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NUMERICAL AND EXPERIMENTAL INVESTIGATION OF FIBER DRAWING PROCESS

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Binani 3B the fibreglass company
BRAJ BINANI GROUP

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Prague - *5 July 2013*

Outline

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- **Motivation**
- Physical model
- Experimental setup
- Numerical investigation
  - Heat transfers
  - Stresses
- Conclusion & future work

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Motivation & objectives

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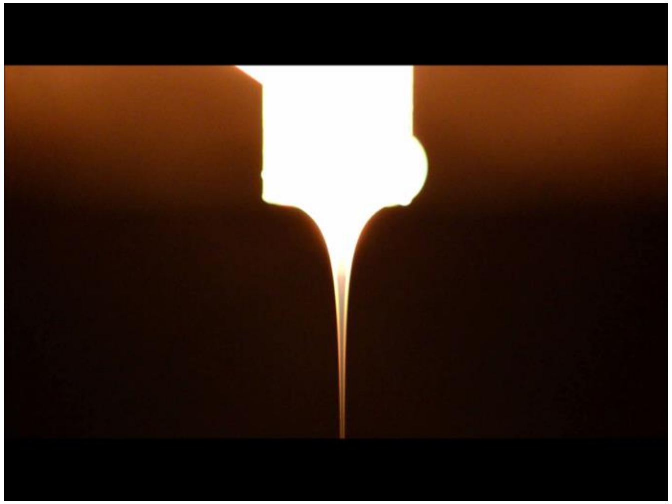
Glass fibers are used for the reinforcement of **composite materials**



Main challenges: **fiber breakage**

- **Shut down** of forming position
- Unrecyclable glass **waste**
- **Barrier** to optimization

<u>Overall Goal</u>

➢ Understand **fiber breaking:**
  - Step 1: Physical modeling of forming glass
  - Step 2: Characterization of breaking mechanisms
    → One single fiber
    → Multi-filaments bushing

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Fiberglass drawing process

General steps

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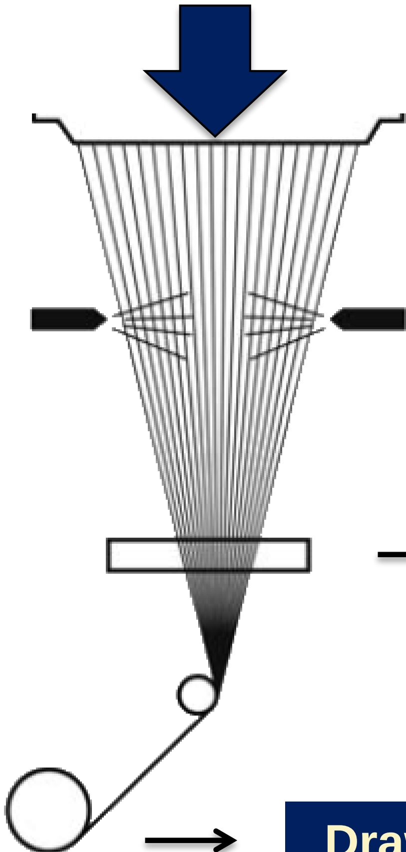
Four main steps

Glass melt



Extrusion of glass melt through > 1000 holes

T ~ 1300°C

Cooling by fins and water spray

Coating

Drawing by a winder

(20 m/s → ~10 μm fibers diameter)

Fiberglass drawing process
Bushing plate & tips

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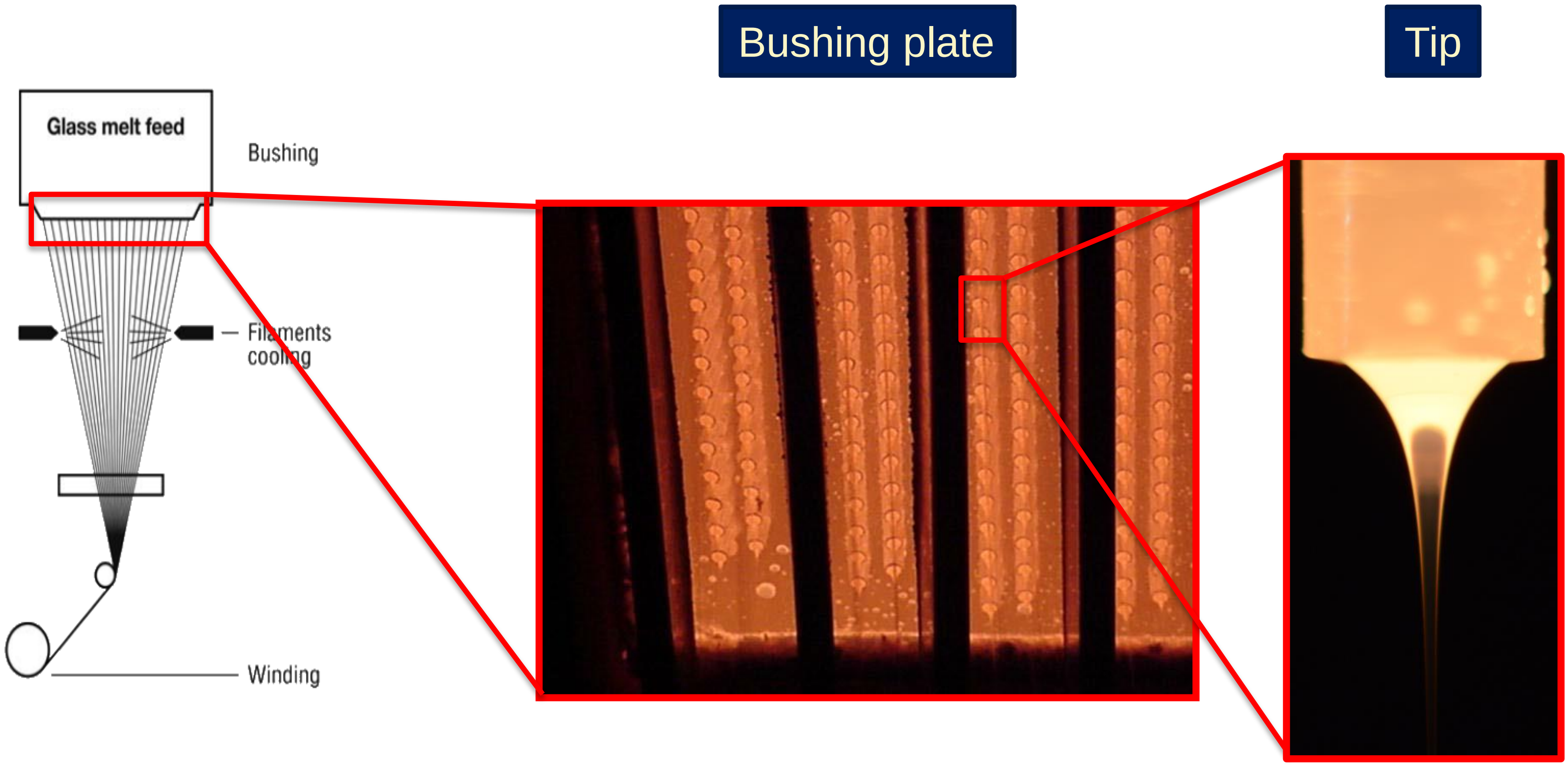

