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Finite Element Model of a complex Glass Forming Process as a Tool for Control Optimization

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1 Motivation

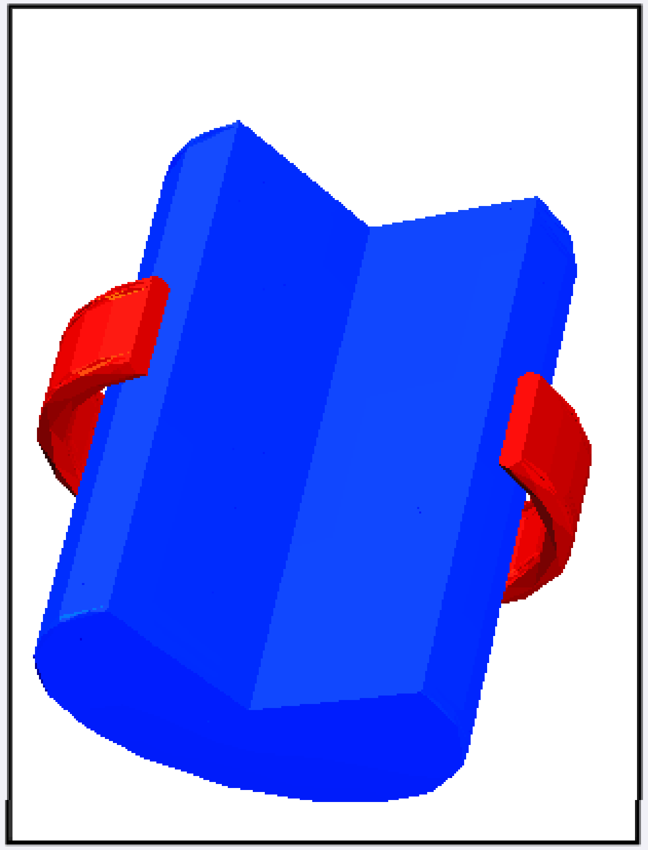
Industrial Glass Tube Drawing Process

Task:

- investigation of ovality / siding
- optimization of process parameters
- investigation of disturbances
- design of process control strategies

1 Motivation

Industrial Glass Tube Drawing Process



Task:

- investigation of ovality / siding
- optimization of process parameters
- investigation of disturbances
- design of process control strategies

model-based approach

Challenges:

- highly nonlinear system behavior
- strongly coupled
- long reaction times (time delay)
- large variety of products and materials

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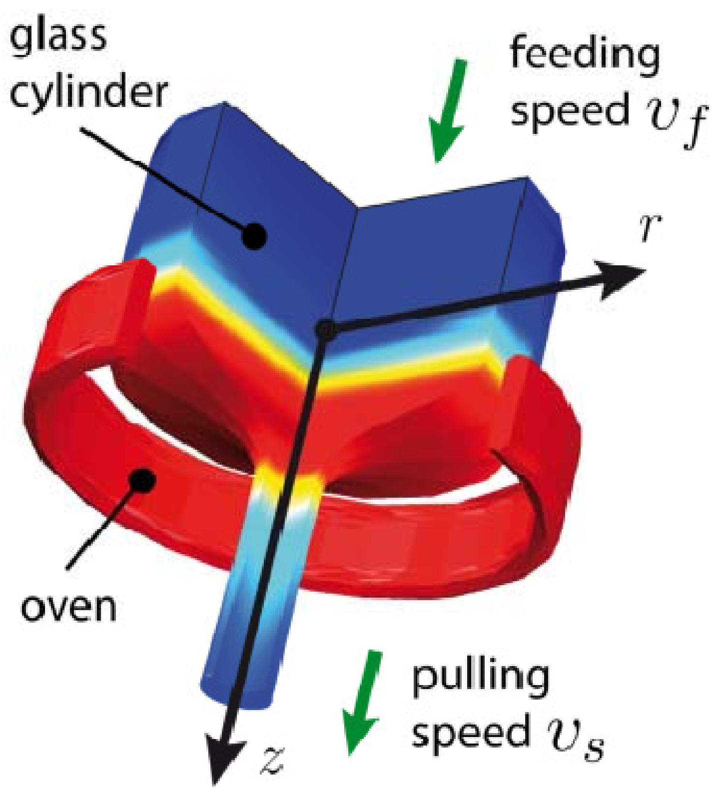
2 Model of the Tube Drawing Process 1/2

