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Influence of Mesh Geometry and Mesh Refinement on Mathematical Models of Thermoplastic Injection Simulation Tools

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Abstract: *The use of polymer materials by different segments of the industry has grown every year due to numerous advantages, being the injection of thermoplastics one of the processes most used to make this application viable. In order for these processes to be efficient and generate quality products, it is necessary that the polymer material be processed correctly. The simulation of thermoplastic injection is an important step in the manufacturing process of polymer products, where errors in the design and manufacture of the mold or product should be avoided even in the initial phase, as they directly affect the quality and cost of the product injected. This paper aims to perform a mesh refinement study between different mathematical models used in two thermoplastic injection systems (SolidWorks Plastics 2016 and Moldflow Synergy 2016), correlating the simulated results with the experimental results obtained in the process of transformation of a product injected. The results showed that both software were able to simulate with certain precision the injection process studied, despite the small differences in injected masses predicted by the software.*

Keywords – *Numerical Simulation, CAE Tools, Mesh Refining.*

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I. INTRODUCTION

In the last decades, the consumption of thermoplastics has increased according to the demands of innovative products and with the increase of the development of parts and components in sectors such as appliances, furniture and automobiles [1]. The thermoplastic injection simulation tools have great precision in their manufacture, since these computational tools are able to simulate different stages of the thermoplastic injection process, generating significant results to aid the execution of molds [2]. These tools are increasingly accepted by the plastics processing industries, especially in the optimization of injection mold design, as well as the parameters used in the resin injection process, allowing designers to develop new forms of mold manufacturing with extreme precision [3]. Each simulation tool uses differentiated mathematical models that have the same objective of calculating the heat and mass transfer phenomena aided by mathematical methods [1,4]. To aid in these calculations of differential equations, thermoplastic products are used as control volume and are discretized in subdomains to facilitate calculations of the resulting phenomena [2,5]. These subdomains, known as meshes, have different geometric aspects, and can also display different sizes [5,6]. These geometries combined with the different mesh sizes may aggregate into different simulation results until a convergence analysis proves that new mesh changes do not influence the expected results [5,7].

In many cases where manufacturers of thermoplastic injection molds do not use simulation engineering as a design tool, the plastics processing industries detect failures in the injected product only after testing the manufactured mold [8]. These failures may be due to incomplete filling of wells, poorly positioned feed points or injection channels, air bubbles, defects caused by inadequate cooling of the wells or degradation of the injected material [9]. This implies that the mold must be rethought and reworked repeatedly until it can inject parts without failures [1,6,9]. The design of the thermoplastic injection molds may still be unsuitable for the injection machine, or even the injected material. These specific cases usually occur due to communication failures and the lack of adequate evaluation prior to the manufacturing process [10].

In this context, we implemented two different mathematical models that are used in the software SolidWorks Plastics 2016 and Moldflow Synergy 2016, to study the influence of mesh refinement, also alternating different mesh types. These tools are specific for thermoplastic injection simulation. In order to compare the simulations with the actual process, injection tests with an injection mold for the production of GPPS (General Purpouse Polystyrene) cups were used to validate The mathematical models of both software's.

II. MATERIALS AND METHODS

The methodology of this work is subdivided in four main stages, being the product analysis, the mathematical model used by the software and the methodology of application of the simulations is identified.

II.I PRODUCT ANALYSIS

In this study, an injection mold a glass of twisted geometry. This product belongs to a beverage company from the region of Joinville - SC, Brazil. Figure 1 is presented as a product model with CAD design and the actual product injected.

(a) (b)

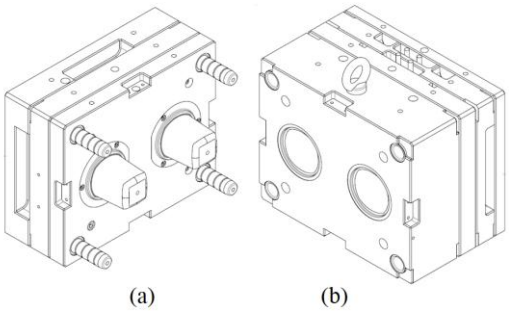
Figure. 1. Product design details: a) product model developed in SolidWorks CAD; b) injected product.

According to CAD SolidWorks, this model has the volume of 45,50 cm^3 is injected into GPPS. Table 1 presents some physical and processing parameters of GPPS according to the material manufacturer [11].