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Physics of the forming of a single fiber

Glass state

Rheology ↔ **Heat transfer**

Coupling

Physics of the forming of a single fiber

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Glass state	Rheology	Heat transfer
Glass melt $T > T_g$	Newtonian viscous flow	Inside the fiber: ***Conduction & Radiation*** Around the fiber: ***Convection & Radiation***
Glass transition $T \approx T_g$	Viscoelastic flow	Inside the fiber: ***Conduction*** Around the fiber: ***Convection***
Glassy state $T < T_g$	Elastic solid	Inside the fiber: ***Conduction*** Around the fiber: ***Convection***

Physics of the forming of a single fiber

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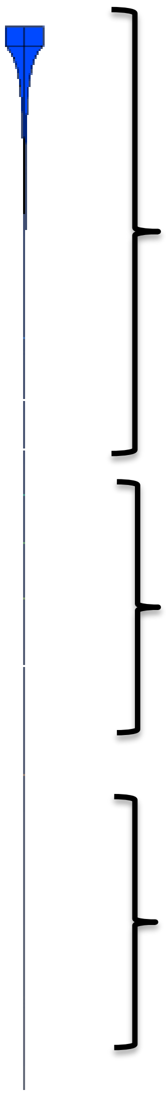

Glass state	Rheology	Heat transfer
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Glassy state $T < T_g$	Elastic solid	Inside the fiber: ***Conduction*** Around the fiber: ***Convection***

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Physical model
Governing equations

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Mass conservation:

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

Momentum conservation:

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

Energy conservation:

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

Assumption: Internal radiation → neglected

Physical model

Governing equations

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Momentum conservation:

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Newtonian flow:
$\sigma = -p\mathbf{I} + 2\eta\mathbf{D}$

Energy conservation:

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Physical model
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Newtonian flow:
$$\sigma = -p\mathbf{I} + 2\boldsymbol{\eta}\mathbf{D}$$

coupled through viscosity

<u>Fulcher law</u>

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

(η = dynamic viscosity)

<u>Assumption</u>: Internal radiation → neglected

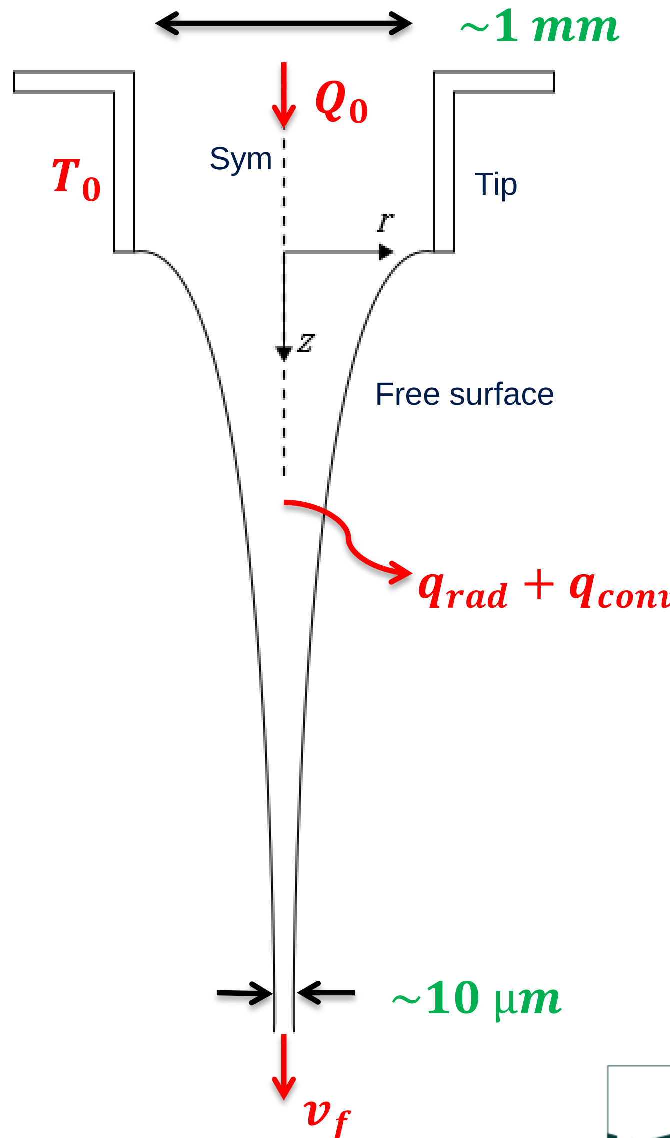
Physical model
Boundary conditions

- **At tip**:
  - *Volumetric flow rate (Poiseuille law)*
  - T_0 *constant*

- **At surface**:
  - *Free surface conditions & surface tension*
  - $q = \varepsilon\sigma(T^4 - T_{ext}^4(z)) + h(z)\big(T - T_{ext}(z)\big)$

