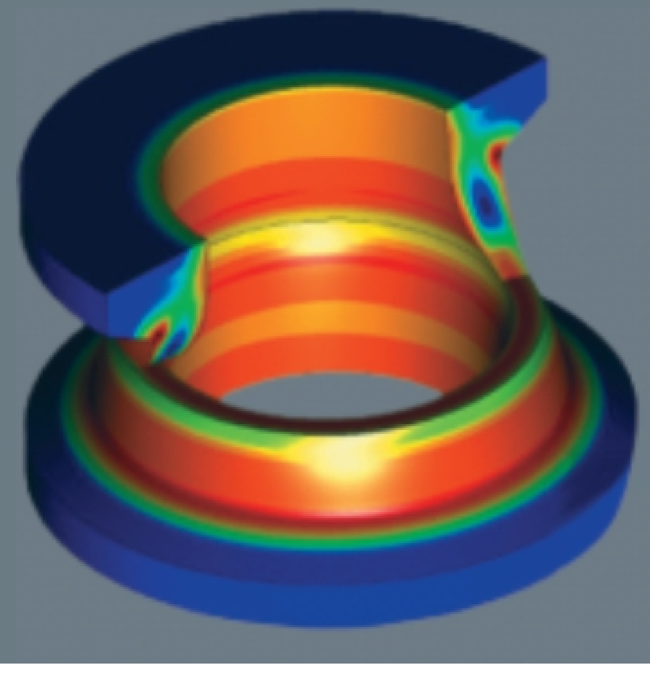

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Development and verification of an open-source computational framework to simulate injection moulding

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Abstract

Injection moulding is one of the most important processing techniques for thermoplastic materials, and due to the high competition and product requirements, it demands continuous optimization. In industrial practice, aiming to minimize the resources spent on the design and manufacturing activities, it is common to resort to appropriate computational modelling tools. However, mainly due to the typical high cost of proprietary software, the support of computational modelling tools in injection moulding design related tasks is not available to medium and small sized companies. This framework, and the clear perspective of the benefit brought by computational modelling, has been motivating the development of codes based on open-source libraries, as happens with OpenFOAM computational library. This work aims to identify the computational framework employed by injection moulding codes well established in industry, and perform the required adaptations on the most appropriate solvers to replicate it in OpenFOAM. Then a few case studies will be employed to compare the predictions and performance of the proprietary and open source codes.

Objectives

- Study in detail the computational framework of Moldex3D, aiming to identify:
  - The governing equations employed to model the filling phase of the injection moulding process;
  - The available rheological models;
  - The model employed for the pressure-volume-temperature relation;
- Evaluation and verification of an open-source solver capable of modelling injection moulding process;

Overview

- Injection moulding process is usually governed through the following three governing equations:
  - Conservation of mass;
  - Conservation of linear momentum;
  - Conservation of energy;
- Moldex3D software simulations are based on these three principles and, coupled with constitutive models that rule the materials rheology. The same happens in the solver developed in OpenFOAM.
- In these codes, polymers are modelled as a generalized Newtonian fluid, which means that the elastic component of the materials behaviour is neglected, and their shear viscosity is function of the shear rate, temperature and pressure. Moreover, to account for compressibility effects, the modified Tait model can also be considered.
- In this work two case studies are presented. The first one covers the general assessment of the solver, and the second aims at performing the comparison of the results achieved with the proprietary software and the open-source solver. In the first study, defining the material as a Newtonian fluid, the velocity and pressure profiles were compared with the analytical ones to verify if the solver was well developed. In the second study, using a constitutive equation appropriate for thermoplastic polymers, the results of the filling stage of injection moulding given by the two softwares are compared.

