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APPLICATION OF NUMERICAL SIMULATION IN THE ABS INJECTION MOLDING ANALYSIS PROCESS FOR IDENTIFICATION OF GAS OUTLETS

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Abstract: *The thermoplastic injection process, in the production of large-scale parts, requires that the molds used in the environment have high quality, in order to maximize their productivity, with the lowest scrap rate. In this context, numerical simulation, as a method for analyzing injection molding processes, can contribute, together with mold manufacturing companies, in solving failures, conventionally detected only in injection, providing their customers with the required quality. The study applies to a product injected in ABS material, through a mold containing four cavities, which showed injection flaws on the apparent surface - posteriorly to the feed channel. Through experimental analysis, an attempt was made to contemplate a technical solution, where, by reading the behavior of the molten material under virtualized processing, it was possible to understand the aspects that influence the malformation of the injected component, as it was already empirically suggested that they were linked, among other factors, to the trapping of gases in the cavities. The numerical diagnosis obtained through the CAE simulation allowed the designer to validate the process and verify the processing reactions, under different injection parameters, and to guide him to the improvement of the gas outlet system.*
Keywords: *Injection parameters, Gas outputs, Numerical simulation, Thermoplastics.*

1. INTRODUCTION

The ability to transform thermoplastic materials into final products quickly, in the widest range of shapes and applications, has required manufacturing industries to streamline their processes and reduce their costs in order to remain competitive. In order to offer products that meet the specifications, according to the customer's requirements, companies that manufacture injection molds must, judiciously, seek to evaluate all stages of project development (Harada, 2004).

The productive performance of the mold is influenced by several factors, such as: the feeding and distribution channels of the material; the number of cavities and their layout; variations in the entry of material into the cavities; the viscosity, mass and shrinkage of the raw material; the mold closing force; mold cooling; the extraction system; and the release of gases (Blass, 1988; Cruz, 2002; Glanvill and Denton, 1989; Harada, 2004 and Sors et al., 2002).

In order to provide the desired quality, CAE (Computer Aided Engineering) simulation technology has long become a common practice in the area of injection mold development, being applied to optimize the cavity filling process, providing a way to minimize errors already in the design of the project, allowing, in this way, to drastically reduce the possible costs of changing the mold to be produced, allowing companies to become more competitive (Carneiro, 2006).

In this context, the resulting project is applied to the study of a product injected in ABS polymeric material (Acrylonitrile Butadiene Styrene), which presents gaps in the apparent surface - in the direction posterior to the feeding channel, resulting from the injection process and its variables . The mold, in turn, has four cavities in its layout, which generates a high rate of rejected parts.

Through numerical analysis with the aid of the SolidWorks Plastics software, an attempt was made to contemplate a technical solution. The simulations used the generalized Hele-Shaw model, considering the polymer as an incompressible fluid and transient laminar flow. By reading the behavior of the molten material under virtualized processing, it was possible to understand the aspects that influenced the malformation of the injected component, which had already been empirically suggested to be linked to the trapping of gases in the cavities, however, under verification, also, of the specific conditions of the properties of the raw material used and the parameters assigned to the injection process.

2. METHODOLOGY

The adopted methodology consists, previously, in an analysis of the product - Capa Porca Belga 32 - and of the process in the initial processing conditions, in which the visual aspect of the product and the parameters used in the injection process, carried out in a machine, as well as as in the evaluation of the constructive aspects of the mold. Then, the methodology used will be demonstrated via computational numerical simulation of the injection process, until the actions projected for the validation of the project at the end of the analysis.

2.1. Injected Product Analysis

The product, called "Capa Porca Belga 32", injected in ABS, showed filling flaws on its surface, in the external region, which needs to have, as a visual aspect, a good appearance. The mold has four cavities and, visually, one can see the flaw present in all injected products, as shown in Figure 1.

