

FLUID DYNAMIC AND THERMAL MODELING OF THE INJECTION MOLDING PROCESS IN OPENFOAM®



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INTRODUCTION



Introduction

■ Polymer injection molding

- communication, medicine, automotive, packaging
- high pressure, high viscosity, high clamping forces
- difficult experiments, location of measurement point

■ Simulation

- Moldflow, PolyFlow, Sigmasoft, Moldex3D, ...
- OpenFOAM®
- Three-dimensional visualization of the process

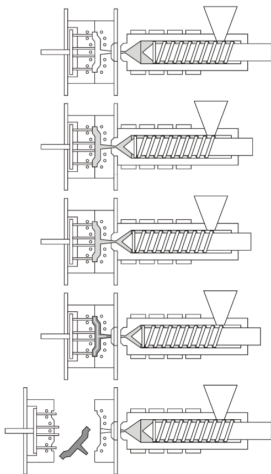
■ Goals

- Optimization of process and geometry
- Coupling with machine simulations in Matlab
- Coupling with machine for self optimizing technology

MOTIVATION



Process



1. Plastification

2. **Filling**

3. **Packing**

4. **Cooling**

5. Part ejection

Motivation

1. How to model different conditions throughout the process (three phases)?
2. Which effects cause the main errors in experiments?
3. Which quantities describe the process quality?
4. How to identify these quantities in the simulation?

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MODEL



FLUID DYNAMIC MODELING

Continuity equation

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

Navier-Stokes equations

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

THERMAL MODELING

Energy equation

$$\frac{\partial \rho T}{\partial t} + \nabla \cdot (\rho \mathbf{u} T) =$$
$$\Delta (\bar{k} T) + \tau : \nabla \mathbf{u} \cdot \left(\frac{\alpha}{c_{v1}} \right) + [\nabla \cdot (p \mathbf{u})] \left(\frac{\alpha}{c_{v1}} + \frac{(1 - \alpha)}{c_{v2}} \right)$$

Temperature gradient

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

MULTIPHASE AND VISCOSITY MODEL

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

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

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

COMPRESSIBILITY MODEL

Tait model

$$T < T_{trans}$$

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

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

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

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

$$T \geq T_{trans}$$

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

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

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

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

$$C = 0.0894$$

MODELING OF THE PHASES THROUGH BOUNDARY CONDITIONS

■ Phases

- Filling phase
- Packing phase
- Cooling phase

■ Differential equations

- Continuity equation
- Navier-Stokes equations
- Energy equation

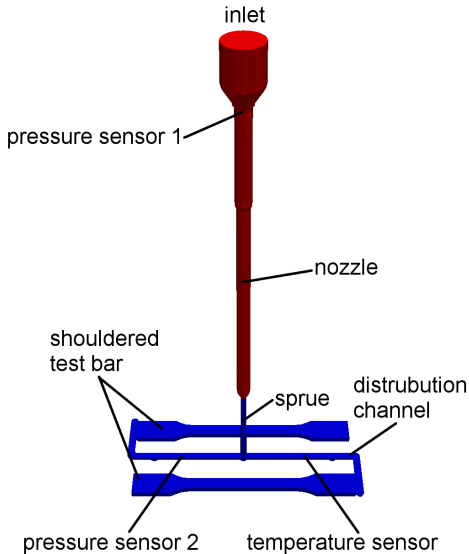
phase	velocity	pressure
filling	time dep. velocity profile	zero gradient
packing	zero gradient	fixed value
cooling	inlet- outlet	1 bar

EXPERIMENT AND SIMULATION



GEOMETRY AND PROCESS CONDITIONS

- Modeling of filling, packing and cooling
- Material: PP HD120MO
- Volume flux: $50 \text{ cm}^3/\text{s}$
- Temperature
 - melt and nozzle: $240 \text{ }^\circ\text{C}$
 - tool: $30 \text{ }^\circ\text{C}$
- Packing pressure: 338 bar
- Packing time: 26 s
- Process time: 40 s
- 2 pressure sensors
- 1 IR temperature sensor



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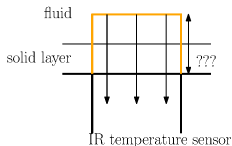
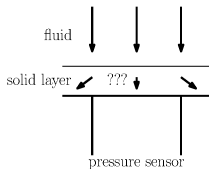
EXPERIMENTAL DEVIATIONS

