MTFC
RESEARCH GROUP

NUMERICAL INVESTIGATION OF FIBER GLASS PROCESS

Q. Chouffart and V. E. Terrapon
Multiphysics and Turbulent Flow Computation Research Group
University of Liège, Belgium

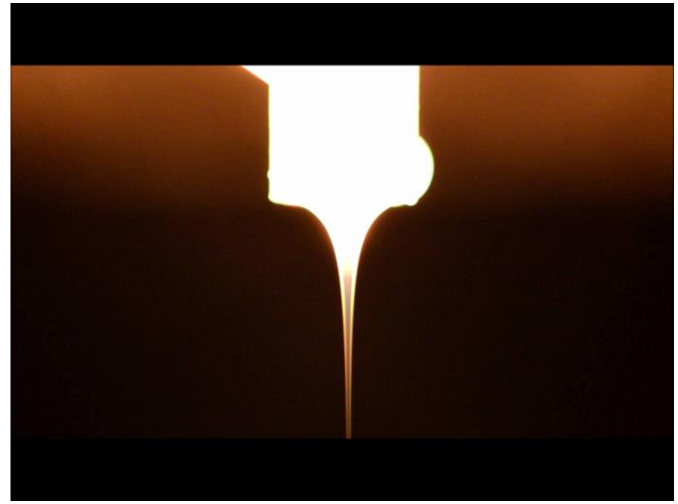
P. Simon
3B The fibreglass company – Binani Group, Belgium

12th ESG Conference
Parma – 24 September 2014

Manufacturing of fiber glass for composite materials

- Manufacturing process consists in **drawing a glass melt into fibers**

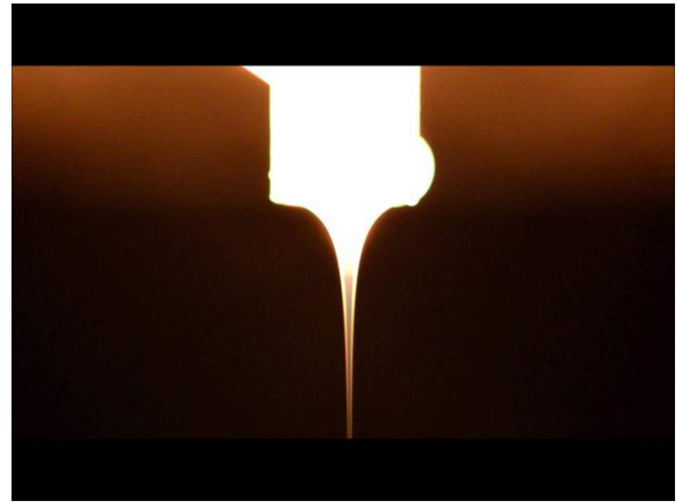
- Main challenge**: fiber breakage**
  - Shut down of forming position
  - Unrecyclable glass waste
  - Barrier to optimization



Manufacturing of fiber glass for composite materials

- Manufacturing process consists in **drawing a glass melt into fibers**

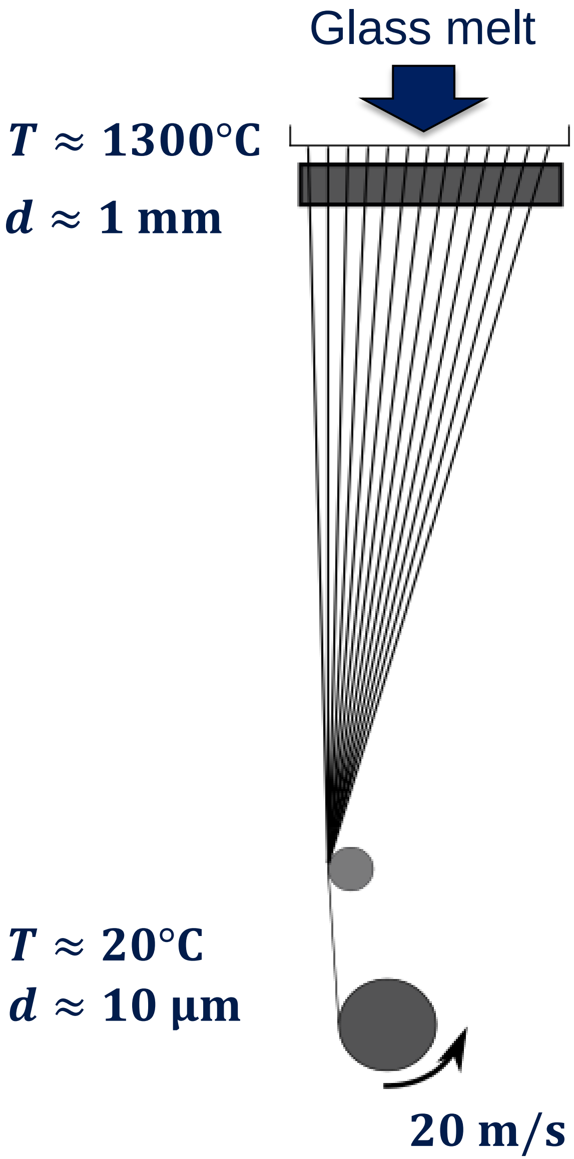
- Main challenge**: fiber breakage**
  - Shut down of forming position
  - Unrecyclable glass waste
  - Barrier to optimization