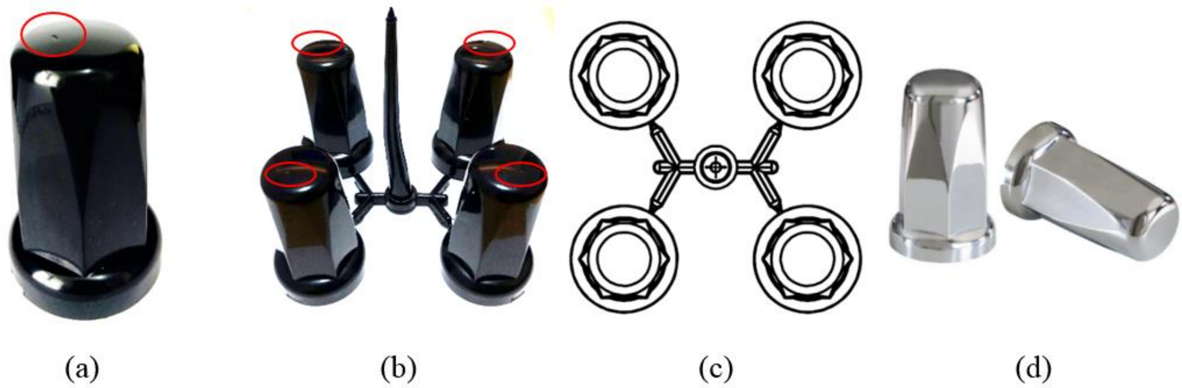


Figure 1. Capa Porca Belga 32: a) Individual failure presentation. b) Joint injection failure. c) Top view of the CAD drawing of the product. d) Final product marketed.

Checking Figure 1.a, one can see the flaw in the surface filling of the product. In Figure 1.b, it is possible to notice that the filling failure is common for the four items that contemplate the respective mold cavities, observing that the failures appear in the opposite direction to the respective material entrances, directing, therefore, to the "outputs" of the cavities, collinear to the entrances. The two pieces that are directed with the cavities above the injection center, have slightly more evident flaws, which may be linked to the gravitational nature. The layout of the cavities is distributed according to the top view, shown in Figure 1.c. In Figure 1.d it is possible to visualize the final, finished product, as it is supplied to the final customer.

Under preliminary investigation, guided by the study applied by Miranda and Nogueira (2017), it is observed that filling failures can be derived from the processing, that is, there is a condition resulting from the entrapment of gases in the cavities and a principle of soldering. cold, also impacting the performance of the process.

The evaluation criteria of the "Capa Porca Belga 32" are given through its physical characteristics and visual aspects that, as it is a finishing element, which, after going through the injection process - being subsequently subjected to a process of chromium plating surface treatment, it is apparent when mounted next to the truck wheel.

2.1.1 Application Material

The raw material used in the product is ABS thermoplastic - Starex SF-0505H. Its application characteristics in the injection process, as well as the physical properties according to the manufacturer, are observed in Table 1.

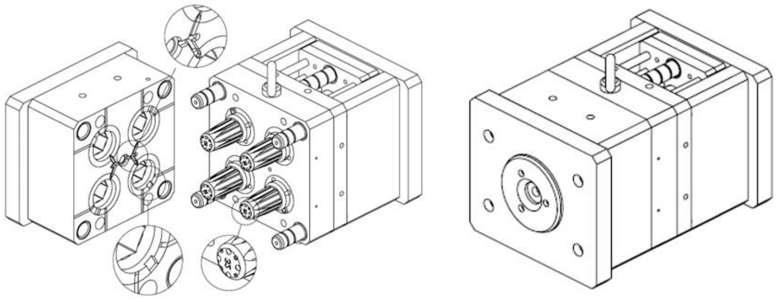
Table 1. Processing Parameters and Physical Properties of ABS.

Process Parameters	**Values**	**Units**
Injection Temperature	190 - 240	°C
Injection Pressure	5 - 60	MPa
Holding Pressure	40 - 80	%
Wall Temperature	40 - 80	°C
Physical properties	**Values**	**Units**
Specific Mass	1,110	$g.cm^{-3}$
Average Fluidity	16,5	$g.10^{-1min}$
Polymer Shrinkage	0,3 - 0,6	%

Density, average fluidity and polymer shrinkage properties are used as a reference for mold design definitions and, along with other characteristics, to specify process control information, such as in the injection equipment parameterization.

2.1.2 Injection Mold

The mold used in the polymer injection process has multiple cavities, which comprise a total of 4 cavities, uniformly distributed, according to the layout shown in Figure 2.



