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A NUMERICAL STUDY OF FIBER GLASS DRAWING PROCESS

Quentin Chouffart, Vincent E. Terrapon
Multiphysics and Turbulent Flow Computation Research Group
University of Liège

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Outline

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- **General context**
- Physics of fiber drawing process
- Numerical study – Heat transfer
- Numerical study – Flow rate
- Conclusion

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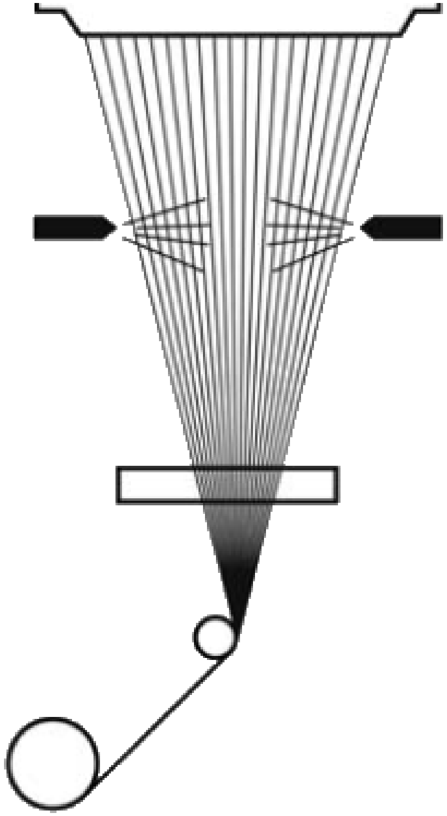
Fiberization process

- Glass fibers are made by drawing thousands of fibers from a bushing plate:

  → Glass melt flows through tip
  → Forming fibers are cooled by fins and water spray
  → Coating is applied to fibers
  → Fibers are drawn by a winder



- Efficiency improvement of fiberglass drawing process is mostly driven by **fiber breakage reduction**

- Break implies :
  1. Shut down of forming station and thus **production loss**
  2. Large amount of **unrecyclable glass waste**
  3. **Barrier to optimization of** manufacturing process

Goal and impact of research

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Goal

- Understand the **origins of fiber breaking** during forming process
- Identify strategy **to reduce** as much as possible the **breaking rate**

Impact

- ***Fiber drawing process***
  - Improved numerical modeling and simulations
  - Better understanding of breaking mechanisms

- ***Manufacturing process***
  - Energy and waste reduction
  - New design of tips, bushing plate, cooling fins …
  - Lower costs to produce the same quantity of fiber glass

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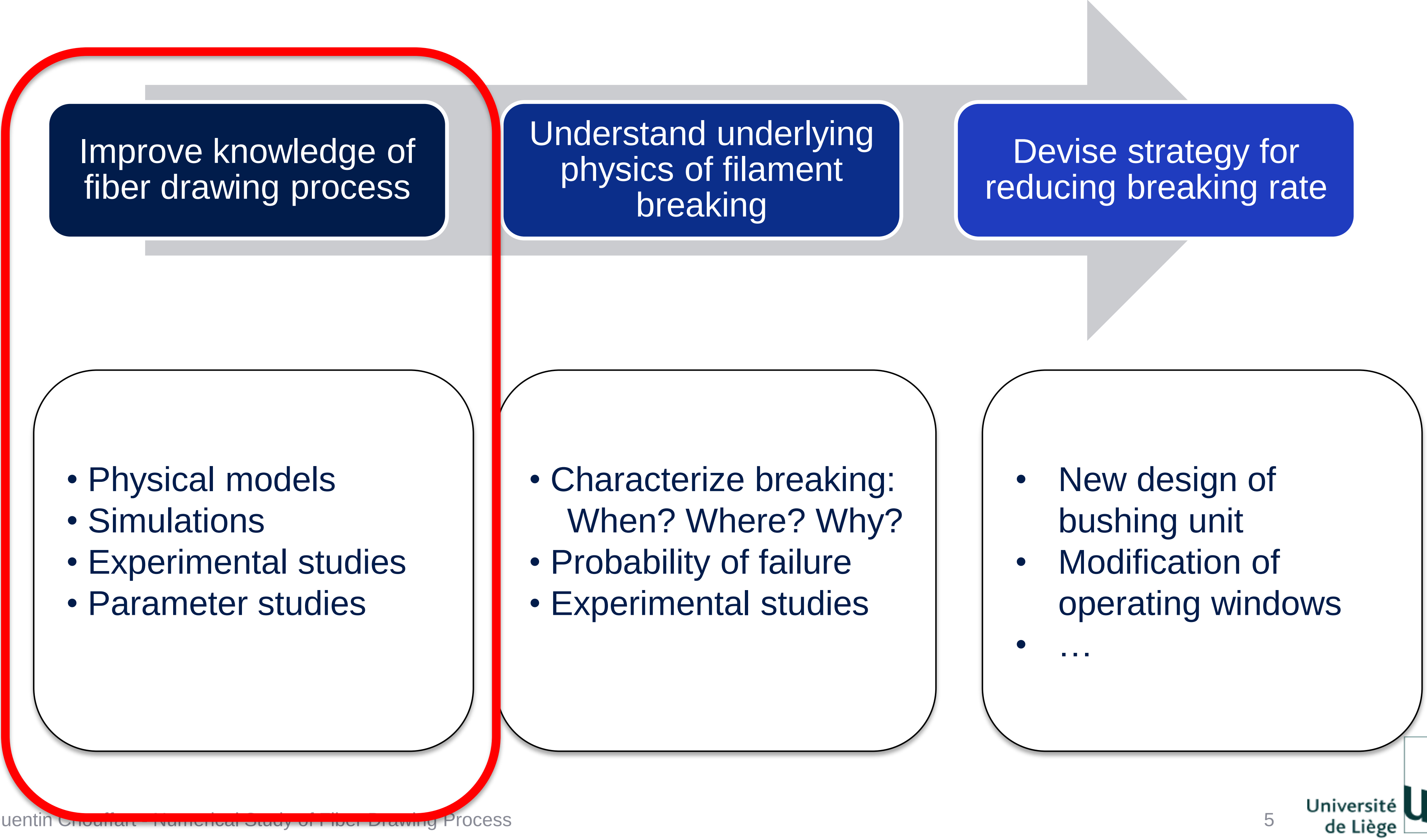
Pathway to improved efficiency



Improve knowledge of fiber drawing process

Understand underlying physics of filament breaking

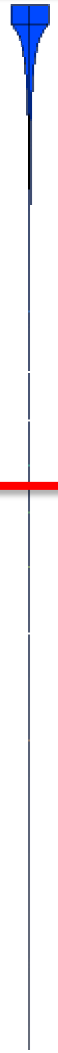
Devise strategy for reducing breaking rate

