Computational Fluid Dynamics Simulation of Compressible Non-Newtonian Biomass in a Compression-Screw Feeder

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Motivation and Objectives

• Lignocellulosic biomass (such as forest and agricultural crop residues) is widely available (annually >0.5 bil tons) for conversion to energy sources (fuel/electricity)
• Compression-screw feeders are used in biorefineries to transport biomass feedstock from hopper to biomass-conversion reactors (pretreatment/pyrolysis reactors)
• Mechanical failure and feed plugging is one of the main challenges in the operation of screw feeder
• Our goal is to use simulation techniques to analyze the challenging operating conditions and predict the mechanical failure.
• Develop a more reliable design to avoid these operating failures
Experimental Setup
NREL Screw Feeder

HOPPER

CONVEYANCE SCREW SECTION

COMPRESSON SCREW SECTION & STATOR

PLUG THROAT

SQUEEZATE DRAIN HOLES

GEARBOX (MOTOR NOT SHOWN)
NREL Screw Feeder

- Forest residue feedstock milled to pass 3/8 inch screen
- ~ 30% moisture
- 16.6 Kg/h flow rate
- 10.3 and 6.9 rpm rotation speed
- Screw inlet diameter: 4 in
- Screw outlet diameter: 3 in
- Screw pitch: 2 inch
- Length: 12.5 inch
Numerical Model
Compressible Bingham Fluid

• Concentrated biomass is a complex multiphase fluid (solid/liquid/gas)
  1. Compressible behavior
  2. Non-Newtonian rheology

• Duncan et al. recently studied biomass behavior in a pressure driven flow.
• They developed a density dependent yield stress model for compressible biomass

The biomass feedstock is treated as a single compressible non-Newtonian fluid.

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \vec{u} = 0
\]

Continuity

\[
\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla P + \nabla \cdot \tau
\]

Conservation of momentum

\[
\tau = \mu_{\text{Bingham}} \left( 2D - \frac{2}{3} \nabla \cdot \vec{u} \right)
\]

Stress tensor for Bingham fluid

\[
D = \frac{1}{2} \left( \nabla \vec{u} + (\nabla \vec{u})^T \right)
\]

Rate of strain tensor
Transport/rheology models

\[ \mu_{\text{Bingham}} = \min(\mu_{\text{max}}, \mu_{p} + \tau_{y}/\dot{\gamma}) \]

Bingham fluid viscosity is capped to avoid infinity values at regions with very small strain rate

\[ \tau_{y} = \tau_{y,\text{ref}} \left( \frac{\rho}{\rho_{\text{ref}}} \right)^b \]

Density-dependent yield stress (Duncan et al.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\rho_{\text{ref}})</td>
<td>395</td>
<td>kg/m(^3)</td>
</tr>
<tr>
<td>(\tau_{y,\text{ref}})</td>
<td>3E+5</td>
<td>Pa</td>
</tr>
<tr>
<td>(\mu_{\text{max}})</td>
<td>1E+5</td>
<td>Pa.s</td>
</tr>
<tr>
<td>(\mu_{p})</td>
<td>1E+3</td>
<td>Pa.s</td>
</tr>
<tr>
<td>(b)</td>
<td>6.2</td>
<td>-</td>
</tr>
</tbody>
</table>

Collaborators (Akbari et al.) from University of Toledo measured yield stress parameters for the feedstock
Equation of State

\[ \rho(P) = \rho_{\text{ref}} \left( \frac{\rho_{\text{max}}}{\rho_{\text{ref}}} \right)^{1-(P/P_{\text{ref}})^{1-\chi}} \]

Pressure-dependent density equation (Duncan et al.)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho_{\text{ref}} )</td>
<td>188</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( \rho_{\text{max}} )</td>
<td>2290</td>
<td>kg/m³</td>
</tr>
<tr>
<td>( P_{\text{ref}} )</td>
<td>1</td>
<td>atm</td>
</tr>
<tr>
<td>( \chi )</td>
<td>1.146</td>
<td>-</td>
</tr>
</tbody>
</table>
CFD implementation

• Used OpenFOAM framework
• Implemented a new thermophysical model for biomass equation of state
• Modified the transient compressible rhoPimpleFoam solver to include the new constitutive model in the momentum equation with density dependent yield stress
• Screw feeder geometry CAD STL files were used in snappyHexMesh to generate the computational domain mesh
Model Verification

Pressure–driven channel flow

- Verifying the pressure-density relation based on the new EOS
- Verifying the Bingham plastic motion in the channel flow
- High strain rate --- low viscosity (wall)
- Low strain rate --- high viscosity (middle)
Screw Feeder
Simulation Results
Mesh and Boundary

- Mesh size: 1.1 mil cells
- CPU-time: 72 hours to simulate 600 s on 324 processors
- NREL’s Eagle HPC system (Intel Xeon Gold Skylake)
- Boundary
  - Inlet: fixed velocity profile to capture the experimental mass flow rate and fill fraction
  - Outlet: fixed pressure
  - Stator: no slip wall
  - Screw: rotating wall
  - Used codeFixedValue to set the velocity BC at inlet and rotating surface

Outlet boundary is moved further out to have a 1 atm uncompressed free flow
Flow Field Results

Subtask 2: Complete validation experiments in NREL's 4 in screw feeder.

Figure 2: Snapshots of (a) pressure (Pa), (b) density (kg/m$^3$), (c) velocity magnitude (m/s), and (d) viscosity (Pa·s) in the AB screw feeder at steady-state for condition 3 in Table 1.
• The low rotation speed has higher fill fraction, leading to a higher biomass compression and shear stress.
• Both cases have same mass flow rate with different fill fraction
Axial torque is calculated on the screw wall surface, from both viscous shear stress and pressure.

<table>
<thead>
<tr>
<th>Screw speed (rpm)</th>
<th>Feed rate (kg/h)</th>
<th>Fill fraction</th>
<th>Measured screw torque (Nm)</th>
<th>Simulation torque (Nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.3</td>
<td>16.6</td>
<td>53%</td>
<td>290</td>
<td>265</td>
</tr>
<tr>
<td>6.9</td>
<td>16.6</td>
<td>80%</td>
<td>488</td>
<td>464</td>
</tr>
</tbody>
</table>
Summary

• Conclusions:
  – Developed a new compressible non-Newtonian fluid flow solver in OpenFOAM for biomass applications.
  – The constitutive model and rheology parameters used in this model are derived from experimental measurements.
  – The CFD simulations were able to predict NREL’s screw feeder measured torque data with less than 10% error.

• Future work:
  – Perform modeling and comparison with high pressure experiments
  – Design a better geometry for a more reliable system
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Thank you

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