechanics, which are applied in the FEM analysis, depend on the type of finite element mesh. The Moldex3D Project module for the FEM analysis of the injection molding process use three models of finite element mesh for the plastic continuum: solid model, shell model and e-design model.

2.1. Runner system design

Taking into account the economic criteria for injection molding of pipe fittings (arcs) Ø75/45° and Ø75/90° the mold with two (different) cavities was designed. Due to asymmetric cavities, it was necessary to design different running system for cavities that distribute melted resin from the conical sprue to the gates. In addition, the flow within the both cavities divides into two substreams. Result of these are different thermodynamic conditions within the mold and cavities, which may lead to different part errors.
Moldex3D Designer module [8] was used for design of the runner and cooling systems in mold plates. The number and locations of the gates for both cavities are defined using the software adviser and the corresponding map (disposition of the best location), as the layout and dimensions of runners are created manually.
In the first iteration, the viscosity of the material at the end of the process of filling both mold cavities, the logarithmic division, ranges from 1.533 to a maximum of 8.064, with an average value of 4.237. Based on the graphic display, it can be observed that there is a quite uneven distribution of viscosity in both molding cavities (Fig.3a). Significantly higher values of viscosity at the end of filling stage are observed for smaller cavity (arc Ø75/45°). Due to the exponential dependence of viscosity on temperature and significant shear effect obtained values are high and cover the "upper Newtonian region" and "shear thinning region" for this polypropylene. Since viscosity is the resistance of a fluid to flow, it can be concluded from these results that melted resin has better progress throughout the cavity arch Ø75/90o (lower viscosity), as confirmed by the analysis of the pressure distribution in the mold cavity. Due to the unbalanced running system, the lower mold cavity was filled first followed by a rise in cavity pressure. Since the flow distance of thermoplastic resin is greater when filling the cavity for the Ø75/90°, the shear rate increases at its front, which is reflected in a rise in polypropylene temperature in that part of the mold, or a drop in viscosity at the end of filling. With a design change in the running system (change of gate locations) in the second iteration a slight decrease in the viscosities was obtained, ranging from the minimum value of 1.468 to the maximum of 8.005. It is observed that higher values of the resin viscosity appear in the cavity Ø75/45°, but with a much more even distribution in the both mold cavities (Fig.3b).

a)

b)

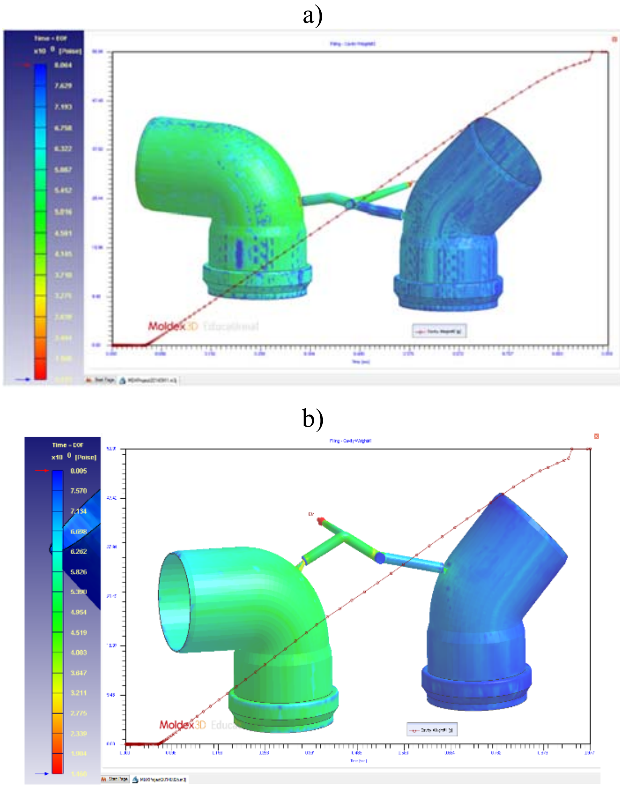

Fig. 3 *Viscosity field and the changes in part weight as a function of time during the first (a) and second (b) iteration*