Results and Discussion

- Figures 2-4 present the first study of this work, and it can be concluded that the open-source solver is well developed, since the velocity and pressure match well with the analytical results;
- Moreover, the flow front inside the channel matches well with the evolution of the flow front in injection moulding, being the corners the last portion of the geometry to be filled;
- In the second case study, it is possible to conclude, from Table 1, that with the increase of mesh refinement the results obtained with openInjMoldSim were closer to the ones obtained by Moldex3D;
- In Figure 5 the cross section from where the contours of velocity, pressure and temperature were taken is located;
- From Figures 6-8 it is possible to conclude that the pressure, velocity and temperature contours obtained with the open-source solver are very similar to the ones obtained with Moldex3D;
- However, the simulation times obtained were very different, with the proprietary software being clearly the most efficient one;
- These results provided the idea that OpenFOAM solver might be well developed, but there is still some work to be done in terms of the calculation procedure, at least.

Conclusions and Future Work

- With this work, the framework of simulations of injection moulding in Moldex3D were shown, especially the governing equations and the constitutive models that rule the filling phase;
- The cases studies employed allowed to verify the open-source solver developed in OpenFOAM, but the results obtained are not sufficient to validate it;
- Future work will comprise some more work with openInjMoldSim in order to validate it, using different geometries and converged meshes;
- Other studies might be taken in order to accelerate and improve the efficiency of the open-source solver;

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Geometry and Processing Conditions

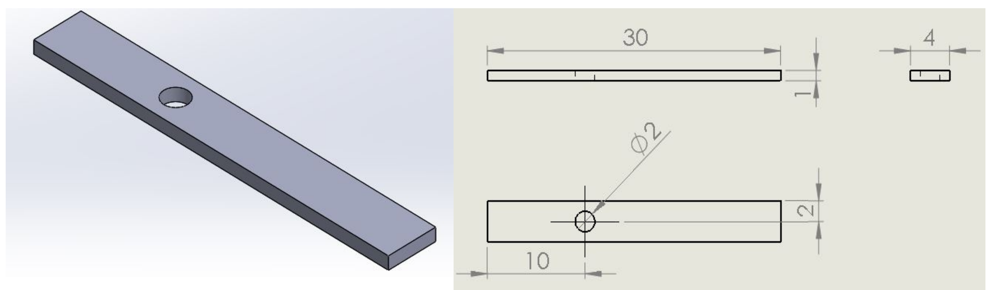

Figure 1: 3D and 2D view of the part to be studied.

The material used was a polystyrene – Styron 678 Americas Styrenics, and the processing conditions used were:

$$T_{melt} = 230°C$$
$$T_{melt} = 50°C$$
$$t_{inj} = 0{,}1\ s$$

Governing Equations

Conservation of Mass

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

Conservation of linear momentum

$$\rho \frac{D\underline{u}}{Dt} = -\nabla p + \nabla \cdot \underline{\underline{\tau}} + \rho \underline{g}$$

Conservation of energy

$$\rho C_p \left[\frac{\partial T}{\partial t} + \underline{u} \cdot (\nabla T)\right] = \beta T \left(\frac{\partial p}{\partial t} + \underline{u} \cdot \nabla p\right) + \nabla \cdot (k \nabla T) + \eta(\dot{\gamma})\dot{\gamma}^2$$

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

$$\eta_0(T, p) = D_1 \exp\left(\frac{-A_1(T - T_0)}{A_2 + (T - T_0)}\right)$$

where $T_0 = D_2 + D_3 p$

$$\underline{\underline{\tau}} = \frac{1}{2}\eta(\dot{\gamma})\left(\nabla \underline{u} + (\nabla \underline{u})^T\right)$$

$$\rho = \left\{\hat{V}_0 \left[1 - C\ln\left(1 + \frac{p}{B}\right)\right] + \hat{V}_t\right\}^{-1}$$

$$\hat{V}_0 = \begin{cases} b_{1s} + b_{2s}(T - b_5), & if\ T \le T_t \\ b_{1L} + b_{2L}(T - b_5), & if\ T > T_t \end{cases}$$

$$B = \begin{cases} b_{3s}\exp(-b_{4s}(T - b_5)), & if\ T \le T_t \\ b_{3L}\exp(-b_{4L}(T - b_5)), & if\ T > T_t \end{cases}$$

