APPLICATION OF OPENFOAM FOR THE SET UP OF THE INJECTION MOLDING PROCESS

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Introduction

- Polymer injection molding
  - communication, medicine, automotive, packaging
  - high pressure, high viscosity, high clamping forces
  - difficult experiments, location of measurement point
- Simulation
  - J. Nagy et al.: *Polymer injection molding simulations in OpenFOAM®*, PFAU 9, Linz, Austria, 03.11.2014
  - J. Nagy et al.: *Fluid dynamic and thermal modeling of the injection molding process in OpenFOAM®*, OFW11, Guimaraes, Portugal, 29.06.2016
  - J. Nagy et al.: *Modeling and optimization of the injection molding process with OpenFOAM®*, 4th Annual OF User Conference, Cologne, Germany, 11.10.2016
  - J.Nagy et al.: *Runtime optimization in injection molding simulations with adaptive and selective grid refinement*, OF12, Exeter, GB, 25.07.2017
  - J. Nagy et al.: Selective, adaptive & manual (SAM) mesh ref. in injection molding simulation in OpenFOAM, 5th OF User Conference, Wiesbaden, Germany, 17.10.2017
- Application of simulations

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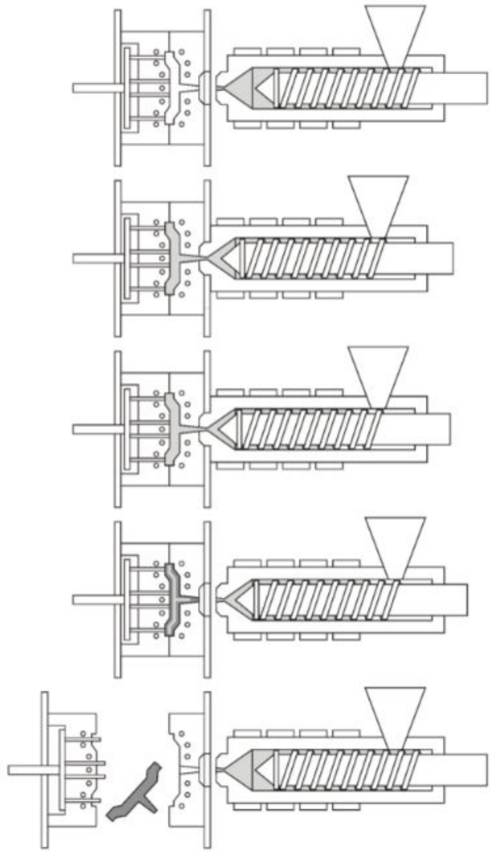
Process



1. Plastification
2. **Filling**
3. **Packing**
4. **Cooling**
5. Part ejection

Theory

Continuity equation

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

Navier-Stokes equations

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot (\rho \mathbf{u}\mathbf{u}) = -\nabla p + \nabla \cdot \tau + \rho g + \mathbf{F}_\sigma$$

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Theory

Energy equation

$$\frac{\partial \rho T}{\partial t} + \nabla \cdot (\rho \mathbf{u} T) =$$

$$\Delta\left(\overline{k} T\right) + \tau : \nabla \mathbf{u} \cdot \left(\frac{\alpha}{c_{v_1}}\right) + \left[\nabla \cdot (p\mathbf{u})\right]\left(\frac{\alpha}{c_{v_1}} + \frac{(1-\alpha)}{c_{v_2}}\right)$$

Temperature gradient

$$\nabla T = \frac{-HTC\left(T_{melt} - T_{wall}\right)}{\widetilde{k}}$$

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Theory

Volume-of-Fluid method

$$\rho = \alpha \rho_l + (1 - \alpha)\,\rho_g$$

$$\frac{\alpha}{\partial t} + \nabla \cdot (\alpha \mathbf{u}) + \nabla \cdot [\alpha\,(1 - \alpha)\,\mathbf{u}_r] = S_p + S_u$$

Cross WLF model

$$\nu(\dot{\gamma}, T, p) = \frac{\nu_0(T,p)}{1 + \left(\frac{\nu_0(T,p)\dot{\gamma}}{D_4}\right)^{1-n}}$$

$$\nu_0(T,p) = D_1 \cdot exp\left(\frac{(-A_1)\cdot(T - D_2 - D_3 \cdot p)}{A_2 + T - D_2 - D_3 \cdot p}\right)$$

Theory

Tait model

$T < T_{trans}$

$$v(p,T) = \left\{ v_s(T) \cdot \left[1 - C \cdot ln \left(1 + \frac{p}{B_s(T)} \right) \right] + W_s(T) \right\}$$

$$v_s(T) = b_{1s} + b_{2s} \cdot (T - b_5)$$

$$B_s(T) = b_{3s} \cdot e^{-b_{4s} \cdot (T - b_5)}$$

$$W_s(T) = b_7 \cdot e^{b_8 \cdot (T - b_5) - b_9 \cdot p}$$

$T \geq T_{trans}$

$$v(p,T) = \left\{ v_m(T) \cdot \left[1 - C \cdot ln \left(1 + \frac{p}{B_s(T)} \right) \right] \right\}$$