- Physical models
- Simulations
- Experimental studies
- Parameter studies

- Characterize breaking: When? Where? Why?
- Probability of failure
- Experimental studies

- New design of bushing unit
- Modification of operating windows
- …

Physics of one fiber forming



Heat transfer	Fluid flow	
• Radiation • Convection • Conduction	Glass melt Viscous flow	$T > T_g$
• Convection • Conduction	Glass transition Viscoelastic flow	$T \approx T_g$
• Convection • Conduction	Glassy state Elastic solid	$T < T_g$

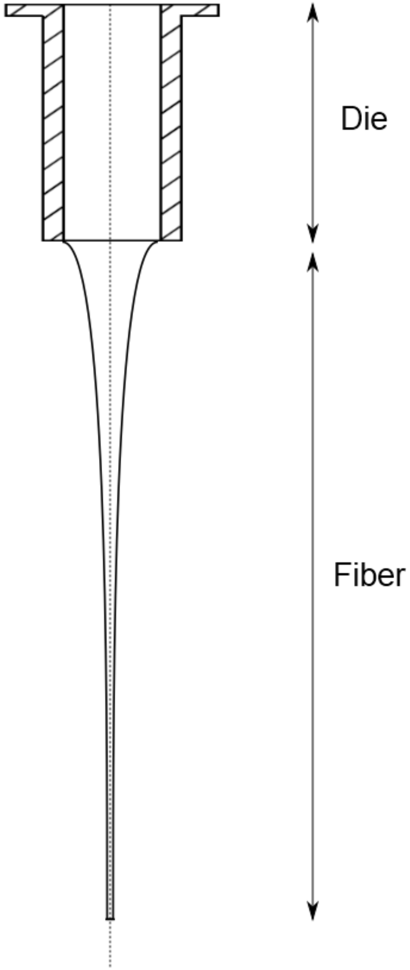
Governing glass flow equations

Gouverning viscous flow equations: *Newtonian flow*

Mass conservation: $\frac{D\rho}{Dt} = 0$

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

Energy conservation: $\frac{D(\rho C_p T)}{Dt} = \sigma : \nabla \boldsymbol{v} - \nabla . \boldsymbol{q} + r$



Assumptions:

- Fulcher viscosity equation: $\eta = 10^{-A+\frac{B}{T-T_0}}$
- Internal radiation, gravity and viscous heating neglected
- External temperature remains constant around fiber

Boundary conditions

Inlet

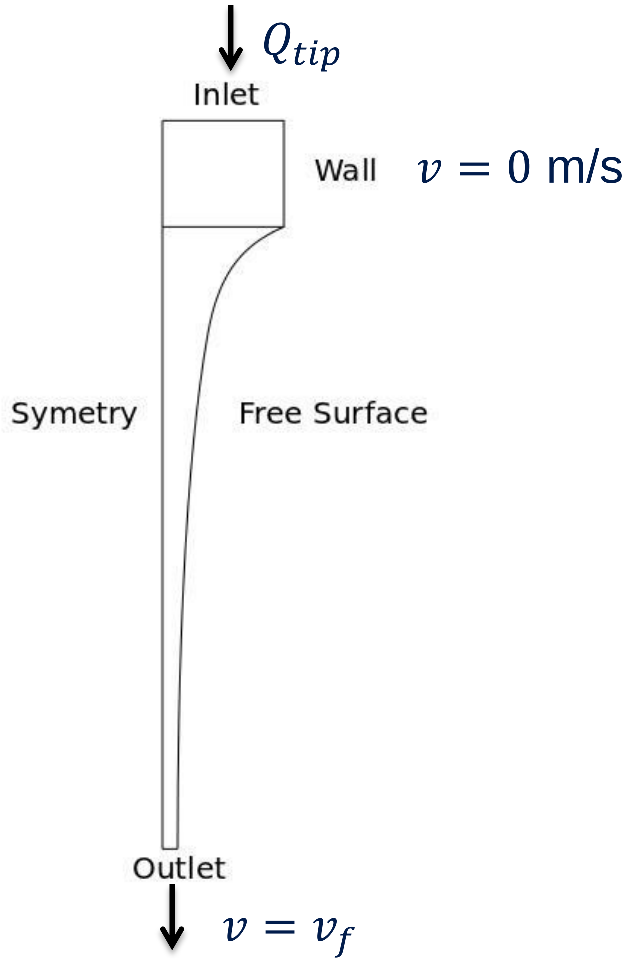
- Volumetric flow rate: $Q_{tip} = \frac{\pi}{8\eta}\left(-\frac{\partial p}{\partial z}\right) r_0^4$
- Constant temperature

Free surface

- Heat flux: $q = h(T - T_0) + \epsilon\sigma(T^4 - T_0^4)$
- Kase-Matsuo convective coefficient: $h = \frac{0.42\, k_a}{D}\left(\frac{u\, D}{\mu_a}\right)^{0.334}$
- Surface tension: γ constant

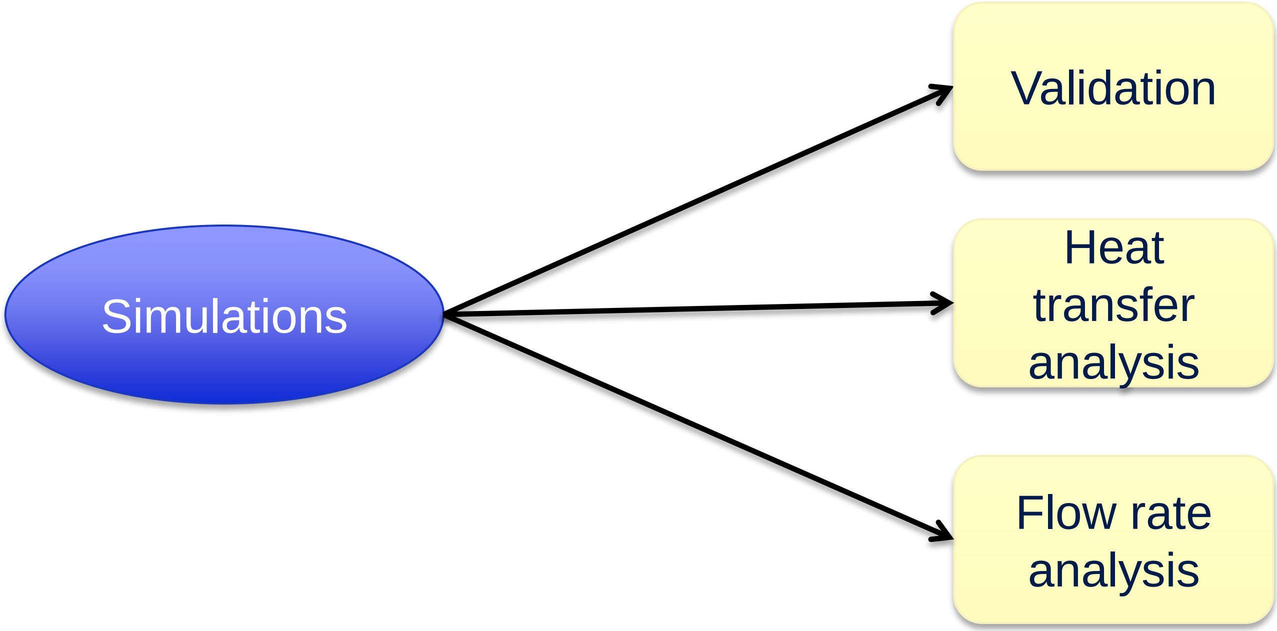
Outlet

- Drawing velocity: $v = v_f$



Numerical study - Plan

- Governing equations are solved numerically with finite elements method with computer simulations
- Simulations performed with ***ANSYS Polyflow*** software
- Three sets of simulation:



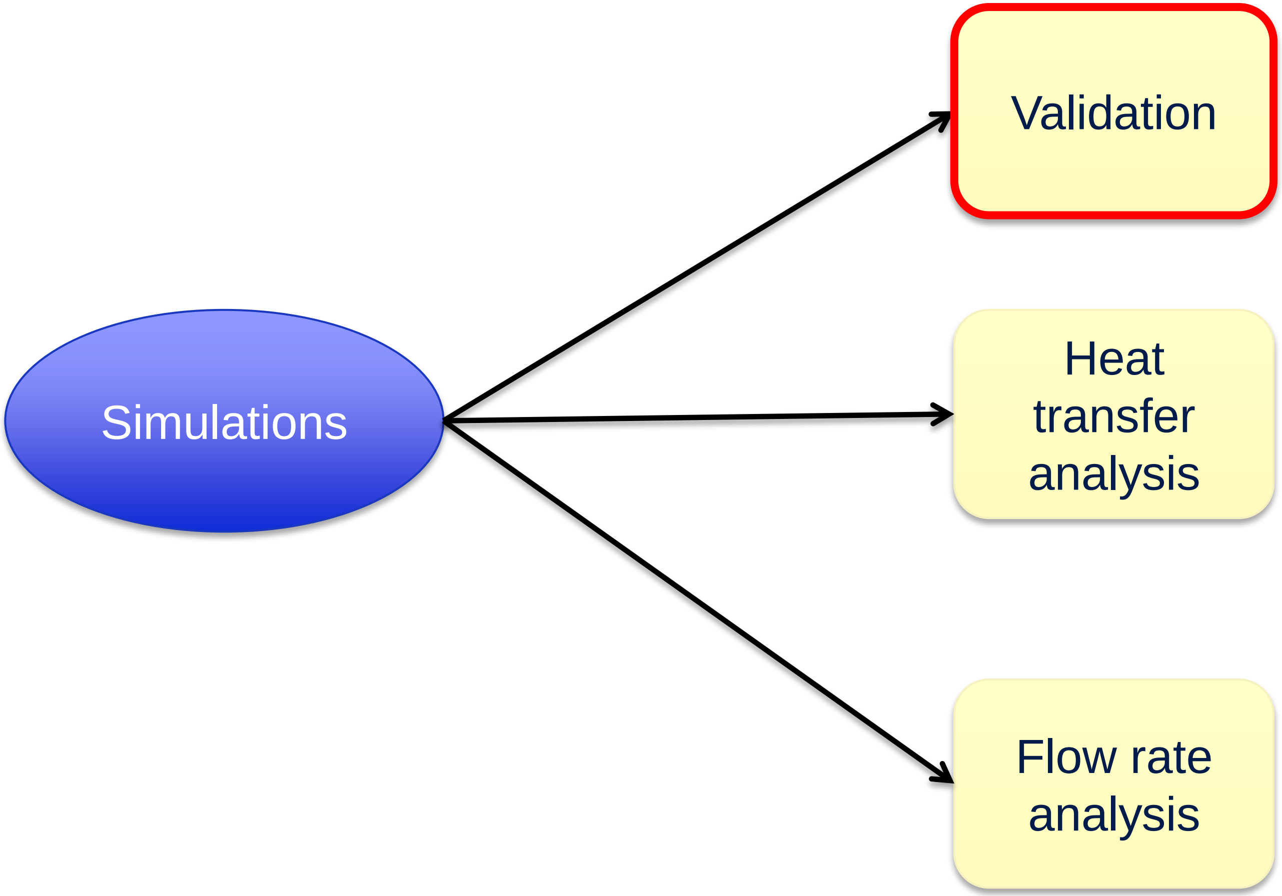
Simulations

Validation

Heat transfer analysis

Flow rate analysis

Numerical study - Plan



Simulations

Validation

Heat transfer analysis

Flow rate analysis

Initial validation of numerical approach

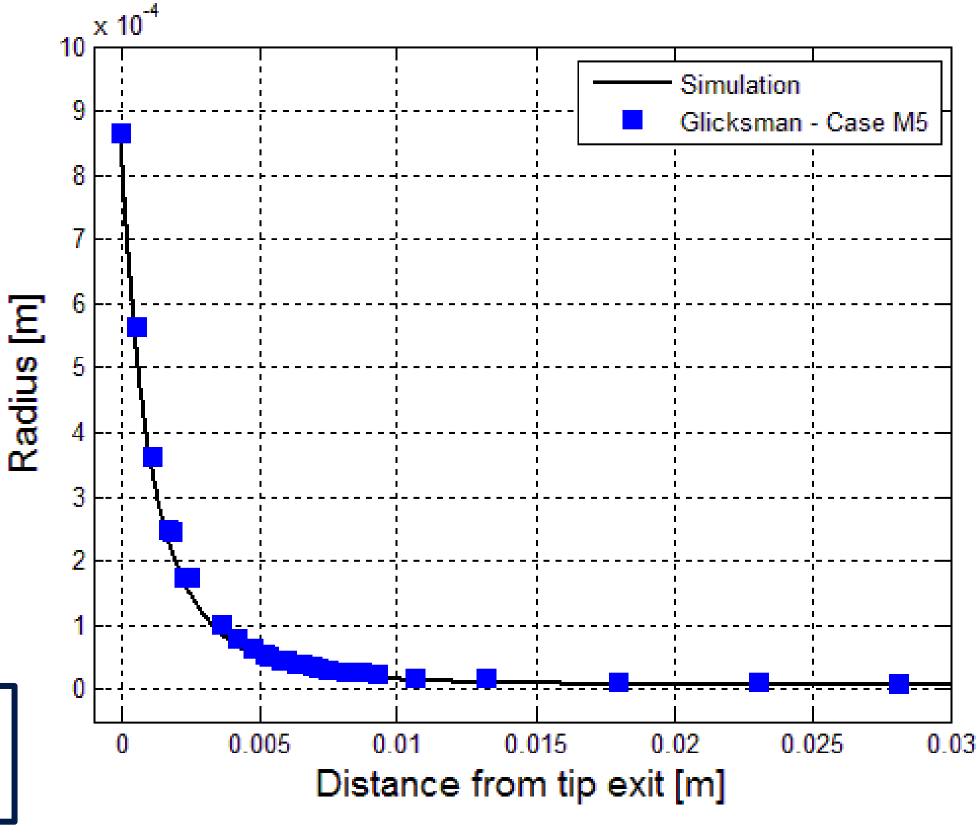
Validation from experimental data *(L. R. Glicksman, PhD thesis, MIT, 1964)*