■ Pressure sensors

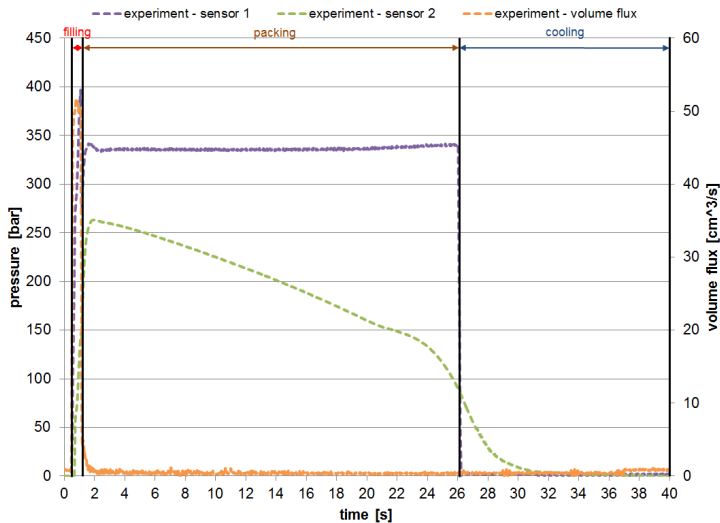
- calibrated for fluid pressure
- frozen solid layer distorts pressure value
- reduction of up to 40 bar

■ IR temperature sensors

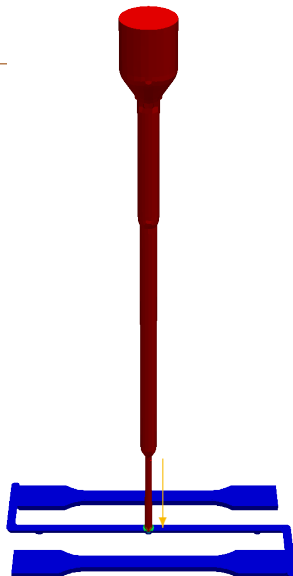
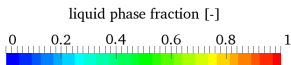
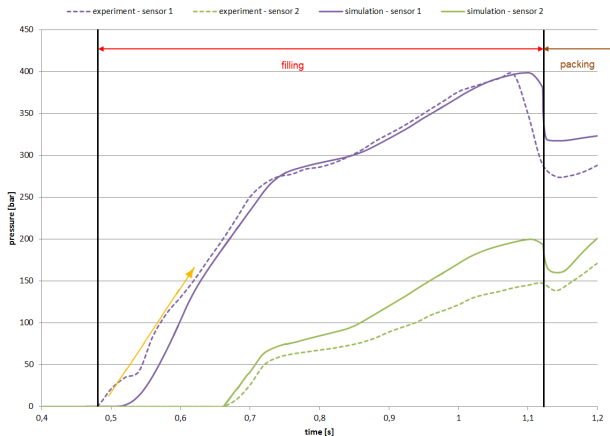
- calibrated for liquid polymer
- measurement up until an unknown thickness - fluid and solid
- intergral temperature over unknown thickness
- reduction of temperature up to 20 °C



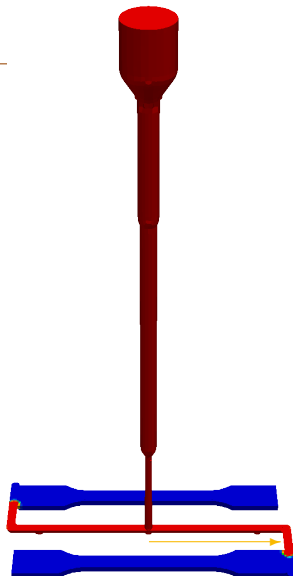
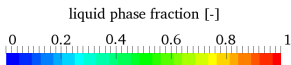
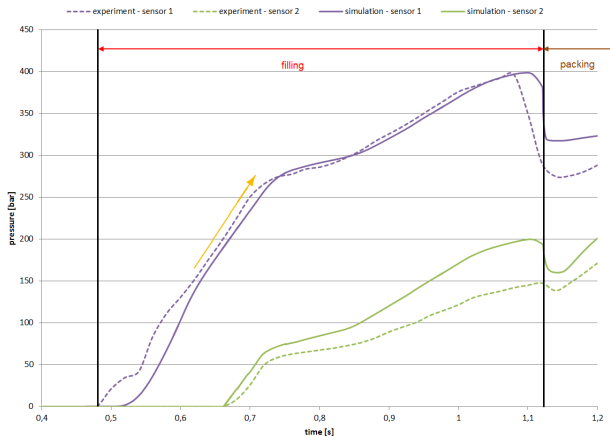
PROCESS



