VERIFICATION AND ASSESSMENT OF AN OPEN-SOURCE SOLVER FOR THE FILLING STAGE OF THE INJECTION MOULDING PROCESS

OIMUO III – Online international Meeting for Users of OpenFOAM III

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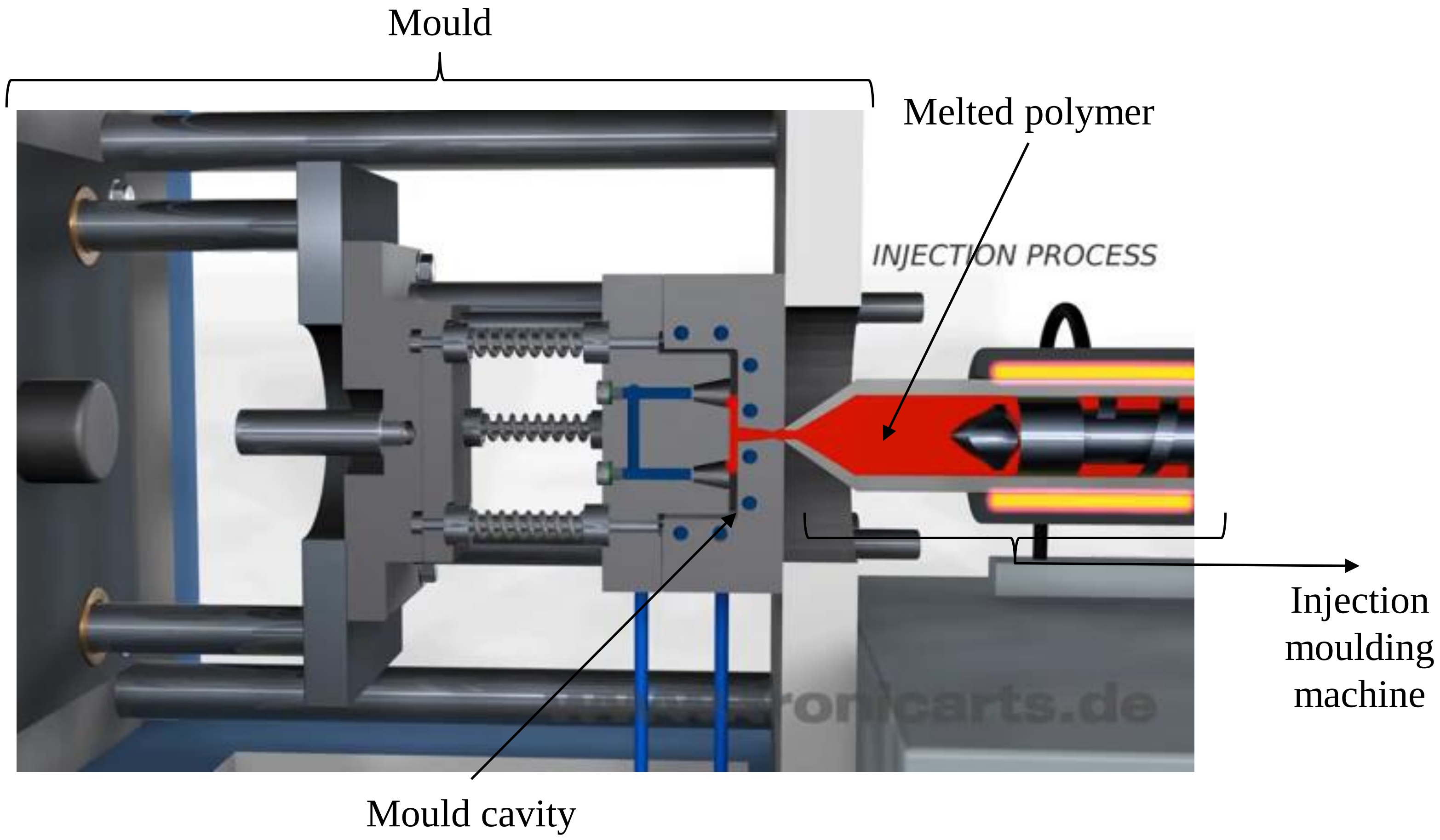
1. Injection Moulding Process



gfycat, GIF retrieved on 21 of February from: https://gfycat.com/adventurouscaringcavy

2. Motivation and Objectives

Motivation

Injection Moulding Process (IM) → **High-cost process** → **Numerical modelling tools** → **Open-source numerical modelling software**

High-cost process:
- Moulds;
- Process conditions;

Numerical modelling tools:
- Proprietary software;
- No access to source code;

Objective

↓

Validation and assessment of *openInjMoldSim*

N. Mole, K. Krebelj, and B. Stok. Injection molding simulation with solid semi-crystalline polymer mechanical behavior for ejection analysis. International Journal of Advanced Manufacturing Technology, 93:4111{4124, 2017. DOI: https://doi.org/10.1007/s00170-017-0847-3.

3. Background: Mathematical foundation

Governing Equations for *openInjMoldSim* and Moldex3D®:

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

Mass conservation equation

$$\frac{\partial (\rho \underline{u})}{\partial t} + \nabla \cdot (\rho \underline{u}\ \underline{u}) = -\nabla p + \nabla \cdot \left(\eta\left(\dot{\gamma}, T, p\right) \underline{\underline{D}}\right) + \rho \underline{g}$$

Linear momentum balance equation

$$\rho c_p \left(\frac{\partial T}{\partial t} + \underline{u} \cdot \nabla T\right) = \underbrace{\beta T \left(\frac{\partial p}{\partial t} + \underline{u} \cdot \nabla p\right)}_{\text{Not accounted in Moldex3D®}} + \eta\left(\dot{\gamma}, T, p\right) \dot{\gamma}^2 + k \nabla^2 T$$

Energy conservation equation

3. Background: Mathematical foundation

Volume of fluid method (VOF):

$$\frac{\partial \alpha}{\partial t} + \nabla \cdot (\alpha \underline{u}) + \overbrace{\underbrace{\nabla \cdot [\alpha(1-\alpha)\underline{u}_r]}_{\text{Interface compression term}}}^{\text{Not accounted in Moldex3D®}} = S_p + S_u$$

The compression velocity $\underline{u}_r$ is given by:

$$\underline{u}_r = \underline{n}_f \, min\left[C_\alpha \frac{|\phi|}{|\underline{S}_f|}, \max\left(\frac{|\phi|}{|\underline{S}_f|}\right)\right],$$

where

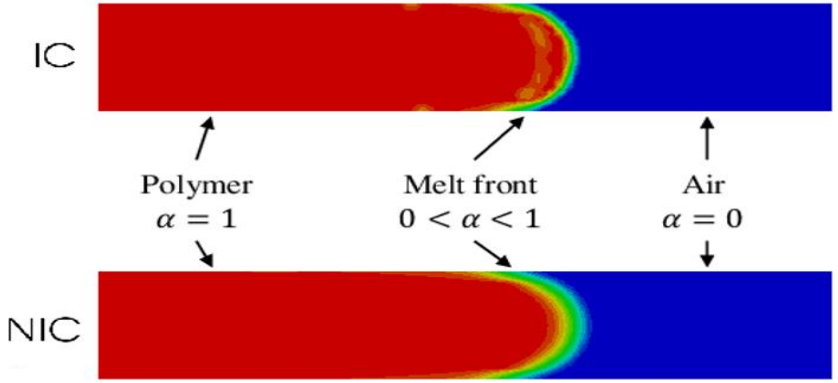
$$\underline{n}_f = \frac{(\nabla\alpha)_f}{|(\nabla\alpha)_f + \delta|}.$$

Physical properties are calculated as:

$$\zeta = \zeta_{melt}\alpha + (1-\alpha)\zeta_{air},$$

where ζ represents either ρ, k, c_P, η.

α distribution in an injection moulding case study.



IC – interface compression;
NIC – no interface compression;

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4. Material Models

Material: GPPS – General Purpose Polystyrene Styron 678, from Americas Styrenics.

Constitutive model:

Cross-WLF

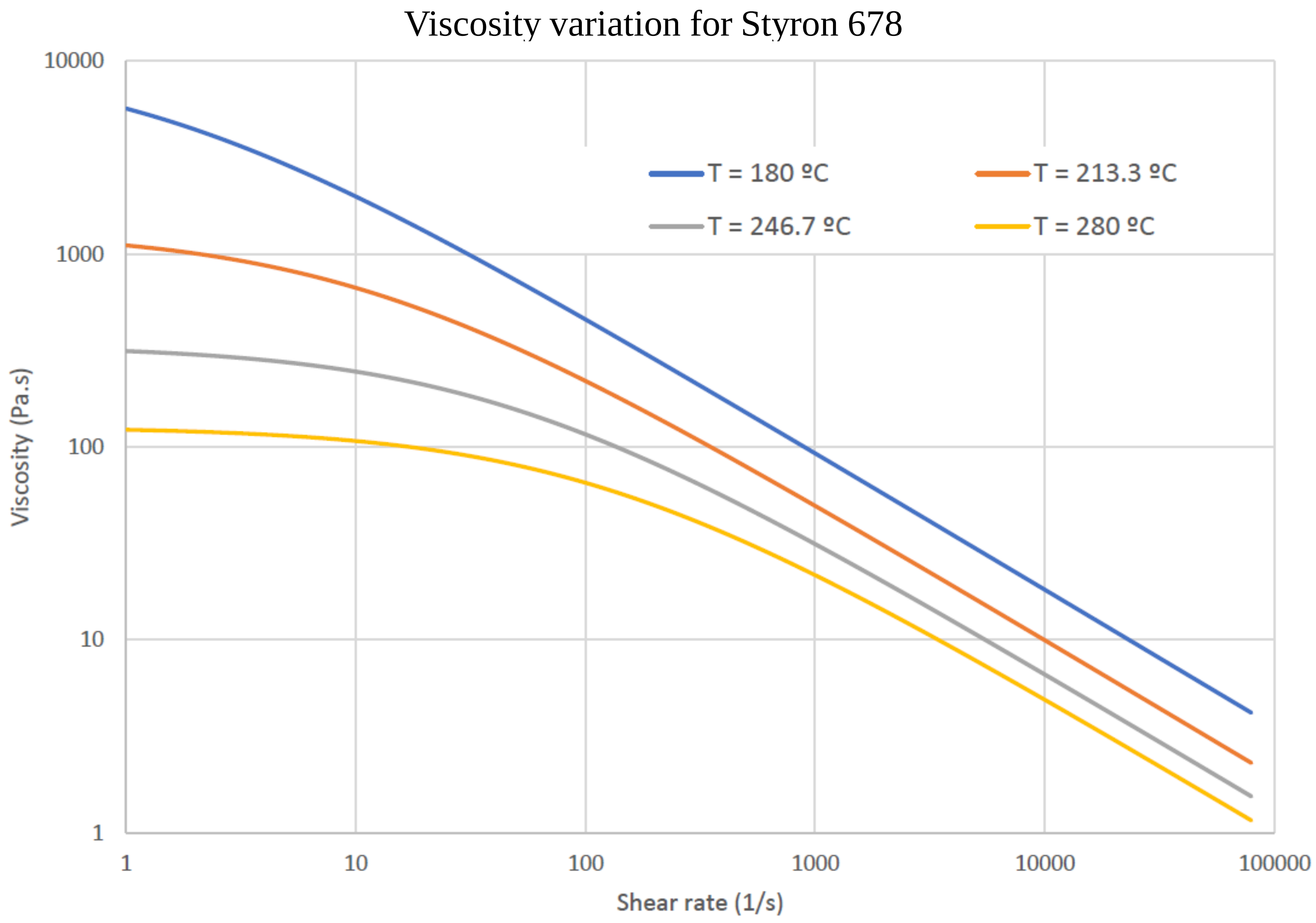
$$\eta\left(\dot{\gamma}, T, p\right) = \frac{\eta_0\left(T, p\right)}{1 + \left(\frac{\eta_0\left(T,p\right)\dot{\gamma}}{\tau^*}\right)^{n-1}}.$$