Case study

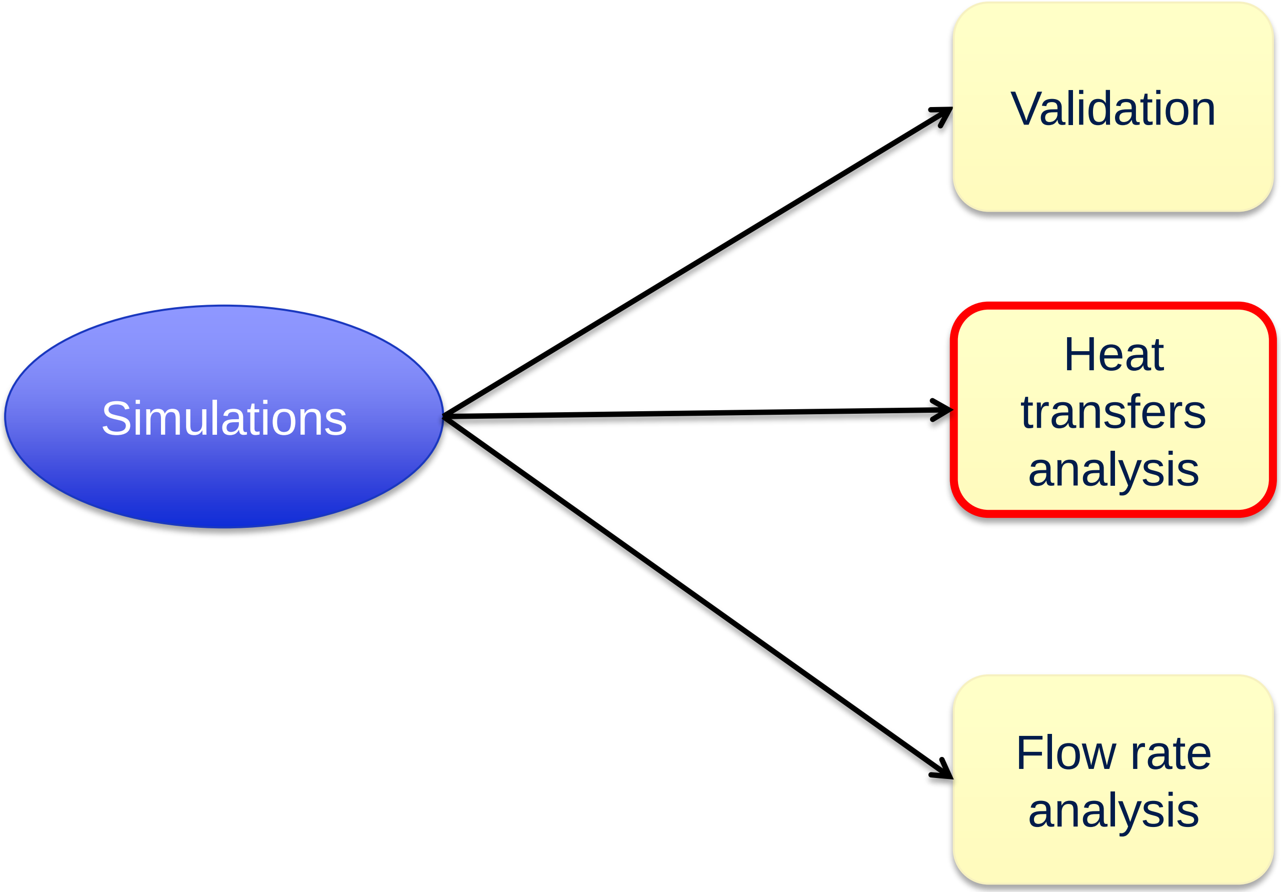
Material	Glass M5
T_0	$1227\ °C$
Q_{in}	$3.17\ 10^9\ m^3/s$
v_f	$25.88\ m^3/s$

→ ***Good agreement** between simulation and experimental data.*

Fiber radius attenuation



Numerical study - Plan



Simulations

Validation

Heat transfers analysis

Flow rate analysis

Heat transfer study

<u>Hypothesis</u> : External temperature of environment T_{ext} *remains constant near tips exit*

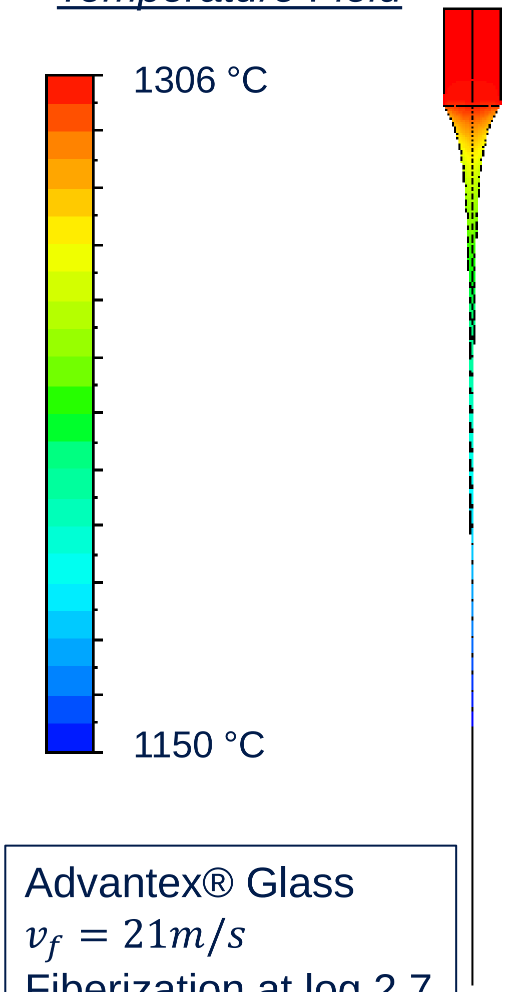
- Heat fluxes acting on fiber surface come from **convection** and **radiation:**

$$q = \underbrace{h(T - T_{ext})}_{\textbf{Convection}} + \underbrace{\epsilon\sigma(T^4 - T_{ext}^4)}_{\textbf{Radiation}}$$

- Kase-Matsuo convective coefficient: $h = \frac{0.42\, k_a}{D}\left(\frac{u\, D}{\mu_a}\right)^{0.334}$
- Convection coefficient is governed by:
  - ➢ Fiber radius
  - ➢ Fiber velocity
  - ➢ Air properties