Industrial Glass Tube Drawing Process



Manipulated Variables

- feeding speed v_f
- pulling speed v_s
- oven temperature T
- pressure p

Physical Phenomena

- fluid dynamics
- heat conduction
- radiation

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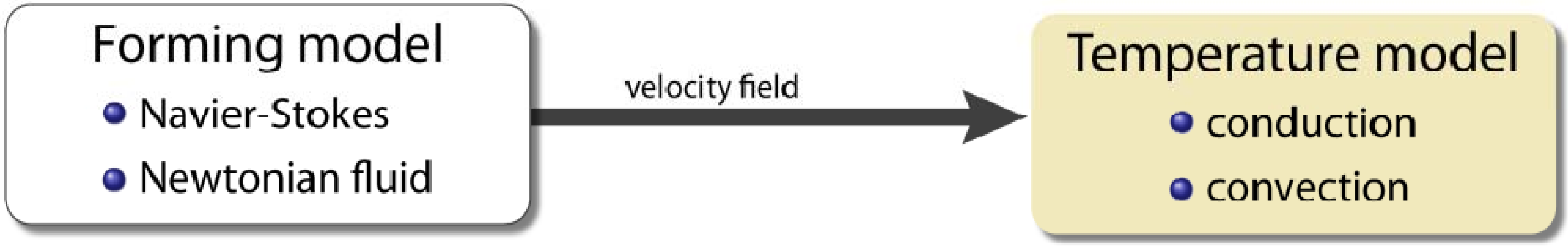
2 Model of the Tube Drawing Process 2/2

Forming model

- Navier-Stokes
- Newtonian fluid

$$
\begin{aligned}
\rho \frac{\partial \underline{u}}{\partial t} &= \nabla \underbrace{\left[-pI + \eta \left(\nabla \underline{u} + (\nabla \underline{u})^T \right) \right]}_{=:\sigma} - \rho \left(\underline{u} \cdot \nabla \right) \underline{u} - \rho\, g \\
\nabla \underline{u} &= 0
\end{aligned}
$$

2 Model of the Tube Drawing Process 2/2



$$\rho c_p \frac{\partial T}{\partial t} = \underbrace{\nabla \cdot (\lambda \nabla T)}_{\text{heat conduction}} - \underbrace{\rho c_p \, \underline{u} \cdot \nabla T}_{\text{convection term}}$$