$$v_s(T) = b_{1m} + b_{2m} \cdot (T - b_5)$$

$$B_m(T) = b_{3m} \cdot e^{-b_{4m} \cdot (T - b_5)}$$

$$T_{trans} = b_5 + b_6 \cdot p$$

$$C = 0.0894$$

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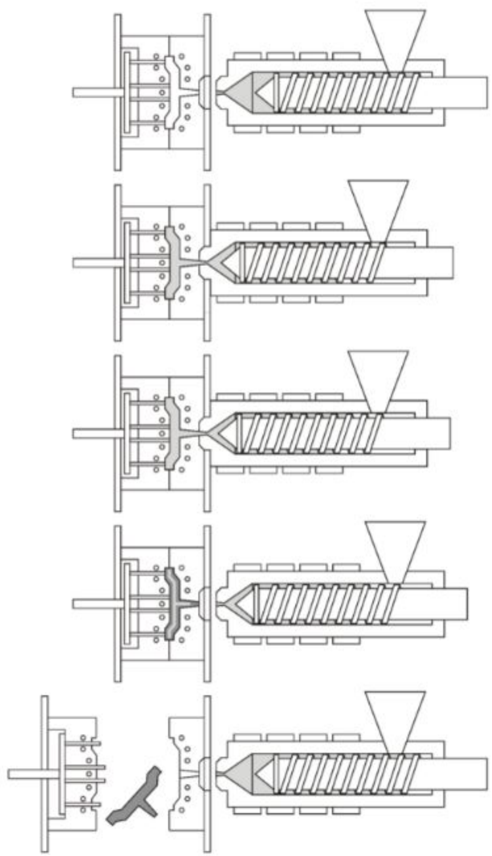
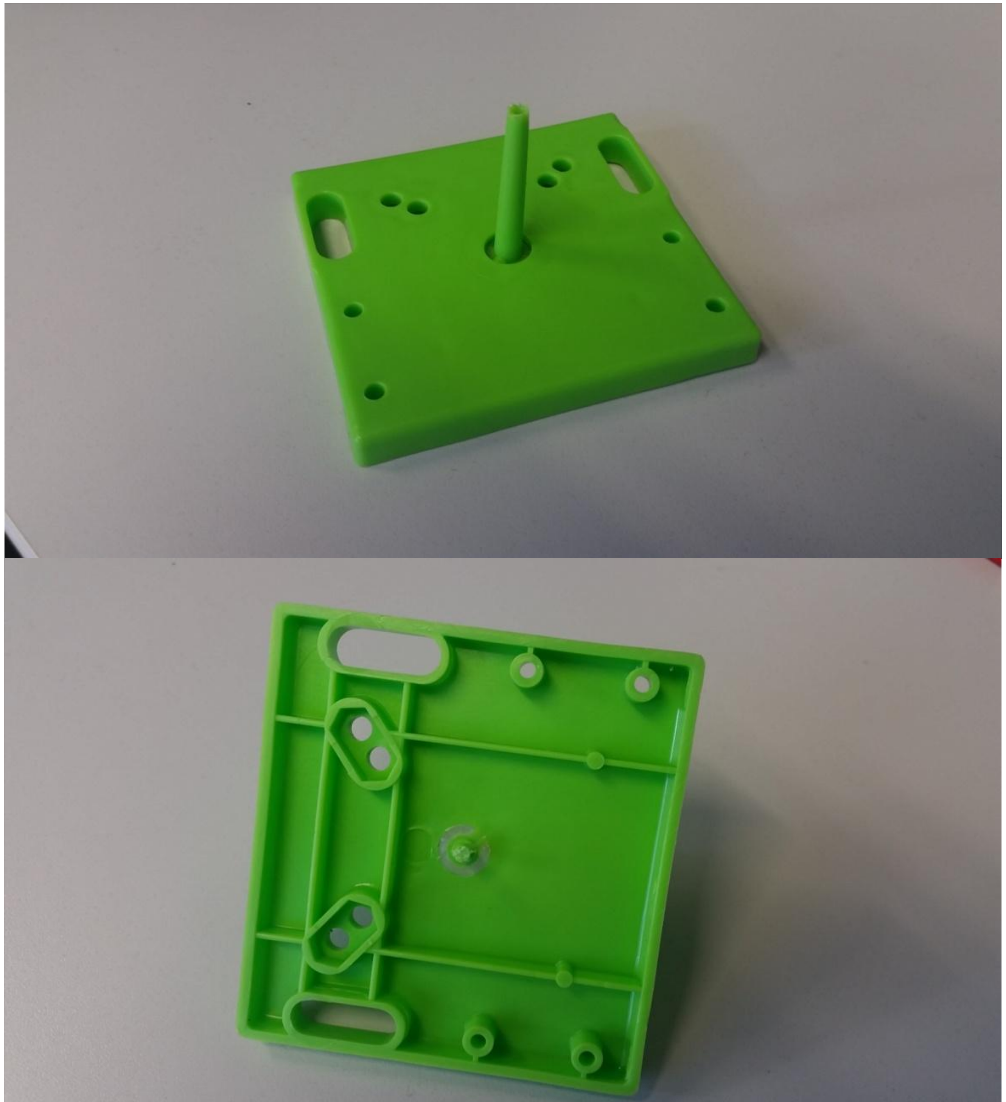
Phases