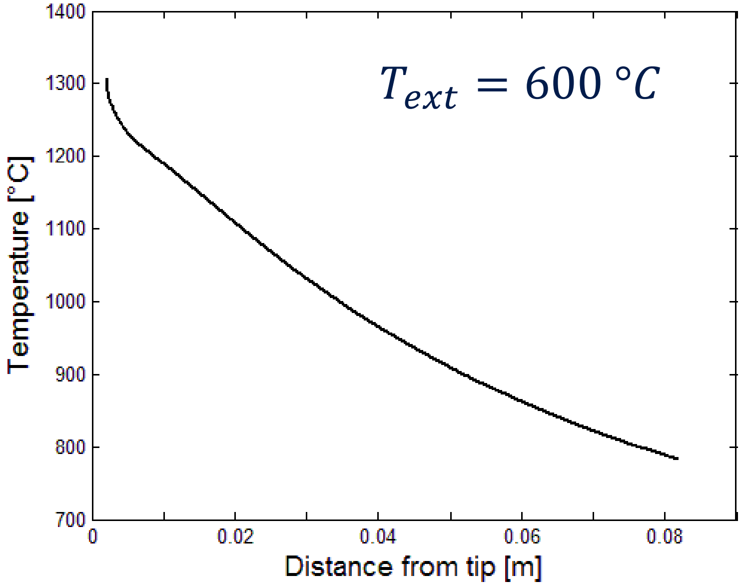
Fiber temperature field

Temperature Field



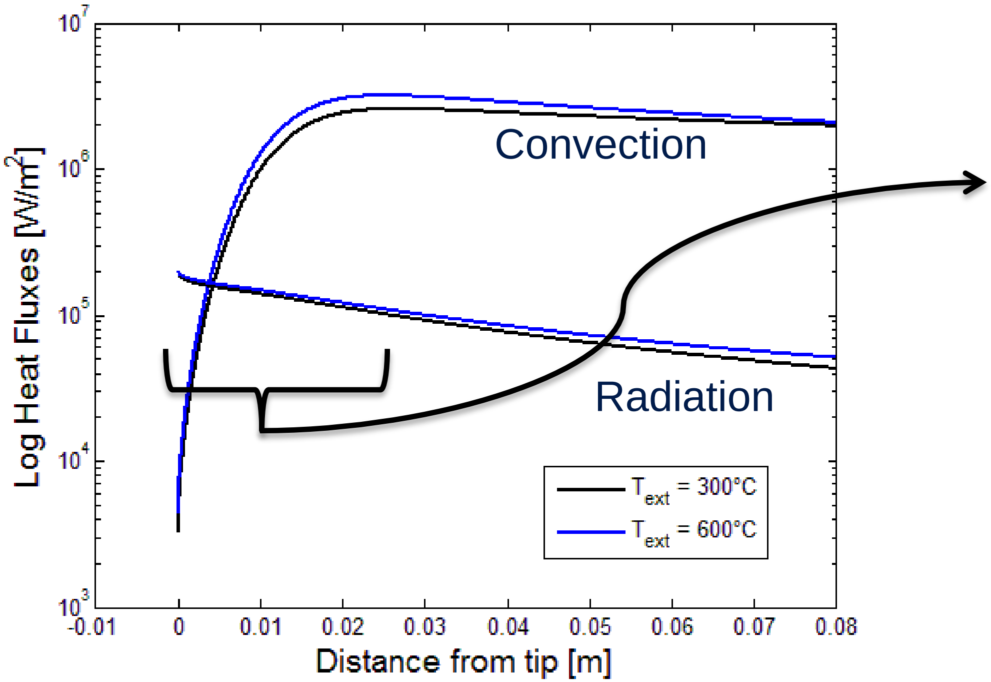
Advantex® Glass
$v_f = 21m/s$
Fiberization at log 2.7

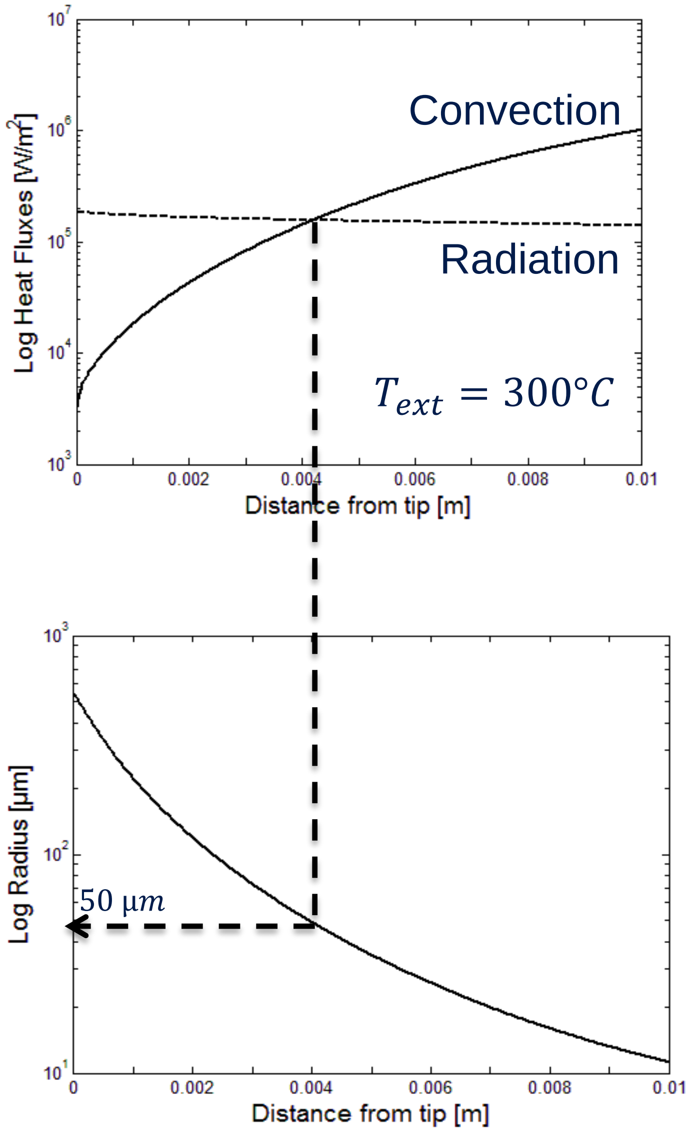
Temperature profile along the fiber boundary



- What is the impact of the external environment?
- Which heat transfer mechanism is the most important?
- Which assumptions are the most critical?