Processing Parameter	Values	Unit
Injection Temperature	190 - 240	°C
Injection Pressure	5 - 60	MPa
Holding Pressure	30 - 60	MPa
Mold Wall Temperature	20 - 50	°C
Polymer Contraction	0.3 – 0.6	%
Physical Property	**Values**	**Unit**
Density	1.078	$g.cm^{-3}$

Table 1. GPPS Processing Parameters.

This information is fundamental to the beginning of the design of the mold and, consequently, to be inserted in the simulations. The injection mold used in this work is the model HAITIAN - PL 860/270 C. Considering the mass of the injected piece of 45,50 cm^3, since the mold has two cavities (Fig. 2), the injection volume will be 91 cm^3.



(a) (b)

Fig. 2. Injection mold details: a) lower cavity detailed in the SolidWorks CAD; b) detailed upper cavity in the CAD.

According to CAD SolidWorks, the mass of a product unit weighs about 49,06 g and therefore two units will have a mass around 98,12 g.

II.II MATHEMATICAL MODEL

In order to perform these calculations in the filling phase of the wells, it is necessary to assume a non-isothermal flow of a non-Newtonian fluid, based on conservation equations in general [12]. Eq. (1), (2) and (3), represent mass conservation, amount of movement and energy conservation, respectively [12,13]:

$$\frac{\partial \rho}{\partial t} + (\vec{\nabla} \cdot \rho \vec{u}) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}\rho \vec{u} = -[\vec{\nabla} \cdot \rho \vec{u}^2] - \vec{\nabla} P + [\vec{\nabla} \cdot \tau] + \rho \vec{g} \quad (2)$$

$$\rho C_v \left[\frac{\partial T}{\partial t} + \vec{u} \cdot \vec{\nabla} T\right] = -\left(\vec{\nabla} \cdot \vec{q}\right) - T\left(\frac{\partial P}{\partial T}\right)_v \cdot \left(\vec{\nabla} \cdot \vec{u}\right) + \left(\frac{\tau}{\vec{\nabla} \cdot \vec{u}}\right) \quad (3)$$

Where ρ is the specific mass (kg/m^3), u is the velocity (m/s), t is the time (s), P is the pressure (Pa), τ is the shear stress (Pa), g is the gravity aceleration (m/s^2), Cv is the specific heat at a constant volume (J/kg.K), T is the temperature (K) and q is the heat flux (W). Eq. (1) and (3) are introduced in the simulations with the following conditions:

- The flow flows in a laminar regime;
- Gravitational forces are negligible;
- The heat flux is expressed by the Fourier law as shown in Eq. (4) [14]:

$$\vec{q} = -k\vec{\nabla} T \quad (4)$$

Where the heat flux is proportional to the temperature gradient, and k is the thermal conductivity (W/m.K);

- Density, specific heat and thermal conductivity can be considered constant;
- The flow is considered to be almost stationary, since the Reynolds number characteristic of the injection process is very low, allowing the convective effects of the momentum equation to be neglected.

Based on these hypotheses, we can make the following weights for each initial equation, in which Eq. (5), (6) and (7) again represent conservation of mass, amount of movement and energy conservation, respectively [15]:

$$\frac{\partial u_i}{\partial x_i} = 0 \quad (5)$$

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_j u_i)}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\eta(T, \dot{\gamma})\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] \quad (6)$$

$$\frac{\partial (\rho c T)}{\partial t} + \frac{\partial (\rho c u_i T)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k \frac{\partial T}{\partial x_i}\right) + \emptyset \quad (7)$$

In the equation of energy quantity (Eq. 7), the specific heat at constant pressure (CP) replaces the specific heat at constant volume (CV) because these values are equal in the cases of incompressible fluids [16]. The viscous dissipation term is represented by the following equation:

$$\emptyset = \eta \dot{\gamma}^2 \quad (8)$$

II.III VISCOSITY MODELS USED BY SOFTWARE'S

The rheological state equations, which relate the shear stress (τ) to the strain rate, are also considered. According to the software Solidworks Plastics [17] and Moldflow Synergy [18] as flow in the injection process, a shear flow, the relevant rheological property is the steady state steady state (η), neglecting the normal stresses and Elastic effects. The shear rate ($\dot{\gamma}$) can be calculated according to Eq. (9):

$$\dot{\gamma}^2 = \left(\frac{\partial u_x}{\partial z}\right)^2 + \left(\frac{\partial u_y}{\partial z}\right)^2 \quad (9)$$