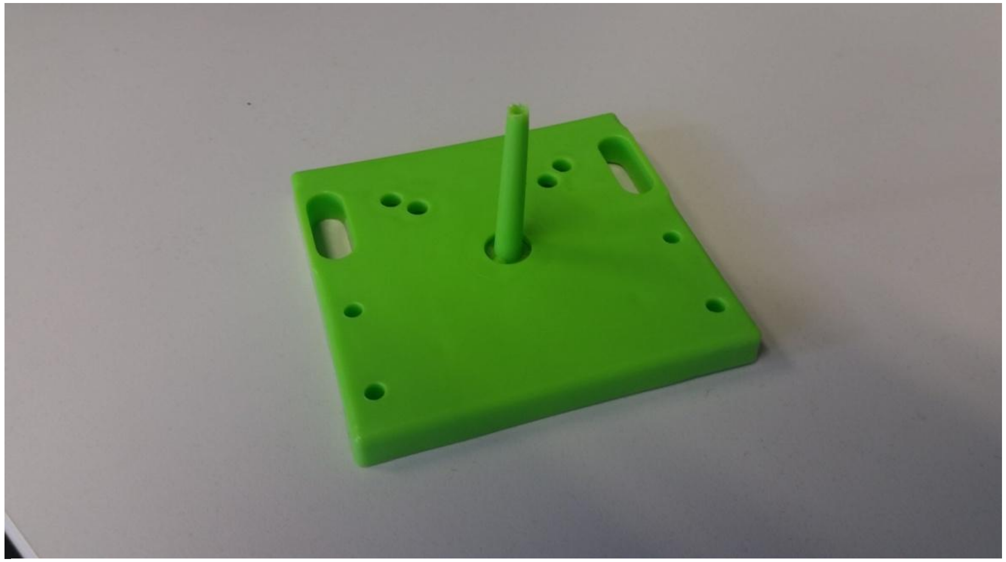


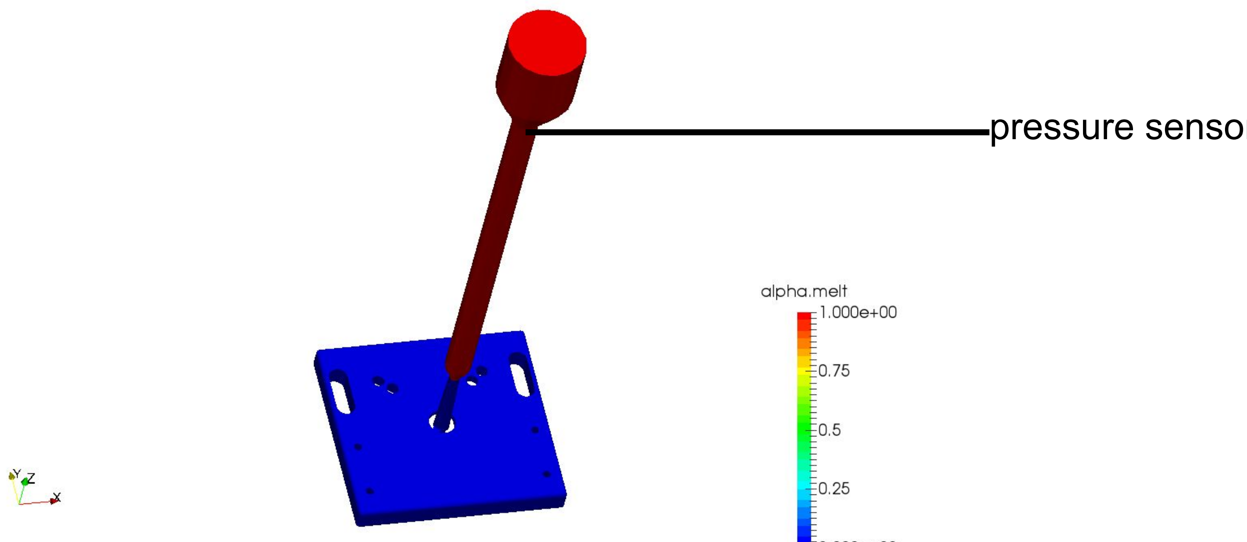
phase	velocity	pressure
filling	time dep. profile	zeroGradient
packing	zeroGradient	time dep. profile
cooling	zeroGradient	1 bar

Filling - Endplate



Filling phase - injection pressure





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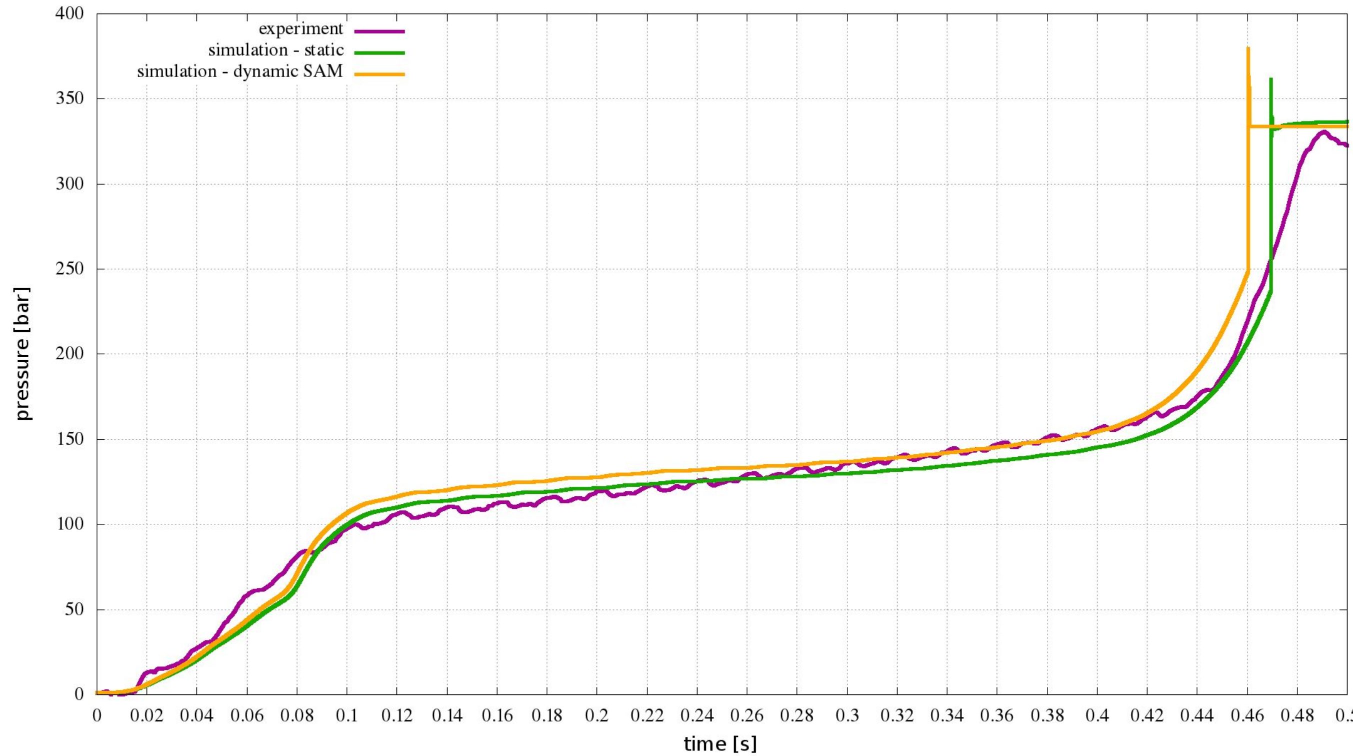
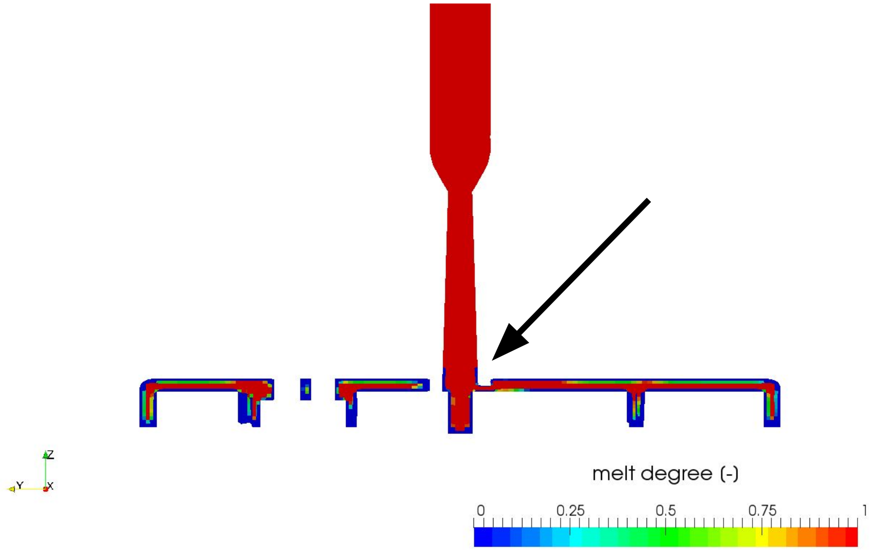
Filling phase - injection pressure