Goal: Understand the underlying physics of the break

→ Physical modelling of the fiber
→ Experimental investigation

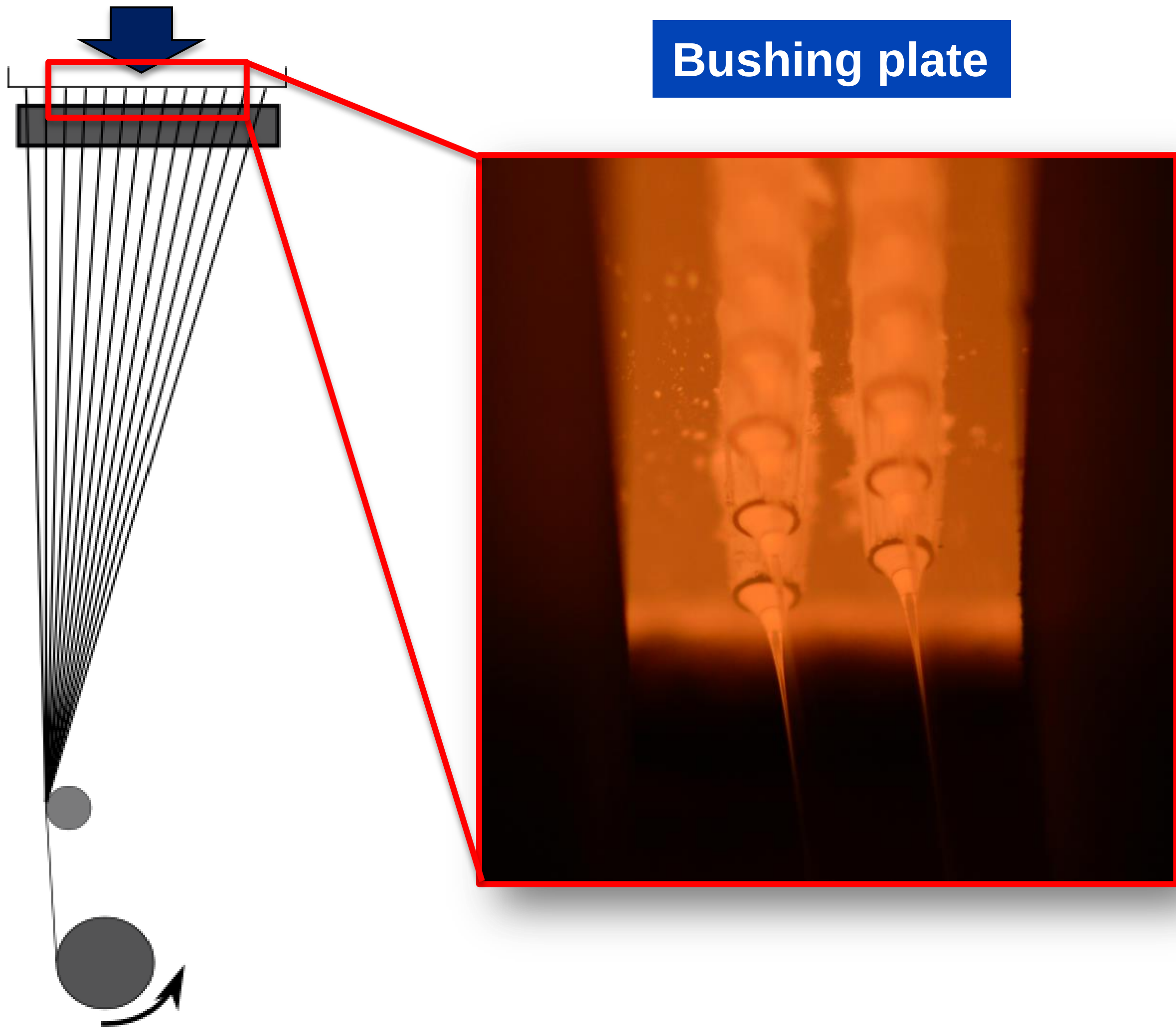
Manufacturing process



Manufacturing process

$T \approx 1300°C$

$d \approx 1\ mm$

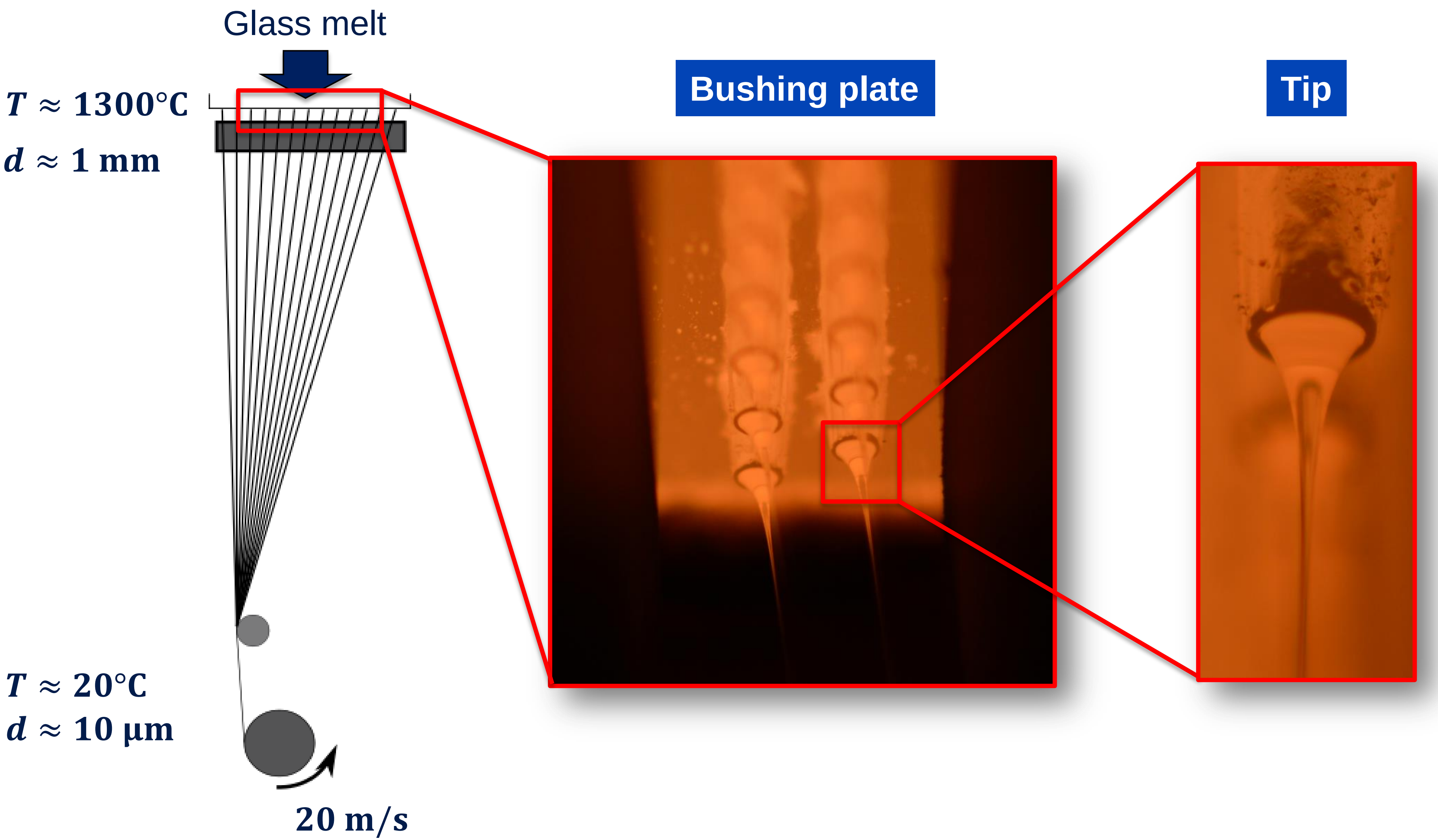


$T \approx 20°C$

$d \approx 10\ \mu m$

$20\ m/s$

Manufacturing process



Physics of the forming of a single fiber

	Glass state	Rheology
$T \approx 1300°\mathrm{C}$	**Glass melt** $T > T_\mathrm{g}$	Newtonian viscous flow
$T_\mathrm{g} \approx 750°\mathrm{C}$	**Glass transition** $T \approx T_\mathrm{g}$	Viscoelastic flow
$T \approx 20°\mathrm{C}$	**Glassy state** $T < T_\mathrm{g}$	Elastic solid

Physics of the forming of a single fiber

$T \approx 1300°C$

$T_g \approx 750°C$

$T \approx 20°C$

Glass state	Rheology
Glass melt $T > T_g$	Newtonian viscous flow
Glass transition $T \approx T_g$	Viscoelastic flow
Glassy state $T < T_g$	Elastic solid

Governing equations

Mass conservation:

$$\frac{D\rho}{Dt} = 0$$

Momentum conservation:

$$\frac{D(\rho \boldsymbol{v})}{Dt} = \nabla . \boldsymbol{\sigma} + \boldsymbol{f}$$

Energy conservation:

$$\frac{D(\rho C_p T)}{Dt} = \sigma : \nabla \boldsymbol{v} - \nabla . \boldsymbol{q_{cond}}$$

Governing equations

Mass conservation:

$$\frac{D\rho}{Dt} = 0$$

Momentum conservation:

$$\frac{D(\rho \boldsymbol{v})}{Dt} = \nabla . \boldsymbol{\sigma} + \boldsymbol{f}$$

Newtonian flow

$$\boldsymbol{\sigma} = -p\mathbf{I} + 2\eta\mathbf{D}$$

Energy conservation:

$$\frac{D\left(\rho C_p T\right)}{Dt} = \sigma : \nabla \boldsymbol{v} - \nabla . \boldsymbol{q}_{\boldsymbol{cond}}$$

Governing equations

Mass conservation:

$$\frac{D\rho}{Dt} = 0$$

Momentum conservation:

$$\frac{D(\rho \boldsymbol{v})}{Dt} = \nabla . \boldsymbol{\sigma} + \boldsymbol{f}$$

Energy conservation:

$$\frac{D(\rho C_p T)}{Dt} = \sigma : \nabla \boldsymbol{v} - \nabla . \boldsymbol{q}_{cond}$$

Newtonian flow

$$\boldsymbol{\sigma} = -p\mathbf{I} + 2\boldsymbol{\eta}\mathbf{D}$$

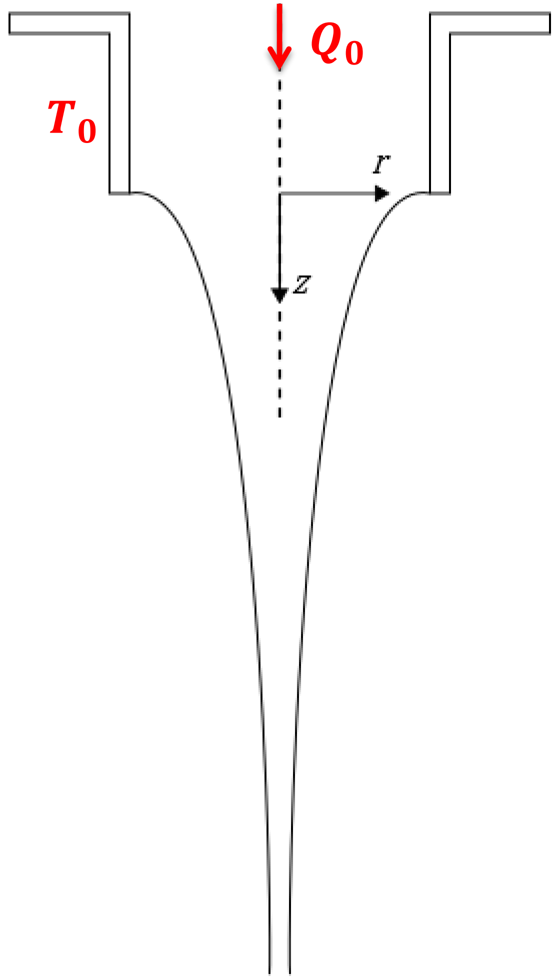
Coupled mainly through **viscosity**

Fulcher law

$$\eta = 10^{-A + \frac{B}{T - T_0}}$$

Boundary conditions

- **<u>At tip</u>**:
  - Flow rate (Poiseuille law) $Q_0(T)$
  - Constant temperature T_0