However, the software calculates the viscosity of the fused polymer with different mathematical models. As viscosity is dependent on the temperature of the polymer [19,022], to represent the viscoelastic behavior of the polymers, Solidworks Plastics uses Power Law Equation. (10) this model is imposed to calculate the viscosity [22]:

$$\eta = m \cdot \gamma^{n-1} \cdot e^{c \cdot T} \quad (10)$$

Where m is the consistency (adm), and c is a temperature-dependent constant, n is the power law index, and when n <1, the polymer exhibits pseudoplastic behavior, that is, the value of n is greater than its pseudoplasticity [17,18,22]:

In the viscoelastic model used by Moldflow Synergy software, steady-state viscosity does not neglect normal stresses and friction loss [18]. The mathematical model used to calculate the viscosity of the polymer is the MoldFlow Second Order Model, it is represented by Eq. (11) [18]:

$$\eta = e^{\{c_1 + c_2 \ln(\dot{\gamma}) + c_3 T + c_4 [ln(\dot{\gamma})]^2 + c_5 T [\ln(\dot{\gamma})] + C_6 T^2\}} \quad (11)$$

II.IV PROCESS PARAMETER TO VALIDATION

The main physical property used in the validation of the mathematical model used in the simulations was the injected mass of the glasses. Thus, the results of the simulated masses by the Ansys Fluent software were compared with the values of the actual mass obtained injection tests, thus extracting the simulation deviation. At each operational condition, the average mass of 20 samples of cups was purposely withdrawn with injection failures, more specifically incomplete filling of cup wells.

The values of the average of injected masses were used to validate the simulations performed. However, for this, deviations were calculated according to Eq. (14):

$$\delta_s = \left[\left(\frac{M_{sim}}{\bar{M}_{inj}}\right) - 1\right] \cdot 100 = \% \quad (12)$$

In that the M_{sim} is the mass simulated by the software (g), and $\bar{M}_{inj}$ is the average of the injected masses (g). These calculations were used to validate simulations of sampled GPPS cups produced.

As the objective of the work is to compare the influence of meshes on mathematical software models, the parameters were performed below and above the values stipulated by the material manufacturer (Table 1). Only to remove data in which the polymer does not completely fill the mold cavities, purposely causing injection failure. The parameters performed in the simulations and in the injection tests can be visualized in Table 2.

Evaluated Parameters			**Variable Processing Parameters**
Type of Mesh	**Geometry**	**Mesh Element (mm)**	**Injection Temperature (°C)**
Solid Mesh	Tetrahedral	5 - 0,1	120, 140
Shell Mesh	Squad		280, 300

Table 2. Injection Parameters for Validation.

The simulation domain is defined as the path in which the polymer mass will flow. An example of the shell-like domain can be seen in Figure 3.a.

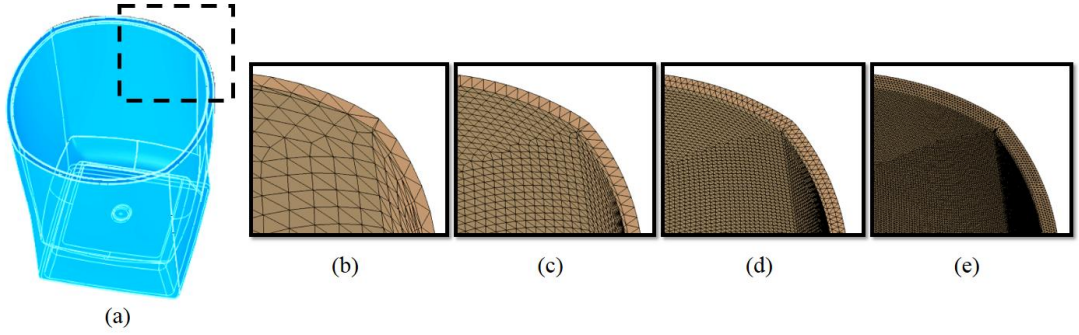


Fig 3. Details of the simulation domain and mesh (triangular elements): a) shell domain; b) mesh element of 5.0 mm; c) mesh element of 2.0 mm; d) mesh element of 1.0 mm; e) mesh element of 0.5 mm.