$$\hat{V}_t = \begin{cases} b_7 \exp(b_8(T - b_5) - b_9 p), & if\ T \le T_t \\ 0, & if\ T > T_t \end{cases}$$

$$T_t = b_5 + b_6 p$$

Case study 1: Filling of a pipe flow

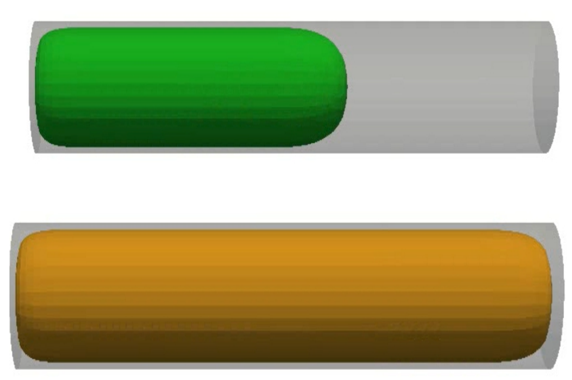

Figure 2: Evolution of the flow front in the filling of a pipe at t=0,015s and t= 0,023s.

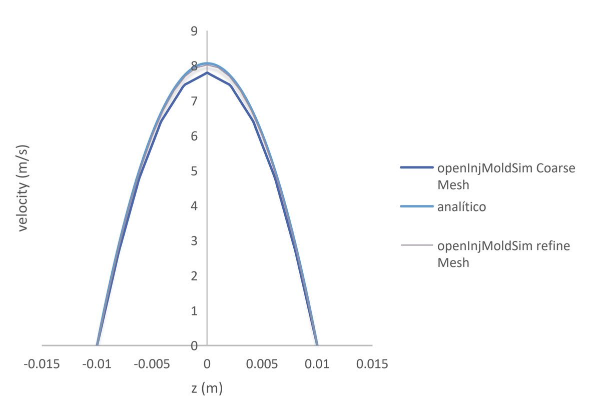

Figure 3: Velocity profile along the channel thickness.

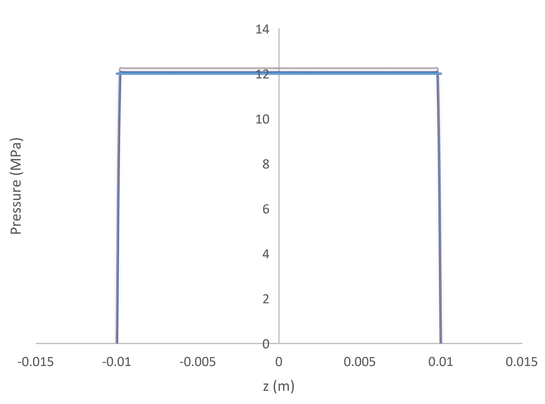

Figure 4: Pressure profile over the channel thickness at the half length of the pipe.

Case study 2: Injection moulding of rectangular cavity with a cylindrical insert

Table 1: Values of maximum velocity and pressure drop obtained with both solvers and their relative errors as a function of the number of cells and simulation time.

Meshes	Number of Cells		Simulation Time (minutes)		u (m/s)		Δp (MPa)		Er (u) (%)	Er (Δp) (%)
	Moldex 3D	OpenInjMold Sim	Moldex 3D	OpenInjMold Sim	Moldex 3D	OpenInjMold Sim	Moldex 3D	OpenInjMold Sim		
Mesh 1	19509	19852	2	43	1,022	0,811	5,498	8,43	$\frac{1{,}022-0{,}811}{0{,}9165}\times 100 = 23\%$	$\frac{8{,}43-5{,}498}{6{,}964}\times 100 = 42\%$
Mesh 2	158322	180600	28	392	1,027	0,869	5,907	4,39	$\frac{1{,}027-0{,}869}{0{,}948}\times 100 = 17\%$	$\frac{5{,}907-4{,}39}{5{,}148}\times 100 = 29\%$
Mesh 3	1297509	1337276	300	5328	0,99	0,95	6,204	5,288	$\frac{0{,}99-0{,}95}{0{,}97}\times 100 = 4\%$	$\frac{6{,}204-5{,}288}{5{,}746}\times 100 = 16\%$