    Radiation — Convection

- **At outlet**: *Drawing velocity*



Outline

Experimental investigation

Fiber drawing unit

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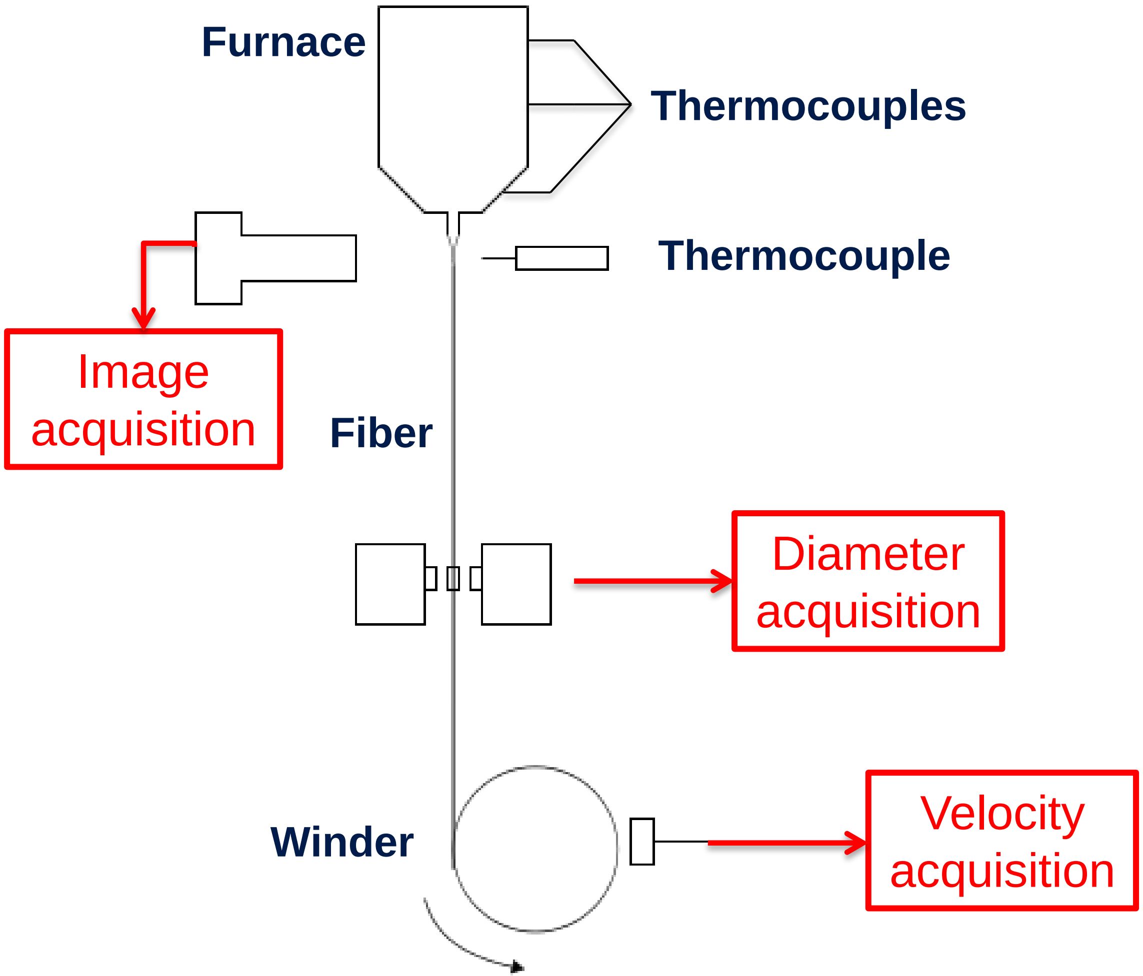

Facilities

1. Velocity acquisition
2. Image acquisition
3. Diameter acquisition

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Experimental investigation

Fiber drawing unit

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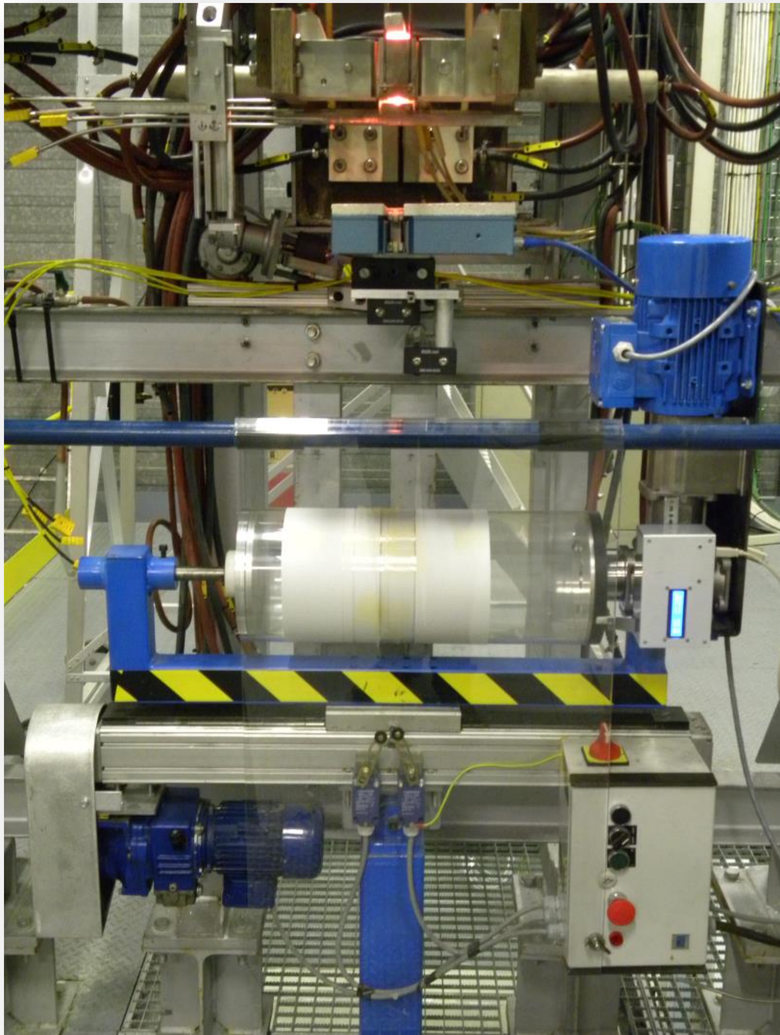

Facilities

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Outline

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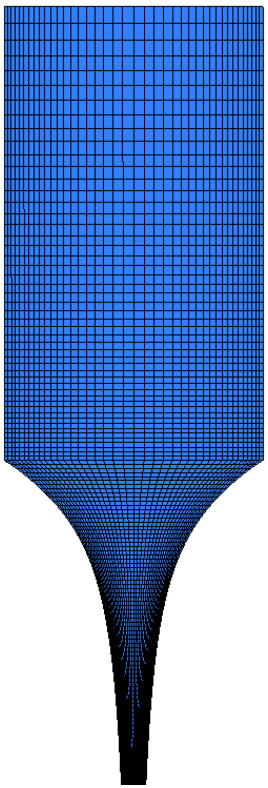
Numerical investigation

Introduction

Simulations are performed with ANSYS Polyflow software



Cases of study

- Validation
- Heat transfers:
  - radiation
  - convection
- Stress: sensitive analysis