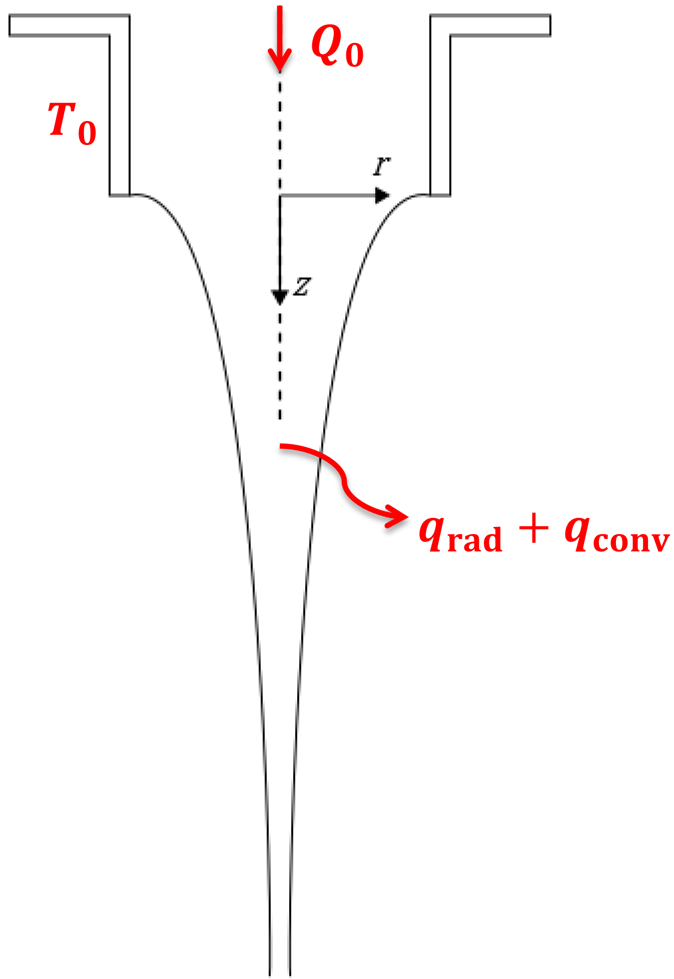


Boundary conditions

- **At tip**:
  - Flow rate (Poiseuille law) $Q_0(T)$
  - Constant temperature T_0

- **At surface**:
  - Free surface & surface tension
  - Heat fluxes:

$$q = \underbrace{\varepsilon\sigma\left(T^4 - T^4_{\text{env,rad}}\right)}_{\text{Radiation}} + \underbrace{h(z)\left(T - T_{\text{ext}}(z)\right)}_{\text{Convection}^1}$$



[1] Empirical coefficient of *Kase-Matsuo* (1965)

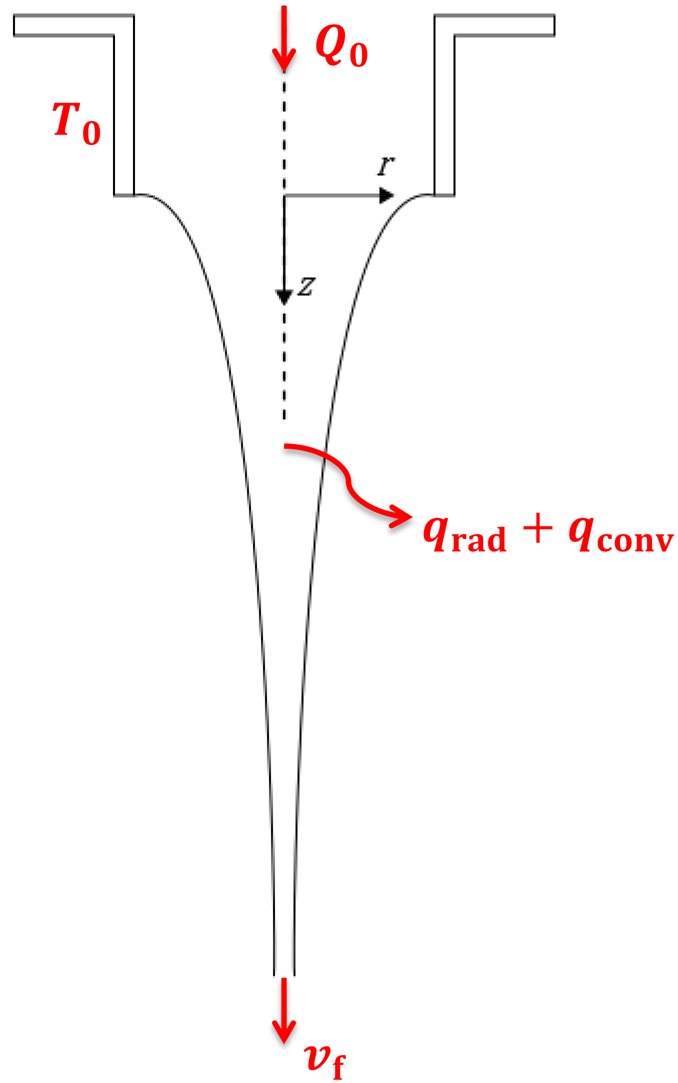
Boundary conditions

- **At tip**:
  - Flow rate (Poiseuille law) $Q_0(T)$
  - Constant temperature T_0

- **At surface**:
  - Free surface & surface tension
  - Heat fluxes:

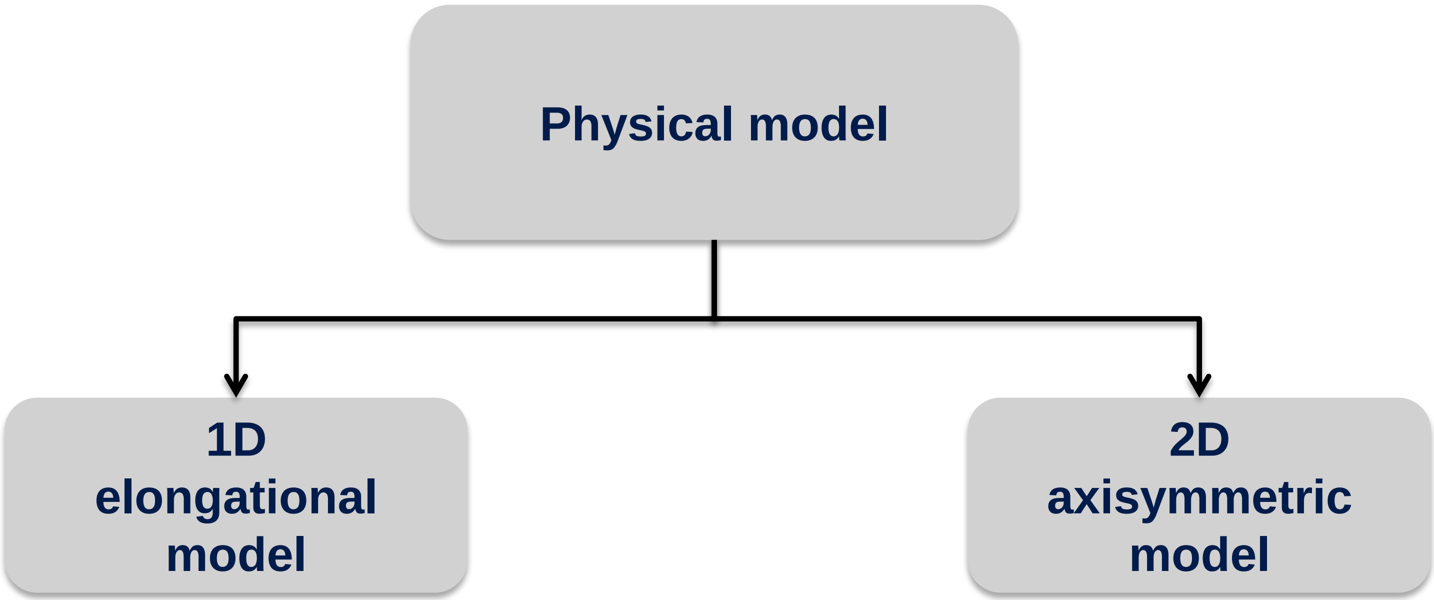
$$q = \underbrace{\varepsilon\sigma\left(T^4 - T_{\text{env,rad}}^4\right)}_{\text{Radiation}} + \underbrace{h(z)\left(T - T_{\text{ext}}(z)\right)}_{\text{Convection}^1}$$

- **At outlet**:
  - Drawing velocity v_{f}



[1] Empirical coefficient of *Kase-Matsuo* (1965)

Solution of the physical model



Semi-analytic solution (ODE solved with *Finite Differences)*

- ***Improved convergence***
- ***Less accurate***
- ***Global information***

Solved with *Finite Elements*

- ***More accurate***
- ***Global and local information***

Solution of the physical model

Physical model

1D elongational model

Semi-analytic solution (ODE solved with *Finite Differences*)

