Microinjection molding of microstructures – Experimental and numerical simulation

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Abstract

The replication of various microstructures with an aspect ratio of 5 using the microinjection molding process (μIM) was studied both experimentally and by numerical simulation. The microstructures were produced on poly(lactic) acid disks using a steel insert made by micromachining. To improve the filing process, the insert was heated at temperatures above the polymer glass transition temperature of 58^{o}C, and then rapidly water-cooled to room temperature. The cavity pressure and the temperature at the gate were monitored during the whole cycle. The experimental and numerical results show that the micro features close to the gate did not fill as well as features far from the gate.

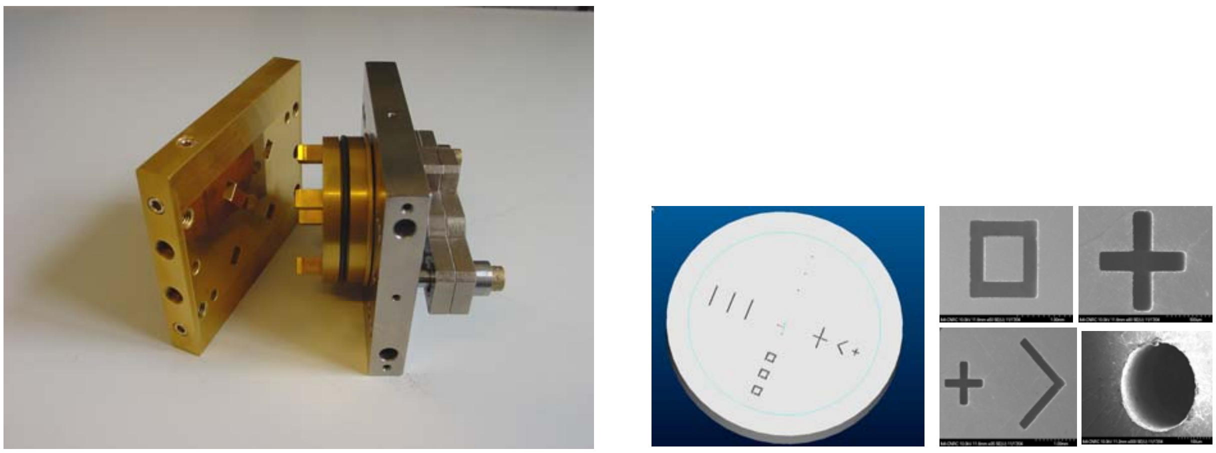
Introduction

Replication of small or micro-structured parts by injection molding raises several challenges compared to macro-sized parts [1]. Theses challenges are even greater for high aspect ratio moldings [2,3]. The difficulties arise mainly from two sources: lack of adequate filling because of premature freezing-off of features with very small thickness and excessive deformation during ejection due to high friction at the polymer-metal interface, often causing tearing at the roots of the part features. Within the thin and sometimes deep channels machined in the molding insert, competing events of molten polymer flow and solidification take place. Flow is much slower in the very thin sections of the molding while heat transfer is fast, with respect to other thicker areas. This will eventually result in short shots. In order to achieve complete filling of small cavities the so-called variotherm heating process may be useful [1,4]. The mold insert surface is heated up sometimes to temperatures close to the melt temperature in order to gain a lower melt viscosity during filling. After holding, the mold temperature is set to a temperature below the glass transition temperature or an appropriate cooling temperature. Compressed air problems are also more evident for μIM as very small cavities need to be filled and dimensional tolerances must be strictly satisfied. For this reason the air mold should be evacuated prior to filling.

In this work we investigate both experimentally and numerically the injection molding of parts with microstructures. The paper focuses on the way the microstructures are filled and on the influence of the thermal behavior on the filling pattern. The numerical approach is based on the resolution of the three-dimensional (3D) equations modeling the momentum, mass and energy conservation, using the finite element method. To locate the polymer/air interface during filling a front-tracking equation is solved simultaneously. Details on the mathematical modeling can be found in [5,6]. The true 3D solution approach to the mold filling problem will provide more accurate and detailed information regarding the filling pattern, temperature and pressure distributions, than the more widely used Hele-Shaw mid-plane solution, which may not apply in the case of complex micro-structures [7]. However, visco-elastic and surface tension effects are not taken into account in this analysis.

