NUMERICAL INVESTIGATION OF THE CONTINUOUS FIBER GLASS DRAWING PROCESS

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Outline

- Motivation
- Physical model
- Numerical investigation
- Conclusion & future work
Motivation & objectives

Main challenge of the process: fiber breakage

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

Overall goal:
→ Understand the fiber breaking

Step 1
Physical modeling of forming glass

Step 2
Characterization of breaking mechanisms
Fiberglass drawing process

General steps

**Four main steps**

1. **Flow of glass melt through > 1000 holes**
   - Glass melt
   - Flow: T ~ 1300°C

2. **Cooling by fins and water spray**
   - Cooling: T cooling

3. **Coating**

4. **Drawing by a winder**
   - Drawing: (20 m/s → ~10 µm fibers diameter)

- **Bushing**
- **Finshield**
- **Water spray**
- **Winder**

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• Motivation

• Physical model

• Numerical investigation

• Conclusion & future work
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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<th>Glass state</th>
<th>Rheology</th>
<th>Heat transfer</th>
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<td><strong>Glass melt</strong></td>
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Physics of the forming of a single fiber

**Glass state**

*Glass melt*

\[ T > T_g \]

Newtonian viscous flow

Inside the fiber: *Conduction & Radiation*

Around the fiber: *Convection & Radiation*

**Rheology**

**Heat transfer**

*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*
Physical model
Governing equations

Mass conservation:
\[
\frac{D \rho}{D t} = 0
\]

Momentum conservation:
\[
\frac{D (\rho \mathbf{v})}{D t} = \nabla \cdot \mathbf{\sigma} + f
\]

Energy conservation:
\[
\frac{D (\rho C_p T)}{D t} = \mathbf{\sigma} : \nabla \mathbf{v} - \nabla \cdot (\mathbf{q}_{\text{cond}} + \mathbf{q}_{\text{rad}})
\]

Assumption: Internal radiation \(\rightarrow\) neglected
Physical model

Governing equations

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Newtonian flow:
\[
\sigma = -pI + 2\eta D
\]
Physical model
Governing equations

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

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\[ \frac{D(\rho\mathbf{v})}{Dt} = \nabla \cdot \mathbf{\sigma} + f \]

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

Assumption: Internal radiation \(\rightarrow\) neglected

Fulcher law
\[ \eta = 10^{-A + \frac{B}{T-T_0}} \]
\( (\eta = \text{dynamic viscosity}) \)
Physical model

Boundary conditions

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

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

- **At outlet:**  Drawing velocity

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Solution of the physical model

Physical Model

1D
Elongational
model

Analytic and ODE solved with
the Finite Difference Method

• Improve convergence
• Less accurate
• Global information

2D
Axisymmetric
model

Solved with the
Finite Element Method

• More accurate
• Local information
Numerical investigation

3. Axial stress

\[ \tau_{zz,f} = \frac{3}{\varphi_g} \nu_f \ln \left( \frac{\nu_f}{\nu_0} \right) \]

Stress depends on:

- Diameter ratio
- Drawing velocity
- Fiber cooling

Stress is a good indicator of the robustness
Numerical investigation

3. Axial stress

\[ \tau_{zz}, f \]

Key questions

- What are the key process parameters controlling the stress?
- How can the operating window be adjusted in order to reduce the stress?

Stress is a good indicator of the robustness
Numerical investigation

The control process parameters:

- **Tip temperature** $T_0$ impacting $\varphi_g$ 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?
4. Stress sensitivity due to the variation of the control parameters

**Stress 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.

**Graph:**
- **Stress** vs. **Final diameter**
- Parameters: Tip temperature, Drawing velocity, Tip radius, Glass height.

**Equation:**

\[ \tau_{zz, f} [\text{MPa}] \]

\[ 2r_f [\mu\text{m}] \]

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4. Stress sensitivity due to the variation of the control parameters

- Decrease in temperature leads to a large stress increase
- The opposite is observed when the temperature increases
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- Decrease temperature leads to a large stress increase
- The opposite is observed when the temperature increases

Given a target radius, what are the velocity and temperature leading to a lower stress?
Numerical investigation

5. What is the optimal choice for the velocity and the temperature?

**Stress**

- Smaller radius amplifies the impact of the temperature on the stress.
- Increasing the tip temperature decreases the stress, even if the drawing velocity increases.

**Drawing velocity**

\[ Q_0(T_0) = \pi r_f^2 v_f \]

\[ v_f = \frac{1}{\pi r_f^2} Q_0(T_0) \]
Bushing: problem statement

6. 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

\[
\sigma < \mu_T \quad \text{and} \quad \mu_T < \mu_T + \sigma
\]
Bushing: problem statement

6. Temperature inhomogeneity on a 6000 tips bushing plate

→ Heat pattern on the bushing plate is critical
Outline

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Conclusion

- **Physical model** of single fiber drawing has been developed
- **Numerical solutions** help to understand the process
- **Fiber** forming is strongly affected by the **temperature at the tip**
- **Stress** is a good indicator to understand the **robustness** of the process
- **Temperature inhomogeneity** across the bushing plate leads to a **large distribution** of stress

Further work

- Add a **radiation model** for the heat transfer inside the glass
- Investigate the **glass transition** region
- Link the **breaking rate** with the stress
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