where,

$$\eta_0\left(T, p\right) = D_1 \exp\left(\frac{-C_1\left(T - T_0\right)}{C_2 + T - T_0}\right),$$

and,

$$T_0 = D_2 + D_3 p$$



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4. Material Models

Material: GPPS – General Purpose Polystyrene Styron 678, from Americas Styrenics.

Equation of state:

Modified Tait model

$$\widehat{V} = \widehat{V_0}\left[1 - C\ln\left(1 + \left(\frac{p}{B}\right)\right)\right] + \widehat{V}_t,$$

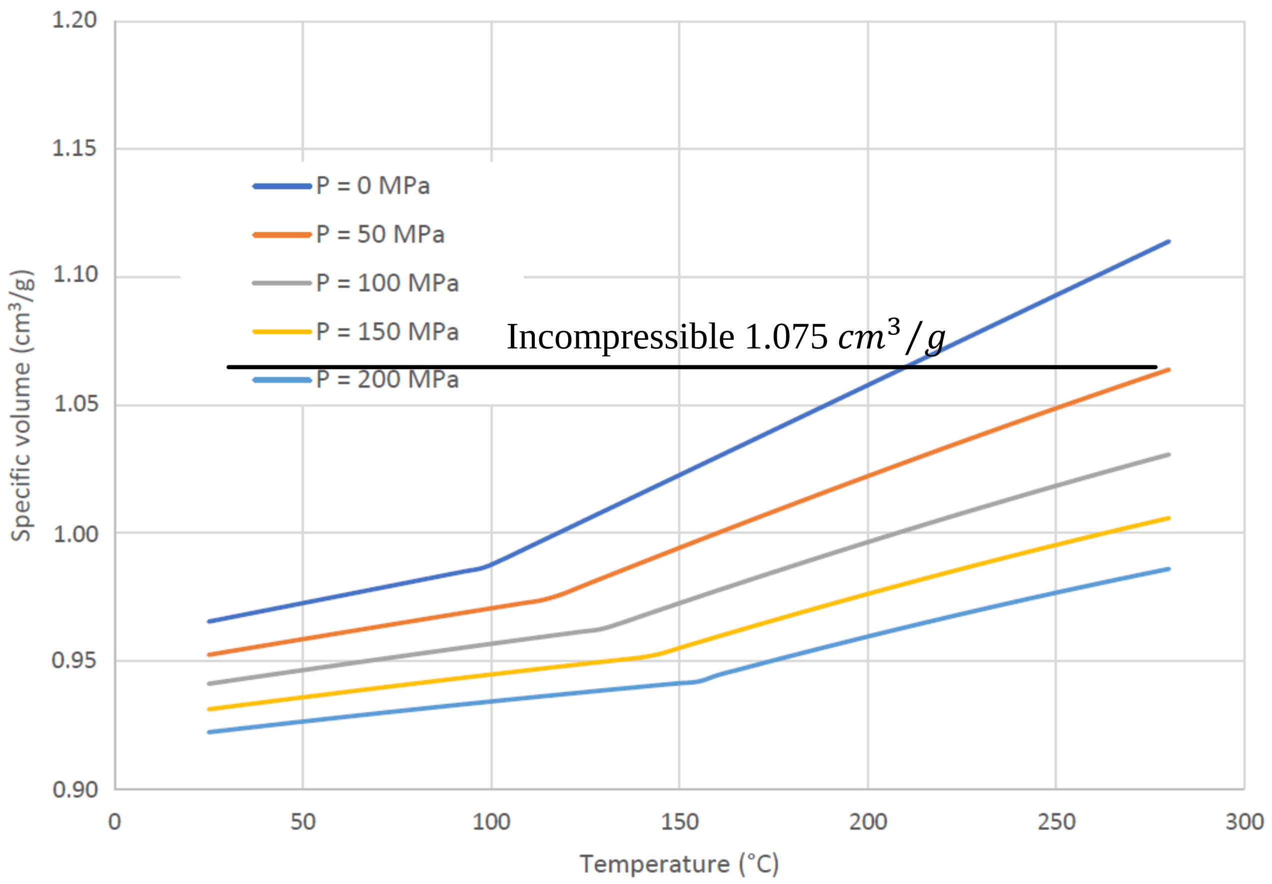
where

$$\widehat{V_0} = \begin{cases} b_{1S} + b_{2S}\left(T - b_5\right), & \text{if } T \leq T_t \\ b_{1L} + b_{2L}\left(T - b_5\right), & \text{if } T > T_t \end{cases},$$

$$B = \begin{cases} b_{3S}\exp\left(-b_{4S}\left(T - b_5\right)\right), & \text{if } T \leq T_t \\ b_{3L}\exp\left(-b_{4L}\left(T - b_5\right)\right), & \text{if } T > T_t \end{cases},$$

$$\widehat{V}_t = \begin{cases} b_7\exp\left(b_8\left(T - b_5\right) - b_9 p\right), & \text{if } T \leq T_t \\ 0, & \text{if } T > T_t \end{cases},$$

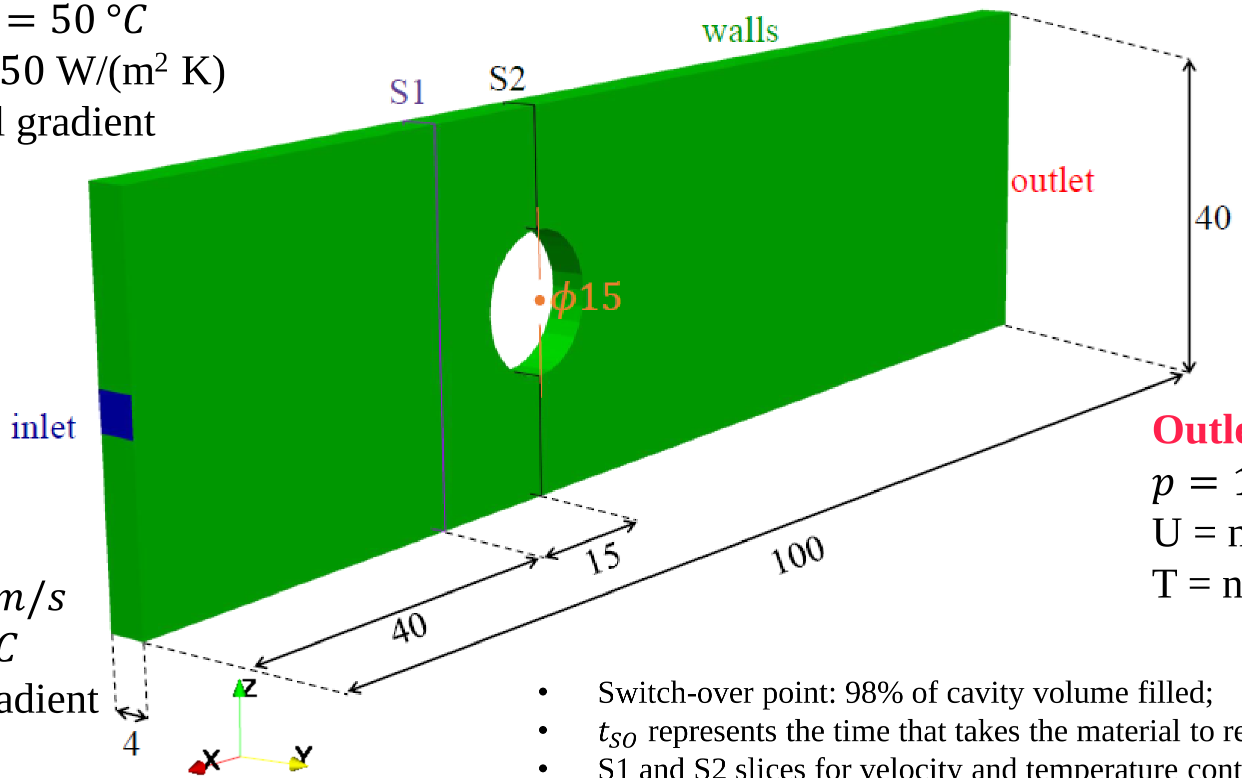
Compressible and Incompressible formulations



5. Case study 1 – Rectangular cavity with cylindrical insert

Geometry, patches and initial and boundary conditions
(Dimensions in mm).