Experimental set-up

The molding tests were done in a Battenfeld Microsystem 50 injection molding machine. The moving plate of the mold used in this study supports a circular cavity, 26.75 mm in diameter and 1.5 mm thickness whose bottom face is made up of a machined insert with a series of variously shaped channels as shown in Figure 1. The channels were all 1 mm deep and 0.2mm wide, resulting in an aspect ratio of h/w=5. The closing face of the cavity is provided by the fixed plate which was centrally gated through a 5mm port.



(a) (b)

Figure 1 – (a) Fixed (left) and moving (right) mold halves. (b) Insert used to mold micro-structured disks. SEM picture shows details.

The molding tests were carried out using poly(lactic) acid, PLA Biomer 9000, a biodegradable polymer. DSC tests carried out on virgin material revealed a glass transition temperature of about 58^{o}C and a small melting peak at 169^{o}C. This grade is basically amorphous but crystallization can occur during molding, depending on the cooling conditions. For the purpose of the simulation work presented in this paper, the mold temperature and the melt temperature at the nozzle were set at 30^{o}C and 200 ^{o}C respectively. Experimentally, in some instances the mold was heated up to 105^{o}C prior to filling, maintained to that temperature during holding then quickly cooled to about 30^{o}C. Various levels of injection speed and holding pressure were tried during the experimental and simulation trials. The material viscosity data was fitted by the Cross-WLF model:

$$\eta = \frac{\eta_0}{1+\left(\eta_0 \dot{\gamma} / \tau^*\right)^{1-n}} \quad , \quad \eta_0 = D_1 \exp\left\{ \frac{-A_1 (T - T^*)}{A_2 + (T - T^*)} \right\}$$

where $T^* = D_2 + D_3 p$, and $A_2 = \tilde{A}_2 + D_3 p$. Model constants used for the numerical simulation are summarized in Table 1. Density, specific heat and thermal conductivity were taken constant.

Table 1: Cross-WLF Model for PLA Biomer 9000

<table>
<tr><td colspan="4">Model constants</td><td colspan="4">Values</td></tr>
<tr><td colspan="2">n</td><td colspan="2">τ^* (Pa)</td><td colspan="2">0.12</td><td colspan="2">3.0×10^5</td></tr>
<tr><td>D_1 (Pa.s)</td><td colspan="2">D_2 (^oC)</td><td>D_3 (^oC/Pa)</td><td>400</td><td colspan="2">225</td><td>0.0</td></tr>
<tr><td colspan="2">A_1</td><td colspan="2">$\tilde{A}_2$ (^oC)</td><td colspan="2">60.0</td><td colspan="2">800.0</td></tr>
</table>

Experimental observations

As mentioned in the introduction, replication of small microstructure by molding techniques such as injection molding can be quite challenging, especially when high aspect ratios are involved. SEM micrographs shown in Figure 2 illustrate the difficulties encountered during filling and de-molding: lack of filling is obvious and microstructures can be deformed and torn during ejection. These microstructures were molded with the mold temperature being constant at 30 ^oC and the melt temperature at the nozzle set at 200 ^oC.