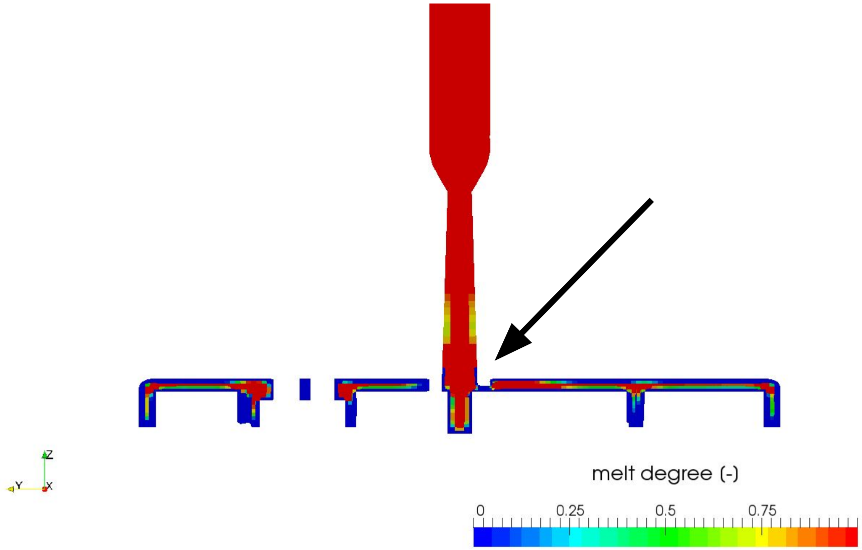


	p_{switch} [bar]	$\triangle\, p_{switch}$ [%]	t_{switch} [s]	$\triangle\, t_{switch}$ [%]
experiment	238	-	0.465	-
fine sim.	233	-2.1	0.468	0.6
dyn. sim.	248	4.2	0.461	-0.8