3. HEAT TRANSFER IN INJECTION MOLDING

The design of cooling systems is highly related to the plastic melt solidification and product warpage/deformation. In addition, the cooling time occupies around 70-80% of a molding cycle, therefore, a well-designed cooling system will result in more efficient cooling and increased productivity. In addition, a uniform cooling rate and proper cooling temperature will result in uniform shrinkage, diminishing the problem of warpage, and ensuring that the plastic melt can flow into the extremities of mold cavities [3]. The overall heat conduction phenomenon is governed by the Fourier equation.

$$\rho_m c_m \frac{\partial \overline{T}}{\partial t} = k_m \left(\frac{\partial^2 \overline{T}}{\partial x^2} + \frac{\partial^2 \overline{T}}{\partial y^2} + \frac{\partial^2 \overline{T}}{\partial z^2} \right) \tag{7}$$

where ρ_m is the density of the mold, c_m is the heat capacity of the mold and k_m is the thermal conductivity of the mold. The cooling phase of the process is described by solving a steady-state Laplace equation for the cycle-averaged temperature distribution throughout the mold:

$$k_m \left(\frac{\partial^2 \overline{T}}{\partial x^2} + \frac{\partial^2 \overline{T}}{\partial y^2} + \frac{\partial^2 \overline{T}}{\partial z^2} \right) = 0 \tag{8}$$

where $\overline{T}$ is the temperature of the mold during each cycle. Equation (8) together with a simplified version of equation (7), where only the gap-wise coordinate is considered, are both used to predict the mold and part temperature during cooling.

The prediction of mold-wall temperatures on both the core and the cavity side during the process is based on the cycle-averaged principle where a steady state is assumed for the metal mold but a transient state for the polymer part. The simulations couple a three-dimensional boundary element method for the Laplace equation (8), used for obtaining the mold temperature, and a finite difference method for the Fourier equation (7), used for obtaining the polymer part. For equation (7), only the gap-wise coordinate is considered yielding:

$$\rho \cdot c \frac{\partial \overline{T}}{\partial t} = k_m \frac{\partial^2 \overline{T}}{\partial \overline{s}^2} \tag{9}$$

$$-k_m \frac{\partial \overline{T}}{\partial N} = h \cdot (\overline{T}^* - T_a) \tag{10}$$

where $\overline{T}*$ and T are the mold-wall temperature of the interface (involving mold surface, double side of cavity polymer, cooling channel surface) and the temperature of the polymer part, respectively, $\overline{s}$ is the gap-wise coordinate of the polymer part, and N is the outward normal direction of the interface. Equation (10) is a general form of boundary condition for the interface of metal/polymer, metal/cooling water and metal/air. h and Ta are the heat transfer coefficient of the interface and the ambient temperature of each interface (i.e. polymer melt, cooling water, or air temperature).

According to the cooling mechanism, the heat is transferred continuously until the temperature is lowered down to the ejection temperature and then the molded part is ejected. The ejected product is cooled constantly by dissipating its thermal energy into air until it reaches the room temperature.

At the beginning, the temperature variation is significant for the first few shots, before the molding process reaches the steady state, and then the mold temperature will not deviate from the average temperature too much; the deviation can be less than 5ºC or even less than that. Therefore, it is reasonable to use the cycle-average temperature as the mold temperature during the process. However, the cycle-average approach might not be appropriate if the conventional cooling system is not for the cooling function only, such as a mold system with a heating rod inside.

In special cases, such as a large temperature deviation, the temperature variation is still significant even in the steady state, since the cycle-average mold temperature approach cannot capture the mold behavior properly [10, 11].