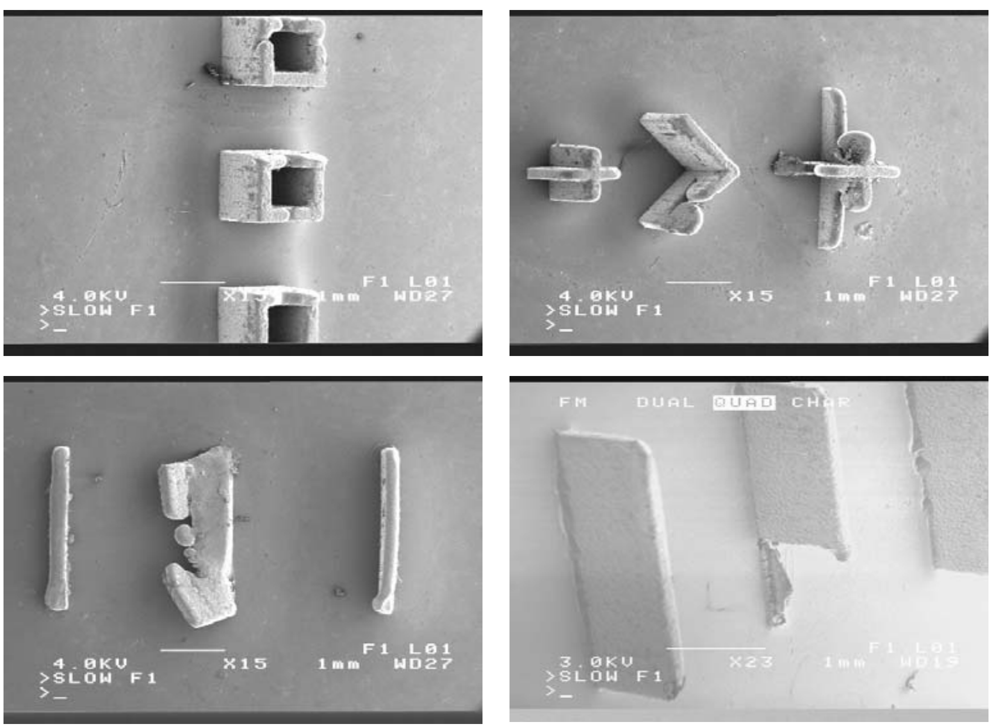
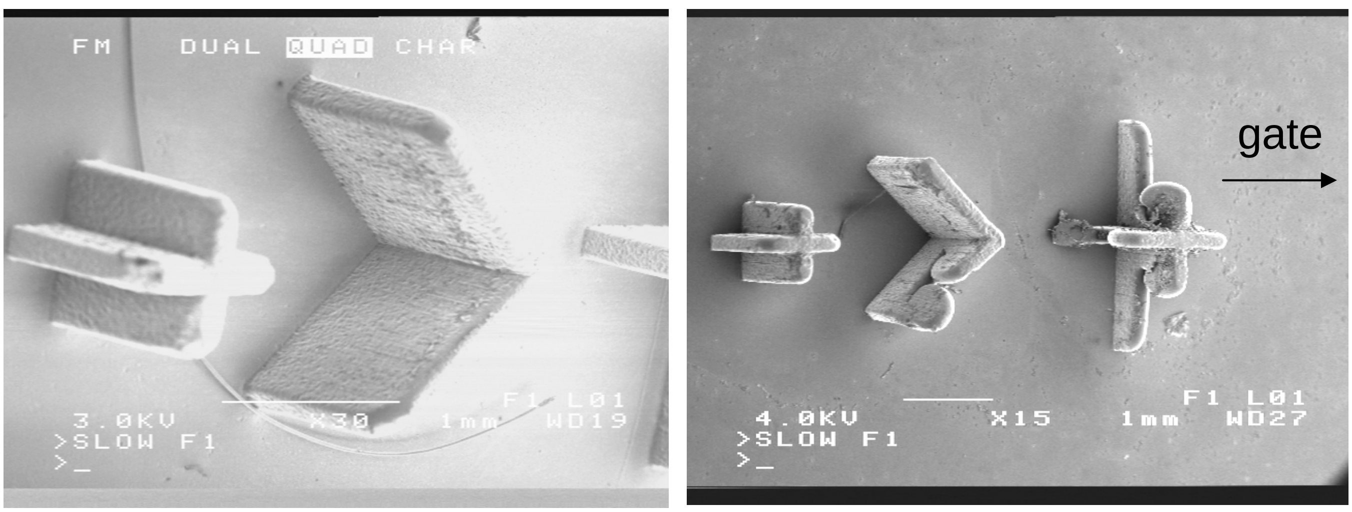


Figure 2 – SEM micrographs of various microstructures molded at a low mold condition.

In the particular conditions of our molding tests, it was generally observed that the features closest to the centrally located gate were the less complete. This can be explained as follows:

as the molten polymer enters the cavity, it will first fill the bulk of the 1.5 mm thick disk, filling only partially the microstructures. When filling of the circular cavity is completed, the microstructures farthest from the gate are last to be partially filled and contain hotter material than those closer to the gate. The material in the latter had enough time to cool down thereby ending up with a higher viscosity. At the packing and holding stages the microstructures closest to the gate necessitate higher pressure drops to be completely filled when fresh hot material is supplied. In the case of micro features with thin walls, the simultaneous premature cooling of the material delays the build-up of the required pressure and constitutes a hindrance for complete filling. Maintaining the cavity walls at the highest possible temperature during filling would therefore be helpful, as was demonstrated by the variotherm process [1]. When the mold temperature was raised to a temperature higher than the glass transition temperature of the polymer (58 ^{o}C), the replication was much better. Figure 3 shows two SEM micrographs of microstructures molded onto of the disk molded with the cavity mold set at 105 and 30 ^{o}C respectively. In the case of the higher temperature, the mold was closed then electrically heated to 105 ^{o}C, while the water lines for cooling were off . When the set temperature was reached, molten PLA was injected at 200 ^{o}C with injection speed of 200 mm/s. Holding pressure was set to 500 bars, holding time to 5 s. At the end of holding, water lines were opened to cool down the mold to 30 ^{o}C for a period of 45 s. The processing conditions were kept the same in the case where the mold was maintained at 30 ^{o}C during the whole cycle.



(a) (b)

Figure 3 – SEM micrographs of microstructures molded at the same conditions except for the mold temperature during filling: (a) 105 ^{o}C and (b) 30 ^{o}C.

Numerical results and discussion

The numerical solution at the end of the filling stage, with an injection speed of V=200mm/s and 30ºC mold temperature, is shown in Figures 4, 5 and 6, where the pressure, temperature and velocity distributions are displayed. At the end of the filling stage the microstructures are not entirely filled as shown by the grey domain at the tip of each feature. The numerical predictions do indicate that the required pressure drop to fill the microstructures is much larger than the pressure drop needed for filling the disk because of higher resistance to flow in the former. As a consequence, the velocity distribution will be lower in the microstructures as can be seen in Figure 6. Combined with the fast heat transfer, this will results in higher viscosities, thick frozen layers and incomplete filling. Similarly, it is predicted that the temperature gradient within the microstructures depends on their position with respect to the gate: those farthest from the gate have a lower thermal gradient and are at a higher level of temperature, which facilitate their filling. Complete filling, if attained, occurs during the packing phase as a much larger pressure is needed to fill the microstructures. Observe that the square shaped structures are more complete, whereas the cylindrical posts are less filled. Filling is easier in microstructures having corners as cooling at these locations is less intense.