Packing phase - freezing time

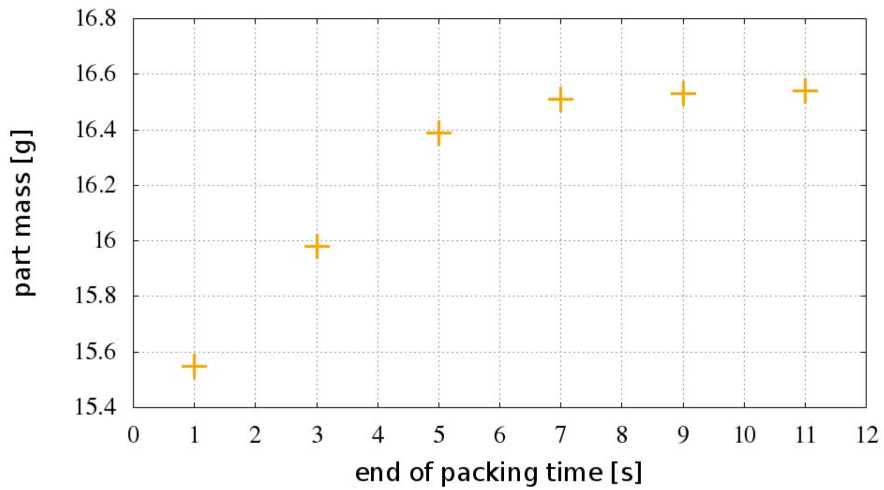


t = 6.5s



t = 7.5s

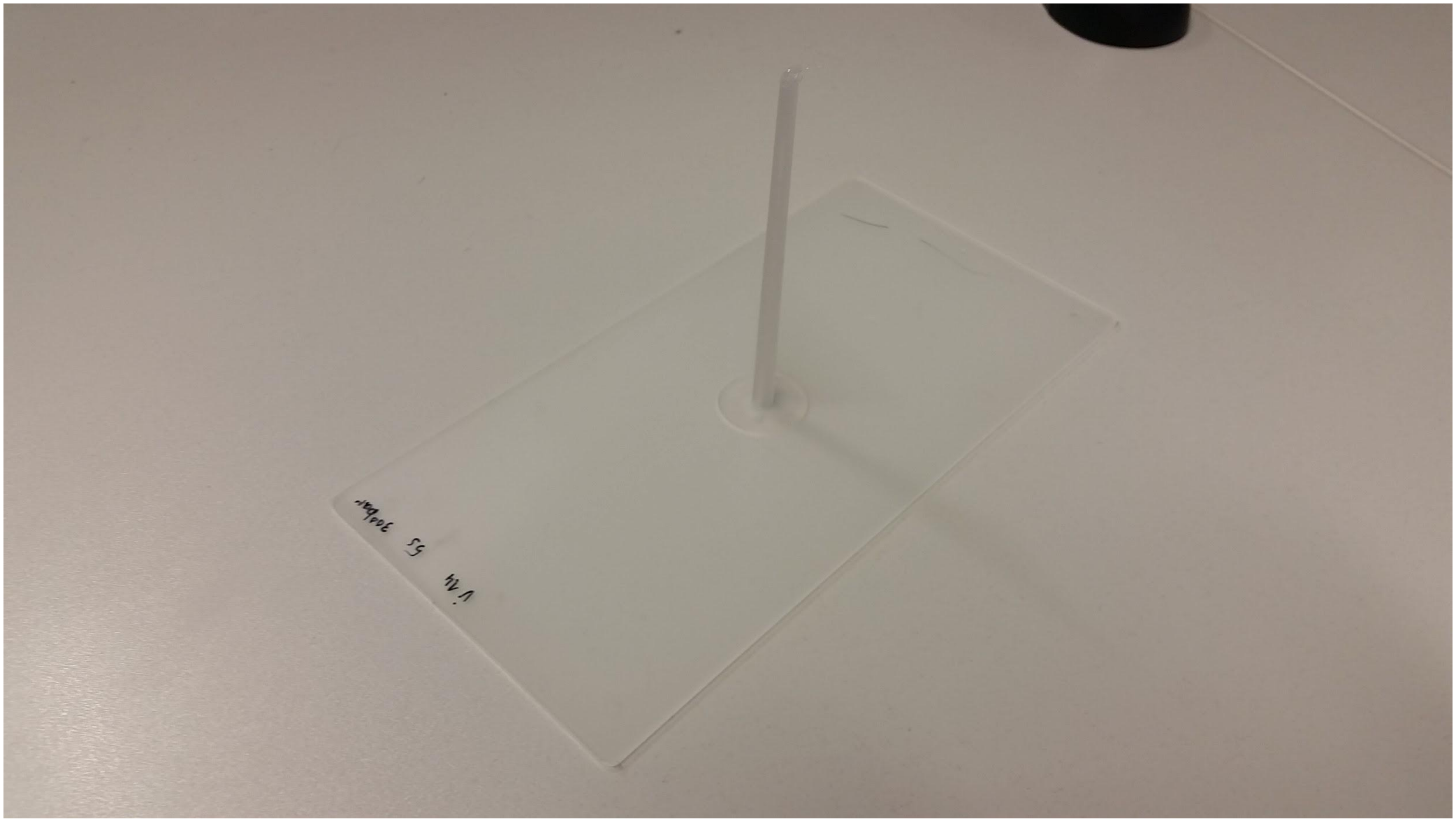
	t_{freeze} [s]
experiment	~7
fine sim.	7.05
dyn. sim.	6.98