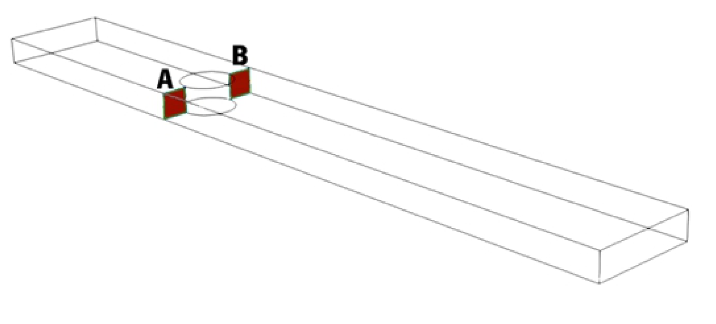

Figure 5: Cross-section for which the results were analysed.

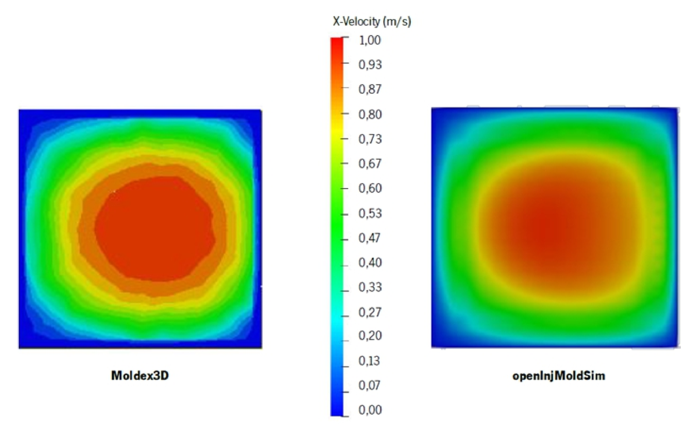

Figure 6: Velocity profile for Mesh 3 in the cross-section.

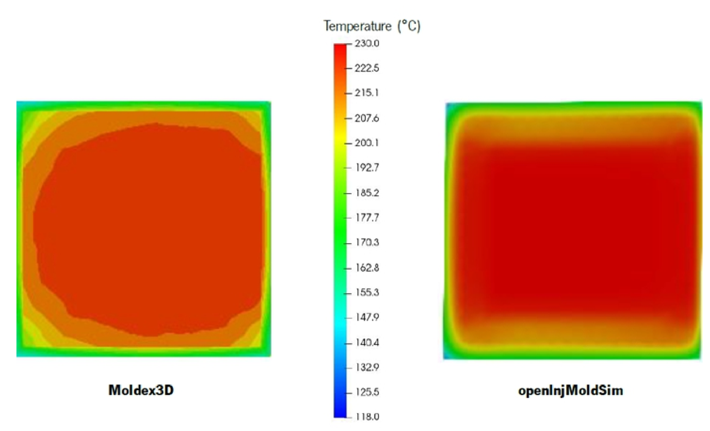

Figure 7: Temperature profile for Mesh 3 in the cross-section.

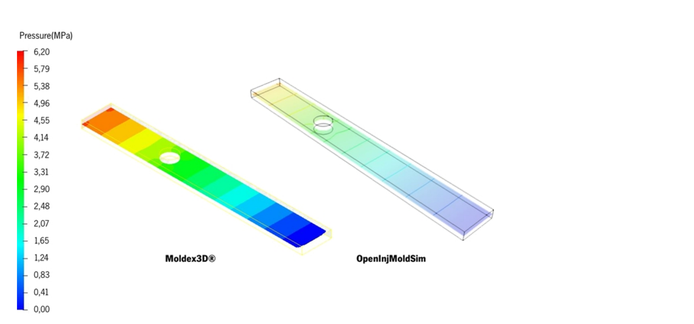

Figure 8: Pressure drop along the mould cavity for Mesh 3, at the end of the filling stage.

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