walls
$U = 0\ m/s$
$T_{mould} = 50\ °C$
$h = 1250$ W/(m^2 K)
P = null gradient



inlet
$U = 1.46\ m/s$
$T = 230\ °C$
P = null gradient

Outlet
$p = 1 \times 10^5 Pa$
U = null gradient
T = null gradient

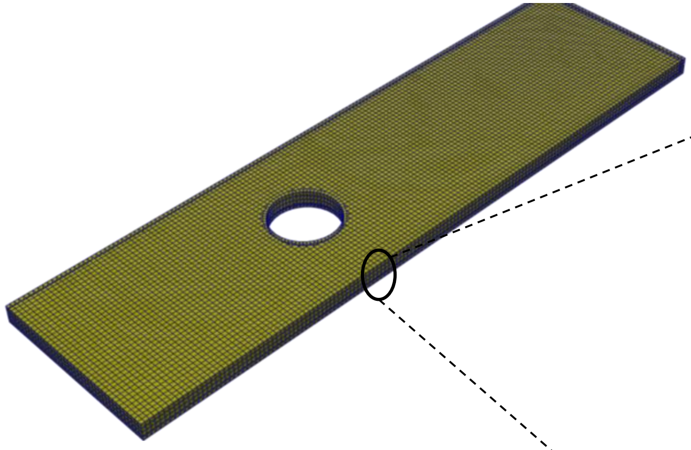
Materials and models

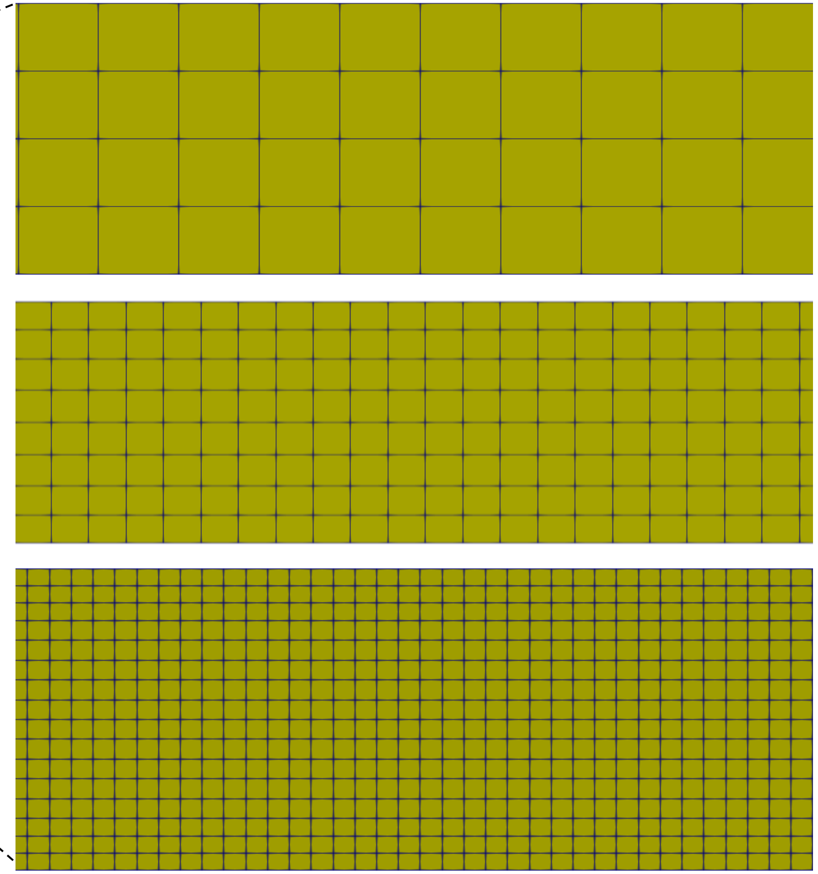
Phase	Constitutive Model	Formulations of Equation of state
GPPS Styron 678	Cross-WLF	Compressible (C)
		Incompressible (I)
Air	Newtonian $\mu = 0.1\ Pa.s$	Ideal Gas

- Switch-over point: 98% of cavity volume filled;
- t_{SO} represents the time that takes the material to reach switch-over point;
- S1 and S2 slices for velocity and temperature contours;

5. Case study 1 – Rectangular cavity with cylindrical insert

Number of cells in the three levels of refinement along thickness direction



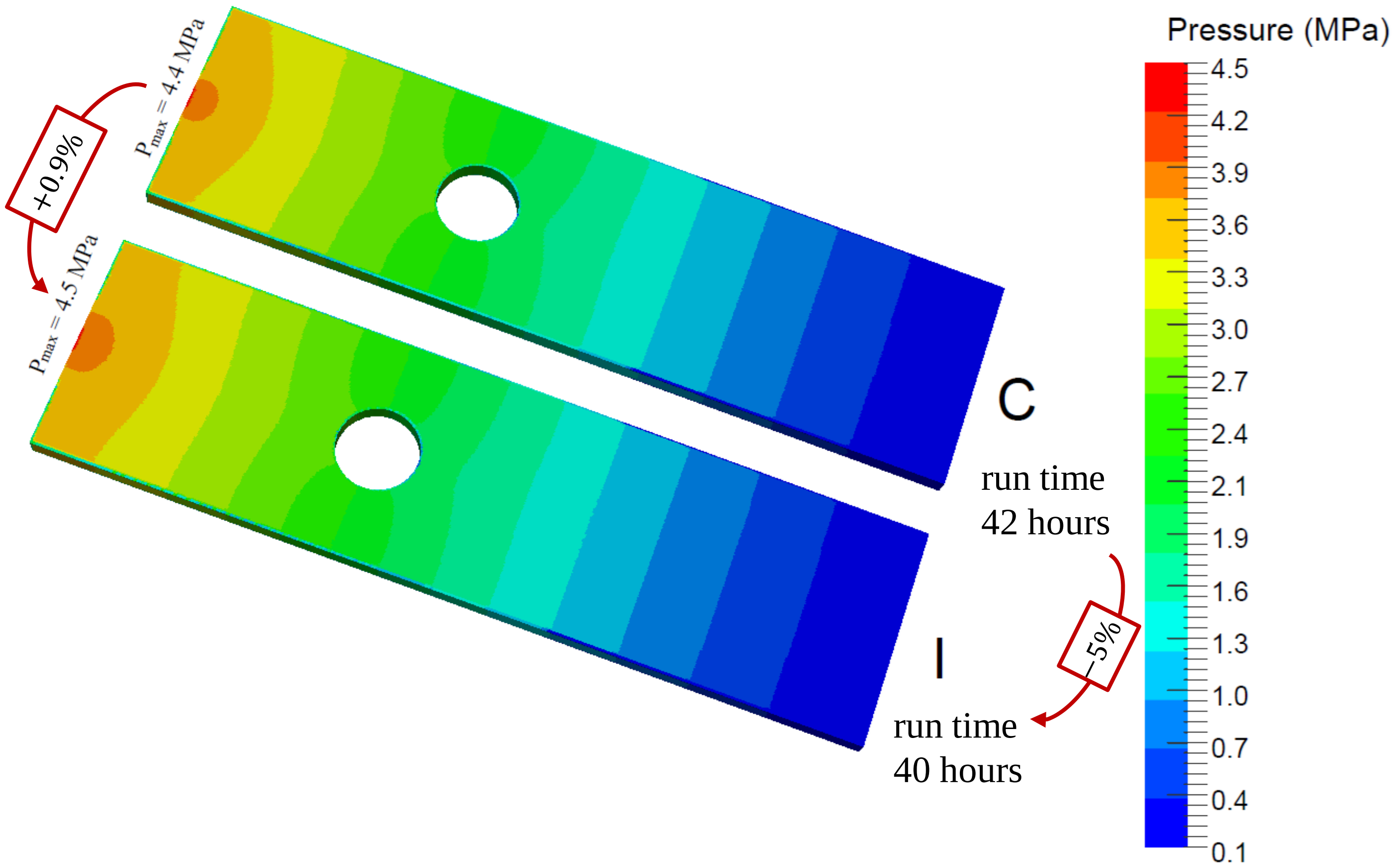


Mesh refinement levels

Mesh	Number of cells	Cells along thickness direction
M1	23 712	4
M2	187 480	8
M3	1 494 064	16

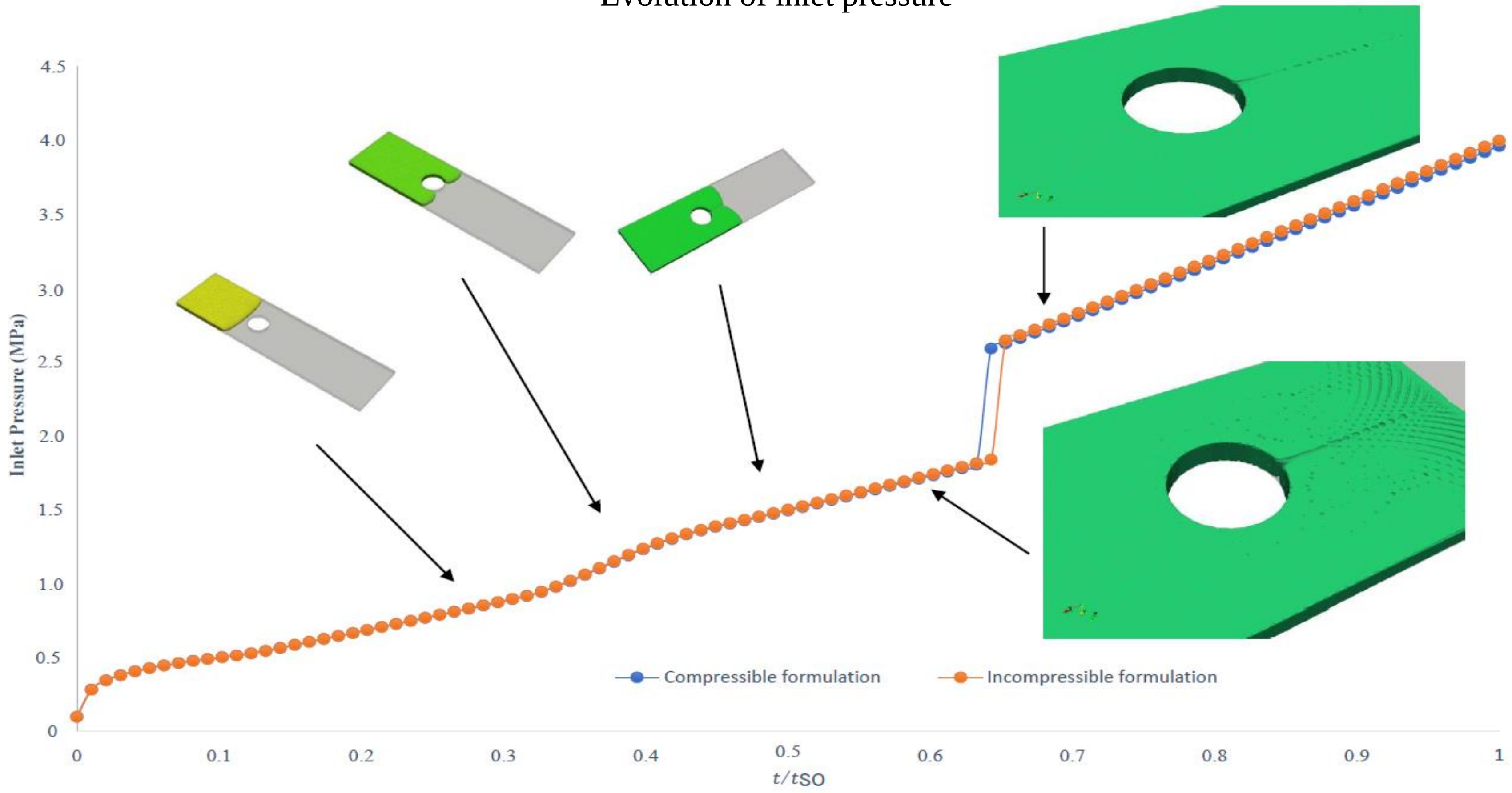
5. Case study 1 – Rectangular cavity with cylindrical insert