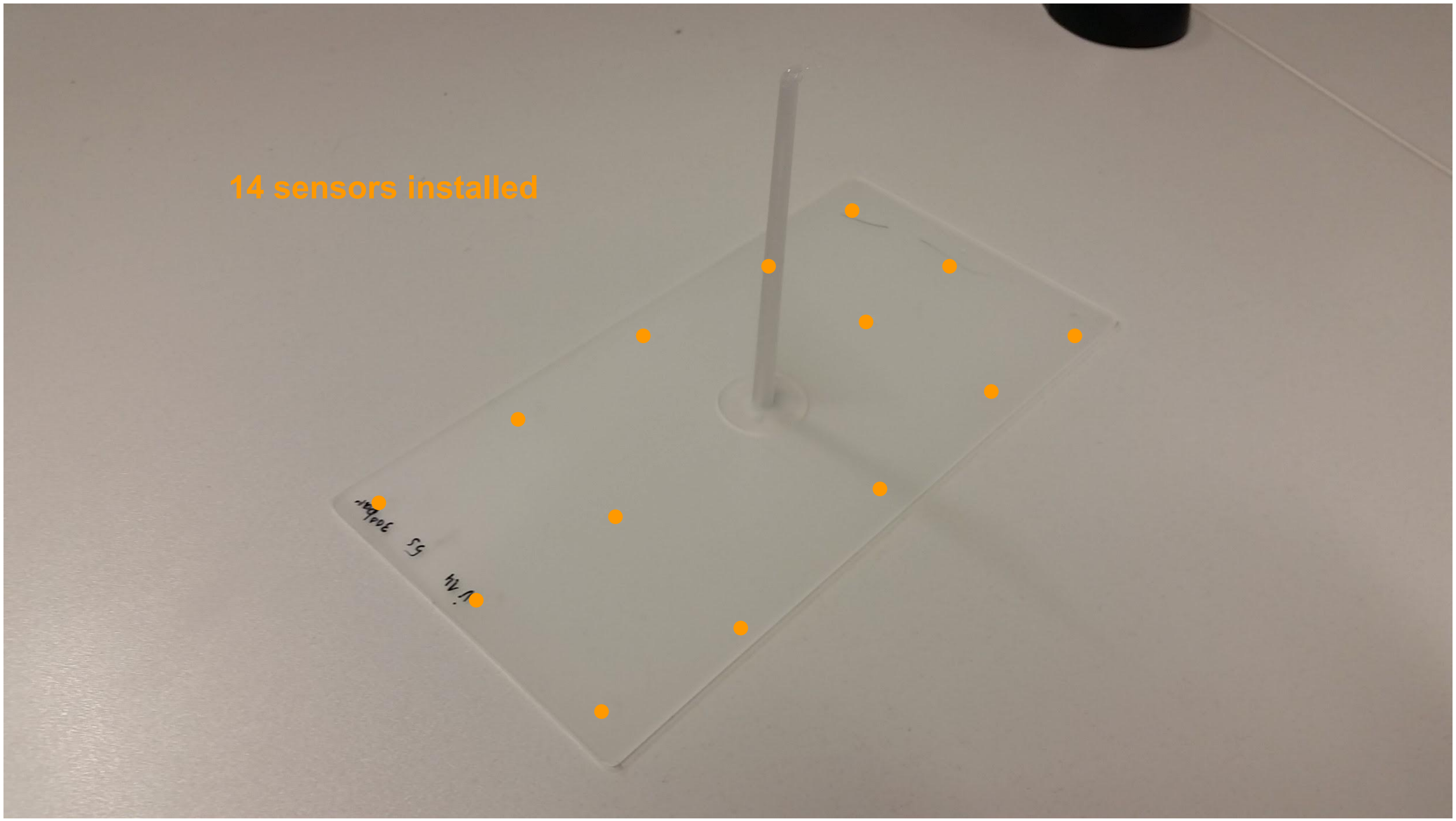
Process set up

- Definition of important parameters
- Filling time - safety (switch over from velocity to pressure)
- Pressure - safety
  - maximum
  - cavity
- Packing time - energy consumption
- New development mold
  - installation of 14 pressure sensors
  - perfect opportunity to apply the simulation