The fundamental rules that should be taken into account in the cooling system design are:

- the water circuits should be symmetrical and relatively independent of the filling zones and impression(s) of the mold;
- thermal variations in the walls of the impressions should not be pronounced, so the lines of water should be designed in function of its distance to the walls of the impressions;
- the cooling fluid input and output should be placed in the back of the mold (the opposite side to the operator), or alternatively in the lower part of the mold;
- it is important to guarantee that the cooling flow in the channels be turbulent, the index of turbulence is given by the Reynolds number.

When the polymer is injected inside the cavityn of the mold, the removal energy of the polymer in the melted state is transmitted by conduction through the mold material up to the channels of the cooling system and to the mold external surface [12]. The heat exchange mechanisms (Fig.4) include the conduction for the structure of the injection molding machine, the forced convection for the fluid that circulates into the cooling channels, and the thermal radiation and natural convection for the air that surrounds the walls of the mold.

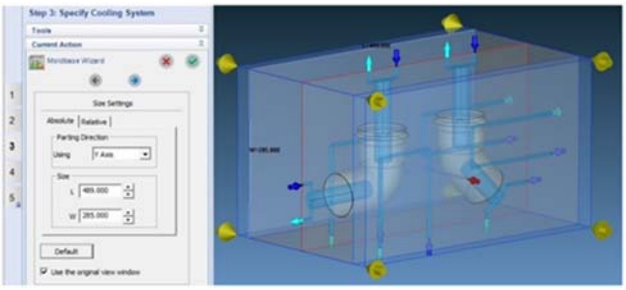

Fig. 4 *3D model of the cooling system*

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

$$\dot{Q}_{PL} + \dot{Q}_a + \dot{Q}_{TM} = \dot{Q}_{ACCUM} \tag{11}$$

where:
$\dot{Q}_{PL}$ - the heat flow supplied by the polymer, $\dot{Q}_a$ - the heat flow transferred to the environment, $\dot{Q}_{TM}$ - the heat flow transferred to the cooling fluid and $\dot{Q}_{ACCUM}$ - the accumulated energy in the mold material per time unit.
The simplified hypotheses [13, 14] put forward to obtain the results are:

– the quasi-static process,
– during the cycles the temperatures and thermal flow fluctuations are undesired,
– during the different periods medium values are considered,

$$\dot{Q}_{PL} + \dot{Q}_a + \dot{Q}_{TM} = 0 \tag{12}$$

where:

$$\dot{Q}_{PL} = \frac{\Delta h \times \rho_{PL} \times V}{t_{ref}} \tag{13}$$

$\Delta h = h_i - h_e$, h_i - the polymer enthalpy at the injection temperature, h_e - the polymer enthalpy at the ejection temperature, ρ_{PL} - the polymer medium density between the injection temperature and the ejection temperature, t_{ref} - the cooling time of the plastic part and V - the volume of the plastic part.

$$\dot{Q}_a = \dot{Q}_{CONV} + \dot{Q}_{COND} + \dot{Q}_{RAD} \tag{14}$$

$\dot{Q}_{CONV}$ - the heat flow by convection on the mold lateral walls,

$$\dot{Q}_{CONV} = A_L \cdot h \cdot (T_a - T_m) \tag{15}$$

A_L - the mold exposed area, h - the heat transfer coefficient, the natural convection, T_a , T_m - the environment and mold temperature, respectively, and $\dot{Q}_{COND}$ - the heat flow by conduction on the injection molding walls.

$$\dot{Q}_{COND} = A_{fix} \cdot \beta \cdot (T_a - T_m) \tag{16}$$

A_{fix} - the contact area mold and fixing system, β - the proportionality factor and $\dot{Q}_{RAD}$ - the heat flow by radiation on the mold lateral walls.

$$\dot{Q}_{RAD} = A_L \cdot \varepsilon \cdot \sigma \cdot \left(\left(\frac{T_a}{100} \right)^4 - \left(\frac{T_m}{100} \right)^4 \right) \tag{17}$$

σ - the Stefan Boltzmann constant and ε - the material emissivity.
When the material is inside, the mold cools supplying heat to it, and $\dot{Q}_{PL}$ is always positive. The heat exchanged with the environment can be positive or negative depending on the temperature of the mold [15, 16].