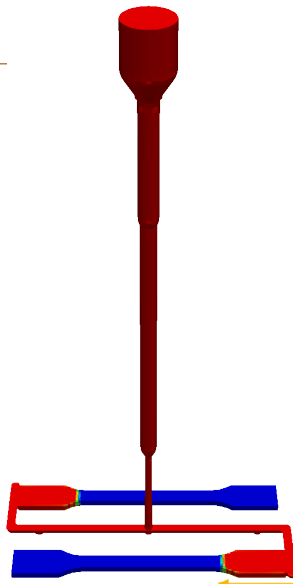
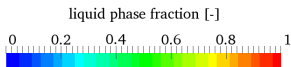
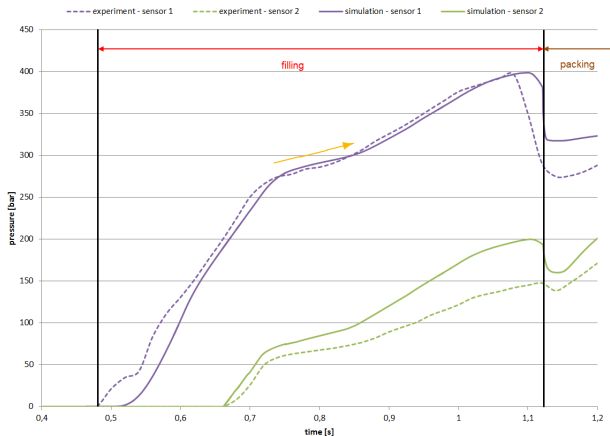
FILLING PHASE



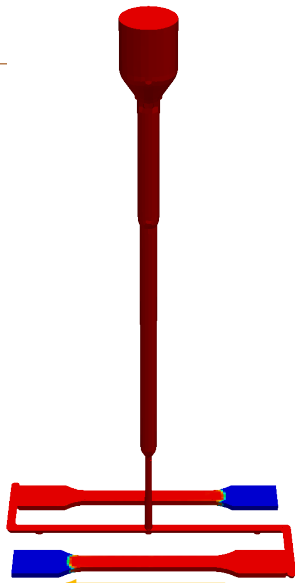
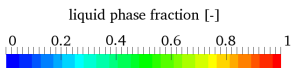
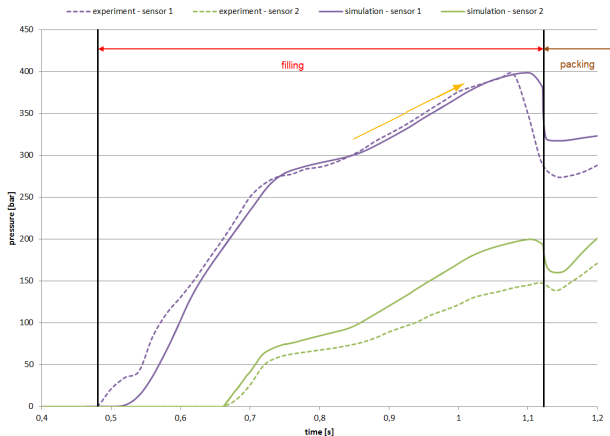
FILLING PHASE