(a) (b)

Figure 2. Capa Porca Belga 32: a) open mold – details of the feed channels and gas outlets; b) closed mold.

The cavities feeding system is formed by channels composed by the injection bushing, by the feeding channels and by semi-circular inlet channels, which have a radius of 1.15 mm. The dimensioning of the feeding system was carried out according to the properties of the material used in the product and according to parameters necessary for the molding process. In order to define the other characteristics of the mold, general aspects were considered, both of the product and of the equipment adopted for the injection.

Due to the high demand for the product, the cavities, developed in the form of inserts to facilitate the manufacturing process and minimize the costs involved with raw materials, heat treatment and finishing, were made in SAE H-13 material and have a heat treatment of 48 -52 HRc, increasing its wear resistance.

The mold design was developed using SolidWorks® 3D CAD-3D (Computer Aided Design) software, which makes it possible to better visualize the context surrounding the product and the injection system, already during the development of the mold. same. In addition, 3D design makes it possible to generate files that go straight to manufacturing operations.

2.2 Injection Process

According to Pahl *et al*., (2016), regarding the state of technology, the information arising from the process forms an important basis for the designer, who, through the collection of data and parameters submitted to processing, stimulate the analysis in the search for results that meet the information initially established.

In monitoring the product injection process, together with the plastics processing company, the parameters assigned to the equipment during the injection process – Romi 200 Primax Injector (with retrofit) – were collected and treated according to Table 2.

Table 2. Parameters Used in the Injection Process.

Process Parameters	**Actual Values**	**Proposed Values**	**Units**
Injection Temperature	194	230	°C
Injection Pressure	30	111.5	MPa
Holding Pressure	40	65	%
Wall Temperature	20 - 50	50	°C
Cooling Time	13	14.2	s

The actual pressure values were collected in barometric units – bar, and were converted to the units shown, in order to comply with the units usually applicable to the methodology that follows. The proposed values were obtained through the spreadsheet "estima", by Anis (2019), which is focused on the thermoplastic injection process, containing in its database relevant technical information, referring to various thermoplastic materials, injection equipment and calculations structured by formulas consistent with those in the literature.

2.3 Simulation Process

In order to carry out the simulations of the injection process, the SolidWorks Plastics® software was used, which is a supplement that operates in the SolidWorks® interface itself. This resource allowed that, amid the simulation analyses, the project could be adjusted and, quickly, through easily customized parameters, allowing to carry out a new filling check, accelerating the ability to predict the results of injection molding (Gruber and Miranda , 2020).

2.3.1 Boundary Conditions

In the simulation process carried out, the values that contemplate the filling of the cavities and the repression of the cast material were parameterized, according to the parameters proposed in Table 2, associated with the "generic material of ABS", from the software database. The calculations that the software used, in the processing of these data, are explicitly presented in the filling and repression sections, respectively.

2.3.2 Filling

The calculation structure that composes part of the architecture for the processing of material flow information, for filling the mold cavities, was based on the Generalized Hele-Shaw model. According to Fernandes *et al*. (2016), this model considers, in the filling phase, the flow of incompressible non-Newtonian fluids under non-isothermal conditions, through shear flow, under geometry with relatively very thin thickness compared to the transient flow area.

The Hele-Shaw equations, therefore, are described by Equations 1 (mass conservation), 2 and 3 (quantity of motion) and 4 (energy conservation), where, x and y form the plane coordinates and z expresses the thickness coordinate.

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x}(\rho u) + \frac{\partial}{\partial y}(\rho v) + \frac{\partial}{\partial z}(\rho w) = 0 \tag{1}$$

$$\frac{\partial p}{\partial x} = \frac{\partial}{\partial z}\left(\eta \frac{\partial u}{\partial z}\right) \tag{2}$$

$$\frac{\partial p}{\partial y} = \frac{\partial}{\partial z}\left(\eta \frac{\partial v}{\partial z}\right) \tag{3}$$

$$\rho C_p = \left(\frac{\partial T}{\partial t} + u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y}\right) = k\frac{\partial^2 T}{\partial z^2} + \eta(\dot{\gamma}, T, p)\dot{\gamma}^2 \tag{4}$$