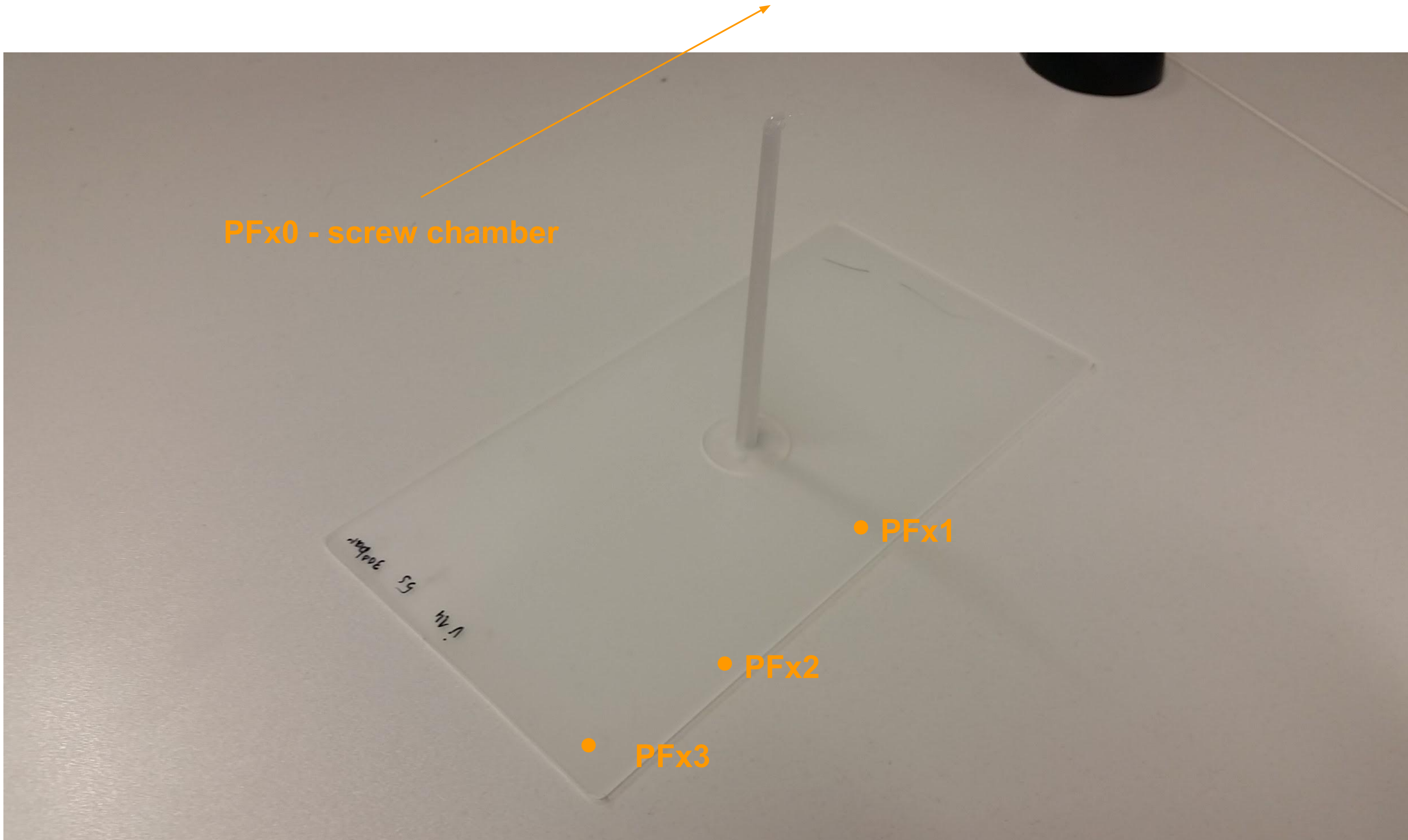
Geometry



Pressure sensors



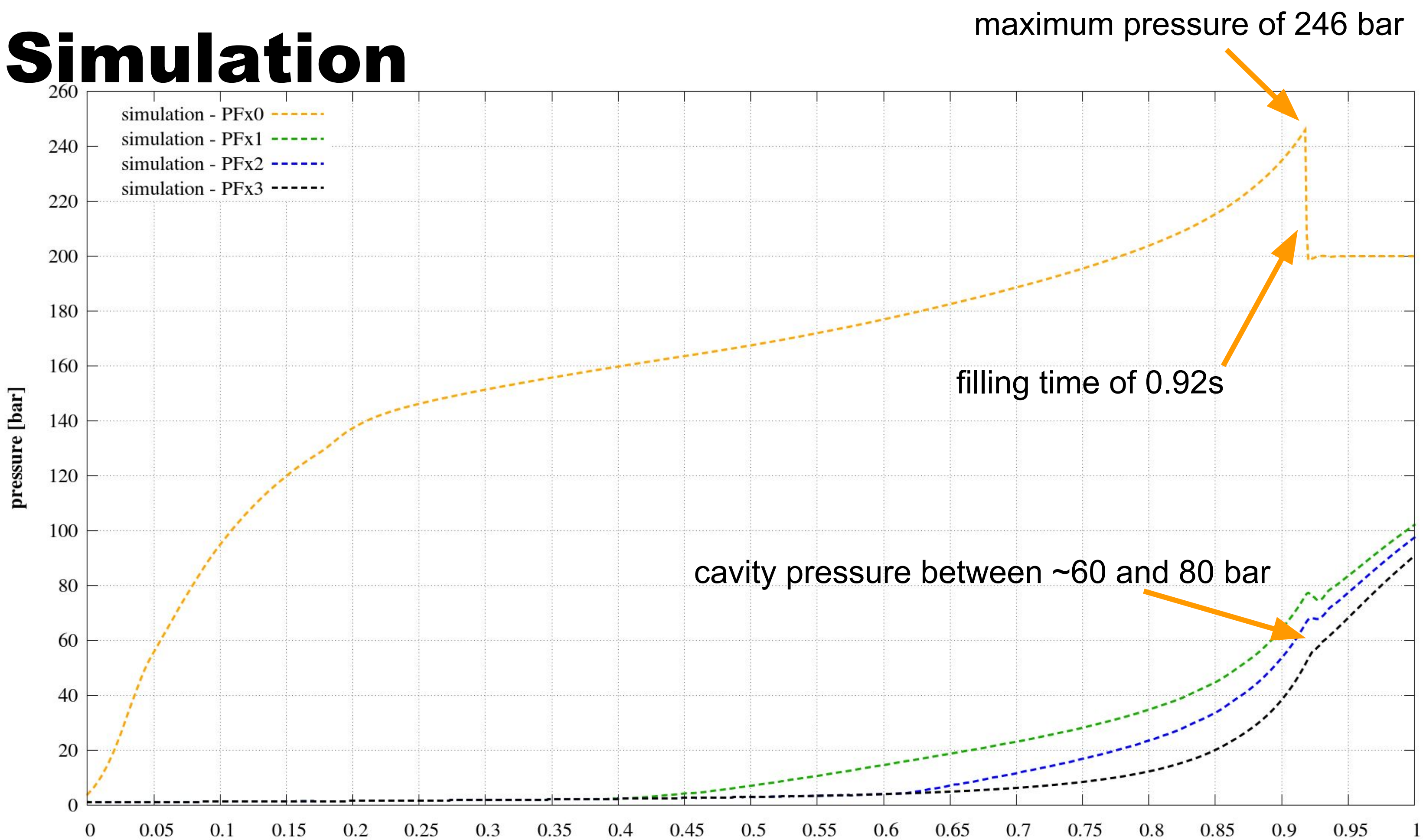
Pressure sensors



Process set up

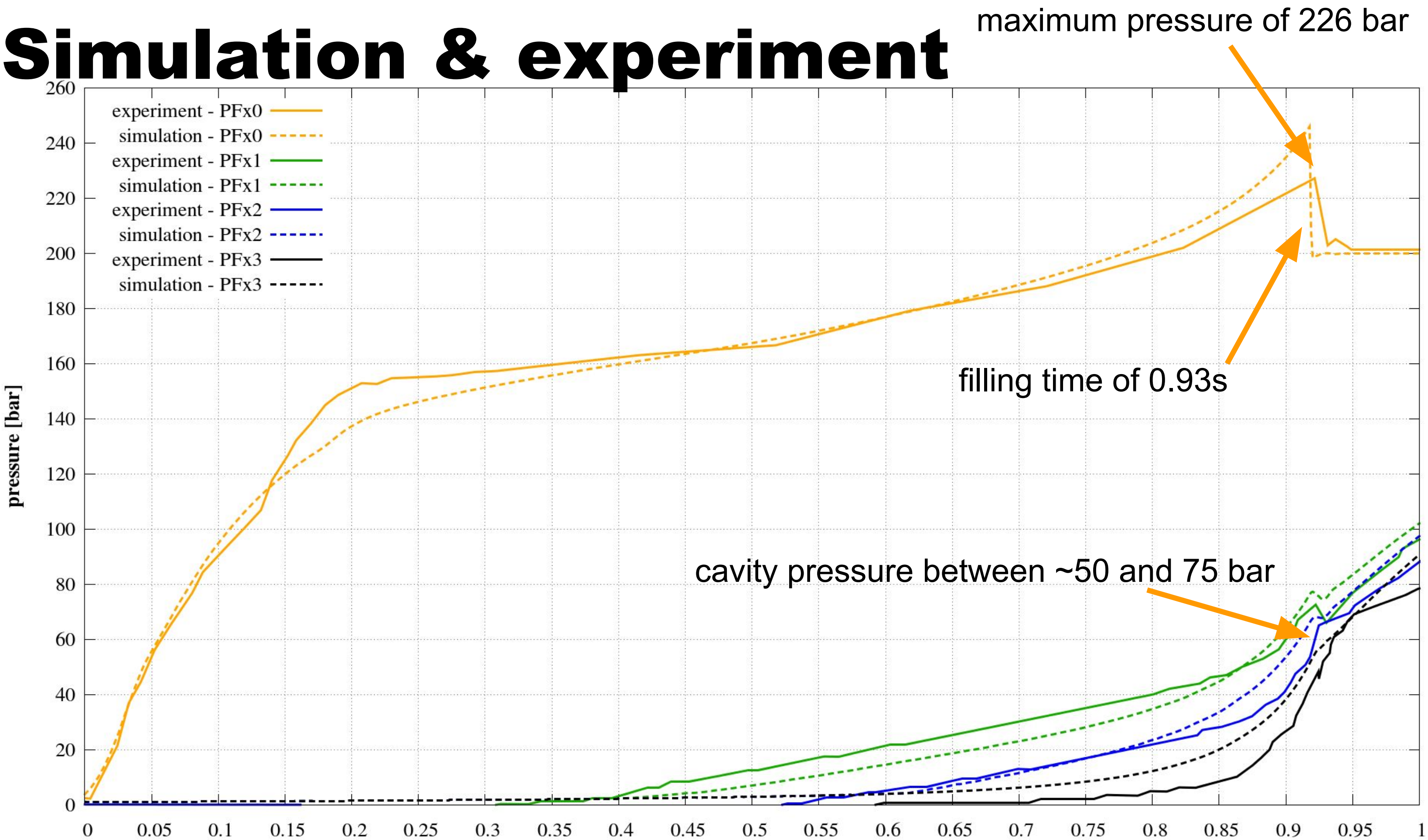
- Definition of important parameters
- Filling time - safety (switch over from velocity to pressure)
- Pressure - safety
  - maximum
  - cavity
- Packing time - energy consumption
- New development tool
  - installation of 14 pressure sensors
  - perfect opportunity to apply the simulation

Simulation



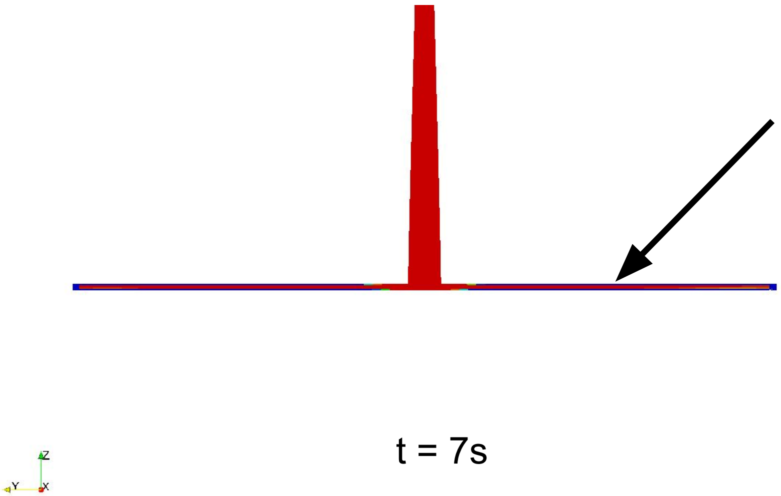
	p_{switch} [bar]	$\triangle p_{switch}$ [%]	p_{cav} [bar]	$\triangle p_{cav}$ [%]	t_{switch} [s]	$\triangle t_{switch}$ [%]
exp.		-		-		
sim.	246		60-80		0.92	

Simulation & experiment