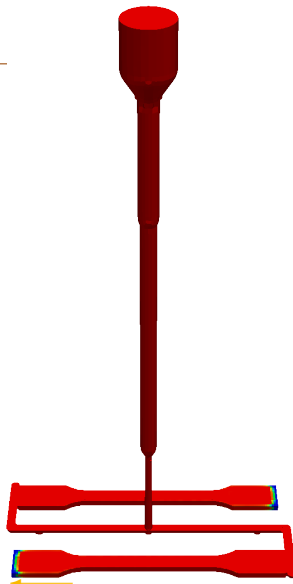
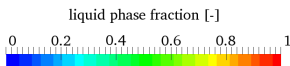
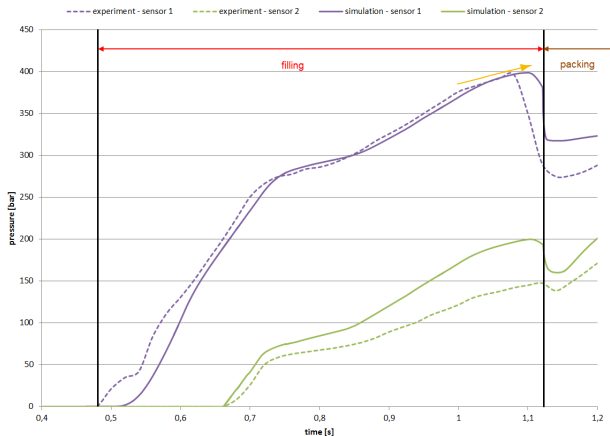
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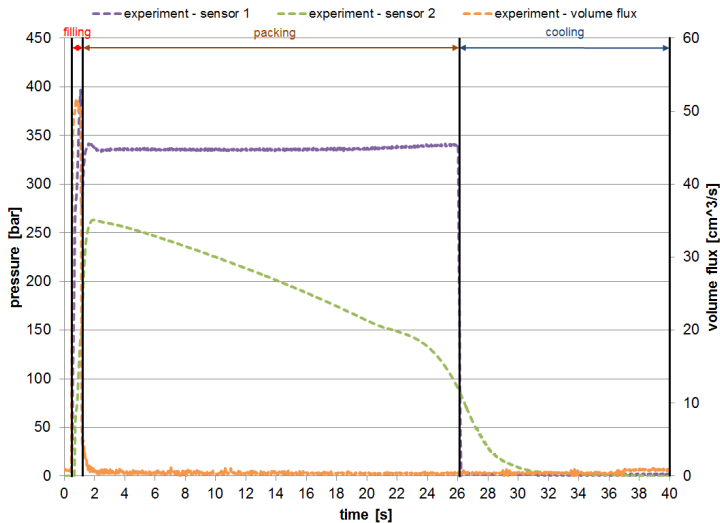
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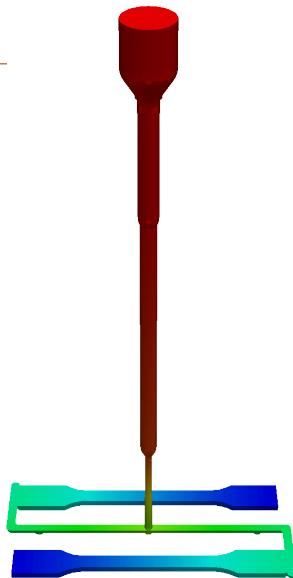
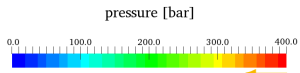
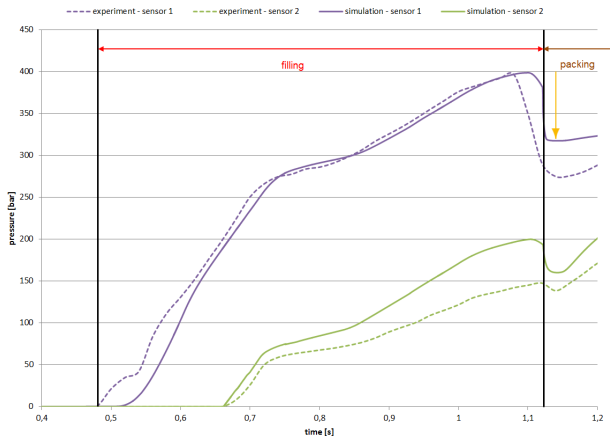
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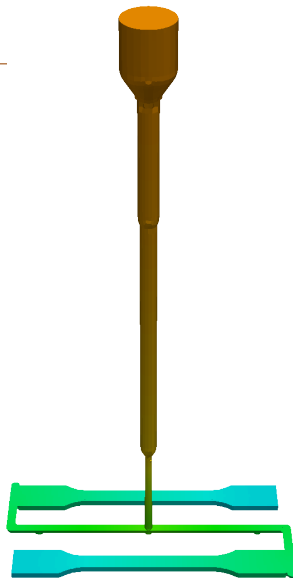
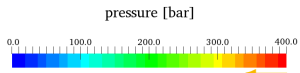
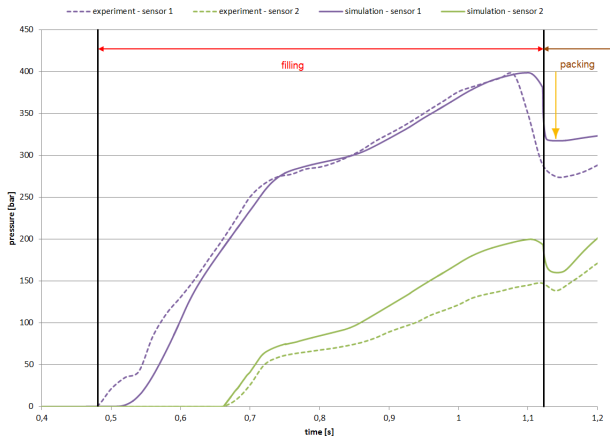
PROCESS