$$\dot{\gamma} = \sqrt{\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2} \tag{5}$$

$$u = v = 0,\ T = T_w = 0 \text{ em } z = h \tag{6}$$

$$\frac{\partial u}{\partial z} = \frac{\partial v}{\partial z} = \frac{\partial T}{\partial z} = 0 \text{ em } z = 0 \tag{7}$$

$$p = 0 \text{ along the flow front} \tag{8}$$

$$\eta(\dot{\gamma}, T, p) = \frac{\eta_0}{1+\left(\frac{\eta_0 \dot{\gamma}}{\tau^*}\right)^{1-n}} \tag{9}$$

$$\eta_0 = D_1 e^{\left(-\frac{A_1(T-T^*)}{A_2+(T-T^*)}\right)} \tag{10}$$

$$A_2 = A_3 + D_3 p \tag{11}$$

$$T^* = D_2 + D_3 p \tag{12}$$

$$v(p,T) = v(0,T)\left[1 - Cln\left(1 + \frac{p}{B(T)}\right)\right] + v_t(p,T) \tag{13}$$

The components *u*, *v* and *w* represent the velocities in the respective directions ($x, y\ e\ z$) for time *t* and under pressure *p*. The acronym ρ is the density of the polymer, $\eta(\dot{\gamma}, T, p)$ is the rheological model of Cross-WLF viscosity, where $\dot{\gamma}$ is the shear rate, *T* is the temperature, *Cp* is the specific heat and *k* is the thermal conductivity. In the *z* coordinate, which represents the thickness direction, the flow will only occur perpendicular to this direction.

The limit and initial conditions for the Hele-Shaw model are given by equations 6, 7 and 8, where T_w is a constant temperature of the mold wall and *h* is the thickness at which the material travels inside the cavity. Thus, the rates of change of fluid particle energy and convection energy equal the rates of increase in heat of the fluid particle, plus the increase in heat due to dissipation of energy resulting from the viscous stress of the material.

According to Kim and Park (2018), the non-linear behavior of the viscosity of the molten polymer is linked to the temperature variation and the shear rates that occur during the process. According to Kim and Park (2018), there are basically seven coefficients that describe the Cross-WLF viscosity model. Together with Plastics®, therefore, the values of the constants identified for the material adopted in the simulation process are presented in Table 3.

Table 3. Visibility Parameters of Starex SF-0505H ABS Polymeric Material.

D_1	D_2	D_3	A_1	A_2	τ^*	n
Pa.s	K	K/Pa	-	K	Pa	-
2.2149×10^{12}	378.15	0	28.8	51.6	72,350	0.2353

Being defined as particular constants, of each specific material, these parameters must be clearly identified, to improve the accuracy of the simulation.

2.3.3 Holding Pressure

In the repression phase, the mold cavity, already filled by the melting of the polymer, receives an increase in pressure on the injected material, to compact the material and reduce the product's contraction rate, stabilizing its physical and dimensional characteristics. At this stage of the process, according to Fernandes *et al.* (2016) and Marin *et al.* (2019), through a pressure and temperature correction term to the specific volume, the equation derived from the ideal gases is thoroughly applied to the simulation process, being described by the Modified Tait Equation - Equation 13. In Equation 13, $v(p, T)$ is the specific volume given at temperature and pressure, and $v(0, T)$ is the specific volume at zero gauge pressure, C = 0.0894 is a universal constant, and B defines the pressure sensitivity of the material (Fernandes et al., 2016).

The values of the constants presented in Equation 13, according to the material adopted in the simulation process (Plastics®). According to Staudt (2010), despite being totally empirical, Tait's equation is one of the most used to represent the *PVT* state (pressure - volume - temperature) of liquid polymers - when subjected to melting temperature. The presented constants and parameters are specific to each specific material, and complement the necessary parameters to obtain the simulation results.

2.3.4 Mesh

Due to the viscosity index of the polymeric material, which varies according to the melting temperature, the refinement of the mesh, in the generation of the solid to proceed with the numerical simulation, has an influence on the reliability of the results. To improve the results of numerical analysis, the greater the quantity and smaller the dimensions of the elements that make up a mesh, the greater the precision (Mirilissena, 2016).