The volumetric contraction of the polymer material was disregarded, since the simulations did not take into account the cooling stages of the material.

Since the size of the mesh elements influences the reliability of the simulated results, a refinement of the mesh was performed varying geometries and sizes in order to specify the ideal conditions to simulate the thermoplastic injection process. As shown in Figures 3.b to 3.f., the smaller the element size, the more defined (rounded) and reliable is the geometry of the simulation domain. The simulations were performed in the Ansys Fluent software, comparing the two mathematical models.

The values of the injection parameters that were kept fixed in the simulations can be better observed in Table 3.

Fixed Parameters			
Injection Pressure (MPa)	**Wall Temperature (°C)**	**Holding Pressure (%)**	**Injection Flow cm^3/s)**
2	40	45	80

Table 2. Fixed Injection Parameters for Validation

Other information that can be inserted in the simulations are the filling phase, packaging and cooling efficiency. These algorithms can be simulated individually and combined according to some work already done [22,23]. The algorithm used in this work was determined only in the fill phase, both for the software.

III. RESULTS AND DISCUSSION

In this chapter, mesh refinement results are presented in simulations performed in SolidWorks Plastics and Moldflow Synergy software, varying mesh size and mesh types, compared to the two experimental GPPS injection results. This comparison is made to validate the mathematical model used by the software.

III.I MESH REFINIMENT

The first set of experimental tests using values below the ideal injection conditions (Table 1) was performed by varying the injection temperature by 120 °C. This temperature was purposely purposely insufficient to completely fill the wells, with a mean of injected masses of 11,06 g. By performing the simulations and varying the conditions according to Table 2 and applying the results of these simulations in Eq. 12, resulted in two comparative graphs of mesh refinement shown in Figure 4.

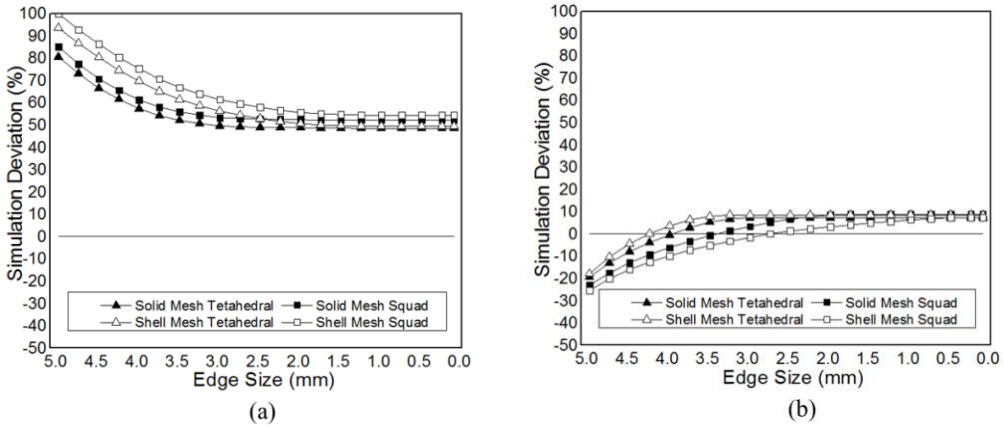


Fig 4. Influence of geometry and mesh refinement in the GPPS injection simulations, with injection temperature of 120 °C. a) Generalized Maxwell Model, b) Power Law Model.

The first mathematical model (Figure 4.a), overestimated the mean values of injected masses. Even though the model converged from a mesh element size of less than 2.0 to 1.5 mm, the simulated masses varied approximately 49 to 54% larger than the actual masses of the injected cups. It is noted that the two solid meshes have been shown to be more efficient than the mesh in the shell. Because they converged first, they were the closest to reality. In the second case (Figure 4.b), the results of the simulations showed that the mathematical model converged with a mesh element size between 1.5 and 1.0 mm. However, while the model had not yet converged, the results were overestimating reality. Only after convergence did the model prove to overestimate reality. However, the values proved to be better and more efficient than the previous model, varying the simulation deviations between 19 and 25% negative. The next step compared the simulations with the experimental tests, also using values below the ideal injection conditions, varying the injection temperature by 140 ° C.