- ***Improved convergence***
- ***Less accurate***
- ***Global information***

2D axisymmetric model

Solved with *Finite Elements*

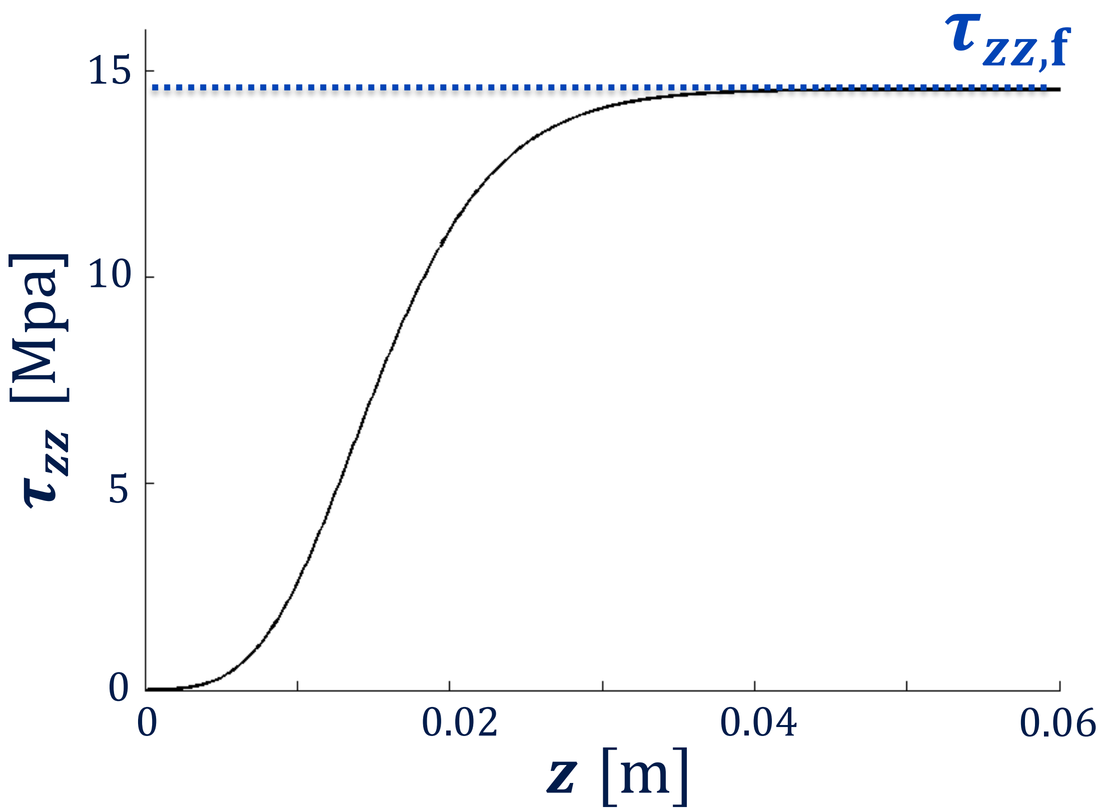
- ***More accurate***
- ***Global and local information***

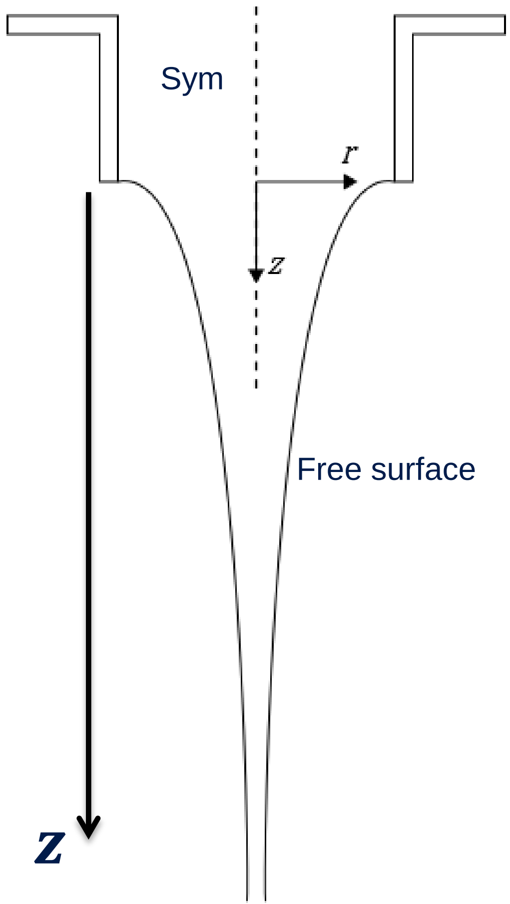
Our quantity of interest: final axial stress $\tau_{zz,\mathrm{f}}$

Axial stress plays a key role in the fiber breaking

Our quantity of interest: final axial stress $\tau_{zz,\mathrm{f}}$

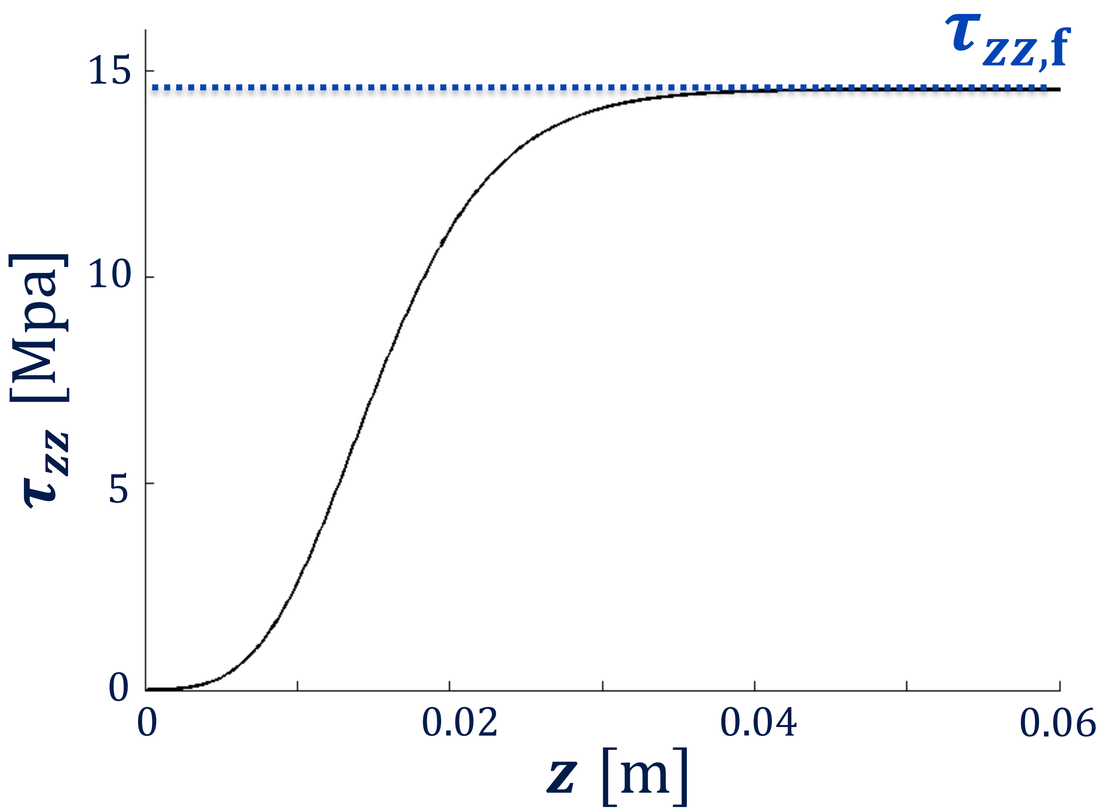
Axial stress plays a key role in the fiber breaking