As evidenced by Miranda (2018), in a study carried out by alternating between melting temperatures (120 °C to 300 °C) of the polymeric material used in that experiment, the method that was stable, without any influence on the simulation results, is the mesh composed of triangular elements, with size defined in 2.0 mm.

2.4 Filling Efficiency Analysis

The study that made it possible to verify the processing conditions of the injection system required a mathematical model (3D) that was adequate to the geometry and dimensions of the physical model to be produced in the machine. Therefore, using SolidWorks®, the product and its branches were designed, according to the layout of the cavities arranged in the mold - shown in Figure 2, as well as the feed channel and the respective material inputs, defining the model to promote computational simulation, according to the injected product.

2.4.1 Verification

In order to carry out the analysis of the filling of the cavities, it was necessary to proceed with the verification of the filling of the molding in the ideal conditions of application, being the data proposed in Table 2 attributed to the parameters of the software, carrying out the simulation of the process.

2.4.2 Analysis of Processing Parameters

With the initial definition of the simulation process, although the mold already has a gas outlet system, the analysis consists of verifying the behavior of the accumulation of ventilation pressure as a function of pressure and temperature variables, according to pre-established values, arranged in Table 4, to make it possible to provide an improvement in the injection process.

Table 4. Parameters used in the injection process.

Variable Parameters		**Fixed Parameters**	
P_i (MPa)	T_i (°C)	$P_{holding}$ (%)	T_{wall} (°C)
60, 80, 100, 120, 140	200, 210, 220, 230, 240, 250, 260	65	50

In Table 4, the variable parameters are equivalent to the injection pressure P_i, which were attributed to the process as a function of the injection temperatures T_i, which correspond to the polymer injection temperatures. The parameters that remained fixed were the holding pressure $P_{Holding}$, and the mold wall temperature T_{wall}. According to Meister and Drummer (2013) and Sacchelli *et al*. (2017), the increase in mold temperature has little influence on the length of flow achievable by the molten material, when pressure and injection temperature are increased.
From the parameters indicated in Table 4, it became possible to carry out a series of interactions, obtaining values for the filling time (t) of the injected component, and for the ventilation pressure (P_g), or gases in the cavity, according to the process conditions, in terms of pressure and temperature.

3 RESULTS AND DISCUSSIONS

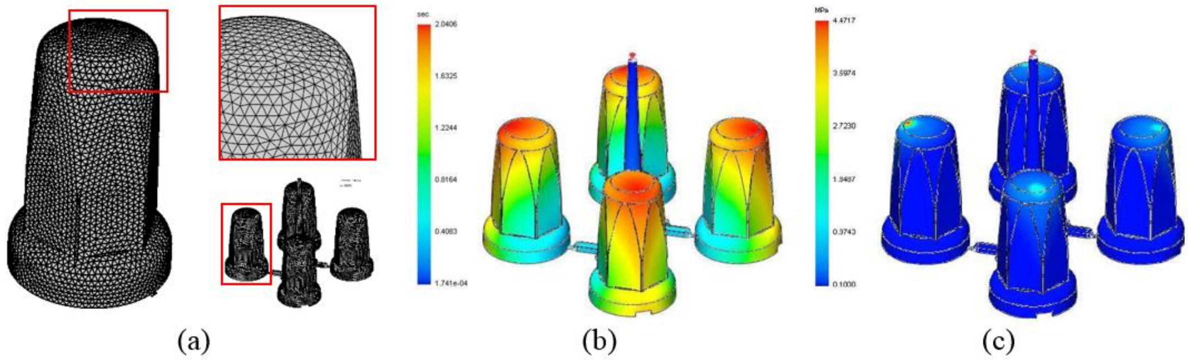
Starting from the estimated values, proposed in Table 2, the results that are presented here were obtained through the process carried out by numerical simulation of injection of the ABS polymer. Analytically, the results obtained in the projection of injection parameters that favor the molding process were conducted, seeking to minimize the existing failures, arising from the processing factors of the molten material.

3.1 Simulation Results

In the optimization of the injection molding process, the combination of mathematical models, numerical methods and user interface programming form the basis of the model - numerical simulation, typical. Through the management of injection settings, characterized by finite element refinement, material classification – available in the SolidWorksPlastics® database, associated with process parameters and boundary conditions, various process parameters for molding can be obtained (MIRANDA and NOGUEIRA, 2019).