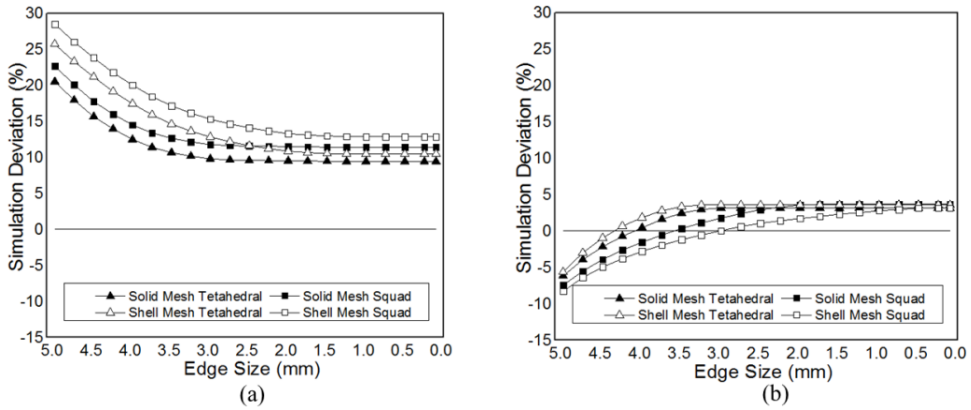


Fig. 5. Influence of geometry and mesh refinement on the GPPS injection simulations, with an injection temperature of 140 °C. a) Generalized Maxwell Model, b) Power Law Model.

Increasing the injection temperature also increased the predictive capacity of the mathematical models and consequently reduced the scales of the simulation deviations to up to 30%. Analyzing the Maxwell model

(Figure 5.a), the model again overestimates reality and solid meshes tend to converge rather than bark in mesh, in addition to demonstrating more reliable results. It is also noticed that tetrahedral meshes are more reliable than quadrilateral meshes. In the power law model, solid meshes are shown to be better than bark but very low approximation values. On the other hand, values take longer to converge.

The next analysis compares the simulations with the experimental tests, now using values above the ideal injection conditions, varying the injection temperature by 280 ° C

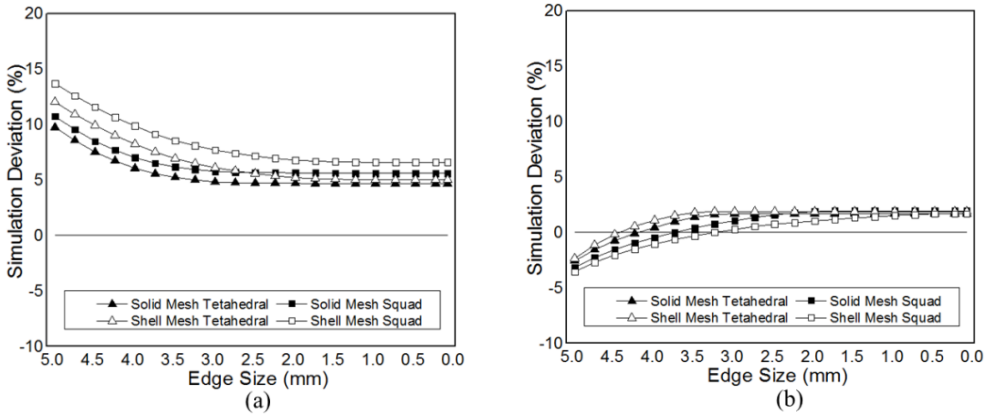


Fig. 6. Influence of geometry and mesh refinement on GPPS injection simulations, with injection temperature of 280 °C. A) Generalized Maxwell Model, b) Power Law Model.

The values above the ideal injection conditions proved to be better than the values below, causing the scale of the simulation deviation to be reduced again to better analyze the models. This demonstrates that the mathematical models calculate well the thermal properties of the polymers. In the Maxwell model (Figure 6.a) Solid meshes converge faster than bark in meshes. However, the mesh in tetrahedral shell is more efficient than the solid quadrilateral mesh even taking longer to converge.

The power law model (Figure 6.b) obtains the same characteristics, however, with values closer to reality. In addition, this model differs from the other because it always overestimates in larger mesh sizes and ends up overestimating when it reaches convergence in smaller mesh sizes. However, both models obtained excellent results, with simulation values very close to reality.