Numerical investigation

Validation

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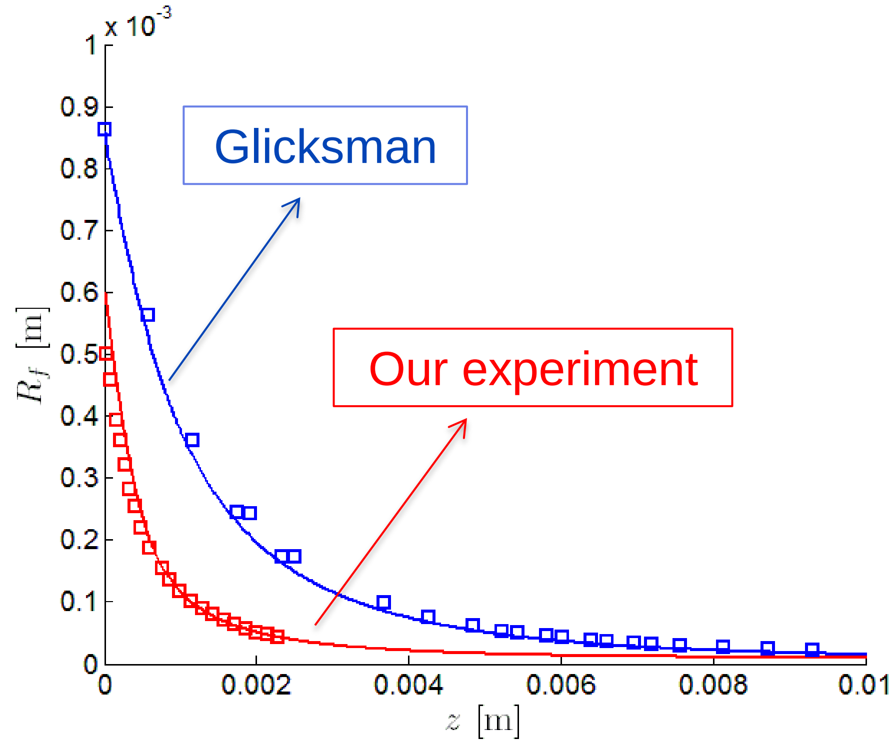
Case study

Material	Glass M5	Advantex®
T_0	1227 °C	1308 °C
Q_0	$3.17\ 10^{9}\ m^3/s$	$4.72\ 10^{10}\ m^3/s$
v_f	$25.88\ \ m^3/s$	$1.55\ \ m^3/s$
	Glicksman 1964	*Our experiment*

Fiber radius



Good agreement between simulation and experimental data

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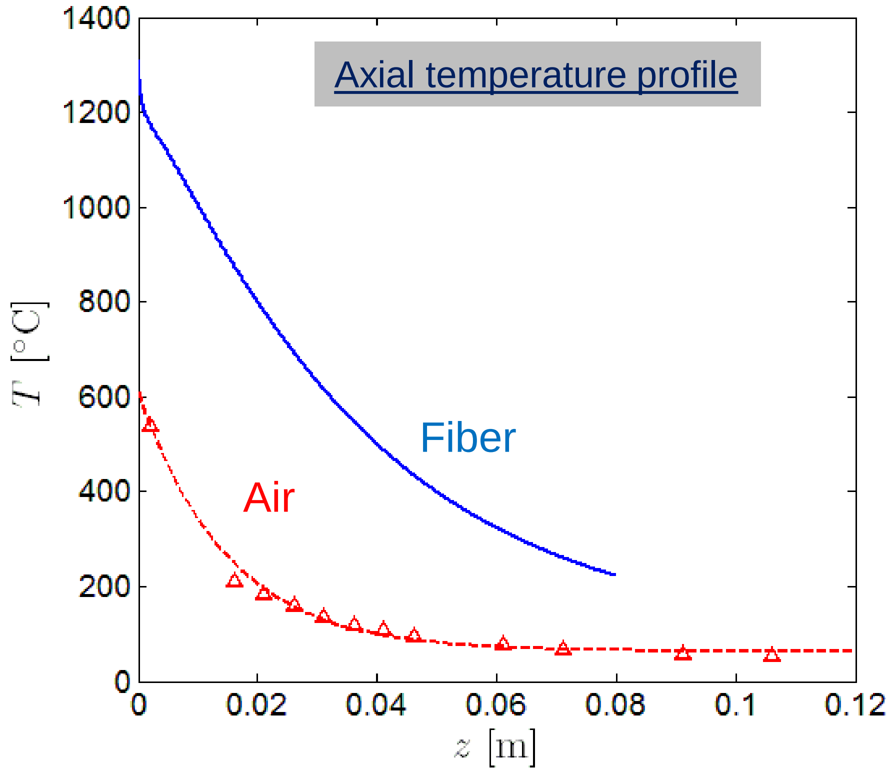
Heat transfer
Temperature profile

Cooling is critical:
- → impact on fiber properties
- → impact on break origins

What are the factors that lead to this high cooling?



Heat flux:

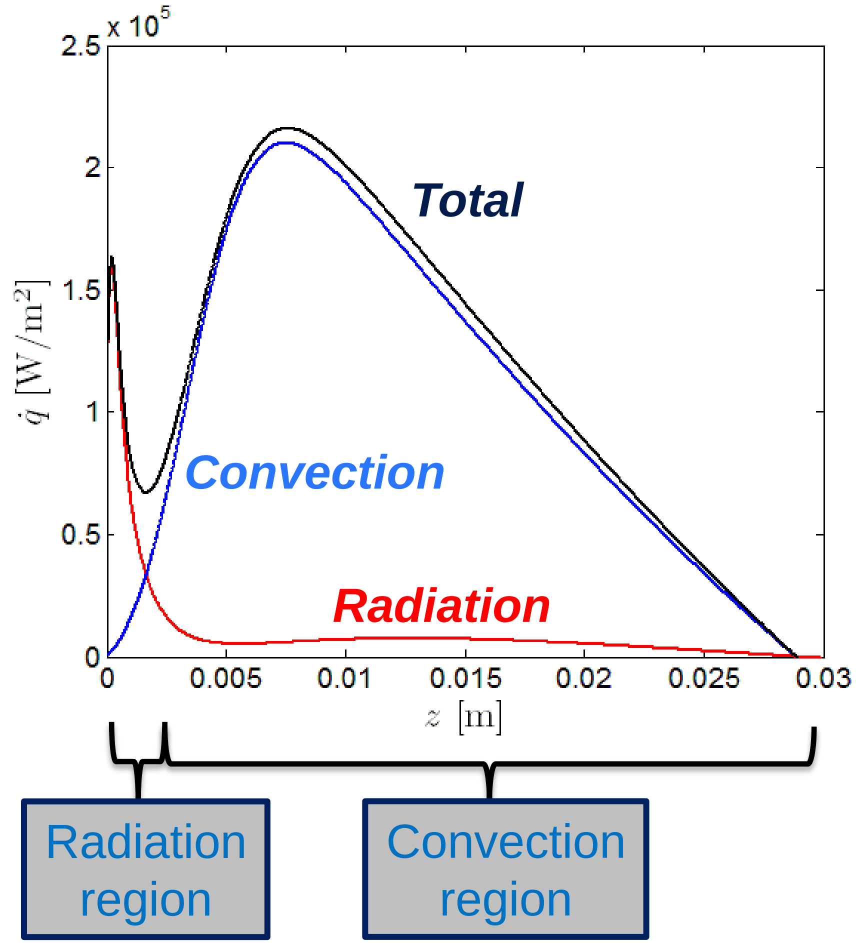
$$\dot{q}(z) = \underbrace{h(T - T_{ext})}_{\text{Convection}} + \underbrace{\varepsilon\sigma(T^4 - T_{ext}^4)}_{\text{Radiation}}$$