Our quantity of interest: final axial stress $\tau_{zz,\mathrm{f}}$

Axial stress plays a key role in the fiber breaking



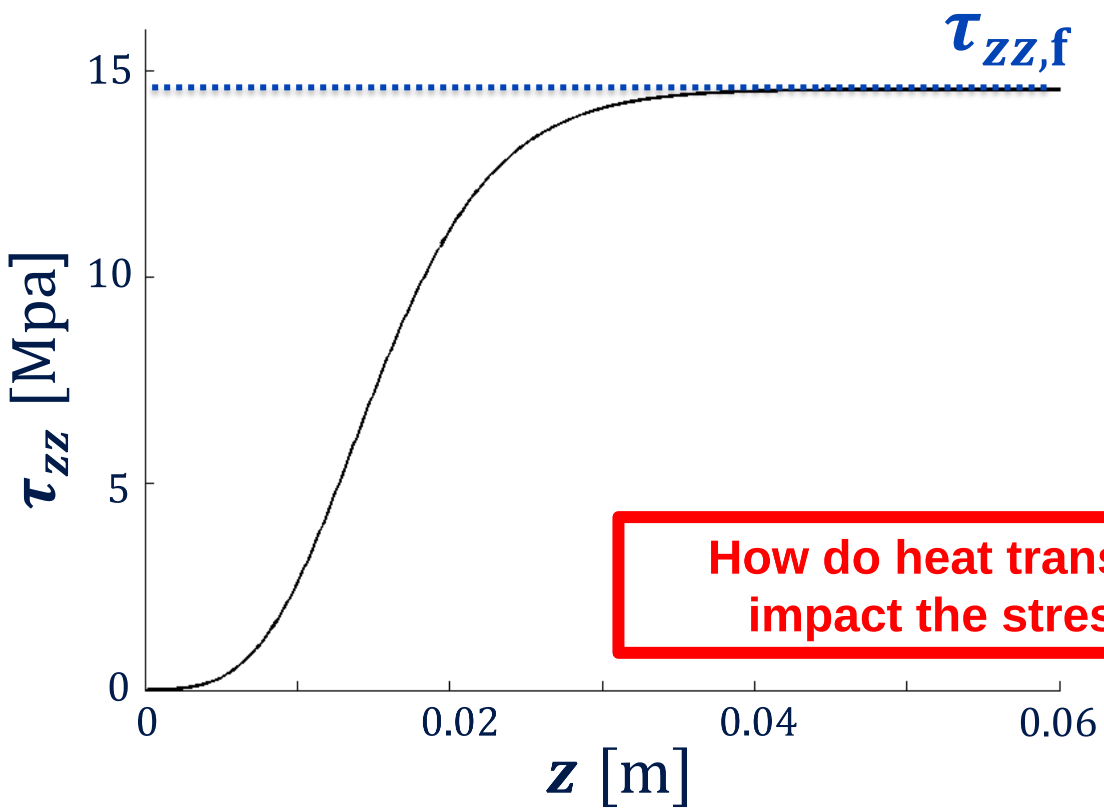
$$\tau_{zz,\mathrm{f}} = \frac{3}{\varphi_{\mathrm{g}}} v_{\mathrm{f}} \, ln\left(\frac{r_0^2}{r_{\mathrm{f}}^2}\right)$$

Final axial stress depends on:

- Diameter ratio
- Drawing velocity
- Cooling history

Our quantity of interest: final axial stress $\tau_{zz,f}$

Axial stress plays a key role in the fiber breaking



How do heat transfers impact the stress?

$$\tau_{zz,f} = \frac{3}{\varphi_g} v_f \ln\left(\frac{r_0^2}{r_f^2}\right)$$

Final axial stress depends on:

- Diameter ratio
- Drawing velocity
- Cooling history

Fluidity φ

Final axial stress

$$\tau_{zz,\mathrm{f}} = \frac{3}{\boldsymbol{\varphi}_{\mathbf{g}}} v_{\mathrm{f}} \ln\left(\frac{r_0^2}{r_{\mathrm{f}}^2}\right)$$

Fluidity

$$\varphi(z) = \int_0^z \frac{1}{\eta(z)} dz$$

$$= \int_{T_0}^{T(z_{\mathrm{f}})} \frac{1}{\dot{c}} \frac{1}{\eta(T)} dT$$

with $\eta = 10^{-A+\frac{B}{T-T_0}}$

Fluidity φ

Final axial stress

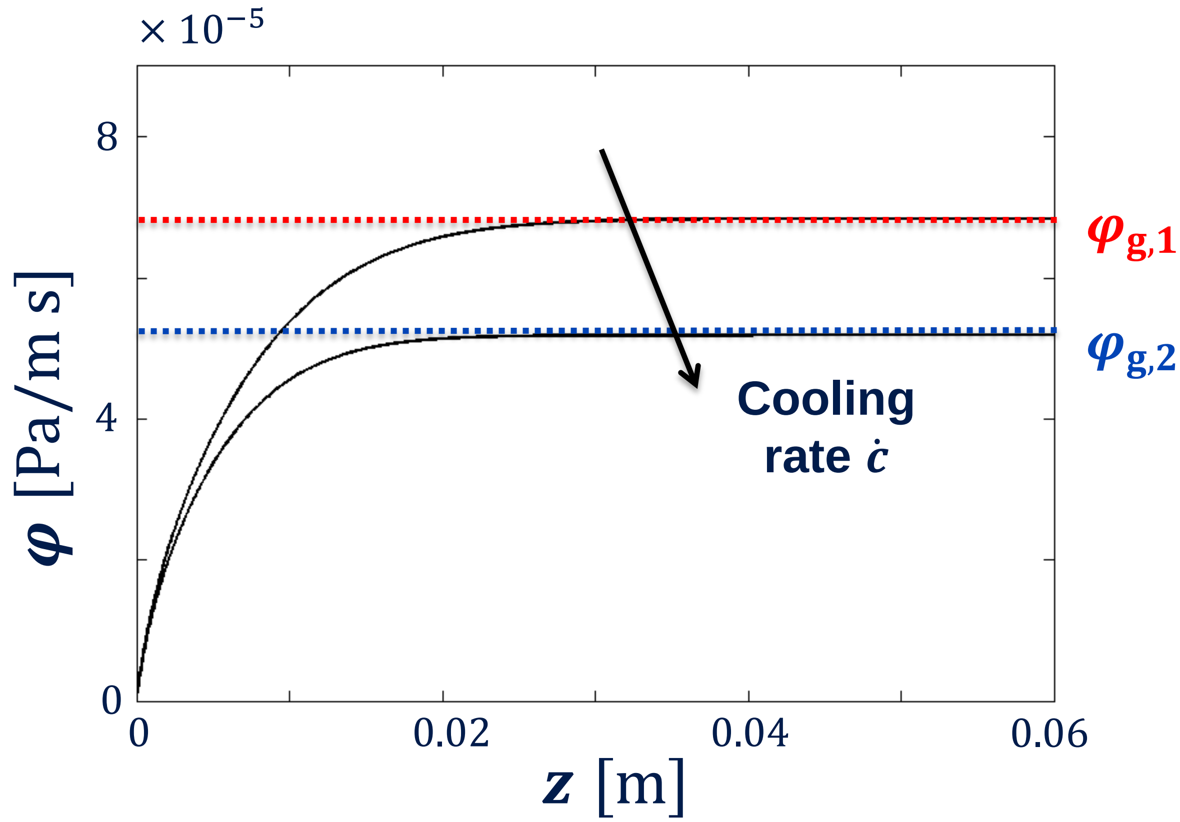
$$\tau_{zz,\mathrm{f}} = \frac{3}{\varphi_{\mathrm{g}}} v_{\mathrm{f}} \ln\left(\frac{r_0^2}{r_\mathrm{f}^2}\right)$$

Fluidity

$$\varphi(z) = \int_0^z \frac{1}{\eta(z)} dz$$

$$= \int_{T_0}^{T(z_\mathrm{f})} \frac{1}{\dot{c}} \frac{1}{\eta(T)} dT$$

with $\eta = 10^{-A+\frac{B}{T-T_0}}$



- $\varphi(z)$ reaches a constant final value φ_{g}
- φ_{g} depends on the cooling rate
- $\tau_{zz,\mathrm{f}}$ increases with higher cooling rate

Fluidity φ

Final axial stress

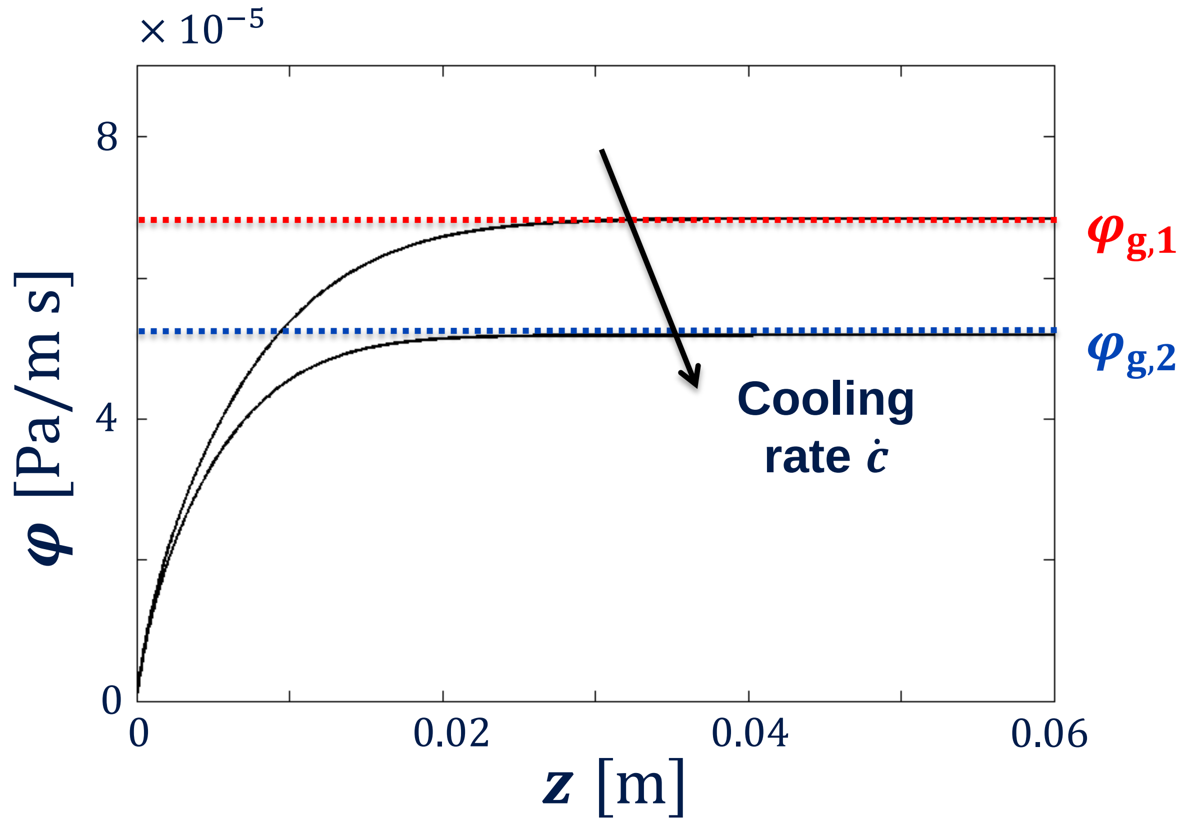
$$\tau_{zz,\mathrm{f}} = \frac{3}{\varphi_{\mathrm{g}}} v_{\mathrm{f}} \ln\left(\frac{r_0^2}{r_{\mathrm{f}}^2}\right)$$