4. DESIGN SOLUTION FOR THE COOLING SYSTEM

An efficient system of cooling, with optimal cooling conditions, leads to the parts uniform distribution of temperatures, minimizing the undesired effects which appear during the 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 to the final intended results. Some of the factors that influence the cooling process are: the geometry of the part, the temperature of the mold, the shape of the cooling channels, the cooling fluid temperature and the speed of the flow [4, 6]. Two reference terms can be identified for an iterative process of characterization of the mold cooling system:

– the increase in the heat transfer rate,
– the uniform temperature distribution in the molding surface.

The design of the cooling channels is performed after defining the dimensions of the plate form of molds. There is a whole range of different forms of cooling channels offered by Moldex3D Designer [8, 9]. It can be applied to any of the offered solutions (Fig.5), but irregular solutions that follow the contour of the finished part can also be created.

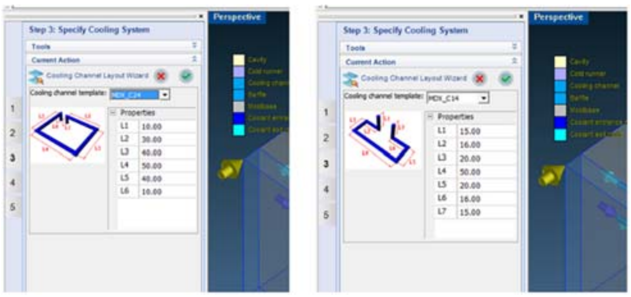

Fig.5 *Samples of the cooling channel with parametric design*

In the case of molds for pipe arcs Ø75/45° and Ø75/90°, the cooling system that was developed in the individual molds was designed in the first iteration. It consists of the cooling channels of 8 mm in diameter which are placed at a depth of 54 mm from the line of the opening of the mold, below the molding cavities in the form of both plates of the mold as well as the channel diameter of Ø 30 mm, through side pins.
The temperature of the mold during the injection molding

cycle is variable and depends on a number of influential parameters:

- temperature and types of molten thermoplastic in the mold cavity,
- dimension of the mold cavity (area, volume and thickness of the walls of the mold cavity)
- cooling time of the mold,
- temperature and flow of coolant in the mold,
- ambient temperature,
- contact surface of the mold with a working desk of machines,
- material and dimensions of the mold.

The result of the distribution of the melt temperature in the selected point shows the temperature field within the volume of the finished part in the mold cavity

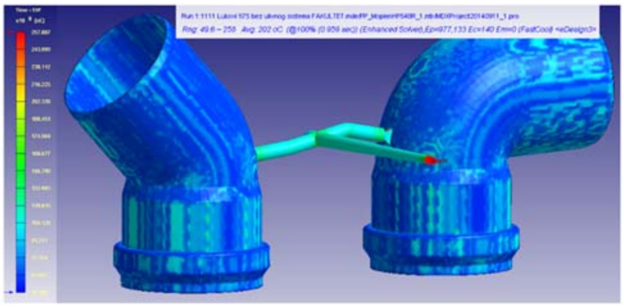

Fig. 6 *Temperature field in the first iteration*

The selected material PP Moplen HP548R has the following thermal characteristics:

- melting temperature range 190-270 ° C,
- mold temperature range 20 - 50 ° C,
- ejection temperature from the mold 148 ° C
- temperature solidification 168 ° C.

The results of the analysis of the first design solution (iteratin) show that at the end of filling the molding cavities in 0.959 seconds, the temperature of the molten plastic ranged in the interval from 49.6 to 257.887 °C. The upper value of the melt is below the maximum recommended value range of melting (270 °C), so that no material degradation can be expected in any area (Fig.6).

However, as seen from the FEM temperature field of the melt at the end of filling the mold cavities, surface layers which cool the fasters in contact with the wall of the mold, have a very uneven distribution of temperature. The fact that the finished elements have a uniform wall thickness negates the possibility that this is the cause of the uneven distribution of temperature. The cause of this can be uneven mold wall temperature, which depends directly on the design of the cooling system (arrangement of cooling channels).