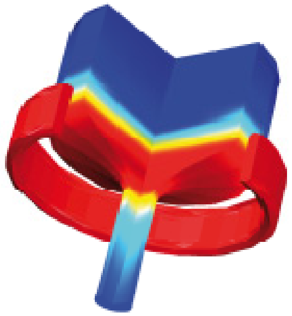
2 Model of the Tube Drawing Process 2/2

Forming model
- Navier-Stokes
- Newtonian fluid

velocity field →

Temperature model
- conduction
- convection

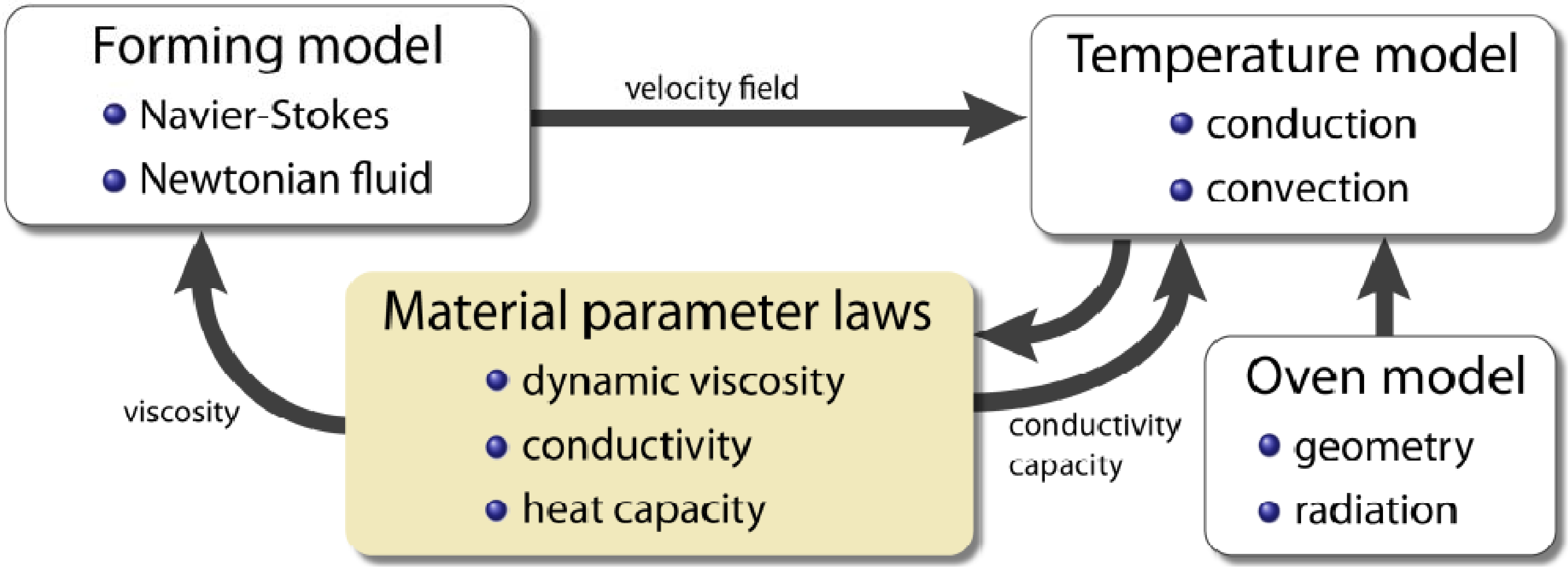
Oven model
- geometry
- radiation



Boundary condition

$$\underline{n} \cdot (\lambda \Delta T) = \epsilon\sigma \left(T_{oven}^4 - T^4\right)$$

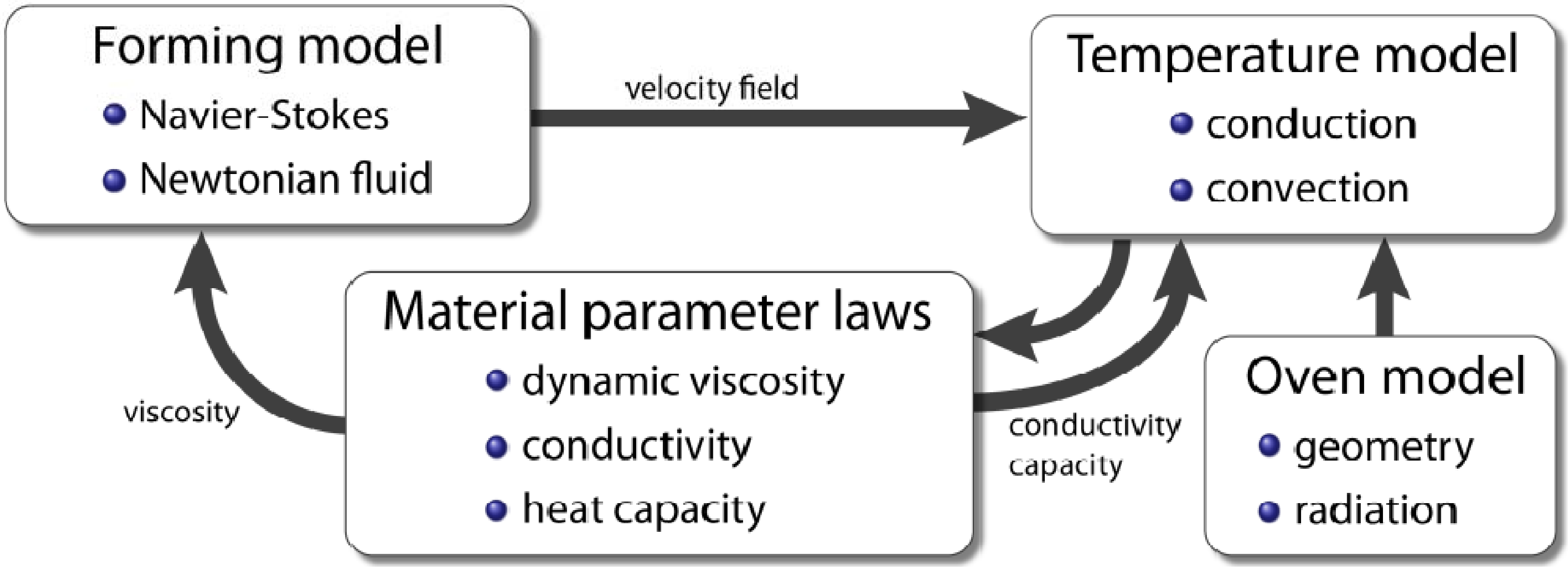
2 Model of the Tube Drawing Process 2/2



Dynamic viscosity

$$\log(\eta) = \eta_{\text{min}} + \frac{1}{2}(\eta_{\text{max}} - \eta_{\text{min}})(\tanh(c_1 T + c_2) + 1)$$