Pressure contours and run time at switch-over point



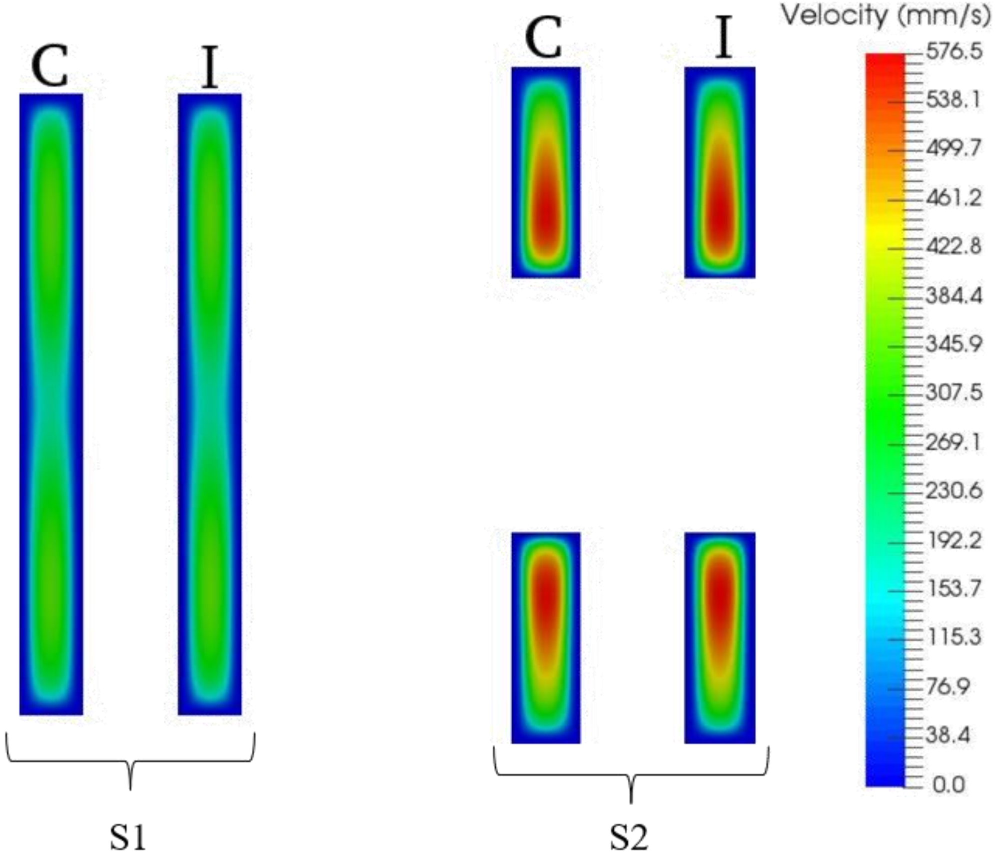
5. Case study 1 – Rectangular cavity with cylindrical insert

Evolution of inlet pressure



5. Case study 1 – Rectangular cavity with cylindrical insert

Velocity contours at switch-over point

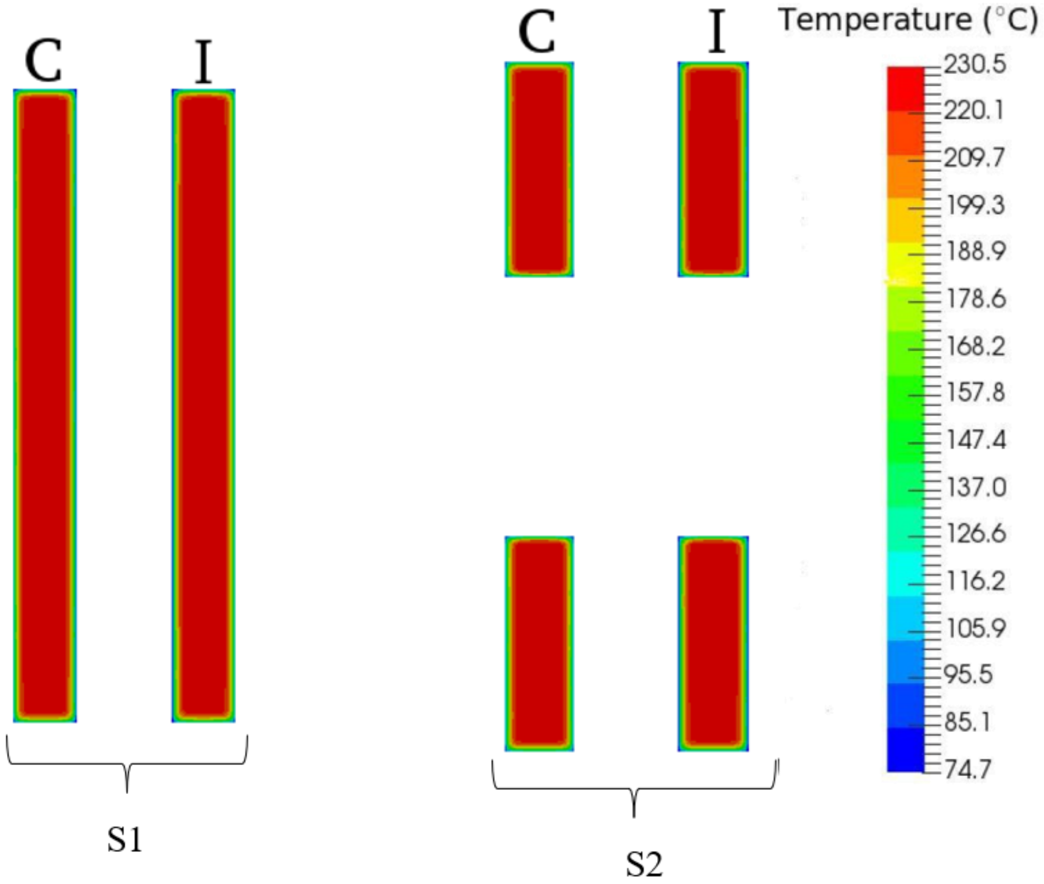


Average and maximum velocity

Slice	Formulation	Velocity (mm/s)		Relative differences (%)	
		U_{ave}	U_{max}	U_{ave}	U_{max}
S1	C (ref)	148.2	342.2	---	---
	I	148.5	344.8	0.2	0.8
S2	C (ref)	232.7	569.6	---	---
	I	233.5	575.5	0.3	1.0

5. Case study 1 – Rectangular cavity with cylindrical insert

Temperature contours at switch-over point

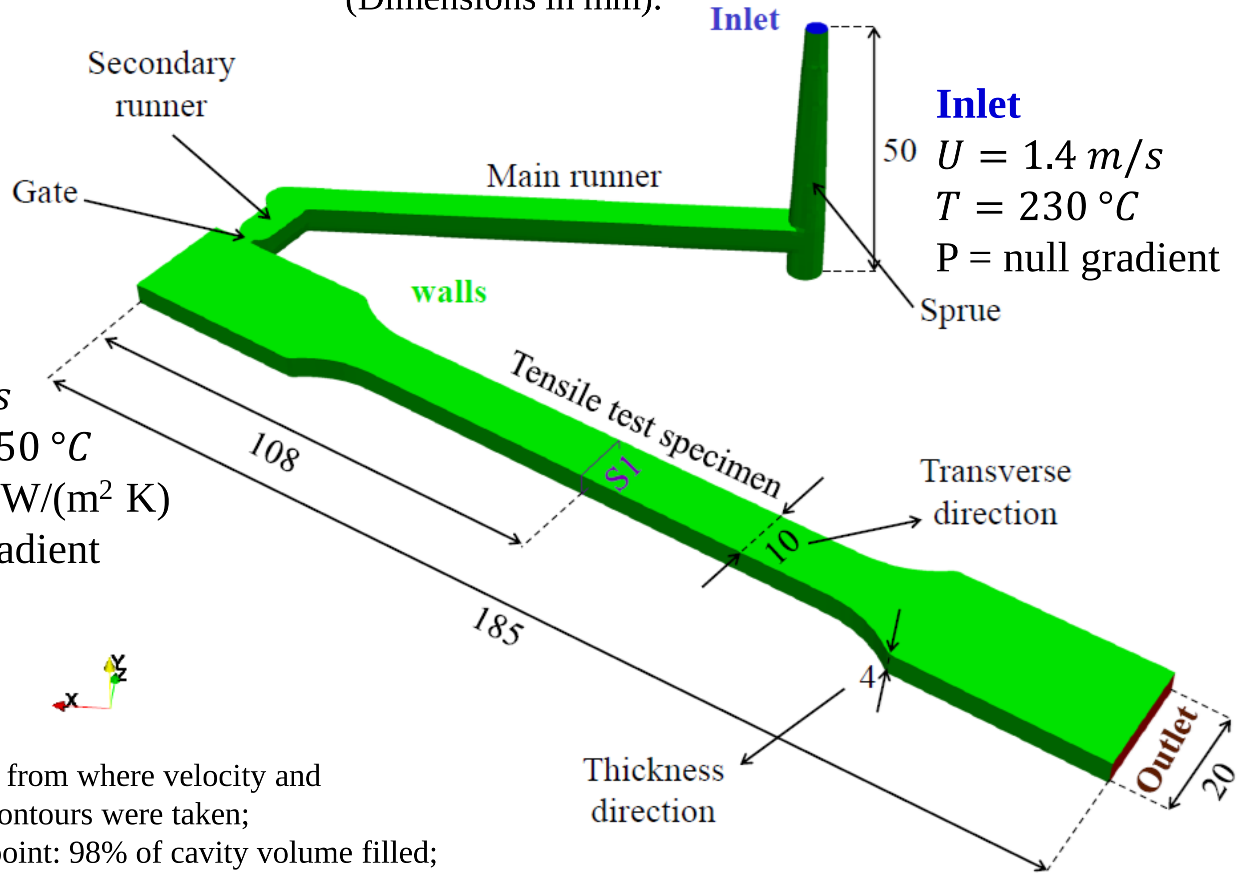


Minimum and maximum temperature

Slice	Formulation	Temperature (°C)		Relative differences (%)	
		T_{min}	T_{max}	T_{min}	T_{max}
S1	C (ref)	98.0	230.2	---	---
	I	94.4	230.4	3.7	0.1
S2	C (ref)	103.3	230.3	---	---
	I	100.0	230.6	3.2	0.1

5. Case study 2 – Tensile test specimen

Geometry, patches and initial and boundary conditions (Dimensions in mm).