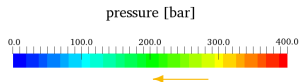
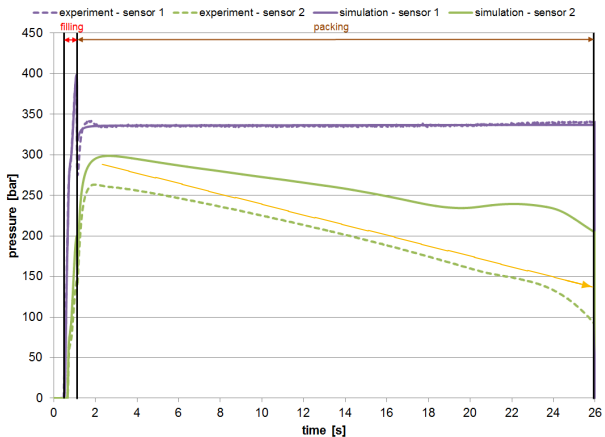
PACKING PHASE



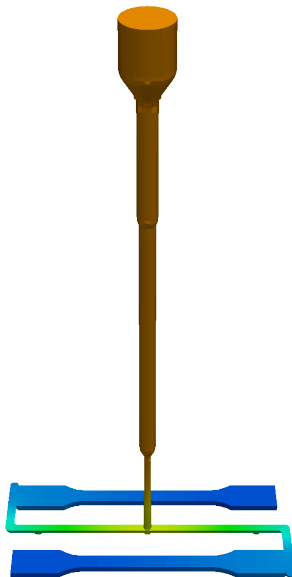
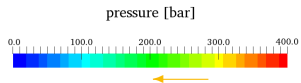
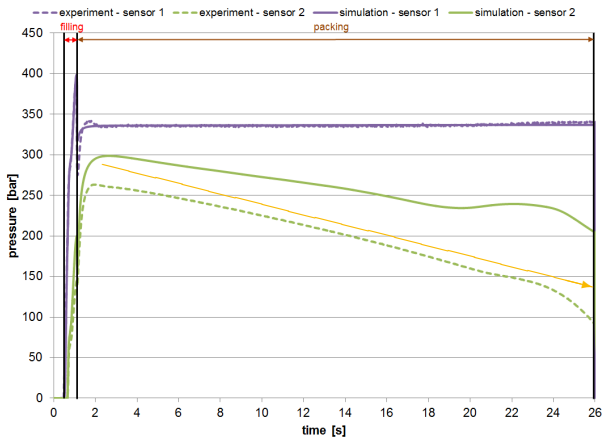
PACKING PHASE



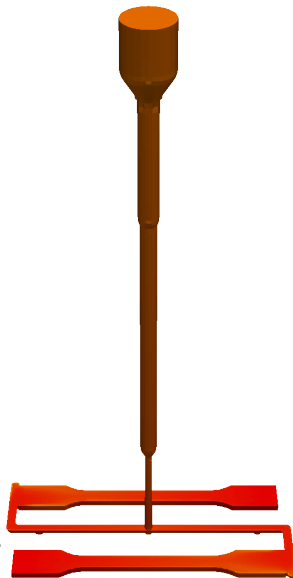
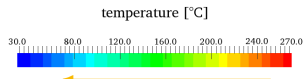
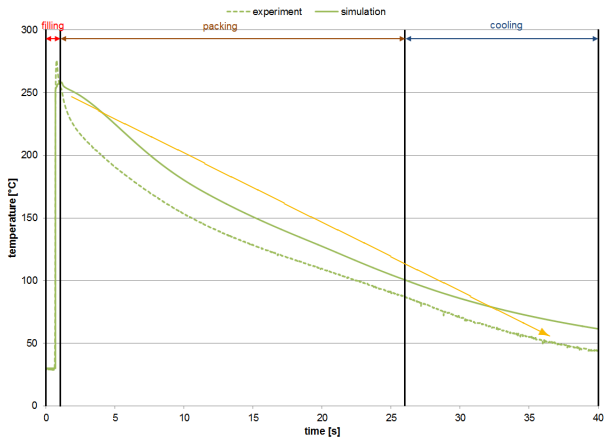
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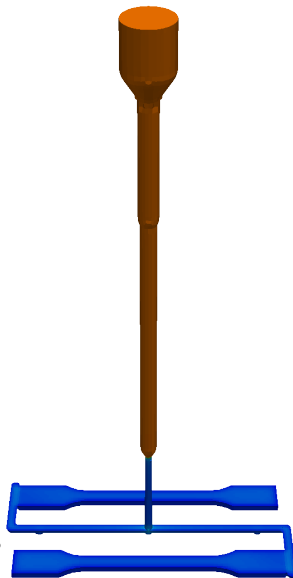
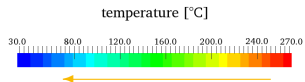
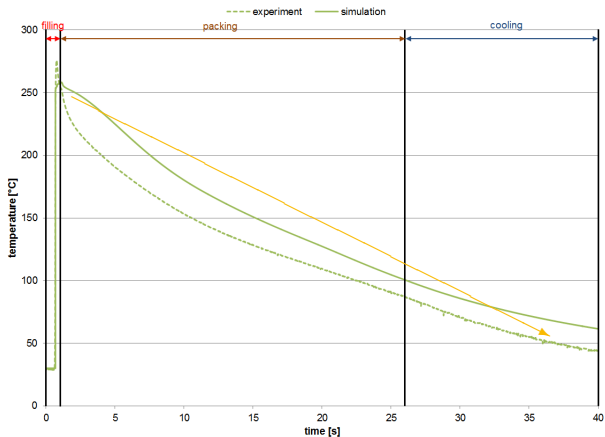
PACKING PHASE