Fluidity

$$\varphi(z) = \int_0^z \frac{1}{\eta(z)} dz$$

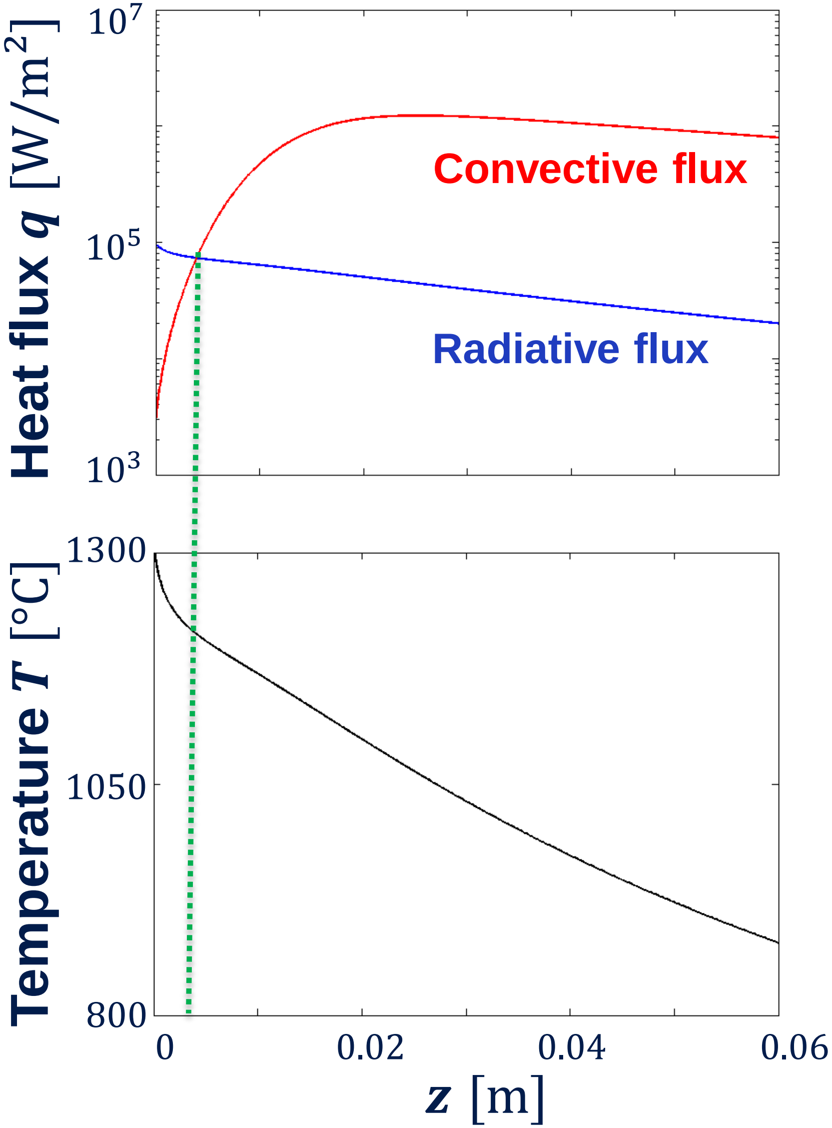
$$= \int_{T_0}^{T(z_{\mathrm{f}})} \frac{1}{\dot{c}} \frac{1}{\eta(T)} dT$$

with $\eta = 10^{-A+\frac{B}{T-T_0}}$



How is the fluidity impacted by the heat fluxes at the surface?

Heat fluxes along the surface



- **Radiation** dominates **near the tip** where the majority of attenuation occurs
- **Convection** dominates **after** the **attenuation**

Heat fluxes along the surface

Sensitivity study

- **Radiative** and **convective** heat fluxes are varied within a physically-defined range

- **Increase** of the **radiative flux** through the emissivity ε

$$q_{\mathrm{rad}} = \varepsilon\sigma\left(T_{\mathrm{s}}^{4} - T_{\mathrm{env,rad}}^{4}\right)$$

- **Increase** of the **convective flux** through the coefficient h

$$q_{\mathrm{conv}} = h(T_{\mathrm{s}} - T_{\mathrm{ext}})$$

with $h = \frac{0.42 k_{\mathrm{a}}}{2r}\,\mathrm{Re}^{0.334}$

Heat fluxes along the surface

Sensitivity study

- **Radiative** and **convective** heat fluxes are varied within a physically-defined range

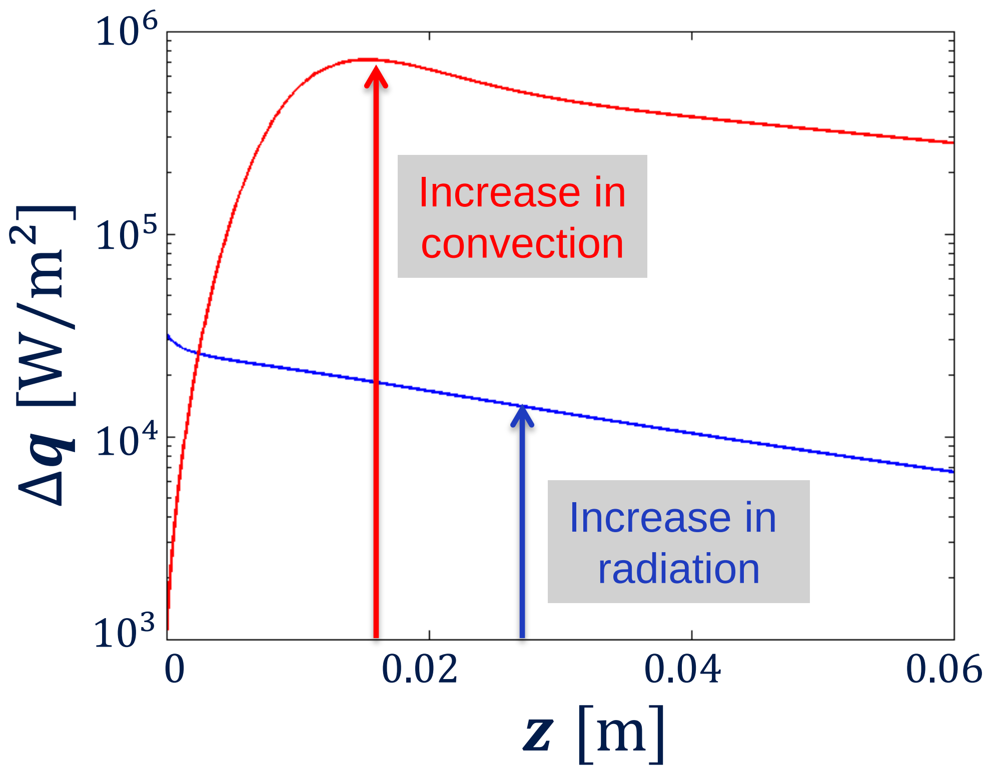
- **Increase** of the **radiative flux** through the emissivity ε