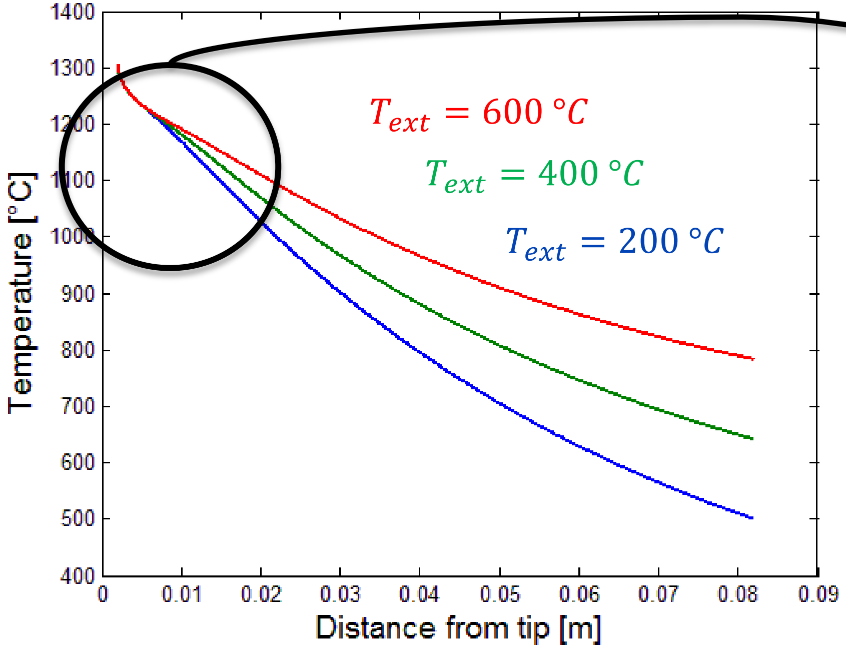
Radiation vs. convection

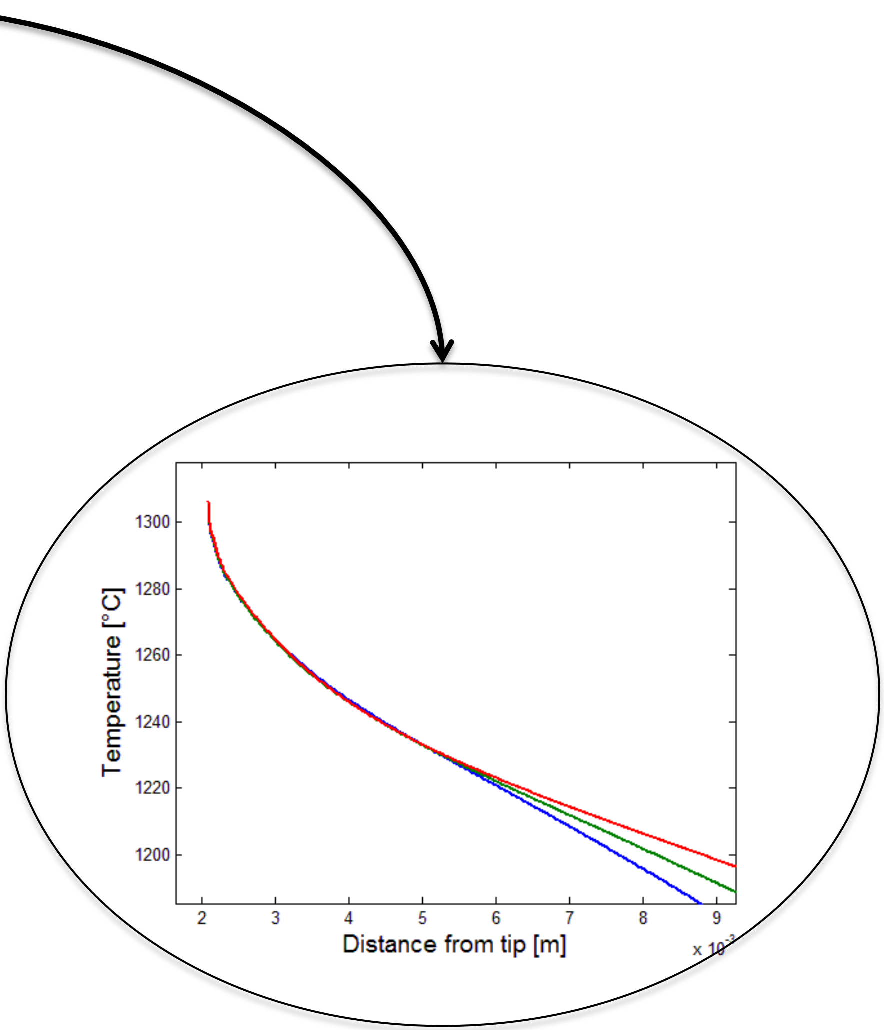


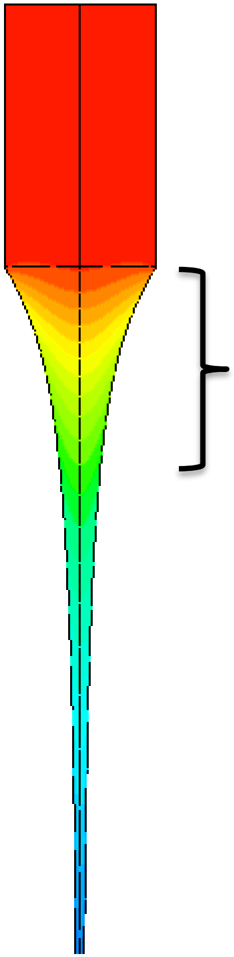


- Convection dominates very rapidly (~ 1 cm from tip)
- Attenuation of fiber radius occurs when radiation dominates