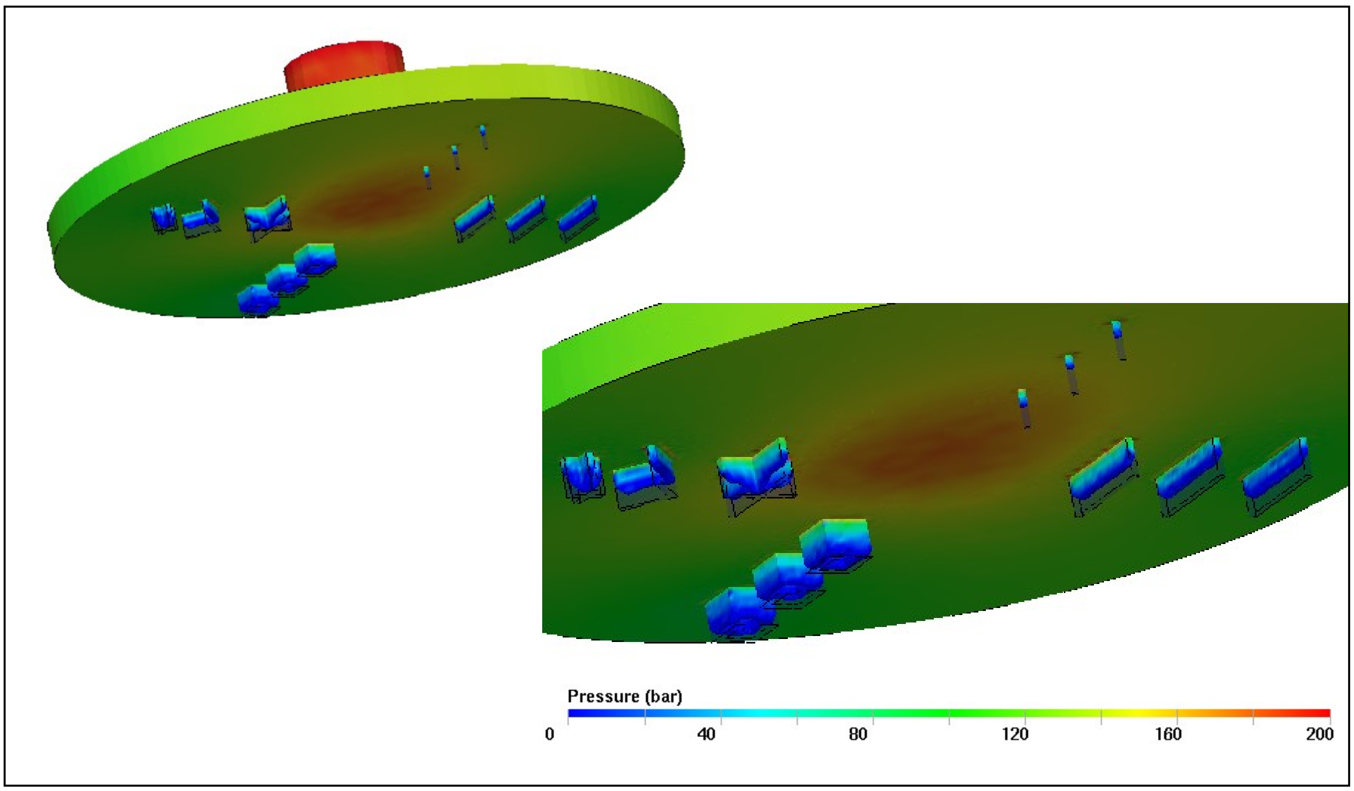


Figure 4 – Pressure distribution at the end of filling

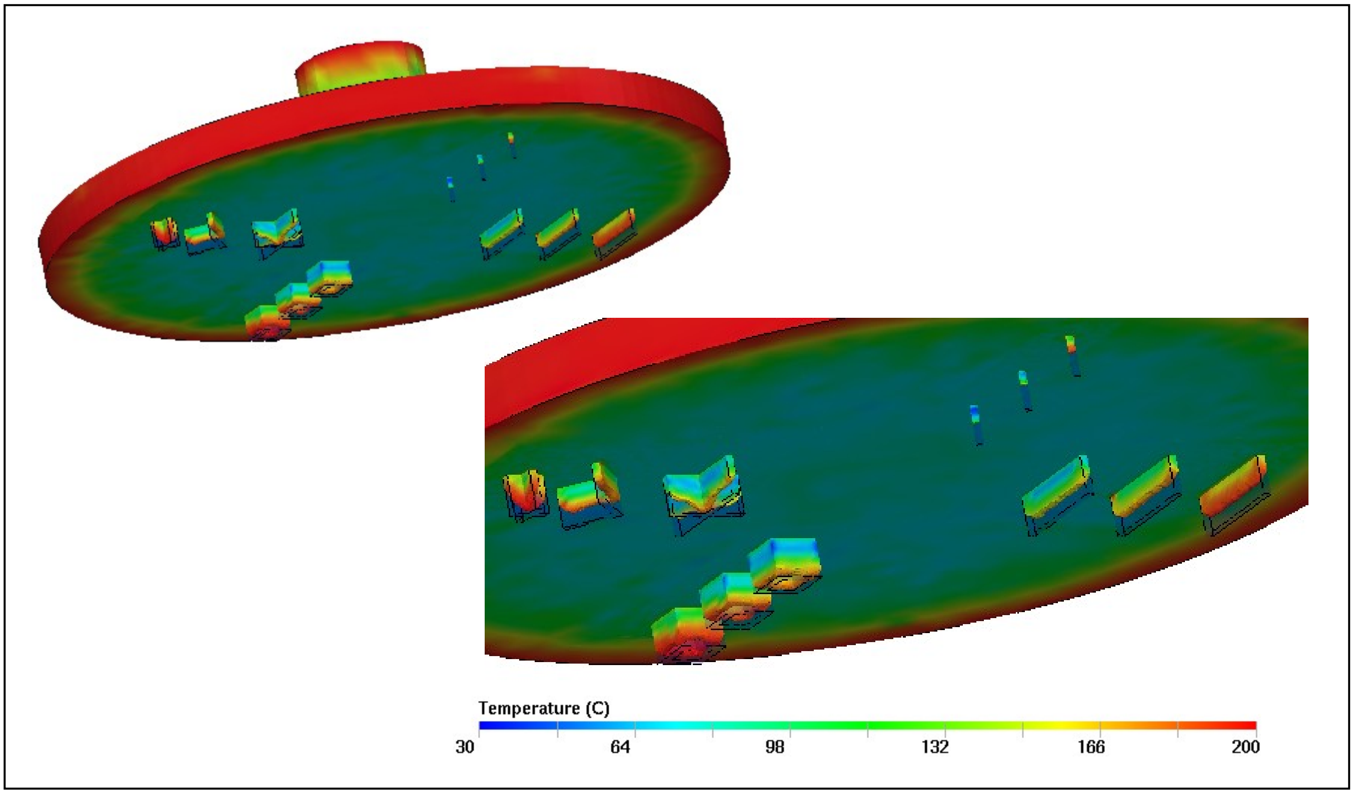


Figure 5 – Temperature distribution at the end of filling

The numerical solution at the end of packing stage for a packing pressure of 500 bars is shown in Figures 7 and 8 along with details of the micro features. The square shaped structures are filled entirely, whereas the post structures are only partly filled. Note also that the post located closer to the gate is filled less than the one at the outer position. This can be explained by the fact that the polymer fills only partially the posts volume during the filling stage. Because the hole closer to the gate is the first to be reached by the polymer the corresponding post is also the one having the longer cooling time. Therefore the polymer at this location has lower temperature and higher viscosity at the time of the packing phase and the filling cannot be completed. The same behavior is observed for the other microstructures, the ones closer to the gate being less filled than those farther from the gate.

Conclusion

Injection molding of micro features having an aspect ratio of 5 onto a 1.5 mm thick disk was carried out using various processing conditions. In particular, the so-called variotherm process was found to be beneficial in filling the micro cavities, limiting the degree of premature freezing off. It was also observed that the microstructures farthest from the gate were the easiest to fill. The experimental observations were numerically predicted using a fully 3D finite element approach. The simulation code also predicts better replication of the microstructures far from the gate, which were shown to display a higher temperature level and smaller thermal gradient.