Cooling rate:

$$\dot{T} = -\frac{\dot{q}(z)}{\rho C_p \, r_f(z)}$$

- Cooling depends both on **heat flux** and **radius attenuation**
- **Radius history** is important due to variation of **viscosity**

Heat flux



Heat transfer

Cooling rate - Radiation

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Radiation:

$$\dot{q}_{rad} = \varepsilon\sigma(T^4 - T_{ext}^4)$$

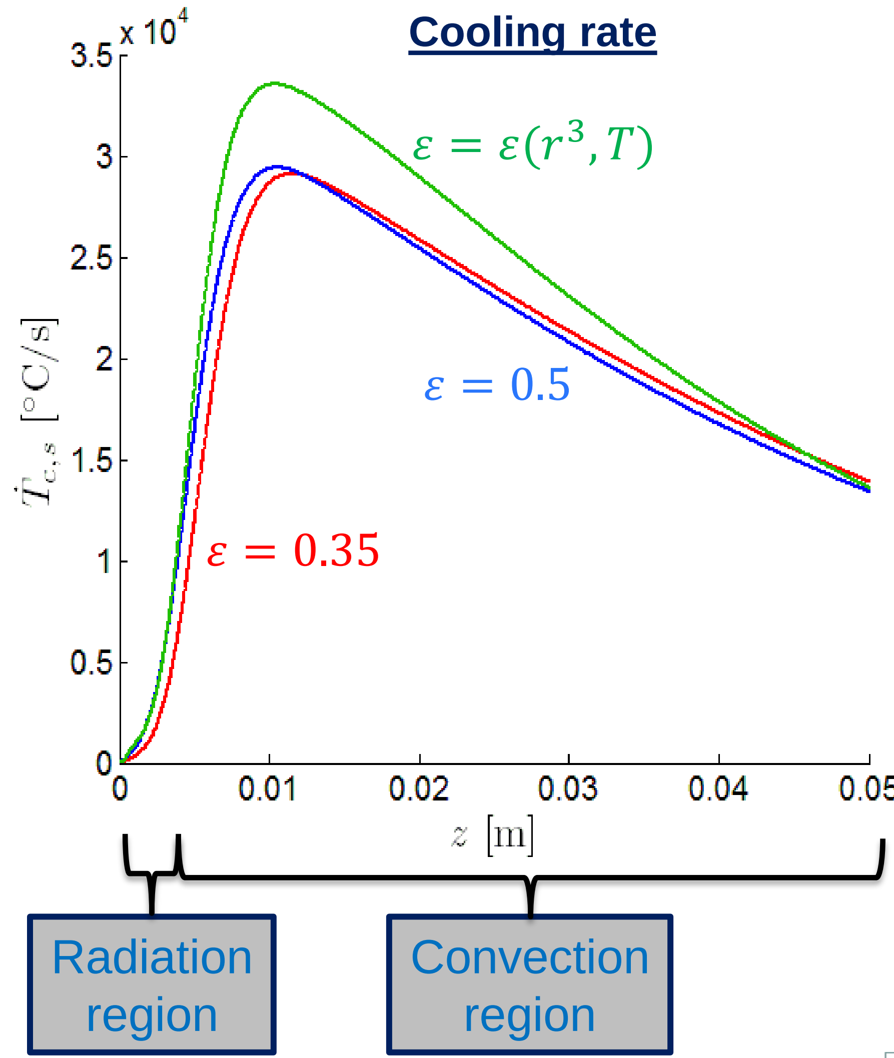
with

$$\varepsilon = \varepsilon(r^3, T)$$

Cooling rate:

$$\dot{T}_{c,s} = -\frac{\dot{q}(z)}{\rho Cp\, r_f(z)}$$

→ Variability emissivity has a significant impact



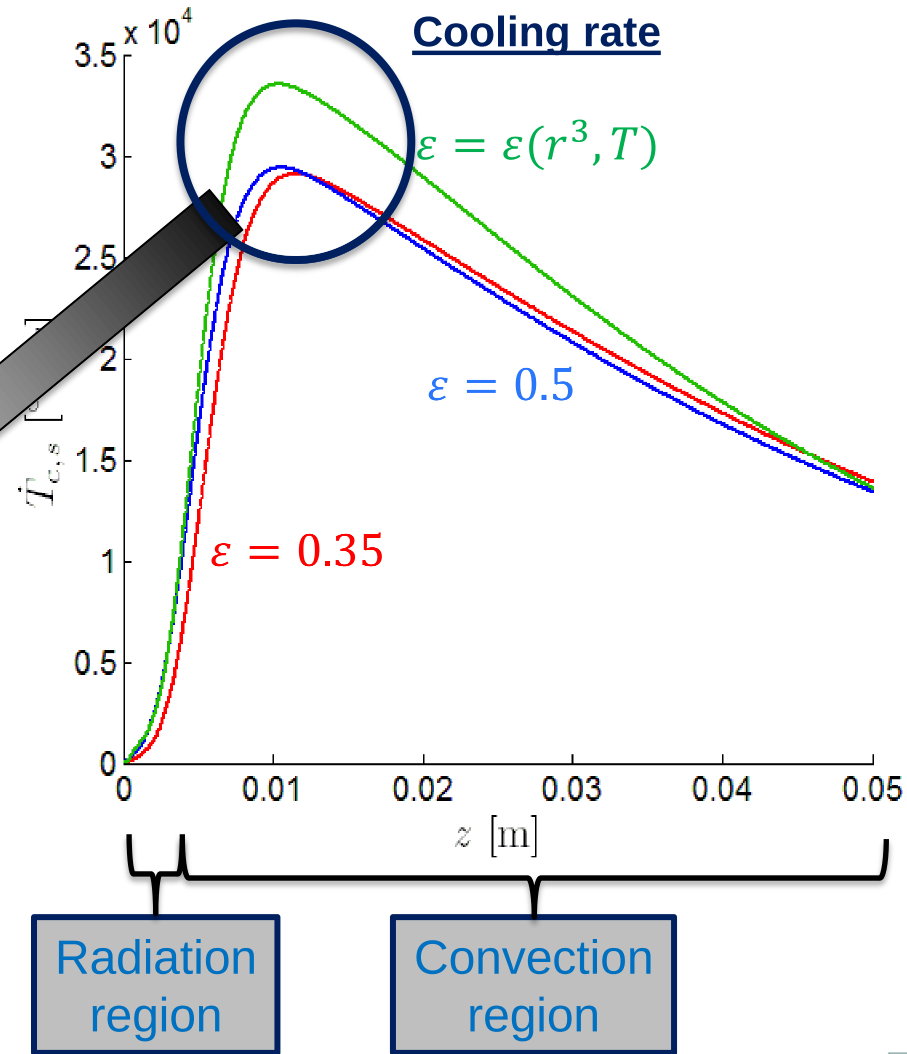
Cooling rate: $\dot{T}_{c,s} = -\frac{\dot{q}(z)}{\rho Cp\, r_f(z)}$