Impact of external temperature : radiation part

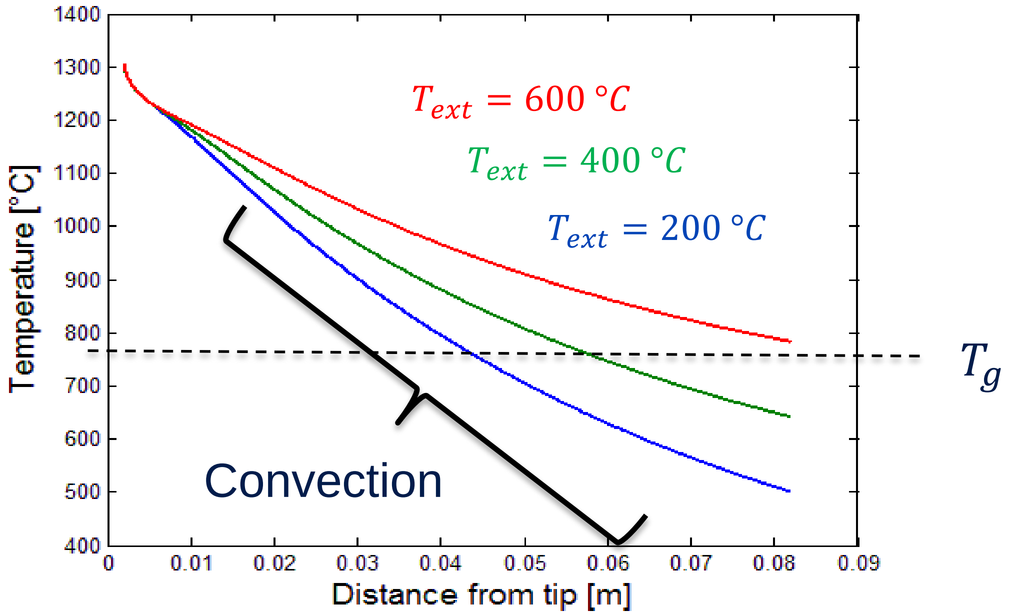


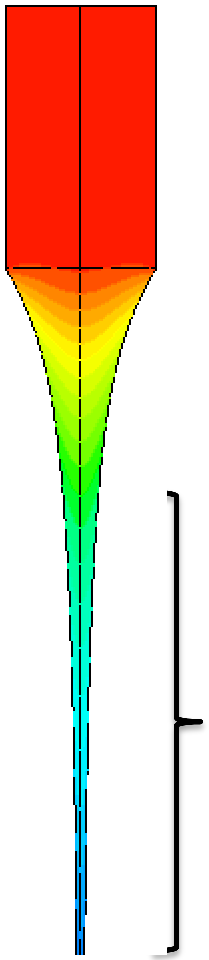




- T_{ext} has no impact when radiation dominates
- Fiber cooling at these temperature is governed by emissivity of glass melt

Impact of external temperature : convection part

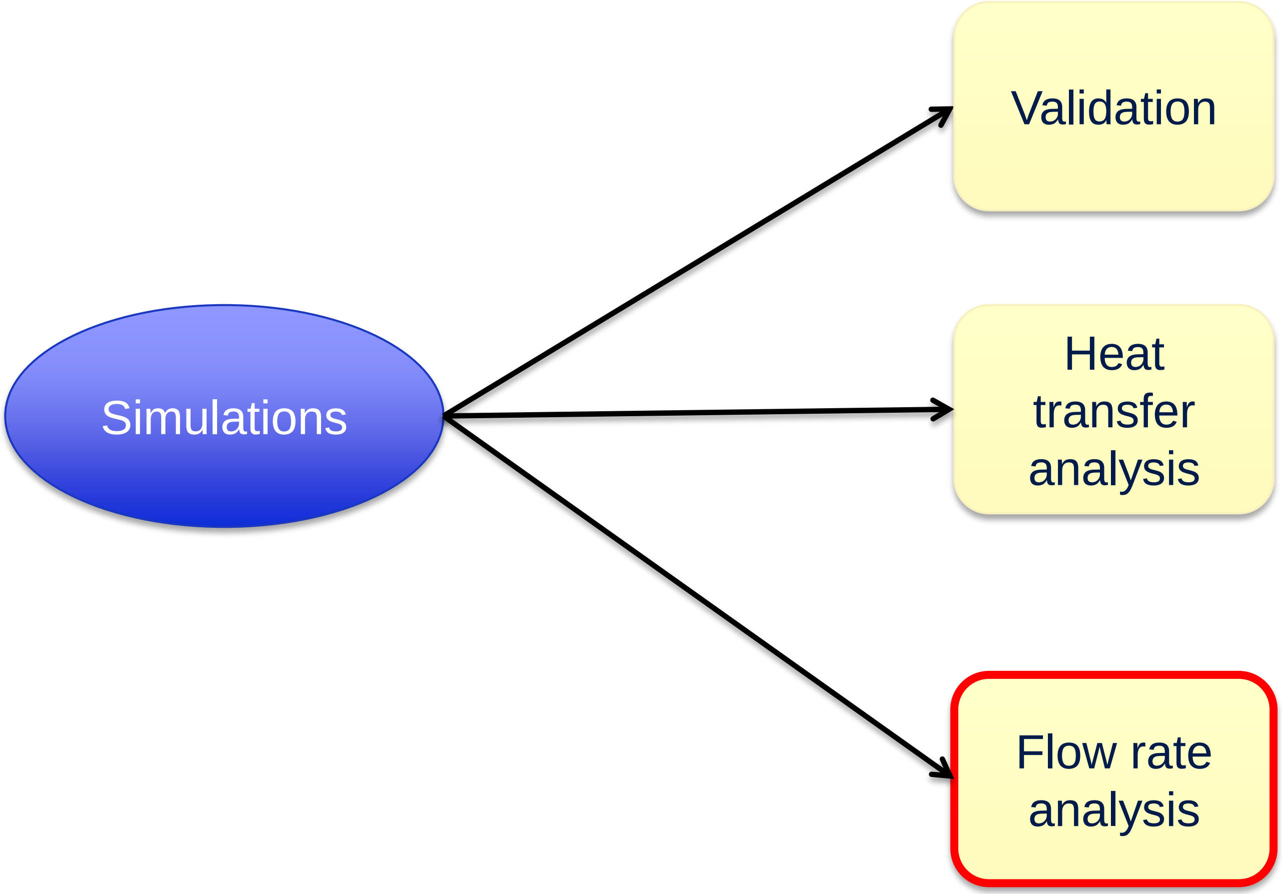




- T_{ext} has an important impact on cooling in case of convection
- Fiber cooling at these temperature is governed by air environment
- T_g does not occurs at the same distance
- Hypothesis of T_{ext} constant becomes not relevant at lower temperature

→ *more accurate if T_{ext} remains no constant*

Numerical study - Plan



Simulations

Validation

Heat transfer analysis

Flow rate analysis

Flow rate impact

Flow rate inside the tip can be described by *Hangen-Poiseuille* law as:

$$Q_{tip} \sim \beta \frac{1}{8\eta}\left(-\frac{\partial p}{\partial z}\right)$$

Main parameters controlling flow rate:

- Tip temperature: $\eta = \eta(T)$
- Tip shape: β
- Glass height (hydrostatic pressure): $-\partial p / \partial z$