2 Model of the Tube Drawing Process 2/2



Glass Forming Model

- strongly coupled multi-physical system
- highly nonlinear (due to radiation and material parameter laws)
- tremendous distortion during forming process

3 Deformed Mesh

Lagrangian-description

- **mesh moves** with the material
- allows easy tracking of surfaces
- restricted to small displacements

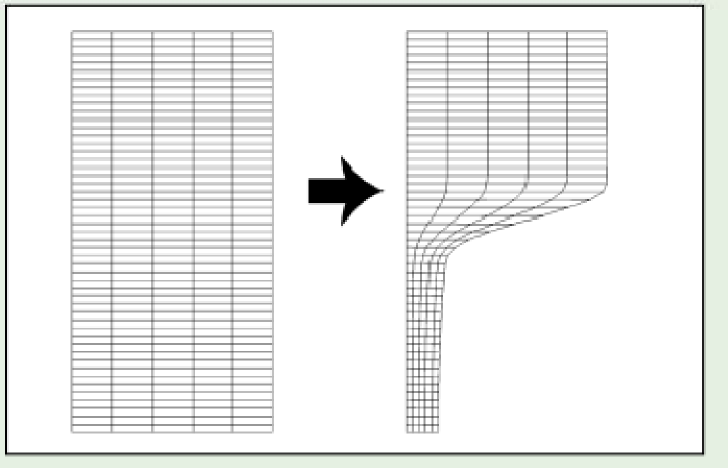
Eulerian-description

- **mesh remains fixed**
- material passes through the mesh
- complex material motion, e.g., fluid

Arbitrary Lagrangian-Eulerian description (ALE)

- combination of both descriptions
- allow the boundaries and the mesh to move
- **however:** without the need to follow the material

→ large distortions for fluid problems



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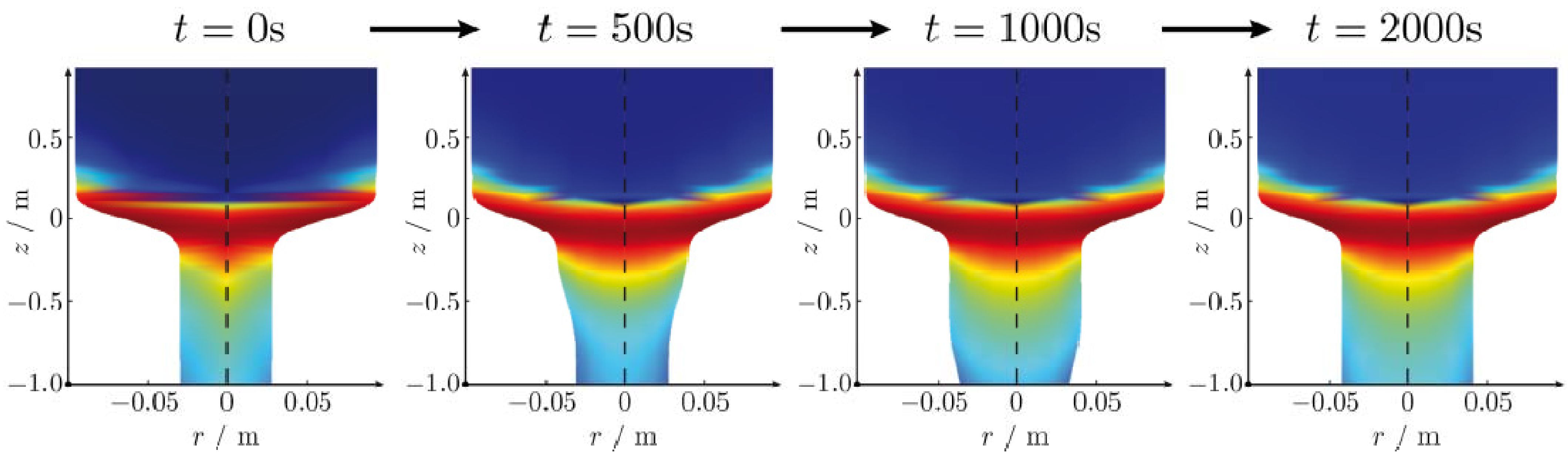
4 Simulation Results 1/2

Time dependent results

- step response with respect to pulling speed $v_s = 2 \rightarrow 1\mathrm{mm/s}$
  - → change in the diameter
  - → change of the temperature distribution