With the development of the numerical model, through the Plastics® parameterization according to the values proposed in Table 2, the full filling of the cavities was obtained, making possible the initial validation of the simulation process, illustrated by Figure 3.

Figure 3. Validation of the injection in the initial conditions of the process: (a) 2.0 mm mesh; (b) completion time; (c) ventilation pressure.



In Figure 3.a, it is possible to see the mesh generated in the software parameterization, which consists of 55,768 triangles – with dimensions of 2.0 mm – and 108372 tetrahedrons, comprising the 204,364 elements and the 86,593 nodes of the solid 3D component. For this type of simulation analysis, the domain generated by solid meshes produces results closer to reality (Miranda, 2018).

Figure 3.b shows the filling result being completed in 2.0406 seconds in the most distant regions of the respective cavities - evidenced by the red color, while in the region where the injection point is located (dark blue color) the associated time filling the impression is equivalent to $1.471x10^{-4}$ seconds.

In Figure 3.c it is possible to see the ventilation pressure, standing out next to the lighter regions (light blue) of the injected component, corresponding to the trapping of gases in the cavities, presenting a pressure of 4.4717 MPa. Observing Figure 3, it can be seen that failure will occur exactly in the regions indicated in Figure 1. Figure 3.b demonstrates that it takes longer to fill the cavities precisely at the points where failures occur. Figure 3.c shows that greater pressure is required exactly at the points where failure is evident. Therefore, this becomes a qualitative validation of the simulation process.

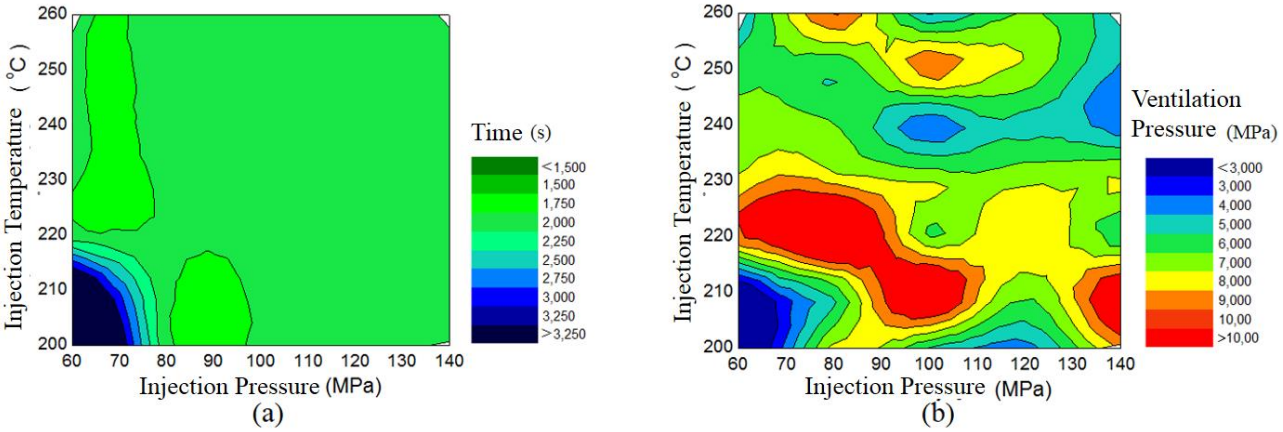
3.2 Filling Analysis

After completing the validation of the simulation of the injection process, in order to make it possible to analyze the filling of the cavities, the simulation was carried out using the parameters shown in Table 4. Among parameters that remained fixed, the Prec corresponds to 65% of the Pi assigned to each process interaction. The Tpar was maintained at

50 °C because, when the injection pressure and temperature are raised, their elevation has little influence on the length of the flow achievable by the molten material (Meister and Drummer, 2013).

Thus, alternating injection pressure and temperature parameters, a total of 35 interactions were obtained, of which the results related to injection times and ventilation pressures are summarized in Figure 4.

Figure 4. Injection results: a) filling time; b) ventilation pressure.