Inlet
$U = 1.4\ m/s$
$T = 230\ °C$
P = null gradient

Walls
$U = 0\ m/s$
$T_{mould} = 50\ °C$
$h = 1250$ W/(m^2 K)
P = null gradient

- S1 is the slice from where velocity and temperature contours were taken;
- Switch-over point: 98% of cavity volume filled;

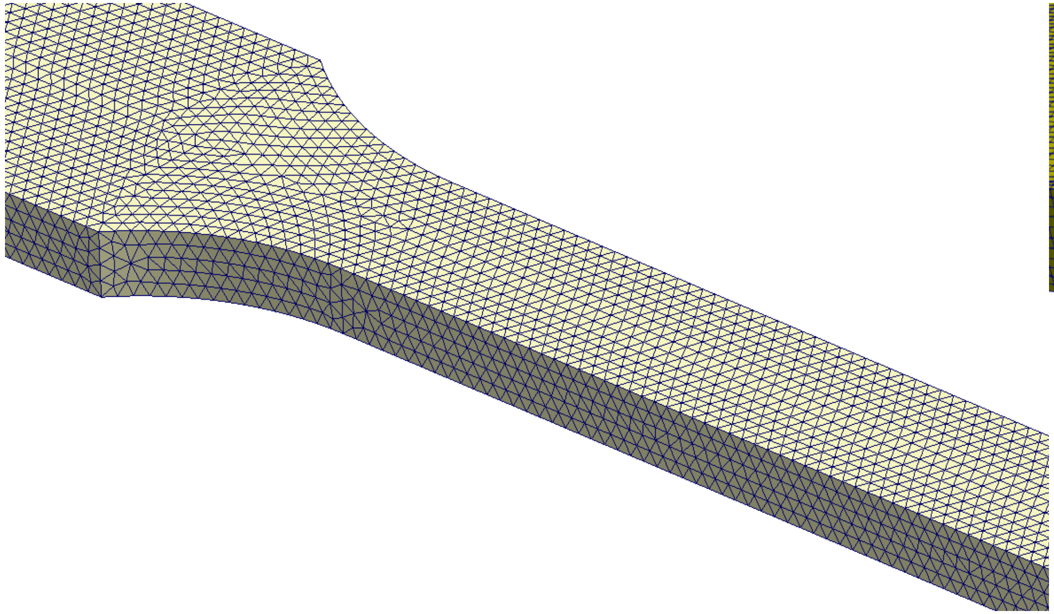
Materials and models

Phase	Constitutive Model	Formulation of Equation of state
GPPS Styron 678	Cross-WLF	Compressible (C)
Air	Newtonian $\mu = 0.1\ Pa.s$	Ideal Gas

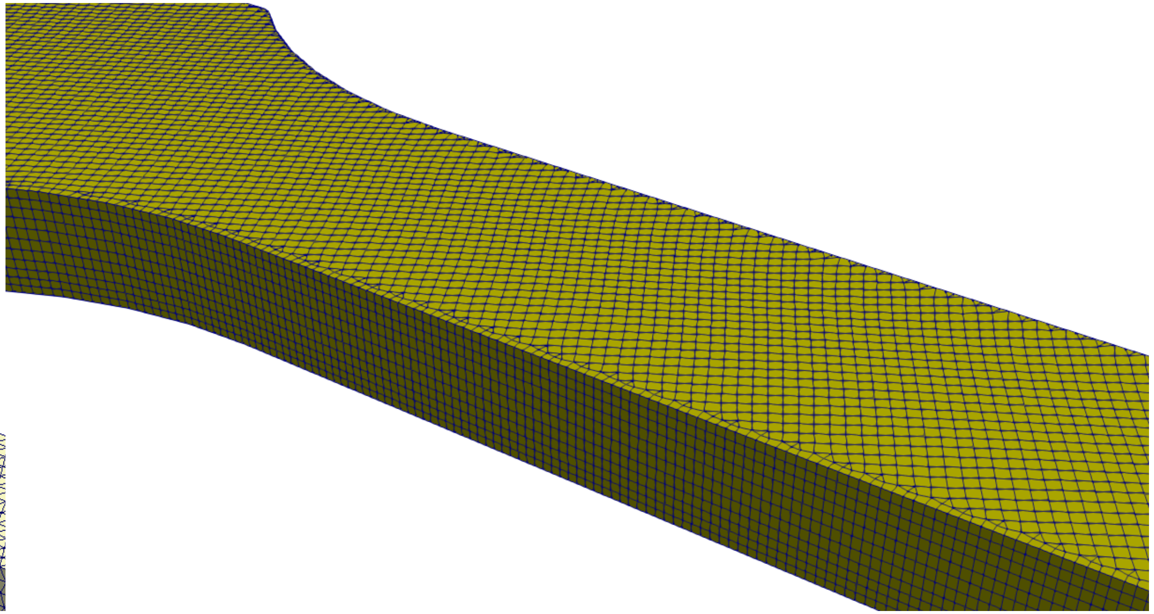
Outlet
$p = 1 \times 10^5 Pa$
U = null gradient
T = null gradient

5. Case study 2 – Tensile test specimen

M2 in both softwares

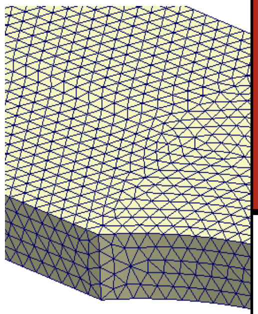


Moldex3D®



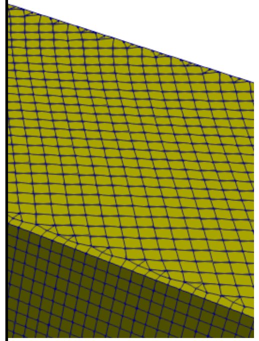
openInjMoldSim

5. Case study 2 – Tensile test specimen



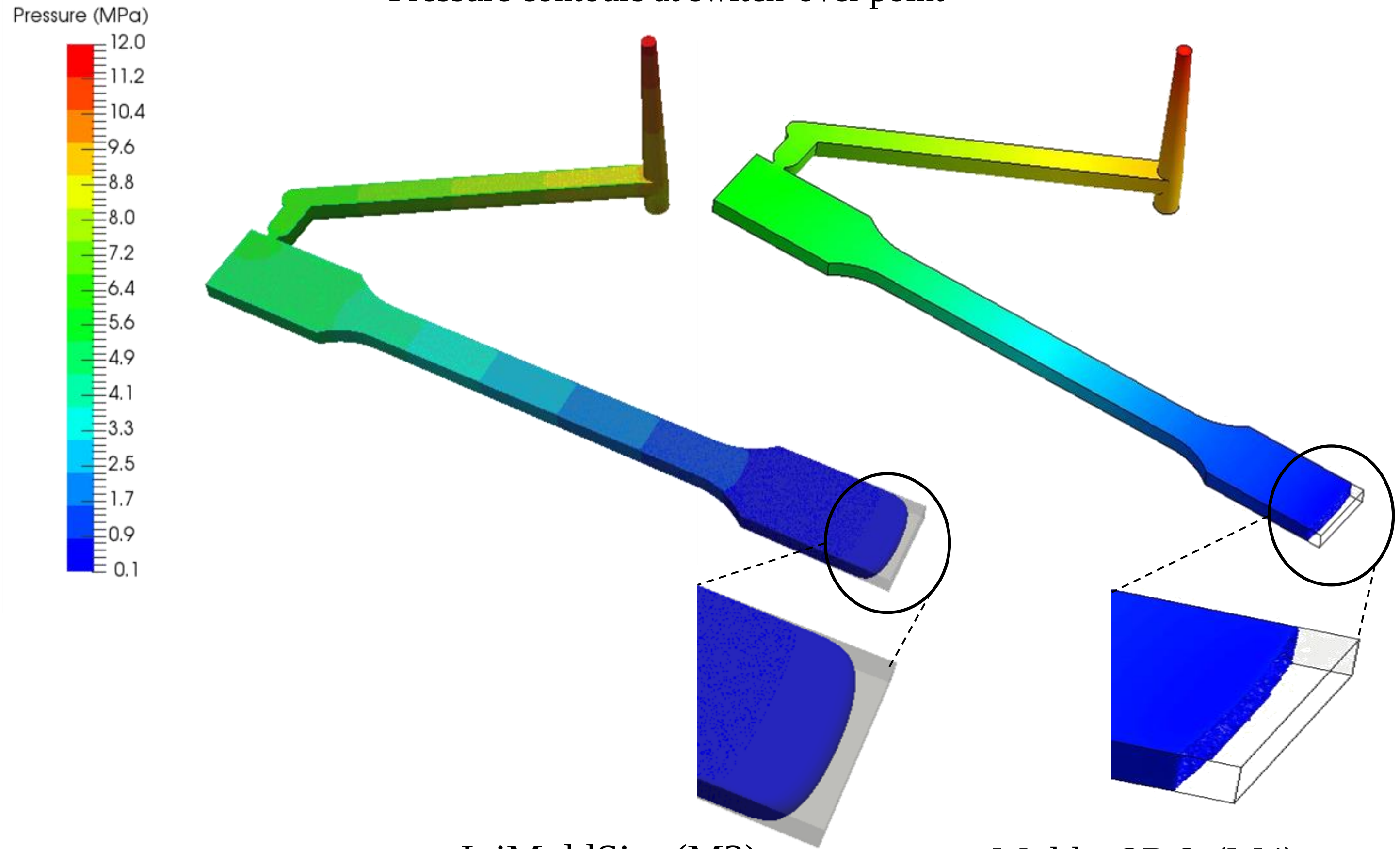
Mesh refinement levels

Mesh	Number of cells		Cells along thickness direction	
	openInjMoldSim	Moldex3D®	openInjMoldSim	Moldex3D®
M1	30 091	29 625	5	2
M2	272 149	272 409	11	5
M3	2 110 987	2 101 139	21	10
M4	---	15 304 010	---	21