COOLING PHASE



COOLING PHASE



Motivation

1. How to model different conditions throughout the process (three phases)?
2. Which effects cause the main errors in experiments?
3. **Which quantities describe the process quality?**
4. **How to identify these quantities in the simulation?**

PROCESS QUALITY

■ Filling phase

- fill time, switch over to packing phase - **location of flow front**
- needed clamping force - **maximum pressure**

■ Packing phase

- freezing - **time of freezing**

■ Cooling phase and part ejection

- ejection temperature - **temperature at the end of process**

PROCESS QUALITY

■ Filling phase

- fill time, switch over to packing phase - **location of flow front**
- needed clamping force - maximum pressure

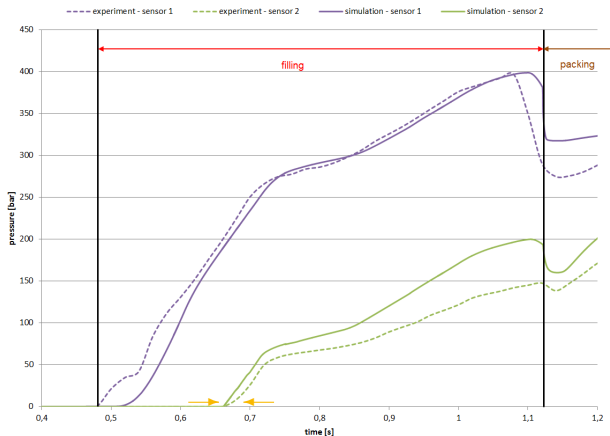
■ Packing phase

- freezing -time of freezing

■ Cooling phase and part ejection

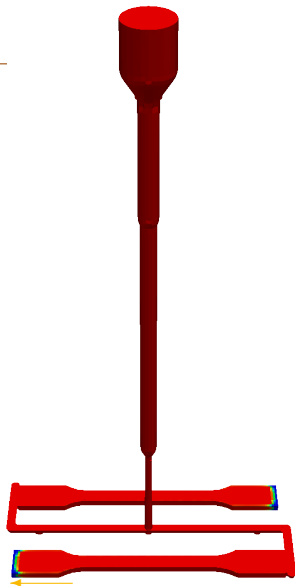
- ejection temperature - temperature at the end of process

FILLING PHASE



Process quality 1: fill time - location of flow front

$$\Delta t_{fill} = \frac{t_{s2,sim} - t_{s2,exp}}{t_{end} - t_{start}} = \frac{0.67 \text{ s} - 0.66 \text{ s}}{0.66 \text{ s}} = 1.5\%$$



PROCESS QUALITY

■ Filling phase

- fill time, switch over to packing phase - location of flow front
- needed clamping force - **maximum pressure**