Under alternating injection pressure - between 60 and 70 Mpa, and injection temperature - between 200 and 210 °C, the area highlighted by the dark blue color, represented in Figure 4.a, corresponds to the filling time of the cavities, the which exceeds 5 seconds. Under the same injection conditions, Figure 6.b shows that the resulting ventilation pressure is less than 3.0 Mpa, lying between 0.641 and 0.983 Mpa.

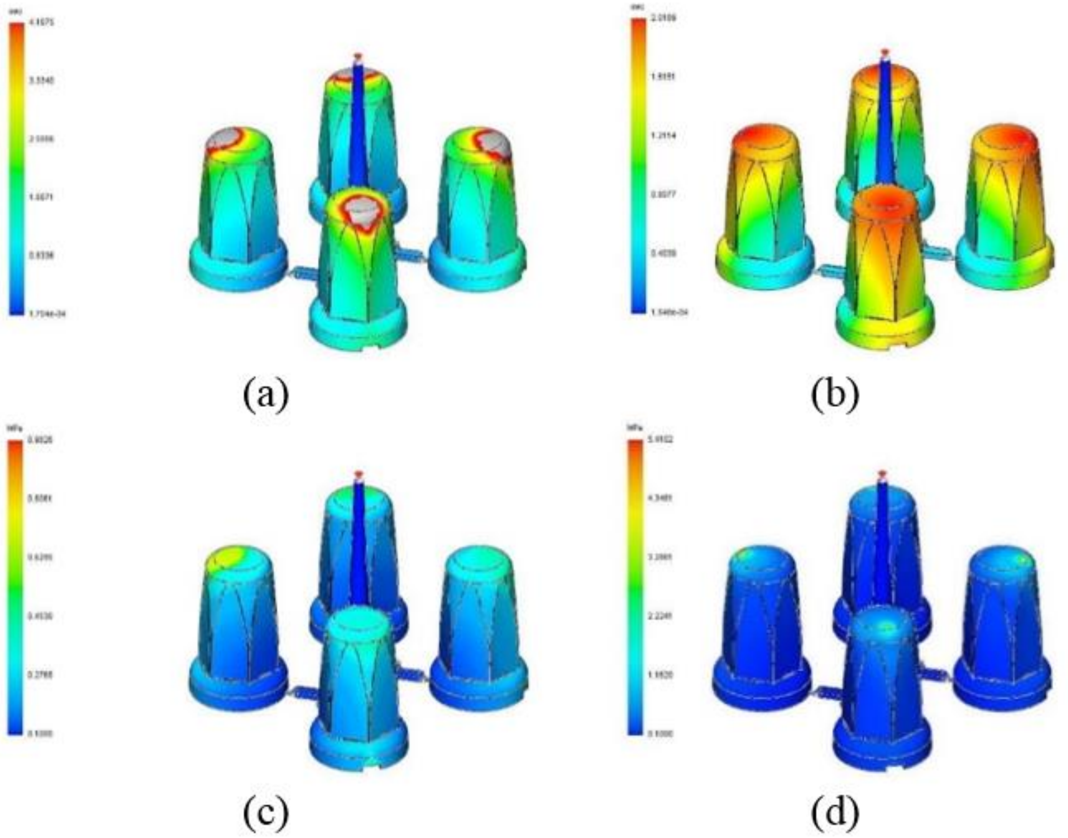
The area that covers most of the graph (Figure 4.a), represented by the medium-intensity green color, is equivalent to a filling time of 2.03 seconds, on average, regardless of the variation in pressure and temperature of polymer injection. The graph shown in Figure 4.b shows that the volatility of the air trapped in the cavities reaches its lowest level (~3.65 Mpa) under conditions of 100 MPa of pressure and 240 °C of injection temperature, remaining relatively low. in equilibrium also in the pressure range of 140 MPa at a temperature between 240 and 250 °C.

At the same time, it is seen that for the temperature range between 205 and 230 °C, with the injection pressure being alternated between 60 and 110 MPa, the ventilation pressure rises considerably. For these pressure and temperature ranges, as the holes in the ventilation system are made up of brass elements - consisting of the double granulation shown in Figure 5, the pressure exerted, associated with the density of the gases inside the cavities, may be insufficient to overcome this porosity.