5. Case study 2 – Tensile test specimen

Pressure contours at switch-over point



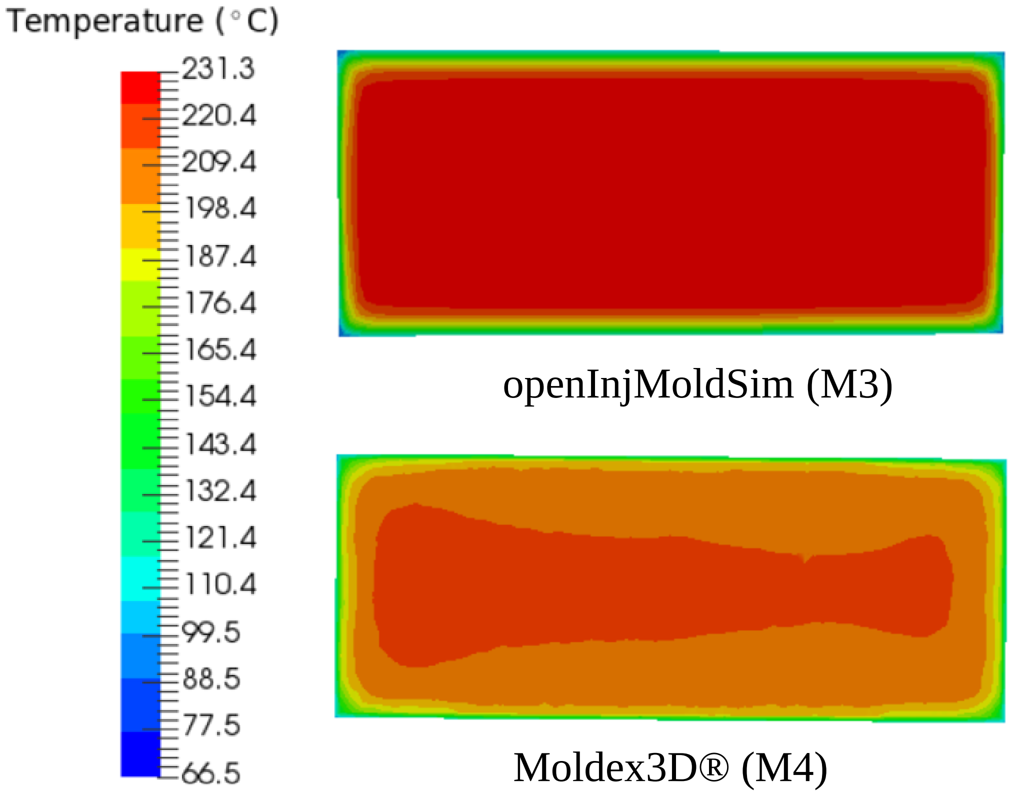
openInjMoldSim (M3)   Moldex3D® (M4)

Pressure at the switch-over point

Mesh	Maximum Pressure (MPa)			
	Moldex3D®	**Error (%)**	**openInjMoldSim**	**Error (%)**
M1	7.18	43.4	7.76	29.6
M2	8.32	34.4	14.07	27.8
M3	9.66	23.8	12.01	9.1
M4	11.61	8.41	---	---
RE	12.68		11.01	

5. Case study 2 – Tensile test specimen

Temperature contours at switch-over point



openInjMoldSim (M3)

Moldex3D® (M4)

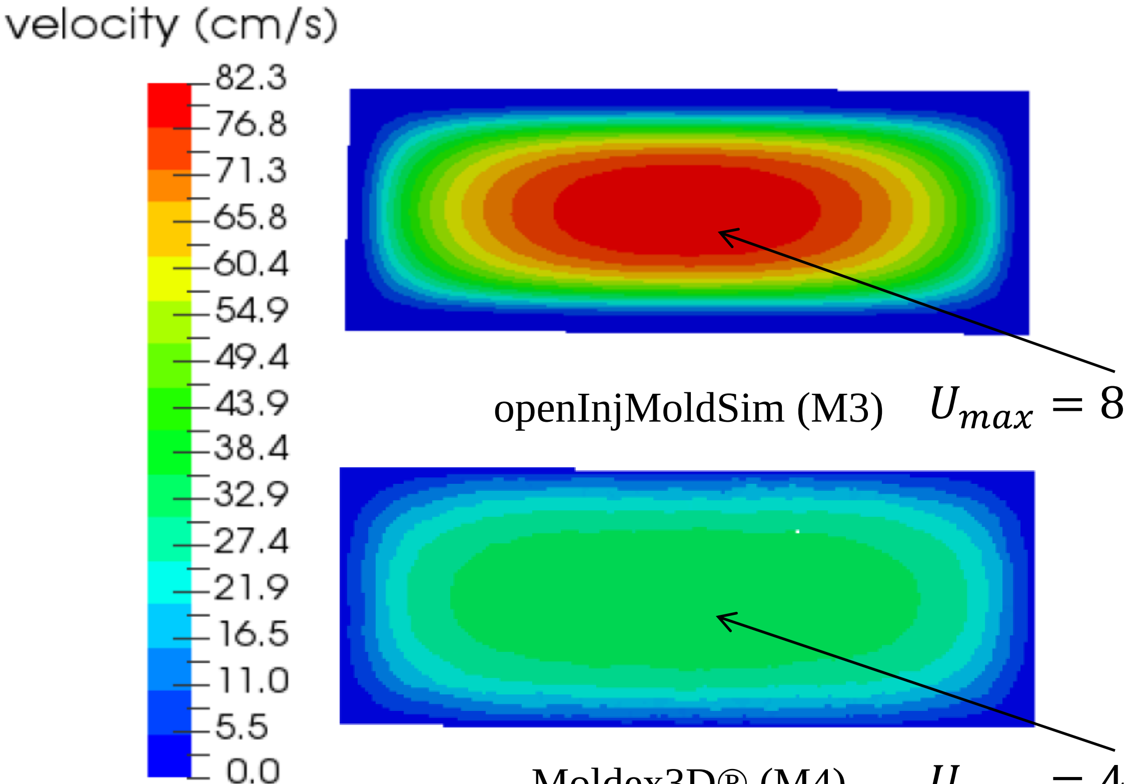
Temperature at the switch-over point

Mesh	**Maximum Temperature (°C)**			
	Moldex3D®	**Error (%)**	**openInjMoldSim**	**Error (%)**
M1	230.2	0.7	230.0	1.0
M2	230.3	0.6	232.2	0.1
M3	230.5	0.5	232.4	0.0
M4	231.3	0.2	---	---
RE	231.7		232.4	