Increasing the number of cooling channels in the second iteration a much more uniform temperature distribution of the surface layers at the end of the filling stage is obtained.

The temperature range at the end of filling stage in the second iteration is slightly higher and ranges from 63.1 to 287.698 °C (Fig.7). The upper value of this range exceeds the recommended value of the melting point of polypropylene by almost 18 °C. The table shows the percentage share in the overall temperature of the mold cavity, and it can be seen that about 6.50% of the volume of the mold cavity has a higher value (272.723 to 287. 698°C) than the upper recommended melting limit of this material (270 °C). This increase in the temperature of melt resin is a consequence of heating the material due to friction by reducing the cross-section of the gate on the smaller mold cavity (75/45°).

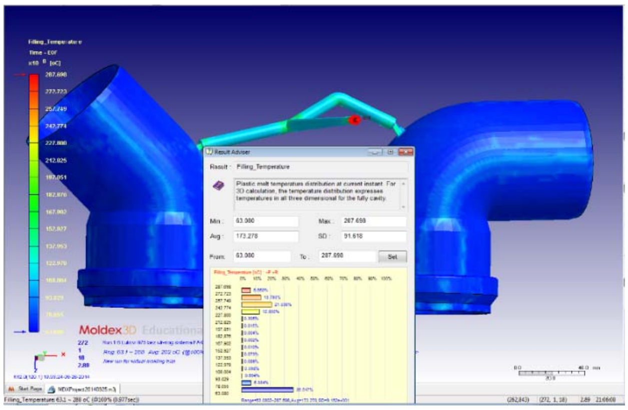

Fig. 7 *Temperature field in the second iteration*

Due to the relatively small share (6.50 %) of tzhe part volume with the temperature that (slightly) exceeds the recommended value and the fact that the average temperature is 173.278 °C, there is no risk of degradation of the material due to the increase in temperature. A possibley decrease in the temperature of the part can be achieved by reducing the speed of injection molding or in extreme cases, by a slight increase in the surface of the gate of this molding cavity. In any case, we should pay attention to the values of shear stress and shear rate of melted polymer in these areas.

In order to validate FEM results, the temperature of the mold and finished parts were measured using a thermal imaging camera “FLIR”. Measurements were made at the very end of the injection process (cycle), i.e., immediately after the mold opening and just before the ejection of the molded part. The results of the temperature measurements indicate that there is a strong interaction between the temperature of the mold and the parts (Fig.8).

The average temperature of the resin n case of main runner for the cavity Ø75/45° was around 88.4°C, with the warmest point having the temperature of 103°C. At the same time, the temperature of the molded part was 52.4°C. Therefore, the temperature of the mold plate close to the running system was higher than the temperature of the cavity surface. For comparison, Fig. 10 shows the propagation of the melt front just before the end of the injection molding process.