$$q_{\text{rad}} = \varepsilon\sigma\left(T_s^4 - T_{\text{env,rad}}^4\right)$$

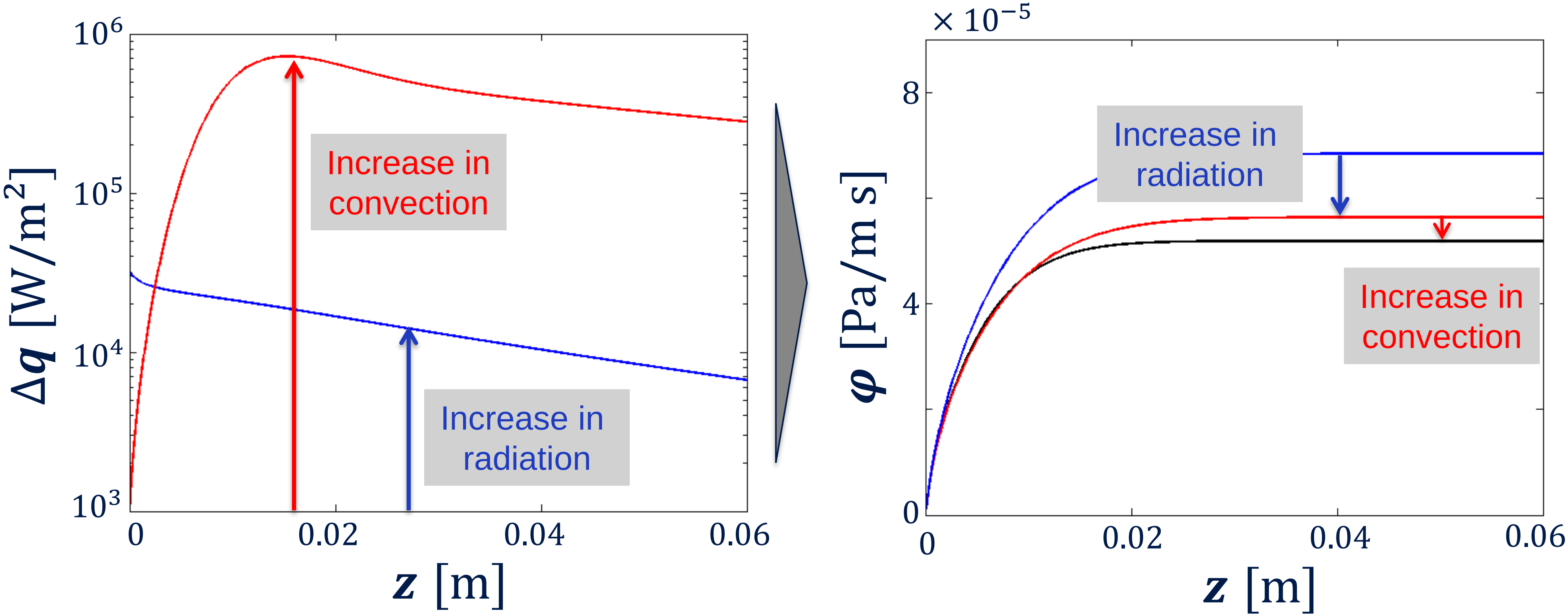
- **Increase** of the **convective flux** through the coefficient h

$$q_{\text{conv}} = h(T_s - T_{\text{ext}})$$

with $h = \frac{0.42 k_a}{2r} \text{Re}^{0.334}$

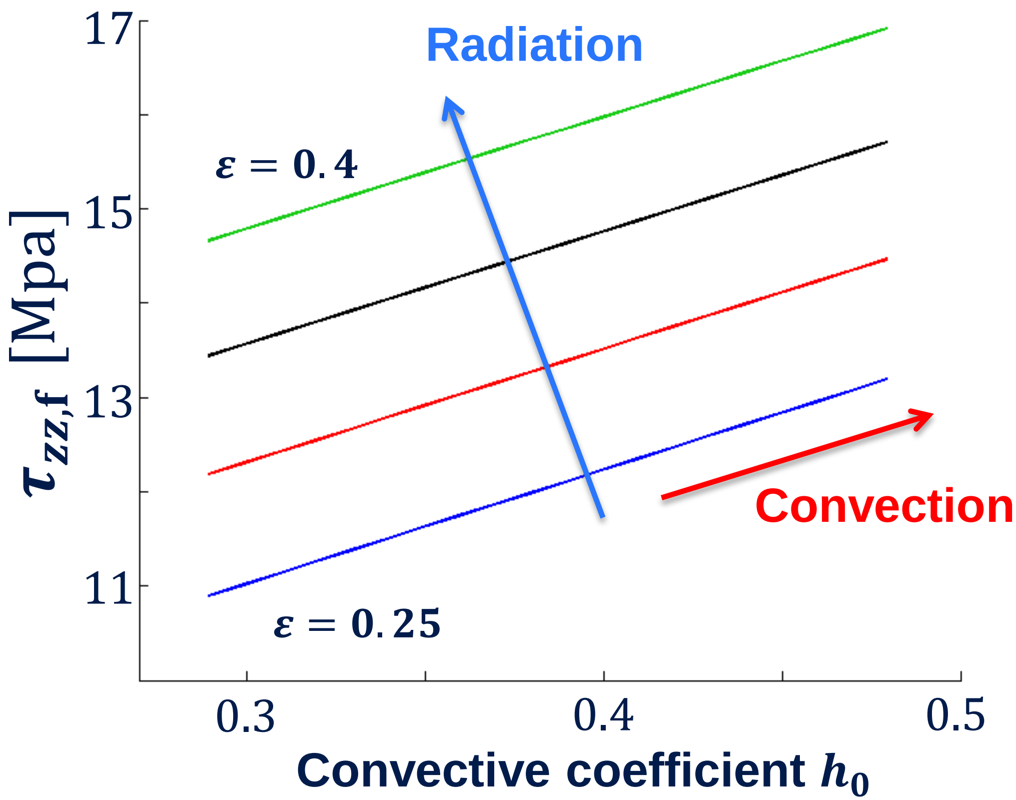


Sensitivity study



- φ_g **is more impacted by an increase in radiation than in convection**
- φ_g **is very sensitive to lower value of viscosity (i.e. at high temperature)**

Sensitivity study



Final axial stress

$$\tau_{zz,f} = \frac{3}{\varphi_g} v_f \ln\left(\frac{r_0^2}{r_f^2}\right)$$

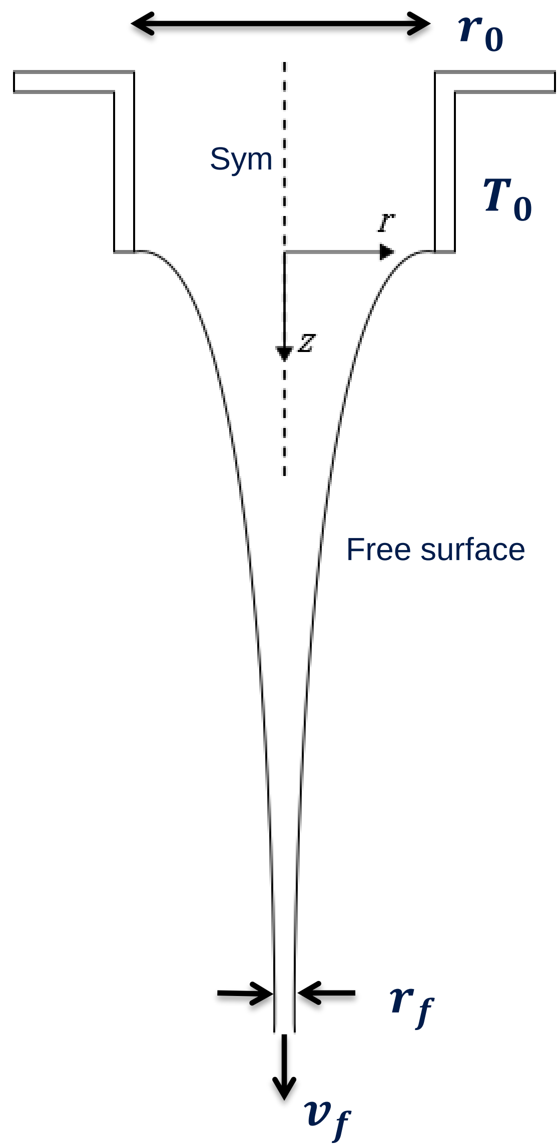
- **Increasing the heat fluxes** at the surface (i.e. increasing the cooling rate) **increases the final axial stress**
- **Radiation** has a **higher impact** due to the high sensitivity of the fluidity on low values of viscosity

The heat transfer in the attenuation region (i.e. radiation) is the most important

