NUMERICAL AND EXPERIMENTAL INVESTIGATION OF FIBER DRAWING PROCESS

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Outline

• Motivation
• Physical model
• Experimental setup
• Numerical investigation
  ➢ Heat transfers
  ➢ Stresses
• Conclusion & future work
Motivation & objectives

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

**Overall Goal**

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

General steps

Four main steps

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

2. **Cooling by fins and water spray**
   - Cooling by fins and water spray

3. **Coating**
   - Coating

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

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Fiberglass drawing process
Bushing plate & tips
Outline

- Motivation

**Physical model**

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  - Stresses
- 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

**Glass state**

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

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# Physics of the forming of a single fiber

<table>
<thead>
<tr>
<th>Glass state</th>
<th>Rheology</th>
<th>Heat transfer</th>
</tr>
</thead>
</table>
| **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 |

**Glass melt**  
$T > T_g$  

**Glass transition**  
$T \approx T_g$  

**Glassy state**  
$T < T_g$
Physical model

Governing equations

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

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

Energy conservation:
\[
\frac{D(\rho C_p T)}{Dt} = \sigma : \nabla v - \nabla \cdot (q_{cond} + q_{rad})
\]

Assumption: Internal radiation $\rightarrow$ neglected
Physical model
Governing equations

Mass conservation:
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\frac{D (\rho C_p T)}{Dt} = \mathbf{\sigma} : \nabla \mathbf{v} - \nabla \cdot (q_{\text{cond}} + q_{\text{rad}})
\]

**Assumption:** Internal radiation → neglected

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

Governing equations

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

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

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

Assumption: Internal radiation \( \rightarrow \) neglected

Newtonian flow:
\[ \sigma = -pI + 2\eta \nabla v \]

coupled through viscosity

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

\[ q_{rad} + q_{conv} \]
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    ➢ Stresses
• Conclusion & future work
Experimental investigation
Fiber drawing unit

Facilities
1. Velocity acquisition
2. Image acquisition
3. Diameter acquisition
Experimental investigation
Fiber drawing unit

Facilities
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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

<table>
<thead>
<tr>
<th>Material</th>
<th>Glass M5</th>
<th>Advantex®</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_0$</td>
<td>1227 °C</td>
<td>1308 °C</td>
</tr>
<tr>
<td>$Q_0$</td>
<td>$3.17 \times 10^9 \text{ m}^3/\text{s}$</td>
<td>$4.72 \times 10^{10} \text{ m}^3/\text{s}$</td>
</tr>
<tr>
<td>$v_f$</td>
<td>25.88 \text{ m}^3/\text{s}</td>
<td>1.55 \text{ m}^3/\text{s}</td>
</tr>
</tbody>
</table>

Good agreement between simulation and experimental data
Cooling is critical:
→ impact on fiber properties
→ impact on break origins

What are the factors that lead to this high cooling?
Heat transfer

Heat fluxes

Heat flux: \[
\dot{q}(z) = h(T - T_{\text{ext}}) + \varepsilon\sigma(T^4 - T_{\text{ext}}^4)
\]

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 transfer

Cooling rate - Radiation

Radiation:
\[ \dot{q}_{rad} = \varepsilon \sigma (T^4 - T_{ext}^4) \]
with
\[ \varepsilon = \varepsilon(r^3, T) \]

Cooling rate:
\[ \hat{T}_{c,s} = -\frac{\dot{q}(z)}{\rho C_p r_f(z)} \]

Variability emissivity has a significant impact

Cooling rate

\[ \varepsilon = \varepsilon(r^3, T) \]
\[ \varepsilon = 0.5 \]
\[ \varepsilon = 0.35 \]
Cooling rate: \[ \dot{T}_{c,s} = -\frac{\dot{q}(z)}{\rho C_p r_f(z)} \]

Cooling rate is very sensitive to the cooling history.
Heat transfer

Cooling rate - Convection

**Convection:** \( q_{\text{conv}} = h(T - T_{\text{ext}}) \)

**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 \( k_a, \mu_a \)
- Air temperature \( T_{\text{ext}}(z) \)

**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

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

Newtonian stress in z direction:

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

Axial stress grows and takes a final constant value
Final value before the transition
Newtonian model seems to be sufficient
Stresses

Stress description

Newtonian stress in $z$ direction:

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

Key question:

What are the key parameters controlling the internal stress?
Stresses

Main parameters

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

Mass conservation:

\[ r_f^2 = \frac{Q_0(r_0,T_0)}{\pi v_f} = \text{cst} \]
Given a target radius \( r_0 \) how the stress can be reduced?

Mass conservation:

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

Main parameters:

- Tip flow rate \( Q_0 \)
- Tip geometry \( r_0 \)
- Tip temperature \( T_0 \)
- Winder velocity \( v_f \)
Mass conservation:

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

**Main parameters:**

- Tip flow rate \( Q_0 \)
- Tip geometry \( r_0 \)
- Tip temperature \( T_0 \)
- Winder velocity \( v_f \)

**Given a target radius \( r_0 \) → how the stress can be reduced?**

![Graph showing the relationship between tip diameter and axial stress with temperature and flow rate variations.](image-url)
Stresses

Winder velocity

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

Mass conservation:

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

Main parameters:

- Tip flow rate \( Q_0 \)
- Tip geometry \( r_0 \)
- Tip temperature \( T_0 \)
- Winder velocity \( v_f \)

Axial stress

Final diameter = 10 µm

Increase of \( T^\circ \)

Increase of \( v_f \)

1260°C

1325°C
Stresses
Main parameters

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

**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
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