Variation of emissivity

Variation of viscosity

Variation of velocity

Variation of radius



Cooling rate is very sensitive to the cooling history

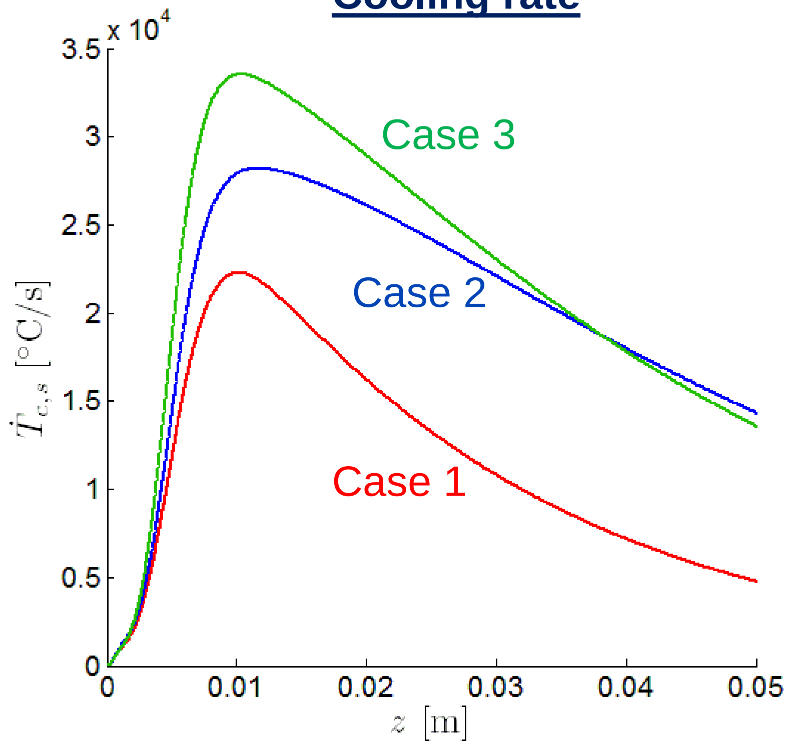
Convection: $q_{conv} = h(T - T_{ext})$

Kase-Matsuo convective coefficient:

$$h = \frac{0.42\, k_a}{D_f} \left(\frac{v_s\, D_f}{\mu_a}\right)^{0.334}$$

- Fiber diameter D_f
- Fiber velocity v_f
- Air properties k_a, μ_a
- Air temperature $T_{ext}(z)$

Cooling rate



- **Surrounding air has a significant impact on the cooling rate**
- **Accurate description of air properties is needed**

Case 1: **Constant** air temperature

Case 2: **Variable** air temperature with **constant** air properties

Case 3: **Variable** air temperature and air properties **depending on temperature**

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  - ➢ **Stresses**
- Conclusion & future work

Stresses
Stress description

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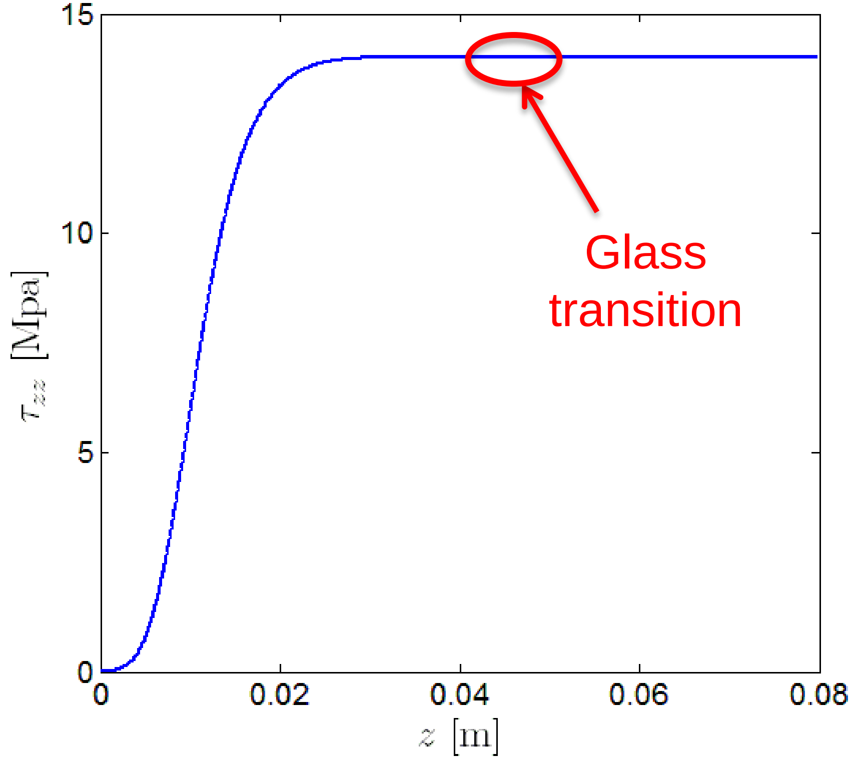
Newtonian stress in z direction:

$$\tau_{zz} = \eta(T)\frac{dv_z(z)}{dz}$$

Axial stress



→ **Axial stress** grows and takes a final constant value

→ **Final value** before the transition

→ **Newtonian model** seems to be sufficient

Stresses
Stress description

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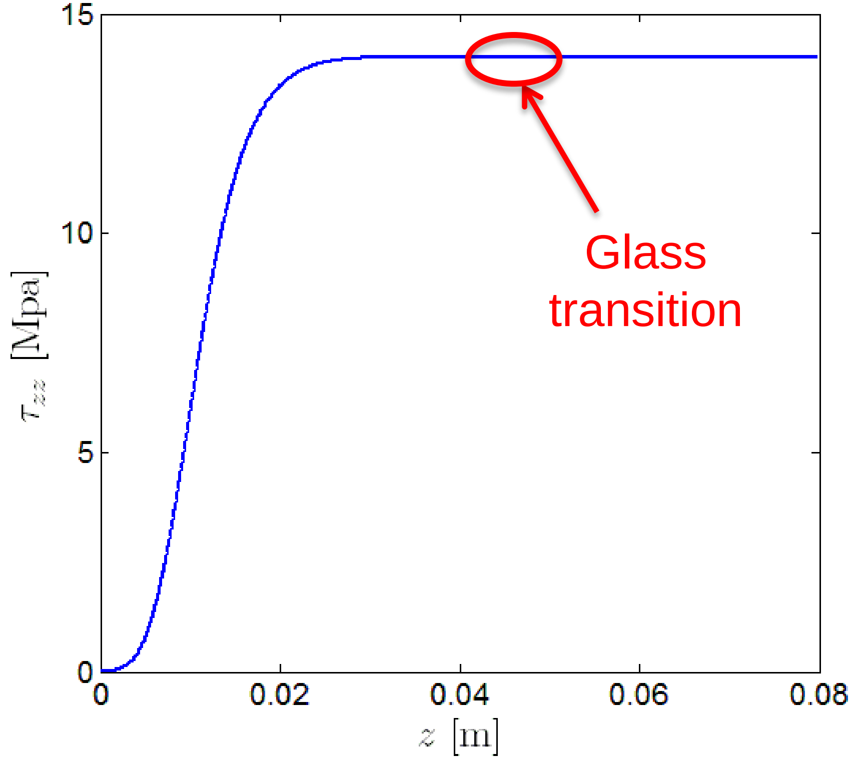
Newtonian stress in z direction:

$$\tau_{zz} = \eta(T)\frac{dv_z(z)}{dz}$$

Axial stress



Key question:

What are the key parameters controlling the internal stress?

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Stresses
Main parameters

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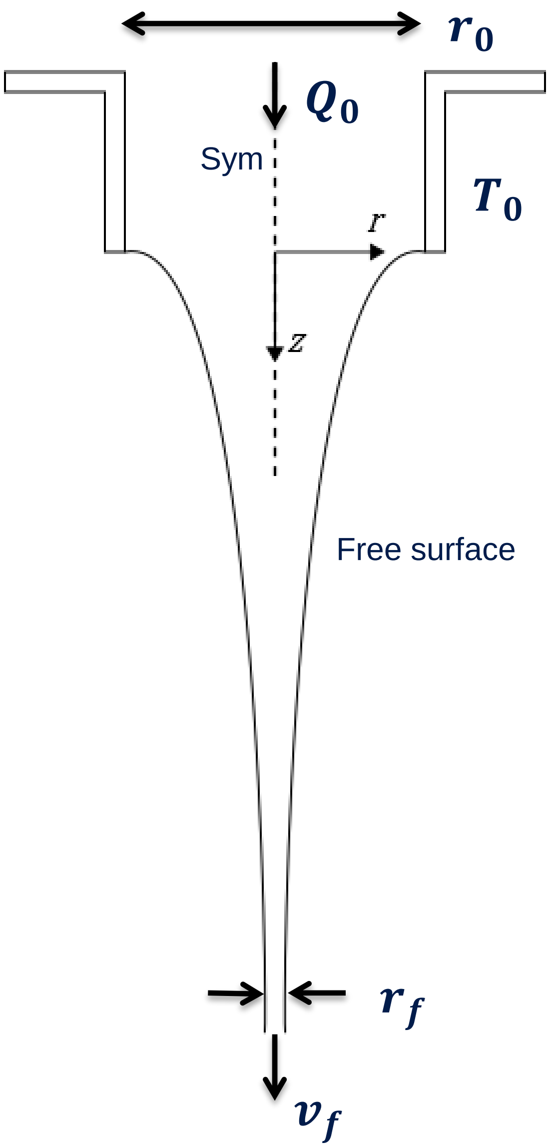
Given a target radius
→ how the stress can be reduced ?

Mass conservation:

$$r_f^2 = \frac{Q_0(r_0, T_0)}{\pi v_f} = cst$$



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Given a target radius
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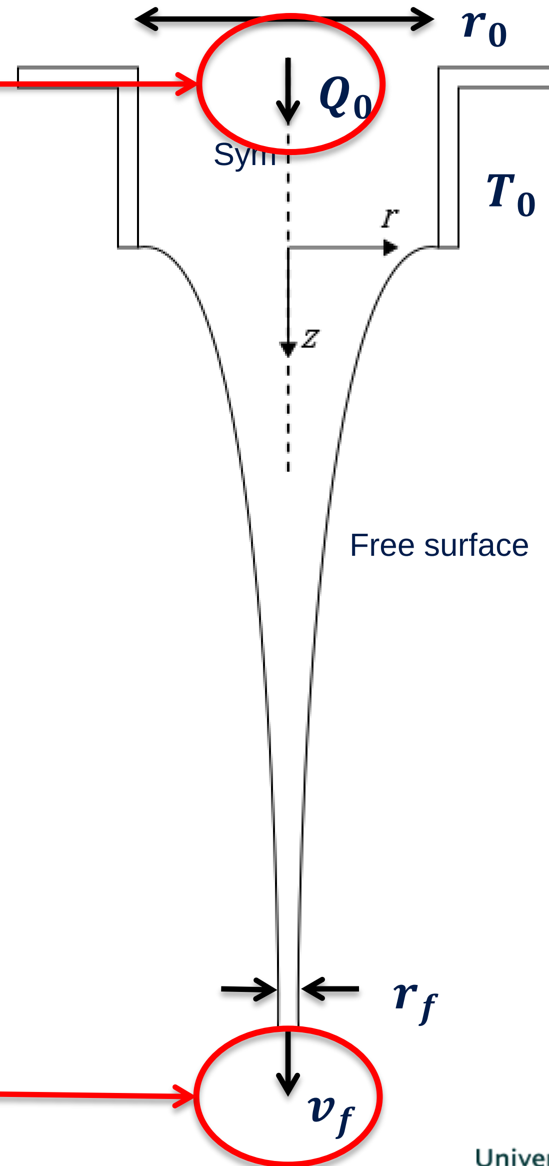
Main parameters:

Tip flow rate Q_0 → Tip geometry r_0, Tip temperature T_0

Winder velocity v_f



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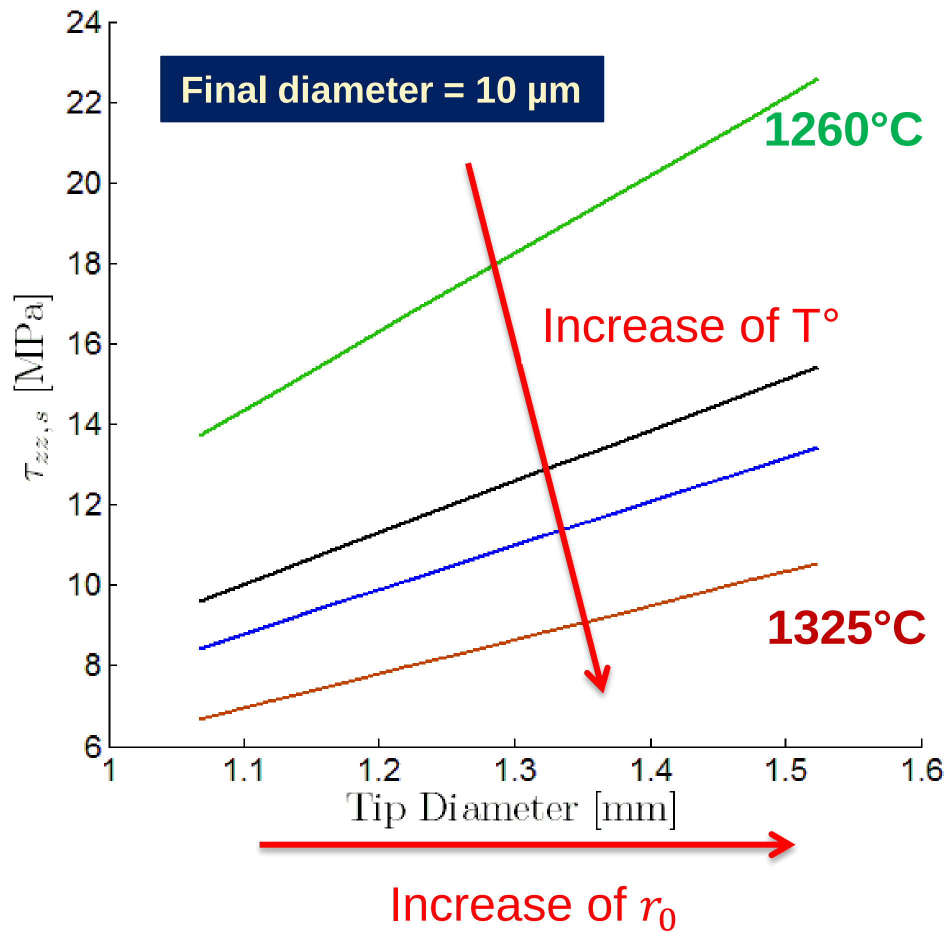
Axial stress



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Main parameters:

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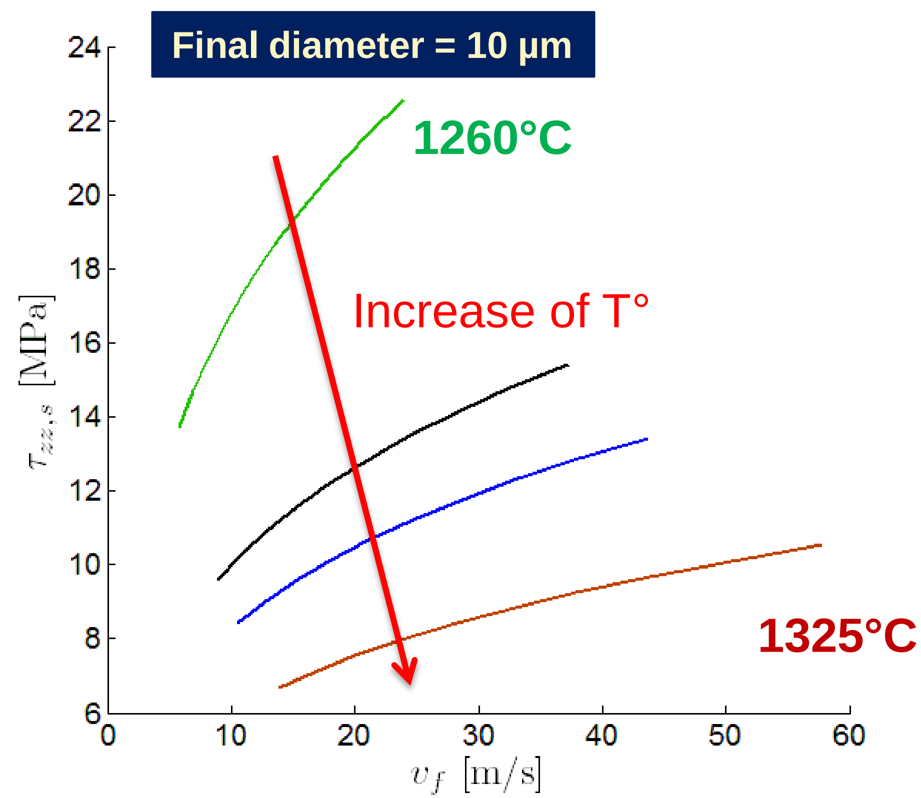
Winder velocity v_f

Axial stress



Increase of v_f

Stresses
Main parameters

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Given a target radius
→ how the stress can be reduced ?

- **Decrease tip radius**
- **Increase the tip temperature**
- **Decrease the winder velocity**

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Conclusion & further work

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Conclusion

- Physical model of one fiber drawing has been developed
- Numerical solutions give a good way to understand the process
- Fiber forming is strongly coupled with the air environment
- Stress in the fiber can be reduced by:
    - decreasing the winder velocity
    - decreasing the tip diameter
    - increasing the tip temperature

Further work

- Add a radiation model for the heat transfer inside the glass
- Investigate the viscoelasticity
- Investigate the origins of the fiber breaks

Acknowledgements

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