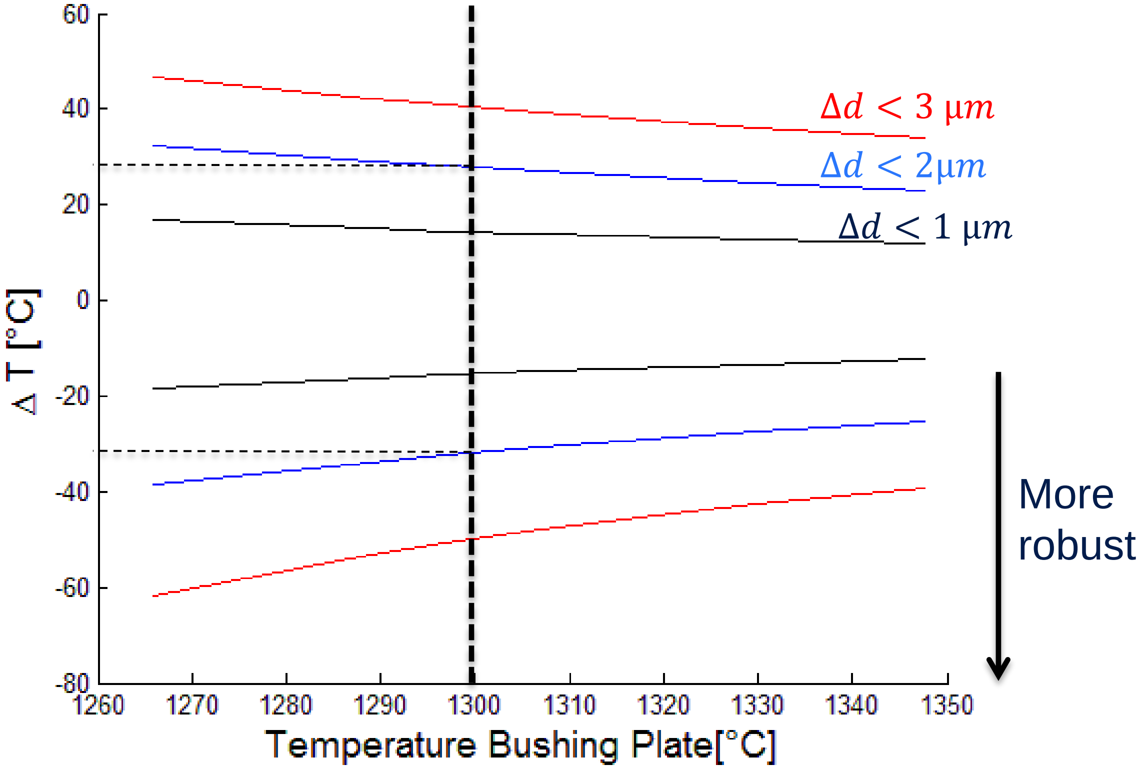
- ➢ Tip shape and glass height remains (almost) constant on the bushing plate
- ➢ Tip temperature has large impact on:
  - → Fiber diameter quality
  - → Fiber cooling

Flow rate impact

Bushing plate may exhibit non-homogeneous temperature : $T + \Delta T$

➔ What is the impact of ΔT on fiber diameter?

Maximum ΔT admissible for fiber diameter distribution given



- Non-linear variation due to viscosity law
- unsymmetrical relative to $\Delta T = 0\ °C$

Goal : $d_{fiber} = 10\ \mu m\ \pm 2\ \mu m$

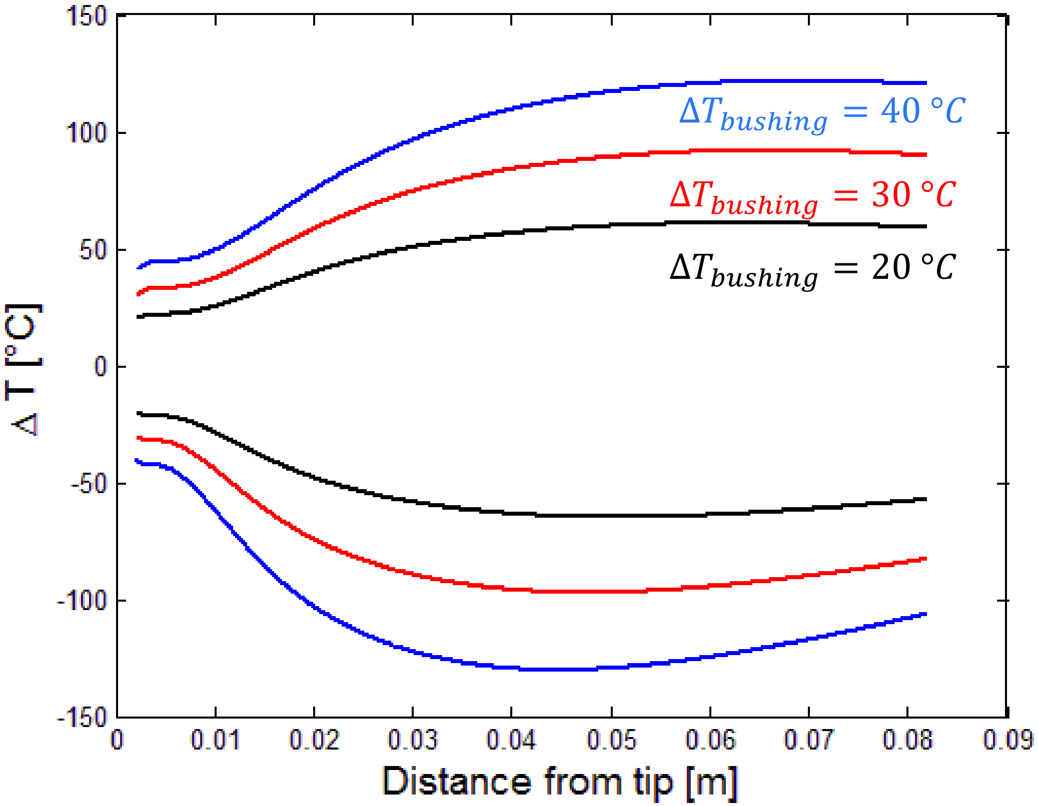
$$T = 1300\ °C$$

$$\boxed{\rightarrow \Delta T = \begin{cases} +28°C \\ -32\ °C \end{cases}}$$

Flow rate impact

→ How does $\Delta T_{bushing}$ impacts on fiberization and fibers cooling ?

ΔT between two fibers along axial component



- Temperature between two fibers may varies since tip plate exhibits $\Delta T_{bushing}$
- ΔT_{fiber} is amplified when fibers are cooling
- ΔT_{fiber} can reach $130\ °C$ at $z = 0.04$ m

→ Important to remove inhomogeneous heat pattern on bushing plate.

Conclusion

- Numerical simulations are very useful to understand physical mechanisms of fiber forming:
    - ➢ Radiation seems to be more important very close to the tip
    - ➢ Convection becomes dominant very quickly due to the decrease in fiber radius
    - ➢ Heat pattern of bushing plate has to be as homogenous as possible to reduce different cooling rates between fibers, and thus a broad diameter distribution

- Mathematical model could be improved using a more complex model for the air environment around the fiber

→ This tool provides a first step to reach the fundamental understanding of fiber breaking

Further work

Physical model of glass fiber drawing

- Take in account viscoelasticity
- Take in account internal radiation heat transfer
- Study unsteady effects (drawing resonance)
- Study impact of uncertainties on simulation results

Experimental devices

- Study air environment around fiber
- Link data to physical model
- And … **characterize of fiber breaking by several experiments**