Figure 5. Capa Porca Belga 32.

It is observed, therefore, that, by alternating the values of temperature and injection pressure, there is a large variation in the ventilation pressure gradient under different combinations of the parameters used. The combination of pressure limits and injection temperature at lower indices can decrease the rates and shear stresses of the molten material, however, it can result in the cooling of the flow front of the molten material and, associated with the back pressure exerted by the gases inside the cavities, lead to non-integral filling of the mold. Although the higher temperature contributes to the decrease in the viscosity of the molten material, the combinations of higher injection pressures and temperatures increase the rates and shear stresses of the material. Both factors tend to cause residual stresses, resulting from the inappropriate accommodation of macromolecules, influencing the flow of the polymer (Miranda, 2017). These behaviors can be seen in Figure 6.

Figure 6. Simulation results: a-1) filling time (60_210); b-1) ventilation pressure (60_210); a-2) fill time (140_260); b-2) ventilation pressure (140_260).



Figures 6.a-1 and 6.b-1 show, respectively, the filling time and ventilation pressure results with the injection pressure parameters at 60 MPa and injection temperature at 210 °C. According to the color bars on the left of each image, the color gradient indicates the injection time interval between the entrance of the material flow front into the mold (blue) and the ends of the filling (red), meeting if above 4.2 seconds, still showing that filling was interrupted. Under the same conditions, it is noted that the ventilation is quite dissipated in the cavity, with its final pressure slightly below 1.0 MPa, that is, as the filling of the cavities was not effective, the gases did not undergo high compression.

In Figures 6.a-2 and 6.b-2, the results were obtained with the parameters of injection pressure at 140 MPa and injection temperature at 260 °C. Graphically, it is seen that the colors related to the filling time are less concentrated, meaning that the plastic casting profile, as it fills the cavity, is more homogeneous, and the filling time of the cavities is ~ 2 .02 seconds. Thus, ventilation is also more concentrated inside the cavity, precisely at the end of the flow front, under a final pressure of ~ 5.41 MPa.

According to Miranda and Nogueira (2018), the mathematical model of finite elements, when subjected to extreme processing conditions, such as low injection pressures and temperatures and very high values for pressure and temperature parameters of the molten material, can be a consequence of the limitations of the model itself, which behaves that way to adequately represent the viscoelastic behavior of the molten polymer, mainly regarding the low values of such process parameters.

4 CONCLUSION

With the identification of causes that potentiated the failures in the process, in view of the analysis of the data collected, obtained from the injection process, now exercised, a numerical simulation of the injection process was carried out, which guided the designer to apply corrections to the cavities of the mold, when, under a new simulation process, the mathematical model was obtained, duly validated.

Making a brief analysis of the results of the simulations, it is possible to perceive that, or even propose, a periodic maintenance of the existing ventilation system comes in handy for the mold - the center of this study. Even some small modification, such as, for example, a mass relief hole, at the center of the insert - in the opposite direction to the face of the cavity, thus reducing the cross section that the air needs to travel through.

Defining the parameters of the injection molding process requires technical qualification, which is often based on the knowledge of the operator, acquired through experience over the years, who applies this knowledge, sometimes combined with information from specific property tables, made available by the suppliers of the raw material used.

The injection parameters that were designed through calculations - Table 2, show that a theoretical approach can be the starting point to obtain approximate parameters, consistent with the values obtained from the numerical simulation results.

Through the wide range of information contained in the software database, the numerical simulation allows computationally to perform the parameterization of the injection process, which can be adjusted to the real application conditions, virtualizing the obtaining of results, making it possible to analyze its efficiency, and make the necessary adjustments to these parameters.

With the boundary conditions initially defined, performing different combinations between pressures and injection temperatures, the simulations show that the formation of faults is a result of the entrapment of gases inside the cavities, however, adjusting the parameters of processing of the molten material, it is possible to favor the injection conditions so that failures are minimized.

It is important to point out that, through an oriented study, the use of technology becomes fundamental for predicting results and boosting a holistic view focused on engineering and its phenomena, making it possible to accelerate responses and justify means that make it possible to optimize processes, as in the case the thermoplastic injection process simulation software, which allows these assessments already during product design.

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