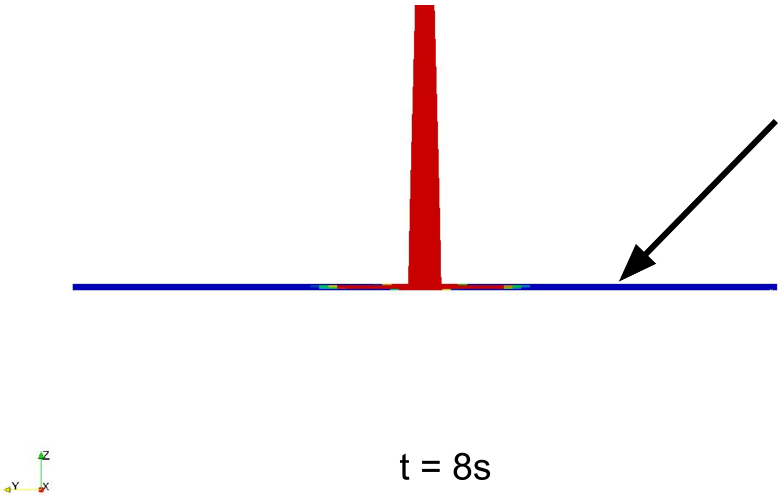


	p_{switch} [bar]	$\triangle p_{switch}$ [%]	p_{cav} [bar]	$\triangle p_{cav}$ [%]	t_{switch} [s]	$\triangle t_{switch}$ [%]
exp.	226	-	50-75	-	0.93	-
sim.	246	< 9	60-80	< 5	0.92	-1.1

Packing phase - freezing time



t = 7s



t = 8s

	t_{freeze} [s]
experiment	~7-8
simulation	7.35

Conclusion

- Simulation of injection molding process
- Good agreement (<5-10%)
- Set up of process possible
- Run time between 30s and 6h
- Runtime here ~2.5 min
- Experimental process set up ~0.5-1h
- Simulation in OpenFOAM is a good alternative
- Next steps:
    - Further analysis of different (curved) geometries
    - Further analysis of different materials (PE, PA, PC etc.)
    - Shrinkage