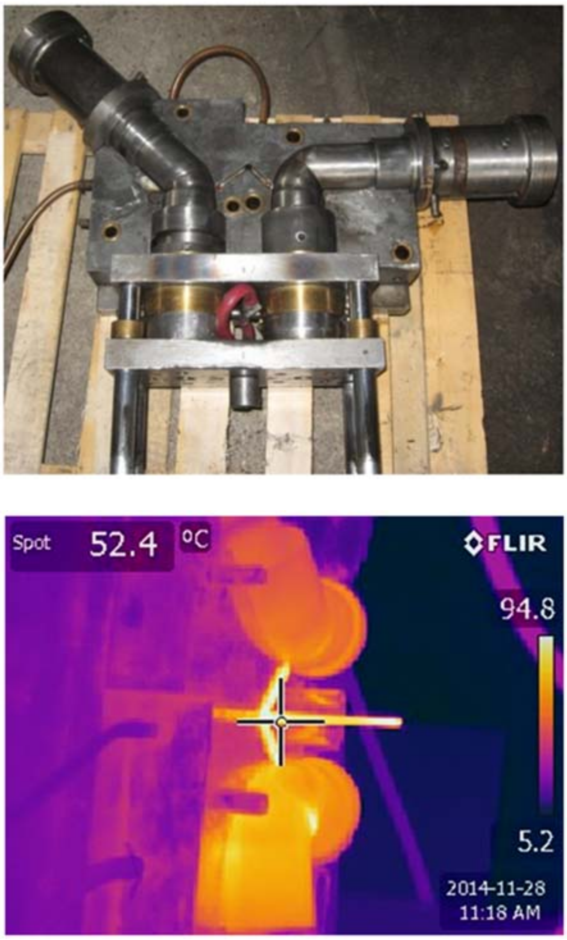

Fig. 8 *Injection molding mold for two parts and temperature measurement*

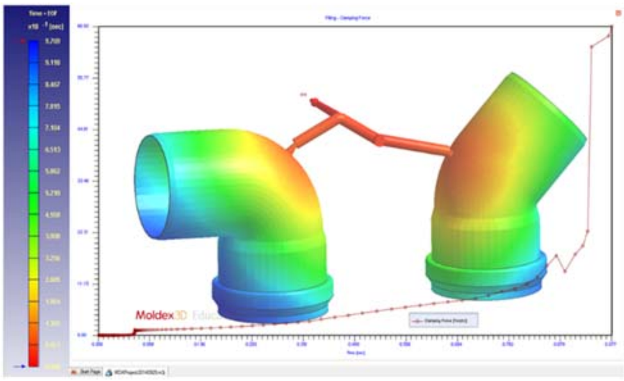

Fig.10. *Propagation of the melt front with a clamping force diagram*

4. CONCLUSIONS

The results of the FEM analysis (MOLDEX3D software) showed significant influence of the design of the running and cooling system on the viscosity distribution and temperature field for the analysed injection molding of fittings Ø75/90o and Ø75/45o. This finding indicates an increased risk of weld lines occurrence and local weakness of the strength of the part around the parting line. With a modification in the gate locations of both mold cavities,, more uniform distribution in the viscosity, cavity pressure and temperature were achieved reducing that way the risk of part error occurrence.

If the cooling channels are not properly designed, the core and cavity mold wall temperature can be different as it was observed in the first iteration. A strong gradient in the cavity between the two halves may results in the part warpage and high residual stresses. Thus, a proper cooling system has to ensure the uniformity of the wall temperature and a gradual reduction of the polymer temperature. (

NOMENCLATURE

A – surface area, [m^2]
B – index of the consistency, [–]
C – shear rate parameter, [–]
c_m – heat capacity, [J·K^{-1}]
D – parameter of the pressure corrected, [–]
h – heat transfer coefficient, [J·kg^{-1}K^{-1}]
h – enthalpy, [kg·m^{-1}s^{-2}]
k – thermal conductivity, [W·m^{-1}K^{-1}]
n – “power-law” index, [–]
N – normal direction, [–]
$\dot{Q}$ – heat flow, [W]
$\bar{s}$ – gap-wise coordinate, [–]
T – temperature, [K]
$\bar{T}$ – average temperature, [K]
t – time, [s]
V – volume, [m^3]

Greek symbols
β – proportionality factor, [–]
$\dot{\gamma}$ – share rate, [s^{-1}]
ρ – density, [kg·m^{-3}]
η – viscosity, [Pa·s]
η_0 – Newtonian viscosity, [Pa·s]
τ * – stress relaxation, [N·m^{-2}]
σ – Stefan Boltzmann constant, [kg·s^{-3}K^{-4}]
ε – material emissivity, [–]

Subscript
a – environment (ambient)
ACCUM – accumulate
b – sensitivity
COND – conduction
CONV – convection
m – mold
PL – polymer
RAD – radiation
ref – referent
TM – transferred
L – exposed
fix – fixing

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