The last set of experimental tests using values above the ideal injection conditions was performed by varying the injection temperature by 300 ° C. The average of the injected masses came close to 97,95 g, that is, almost close to 98,08 g of the two completely filled cups in the wells. Figure 8a shows that for the model used by SolidWorks Plastics, it was very efficient, since even when it was not converging in a coarse mesh, the simulation deviation did not exceed 10%. Which means the results were pretty convincing.

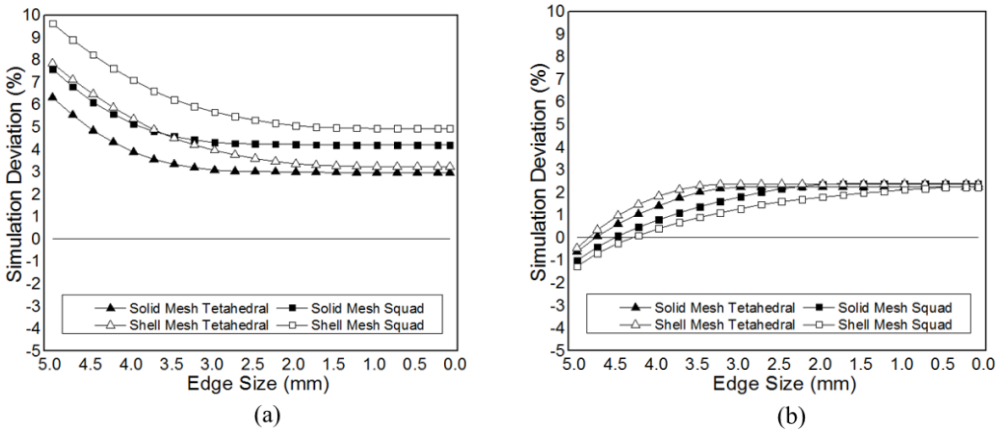


Fig. 7. Influence of geometry and mesh refinement on GPPS injection simulations, with injection temperature of 300 °C. A) Generalized Maxwell Model, b) Power Law Model.

All geometries and mesh types proved to be very efficient and converged almost together. However, the tetrahedral meshes obtained results closer than the quadrilateral meshes. The model used by Moldflow Synergy (Figure 7.b) was once again the most efficient, since the model did not overestimate over 3% of reality either before or after convergence. This implies that this type of software can demonstrate more efficient results, because it has a mathematical model that compiles well the rheological phenomena of the polymers. However, this does not take the merit of the model used by SolidWorks Plastics that obtained excellent simulation results.

IV. CONCLUSION

The findings obtained in this work provided important information on the effects of mesh geometries and types in mathematical models used in the injection simulation process. Ideally, temperatures were placed below the ideal processing parameters, and it was observed that the models compared well the thermal analysis of the flow, approaching the injected mass flow with the reality of the experimental tests. As the polymers need high temperatures to decrease viscosity, the models simulated the difficulty of the polymer filling the cavities. At too high temperatures, the viscosity of the polymer reduces and the shear rate is likely to become greater than the maximum value allowed for the GPPS, hampering the flow of hot polymer toward the final end of the mold cavities. In the same way the polymers, the simulations became even closer to reality, demonstrating that both mathematical models confront well the thermal and viscoelastic phenomena. The simulations performed generated overestimated results for the injected mass with a reasonable error, becoming sufficient to provide qualitative information.

Solid meshes have been shown to be more efficient than bark meshes in this type of numerical simulation analysis. These still converged first that the meshes in shell. The geometry that best obtained results close to reality were the tetrahedral meshes. This is because they can delineate rounded geometries, which square meshes have the most difficulty for this. mathematical models.

REFERENCES

[1]. kazmer, D. O. (2007). *Injection Mold Design Engineering*. Massachusetts: Hanse.

[2]. Dimla, D. E., Camilotto, M., & Miani, F. (2005). Design and Optimisation of Conformal Cooling Channels in Injection Moulding Tools. *Journal of Materials Processing Technology*, *n*(165), p. 1294-1300.

[3]. Kovacs, J. G., & Bercsey, T. (2005). Influence of Mold Properties on the Quality of Injection Molded Parts. *Polytechnica - Mechanical Engineering Series*, n.2, vol. 49, p.115-122.