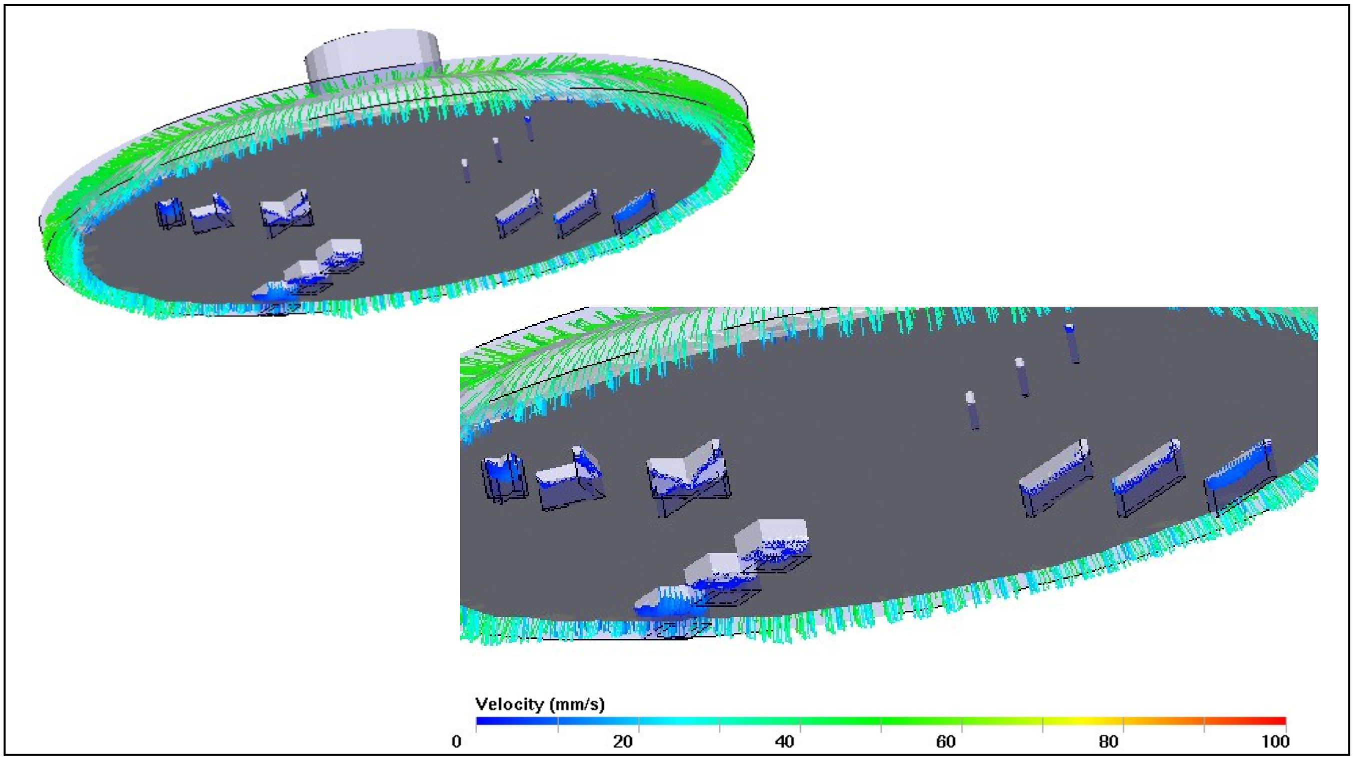


Figure 6 – Velocity distribution at the end of filling

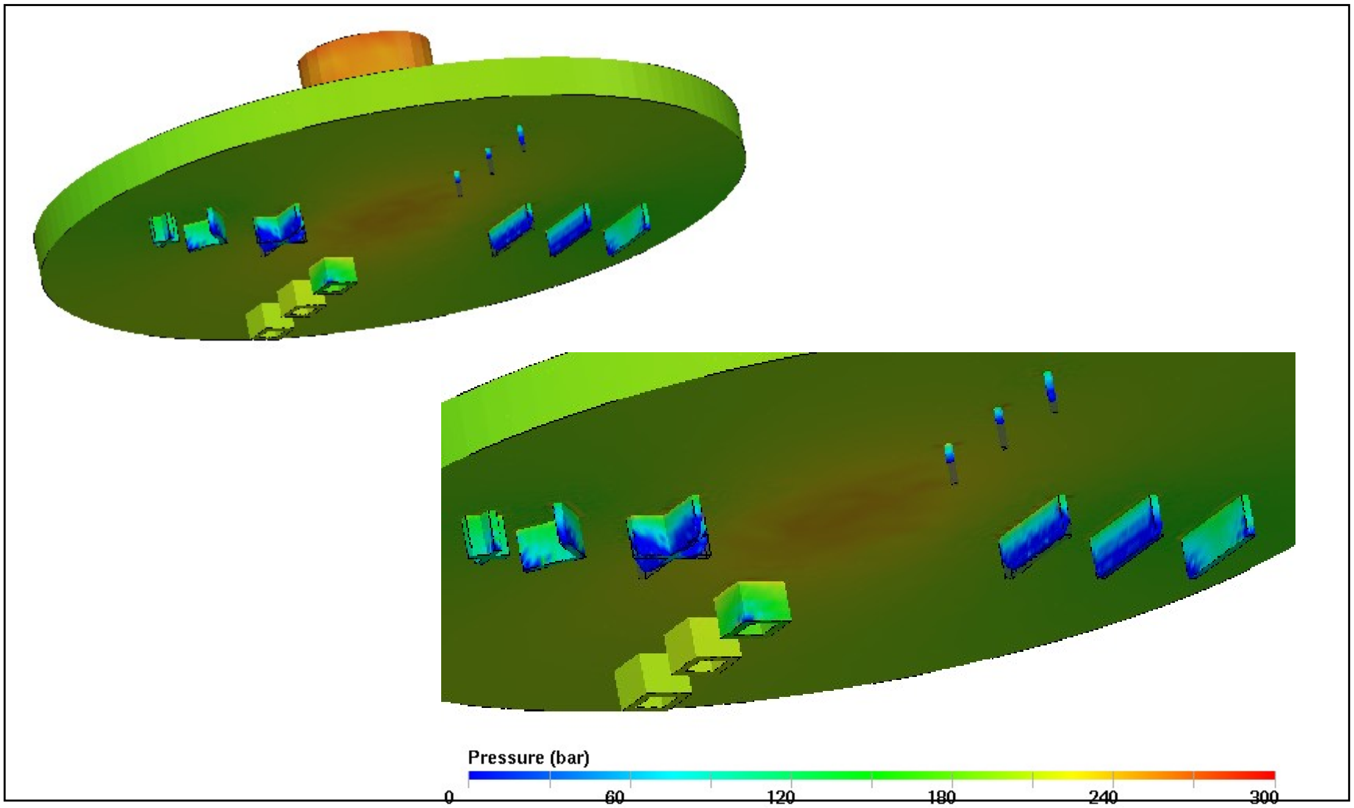


Figure 7 – Pressure distribution at the end of packing