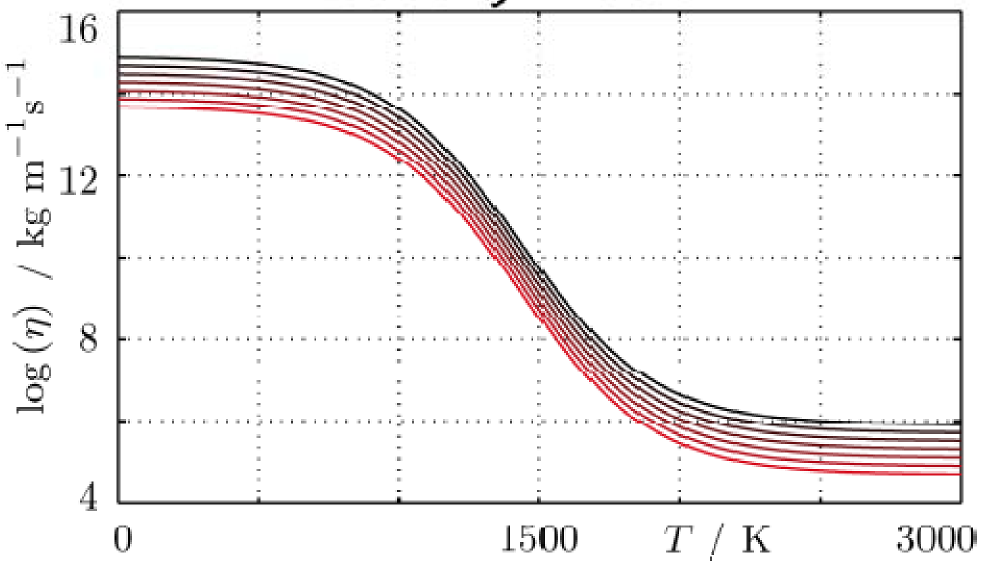
4 Simulation Results 2/2

Variations in the Viscosity Model

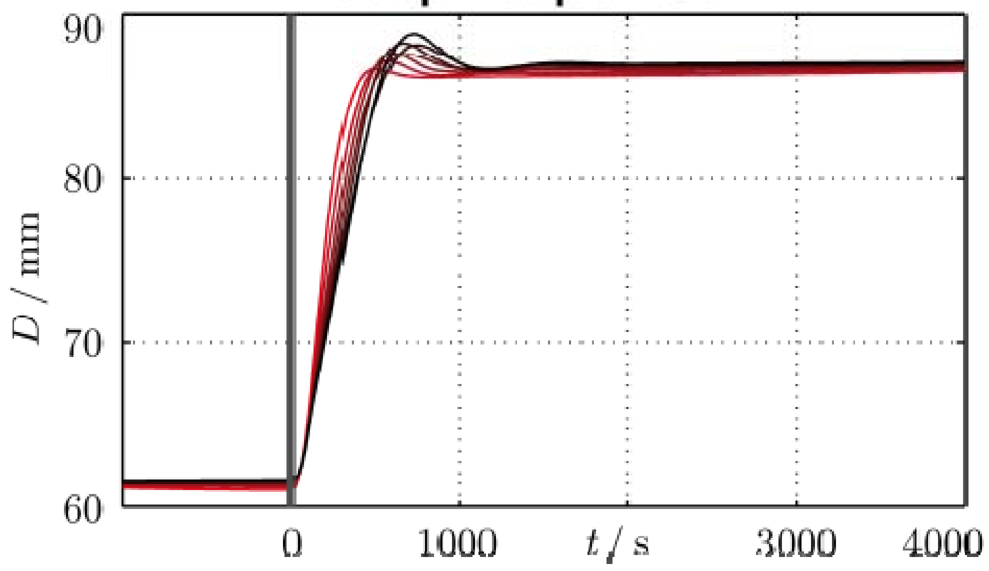
- dynamic viscosity is a crucial parameter for the system behavior
- step response for different viscosity models

→ change of the forming dynamic

Viscosity model



Step response



Conclusion and Future Work

Conclusion

- different extensive tasks in control engineering require realistic model
- model of complex glass forming process
- strongly coupled multi-physic system, nonlinear due to radiation
- large distortion → ALE formulation

Future Work

- identification of model parameters (viscosity model, oven model)
- investigation of different control strategies based on the finite element model
- reduction of model complexity for real-time computation (exploitation in model-predictive control)