[4]. Guilong, W., Cuoqun, Z., Huiping, L., Yanjin, G. (2010). Analysis of Thermal Cycling Efficiency and Optimal Design of Heating/Cooling Systems for Rapid Heat Cycle Injection Moulding Process. *Material & Design*, *n*(31), p.3426-3441.

[5]. Kim, S. W., & Turng, L. S. (2004). Developments of Three-dimensional Computer-aided Engeineering Simulation for Injection Moulding. *Modelling and Simulation in Materials Science and Engineering*, n. (12), p.151-173.

[6]. Zhou, H., *Computer Modeling For Injection Molding*. (2013). A John Wiley & Sons, Inc., Publication.

[7]. Zhuang, X., Ouyang, J., Jiang, C., Liu, Q. (2016). New Approach to Develop a 3D non-Isothermal Computational Framework for Injection Moulding Process Based on Level Set Method**.** *Chinese Journal of Chemical Engineering*. n. 30.

[8]. Lou, J., Li, Y., He, H., Li., Wang, G., Feng, J., Li, C. (2017). Interface Development and Numerical Simulation of Powder Co-Injection Moulding. Part. I. Experimental Results on the Flow Behaviour and Die Filling Process. *Powder Technology*. n (305) p. 405-410.

[9]. Zhang, L., Zhao, G., Wang, G., Dong, G., Wu, H. (2017). Investigation on bubble morphological evolution and plastic part surface quality of microcellular injection molding process based on a multiphase-solid coupled heat transfer model. International *Journal of Heat and Mass Transfer n*(104), p.1246–1258.

[10]. Lopez, A., Aisa, J., Martinez, A. Mercado, D. (2016). Injection Moulding Parameters Influence on Weight Quality of Complex Parts by Means of DOE Application: Case of Study. *Journal of Materials Processing Technology*, *n*(90), p. 349-356.

[11]. Braskem. (2015). Data Sheet of General Purpose Polystyrene (GPPS – 500).

[12]. Hassan, H., Regnier, N., Le Bot, C., Defaye, G. (2010). 3D Study of Cooling System Effect on the Heat Transfer During Polymer Injection Molding. *International Journal of Thermal Sciences*, n (49), p.161-169.

[13]. Chiang, H. H., Hieber, C. A., Wang, K. K. (1991). A unified simulation of the filling and post filling stages in injection molding. Part I: formulation, Polymer Engineering and Science. 31 p.116–124.

[14]. Kim, B. Min, J. (2017). Residual stress distributions and their influence onpost-manufacturing deformation of injection-molded plastic parts. *Journal of Materials Processing Technology*. n. 245, p. 215-226.

[15]. Chen, Q., Donald, G., Baird, G. (2016). The Transient Shear rheology of a Thermotropic Liquid Crystalline Polymer in the Super-Cooled State. *Polymer*. n. (102) p. 63-72.

[16]. Kim, S. W.; Turng, L. S. (2004). Developments of Three-Dimensional Computer-Aided Engeineering Simulation for Injection Moulding. *Modelling and Simulation in Materials Science and Engineering*, n. (12), p151-173.

[17]. Solidworks. HELP. (2016)**.** Introduction to SolidWorks *Plastic using simulation*.

[18]. Moldflow On Line Help. (2016). Autodesk Corporation.

[19]. Guerrier, P., , Tosello, G., Hatte, L J. H. (2017). Flow visualization and simulation of the filling process during injection molding, *CIRP Journal of Manufacturing Science and Technology*. n16 p12-20.

[20]. Menges, G., W. Michaeli, and P. Mohren. (2001). *How to Make Injection Molds*, 3rd ed., Hanser.

[21]. Chen. S. C., Chien, R. D., Lin, S. H., Lin, M. C., Chang, J. A. (2009). Feasibility Evaluation of Gas-assisted Heating for Mold Surface Temperature Control During Injection Molding Process. International Communications in Heat and Mass Transfer. n36, p806-812.

[22]. Abdullahi, A. A., Choudhury, I. A., Azuddin, M. (2016). Effect of Runner Dimensions on Cavity Filling in Microinjection Moulding For Defect-Free Parts. Asian Research Publishing Network. V11 n12 p7788-7793.

[23]. Moayyedian, M., Abhary, K., Marian, R. (2015). New Design Feature of Mold in Injection Molding For Scrap Reduction. *Procedia manufacturing.* n. (2) p.241-245.