5. Case study 2 – Tensile test specimen

Velocity contours at the switch-over point

$$Q = 15.7\ (cm^3/s) \approx U_{ave} = 40\ (cm/s)$$



openInjMoldSim (M3) $U_{max} = 80(cm/s)$

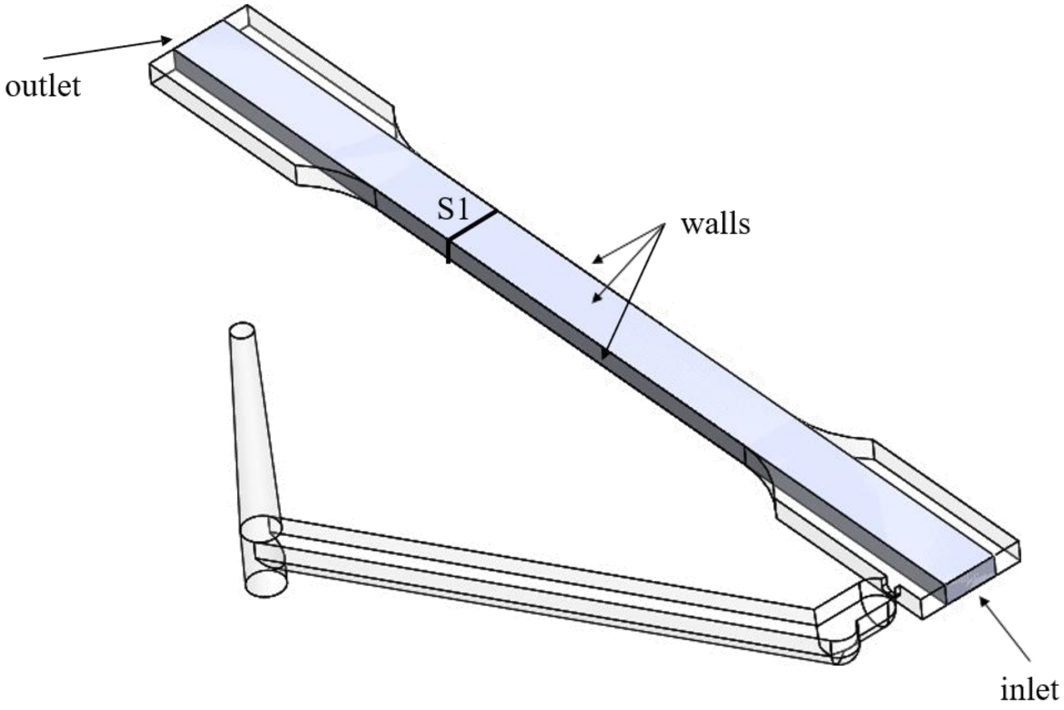
Moldex3D® (M4) $U_{max} = 40(cm/s)$

Velocity at the switch-over point

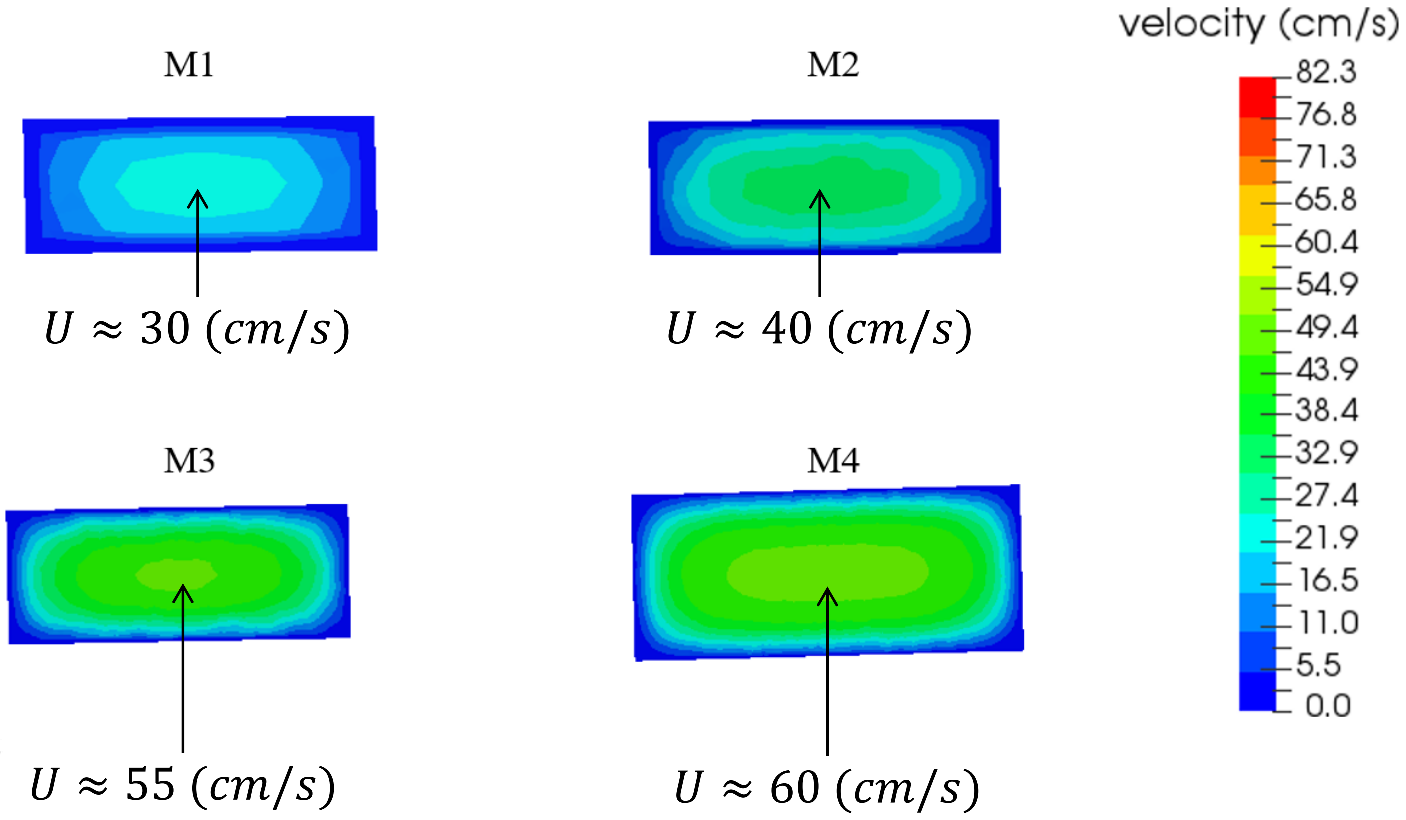
Mesh	Maximum Velocity (mm/s)			
	Moldex3D®	Error (%)	openInjMoldSim	Error (%)
M1	2080	14.2	2530	33.2
M2	1950	19.6	4800	26.7
M3	1930	20.4	4100	8.2
M4	2250	7.22	---	---
RE	2430		3790	

5. Case study 2 – Tensile test specimen

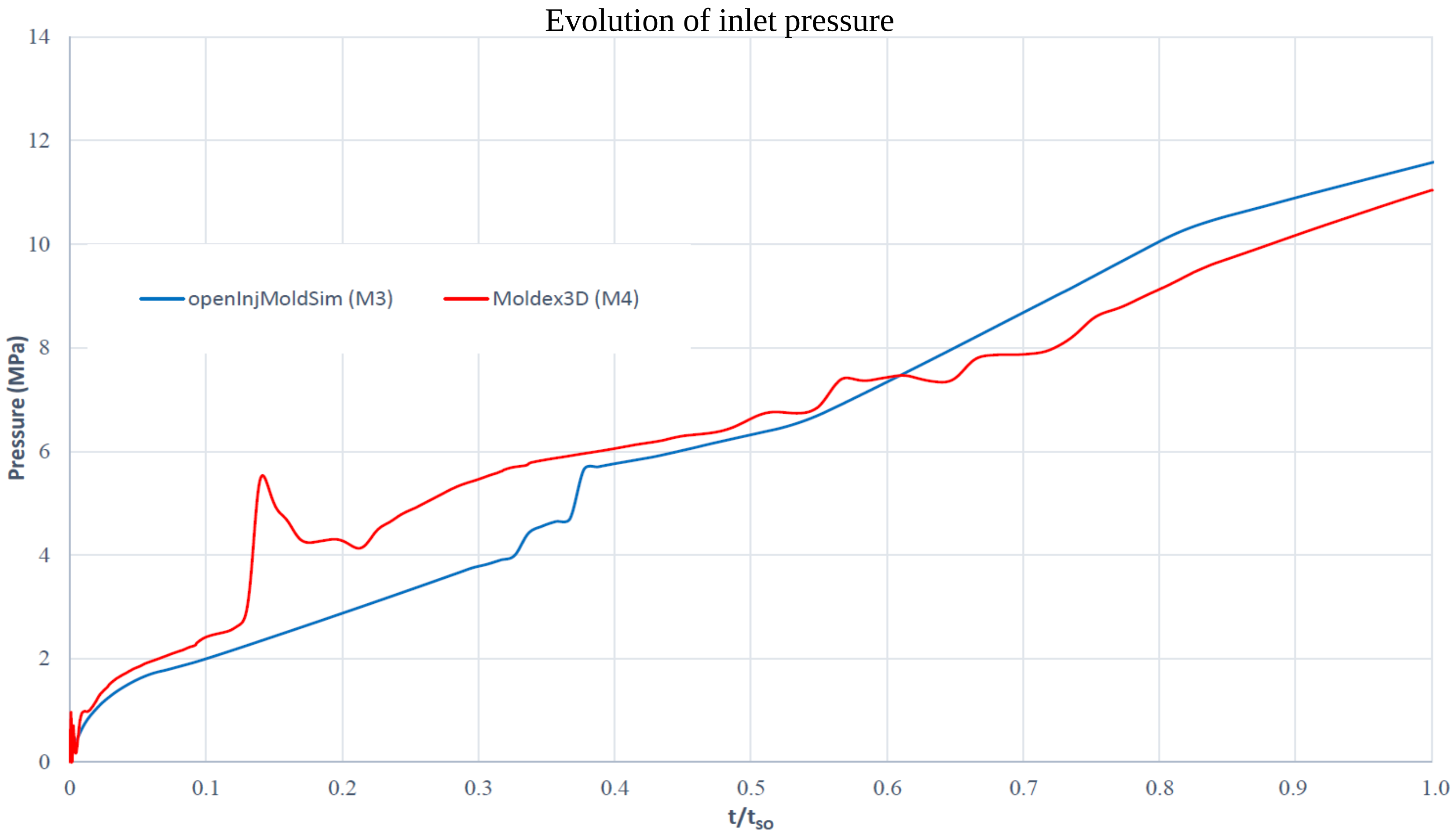
Simplified tensile test specimen geometry