Control process parameters

Axial stress

$$\tau_{zz,f} = \frac{3}{\varphi_g} v_f \, ln\left(\frac{r_0^2}{r_f^2}\right)$$

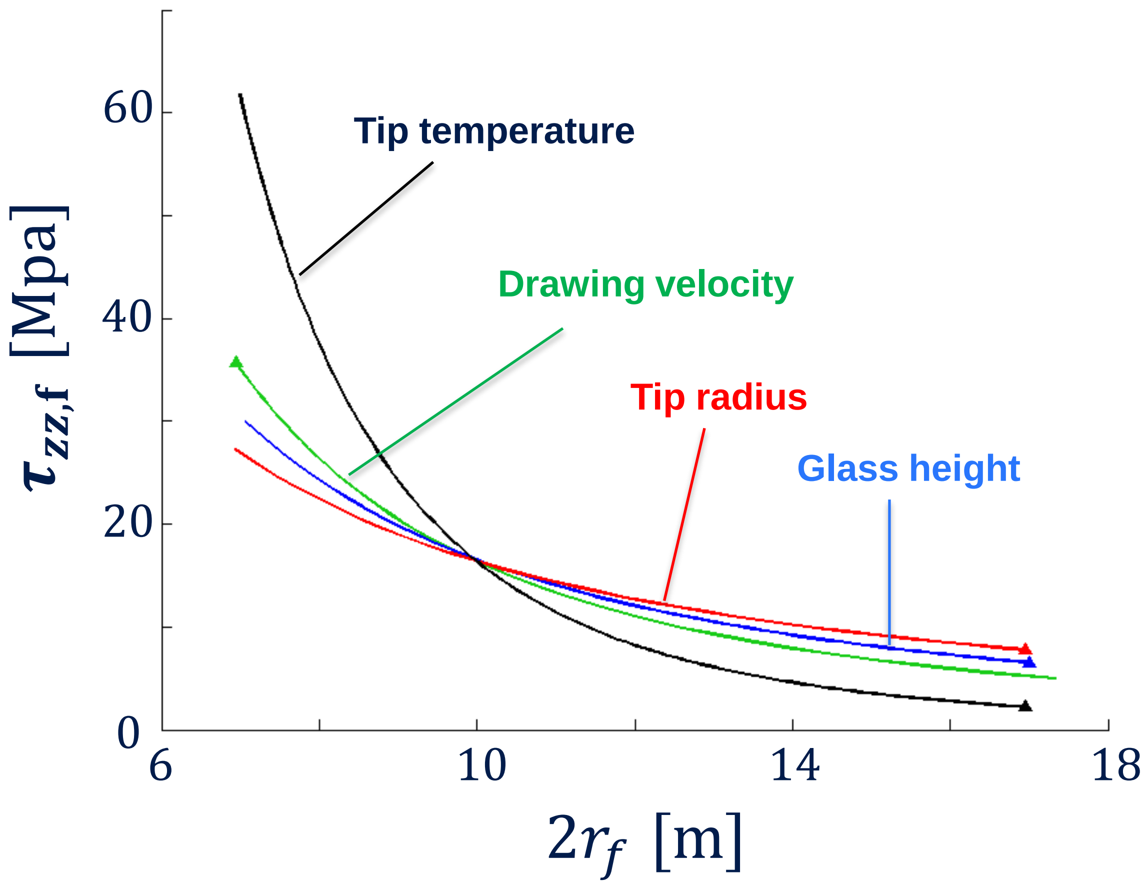


The control process parameters:

- **Tip temperature T_0** impacting φ_g and v_0
- **Tip radius r_0** impacting v_0
- **Drawing velocity v_f**
- **Glass height above the bushing plate** impacting v_0

How is the stress affected by these parameters?

Sensitivity study



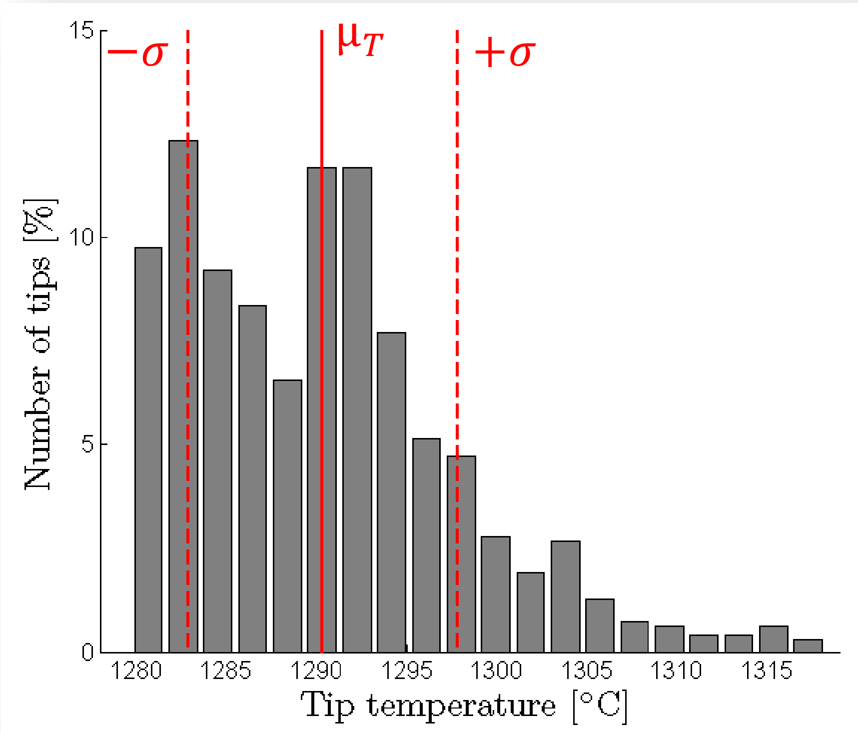
Sensitivity study

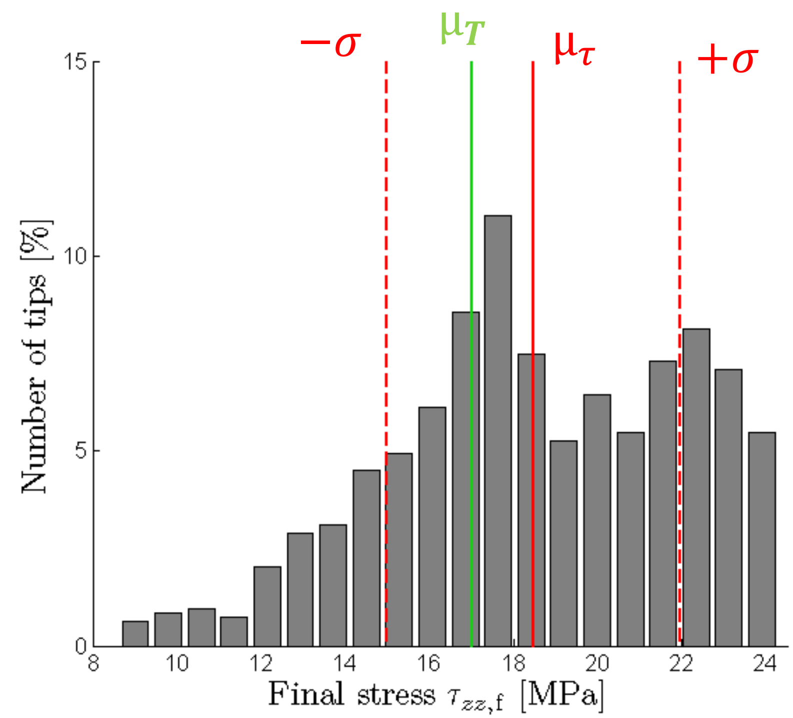
- Each parameter is varied independently, while keeping the others constant
- Range of variation is set to have the final radius between 7 and 17 µm

- **Stress increases** when the **diameter decreases**
- **Glass height** and **tip radius** have almost the **same effect**
- **Tip temperature** is the most **critical** parameter (due to the **fluidity**)

Bushing: problem statement

Temperature inhomogeneity on a 6000 tips bushing plate





- **Temperature inhomogeneity** leads to a **distribution of fiber radius**
- And leads to a **large variation in stress**
- **Mean stress** is **larger** than the stress corresponding to the **mean temperature**

Conclusion & future work

Conclusion

- Cooling history is a key factor in the stress characterization
- Increasing the cooling rate increases the final axial stress
- Tip temperature is critical

Reduction of the stress in the industrial process:

- Radiative properties of the glass
- Fin shields/HVAC adjustment
- Higher tip temperature
- Lower winder velocity

Conclusion & future work

Conclusion

- Cooling history is a key factor in the stress characterization
- Increasing the cooling rate increases the final axial stress
- Tip temperature is critical

Reduction of the stress in the industrial process:

- Radiative properties of the glass
- Fin shields/HVAC adjustment
- Higher tip temperature
- Lower winder velocity

Future work

- Investigate the **unsteady** state
- Link the **breaking rate** to the stress

Acknowledgements

- **Our industrial partner**: *3B – the fibreglass company, Binani group*
- **Financial support**: *3B – the fibreglass company & Walloon region*
- **R&D team from 3B**: *D. Laurent, Y. Houet, B. Roekens, V. Kempenaer and technicians*

MTFC
RESEARCH GROUP

Université de Liège

Binani 3B the fibreglass company
BRAJ BINANI GROUP

RÉGION WALLONNE