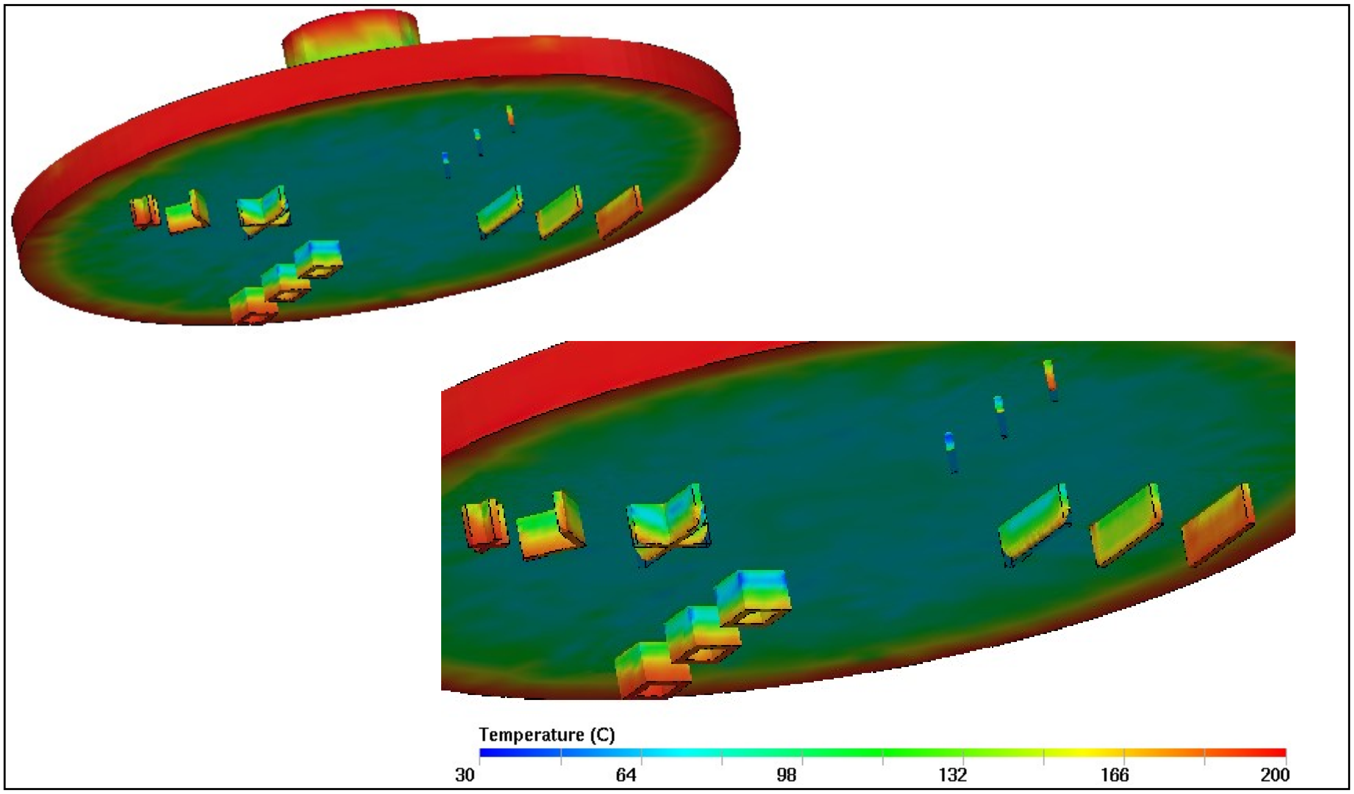


Figure 8 – Temperature distribution at the end of packing

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Acknowledgements

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