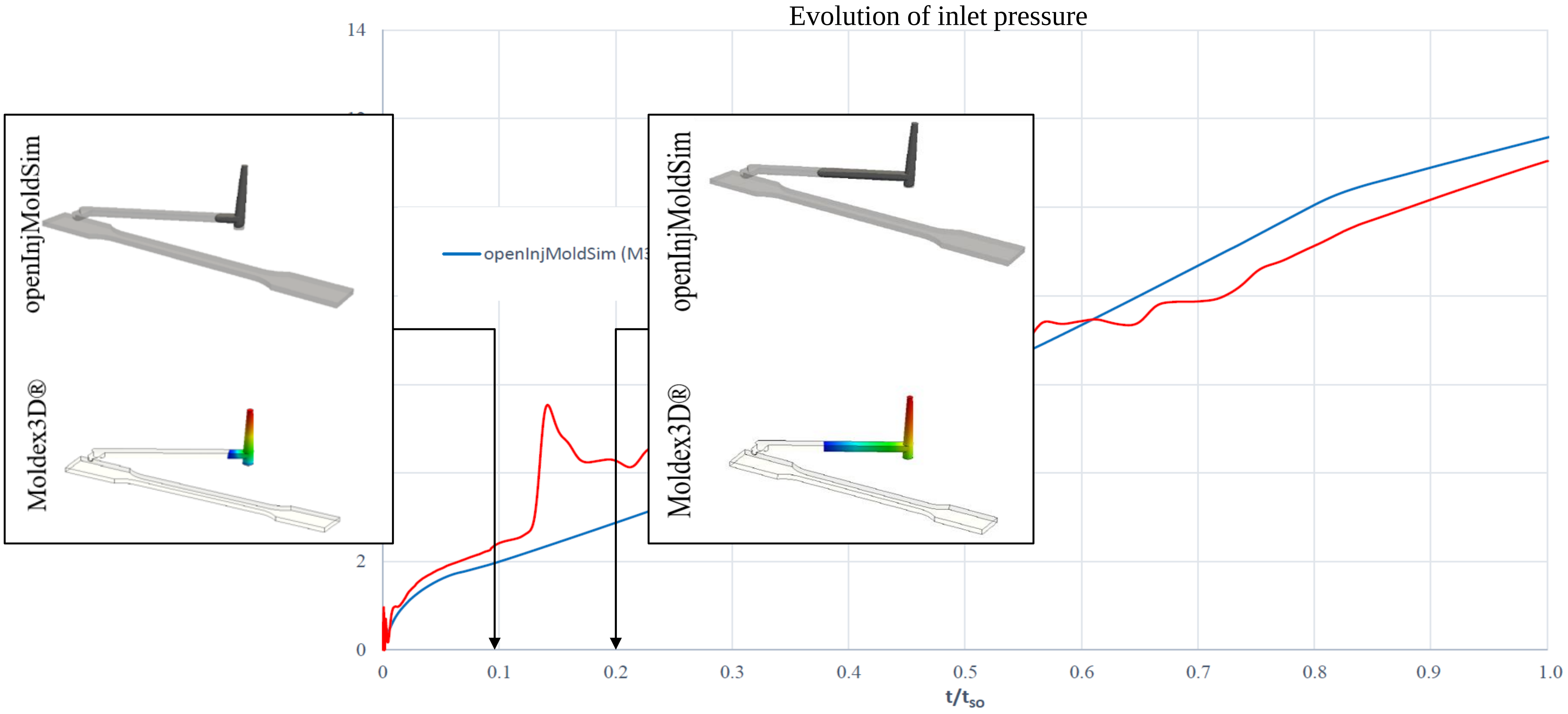
Velocity contours for Moldex3D®



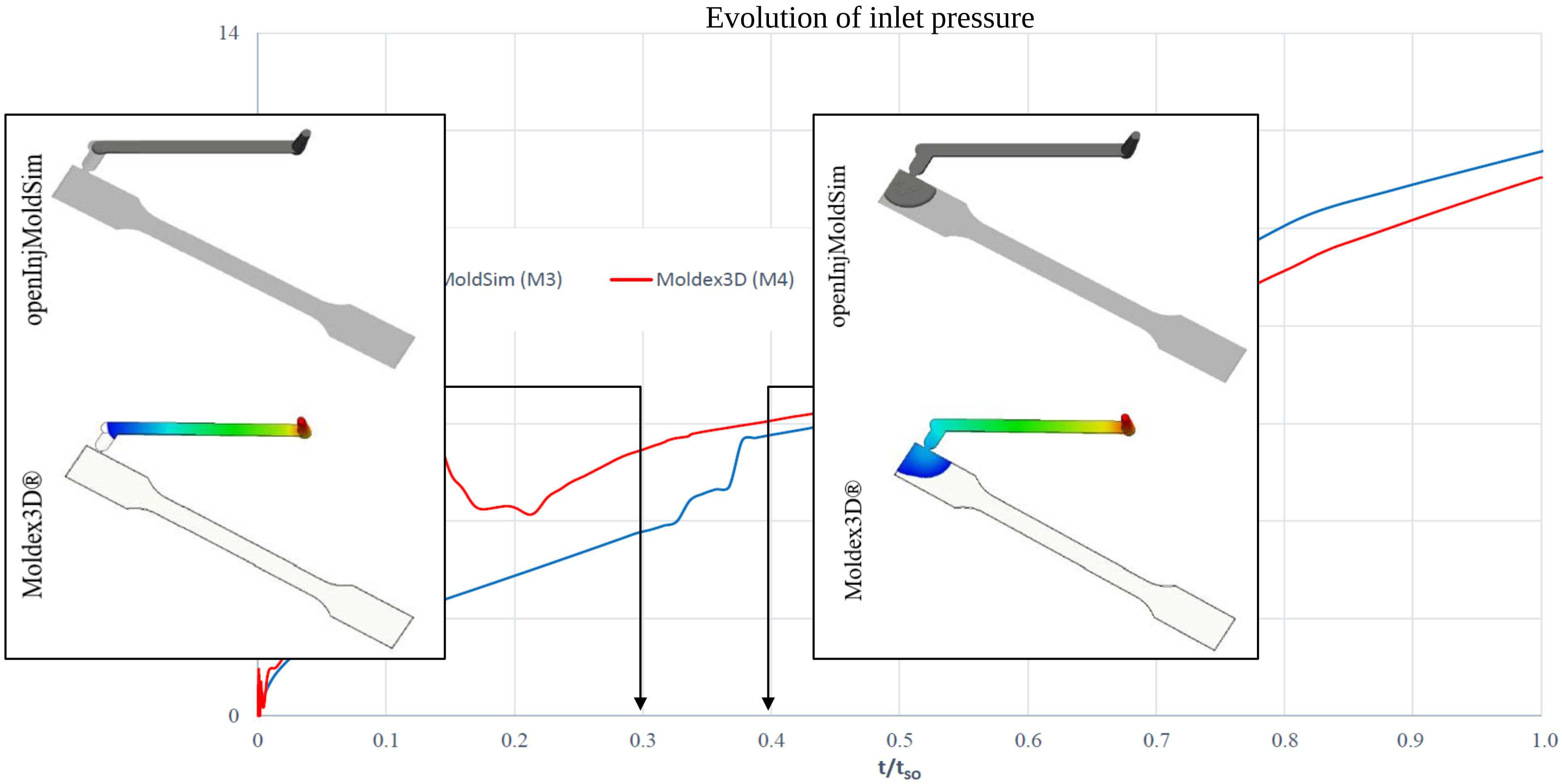
5. Case study 2 – Tensile test specimen



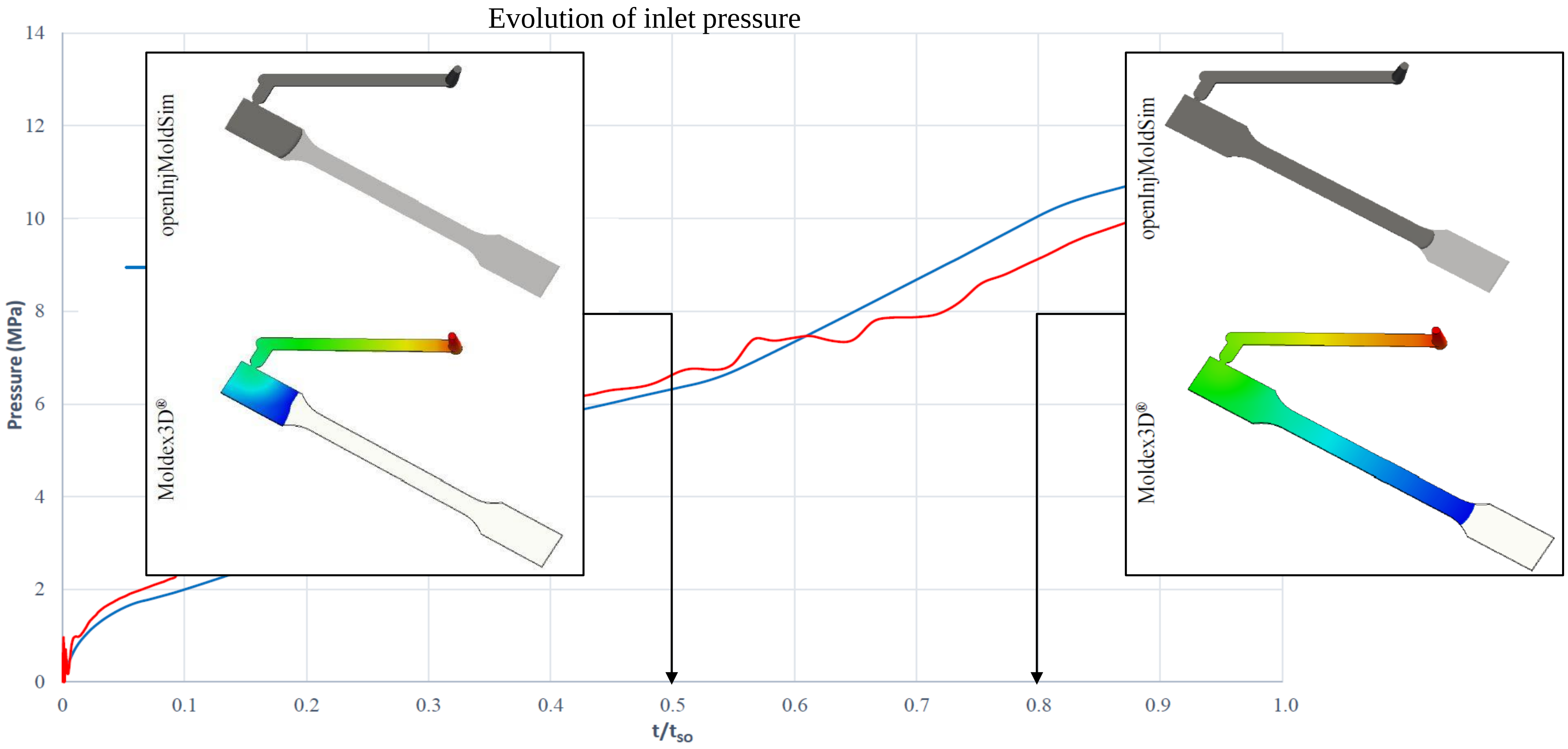
5. Case study 2 – Tensile test specimen



5. Case study 2 – Tensile test specimen



5. Case study 2 – Tensile test specimen



5. Case study 2 – Tensile test specimen

Performance and accuracy

Software	Mesh	Errors (%)			Number of cores	Run Time
		p_{max} (inlet)	U_{max} (S1)	T_{max} (S1)		
Moldex3D®	M1	43.4	14.2	0.7	1	88 seconds
	M2	34.4	19.6	0.6	1	23 minutes
	M3	23.8	20.4	0.5	8	3.8 hours
	M4	8.41	7.22	0.2	8	24.5 hours
openInjMoldSim	M1	29.6	33.2	1.0	1	12.8 hours
	M2	27.8	26.7	0.1	8	41 hours
	M3	9.1	8.2	0.0	48	98.5 hours
					96	59 hours
					192	34 hours

6. Conclusions

- Incompressible formulations might be a good assumption to consider on the filling stage of the injection moulding process;

- *openInjMoldSim* presents a better accuracy than Moldex3D®;

- The velocity contours provided by Moldex3d® require a more detailed analysis;

- In terms of performance Moldex3D® is clearly faster than *openInjMoldSim*;

- If we take the full potential of parallelization power of OpenFOAM®, the open-source solver can match the performance of the proprietary one.

6. Future work

- Experimental assessment of the numerical results obtained;
- Prepare similar studies with other parts and different polymeric materials;
- Implement a fully incompressible formulation for the filling stage of the injection moulding process;
- Improve of the numerical algorithm to make the solver more efficient;
- Perform additional studies to identify the calculation accuracy required in industrial practice;
- Introduce numerical solution for the packing and cooling stages;

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Thank you for your attention