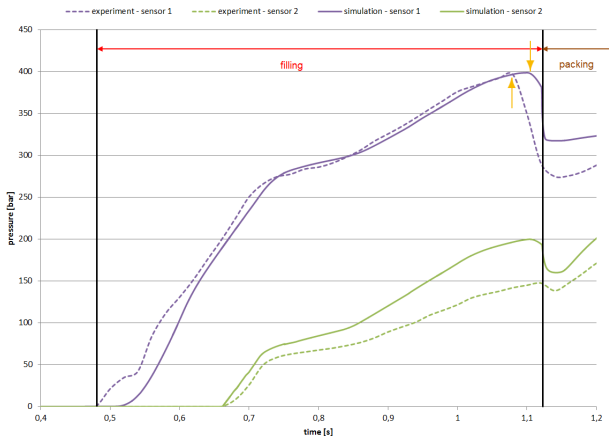
■ Packing phase

- freezing - time of freezing

■ Cooling phase and part ejection

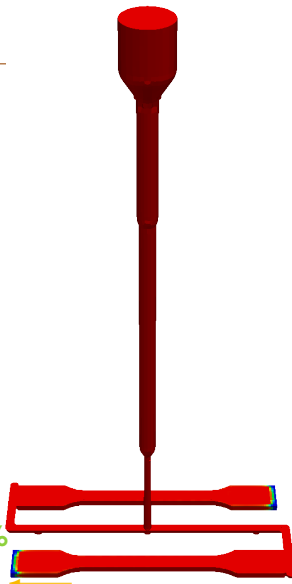
- ejection temperature - temperature at the end of process

FILLING PHASE

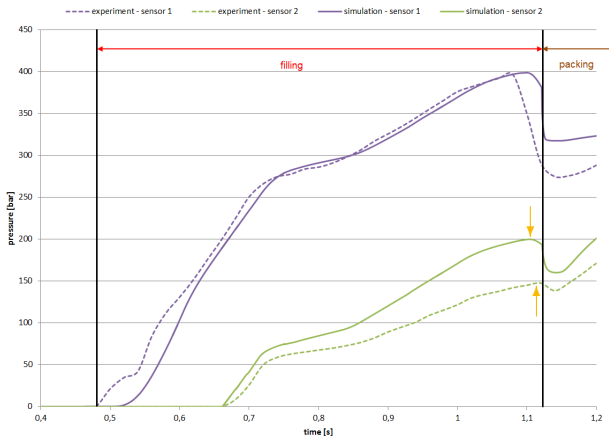


Process quality 2: clamping force - max. pressure

$$\Delta p_{max} = \frac{p_{s1,sim} - p_{s1,exp}}{p_{max} - p_{start}} = \frac{398.7 \text{ bar} - 396.3 \text{ bar}}{396.3 \text{ bar} - 1 \text{ bar}} = 0.6\%$$



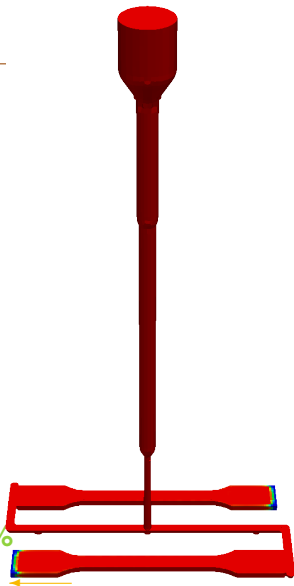
FILLING PHASE



Process quality 2: clamping force - max. pressure

$$\Delta p_{cav} = \frac{p_{s2,sim} - p_{s2,exp}}{p_{max} - p_{start}} = \frac{199.8 \text{ bar} - 147.7 \text{ bar}}{396.3 \text{ bar} - 1 \text{ bar}} = 13.1\%$$

Up to 40 bar deviation due to freezing issues!



PROCESS QUALITY

■ Filling phase

- fill time, switch over to packing phase - location of flow front
- needed clamping force - maximum pressure

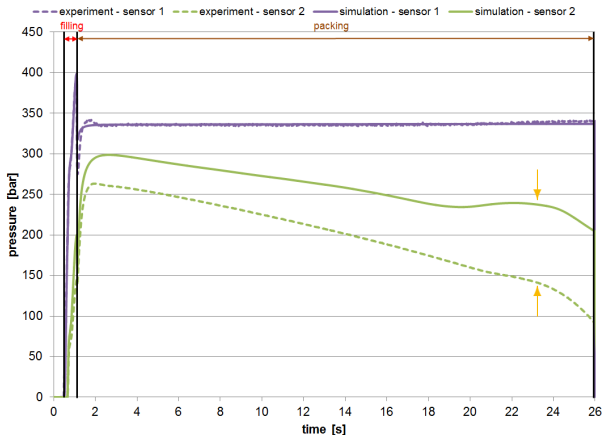
■ Packing phase

- freezing - **time of freezing**

■ Cooling phase and part ejection

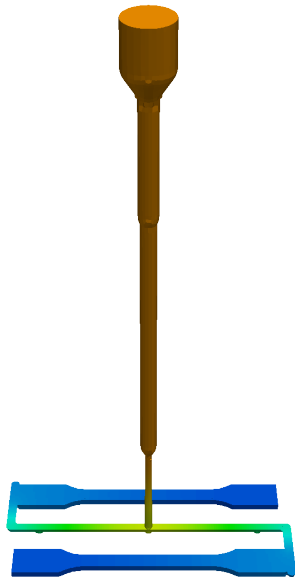
- ejection temperature - temperature at the end of process

PACKING PHASE



Process quality 3: freezing - time of freezing

$$\Delta t_{freeze} = \frac{t_{fr,sim} - t_{fr,exp}}{t_{p+f} - t_{start}} = \frac{20.6 \text{ s} - 21.3 \text{ s}}{26 \text{ s}} = -2.7\%$$



PROCESS QUALITY

■ Filling phase

- fill time, switch over to packing phase - location of flow front
- needed clamping force - maximum pressure

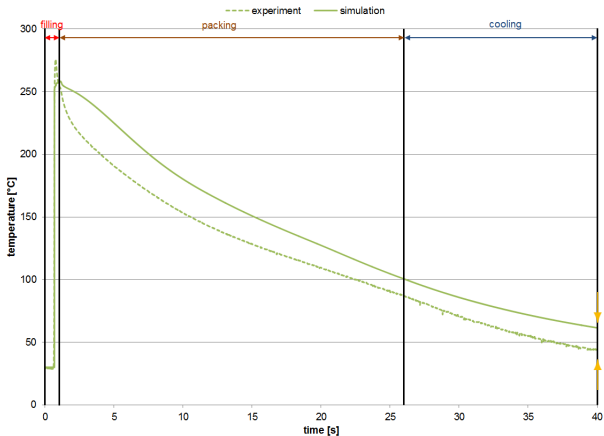
■ Packing phase

- freezing - time of freezing

■ Cooling phase and part ejection

- ejection temperature - **temperature at the end of process**

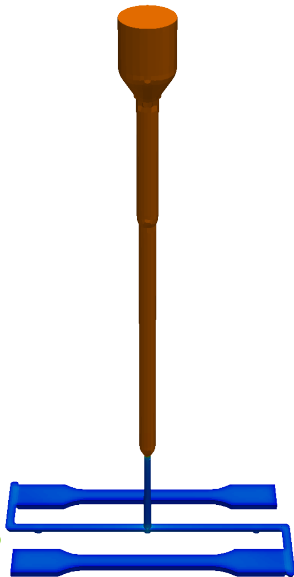
COOLING PHASE



Process quality 2: clamping force - max. pressure

$$\Delta T_{end} = \frac{T_{end,sim} - T_{end,exp}}{T_{max} - T_{tool}} = \frac{61.5^{\circ}C - 43.7^{\circ}C}{275^{\circ}C - 30^{\circ}C} = 7.3\%$$

Up to 20 °C deviation due to experimental issues!



Parameter study

volume flux	Δt_{fill}	Δp_{max}	Δp_{cav}	Δt_{freeze}	T_{end}
5 cm ³ /s	1.1%	-4.3%	9.4%	0.33%	10.9%
30 cm ³ /s	-0.9%	1.5%	14.0%	-2.3%	8.6%
50 cm ³ /s	1.5%	0.6%	13.1%	-2.7%	7.3%
70 cm ³ /s	1.9%	0.3%	10.9%	-3.9%	6.6%
90 cm ³ /s	2.0%	2.5%	12.6%	-4.3%	6.7%

CONCLUSION AND OUTLOOK



CONCLUSION

- OpenFOAM[®] simulations of injection molding process
 - filling
 - packing
 - cooling
- Dynamic change of boundary conditions
- Good agreement between simulation and experiment in
 - location of flow front ($\leq 2.0\%$)
 - pressure ($\leq 14.0\%$)
 - temperature ($\leq 11.0\%$)
- Calculation time 10 min-6 h

OUTLOOK

- Further analysis of the influence of
 - material
 - geometry
- Additional quantities related to process quality
 - flow front velocity
 - inner shearing
 - crystallization
 - shrinkage
- Coupling with
 - machine simulations
 - injection molding machine

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