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

Mohammad Rahimi, Hari Sitaraman, James Lischeske, David Sievers, and Jonathan Stickel

National Renewable Energy Laboratory, Golden, CO

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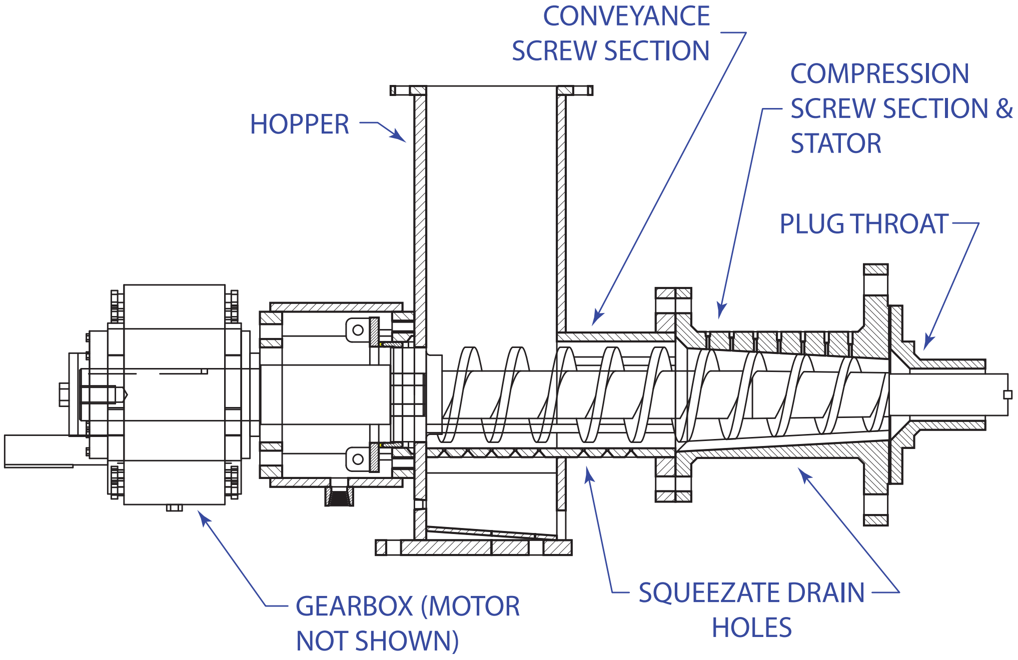
Motivation and Objectives

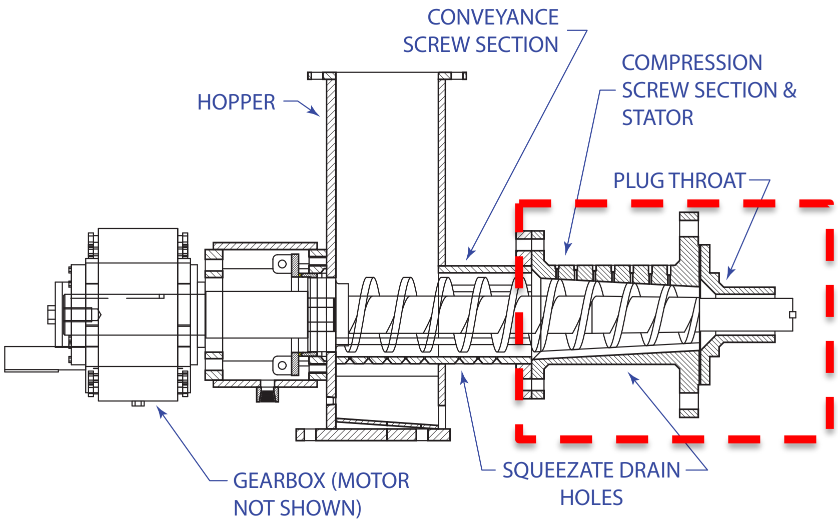
- Lignocellulosic biomass (such as forest and agricultural crop residues) is widely available (annually >0.5 bil tons) for conversion to energy sources (fuel/electricity)
- Compression-screw feeders are used in biorefineries to transport biomass feedstock from hopper to biomass-conversion reactors (pretreatment/pyrolysis 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



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

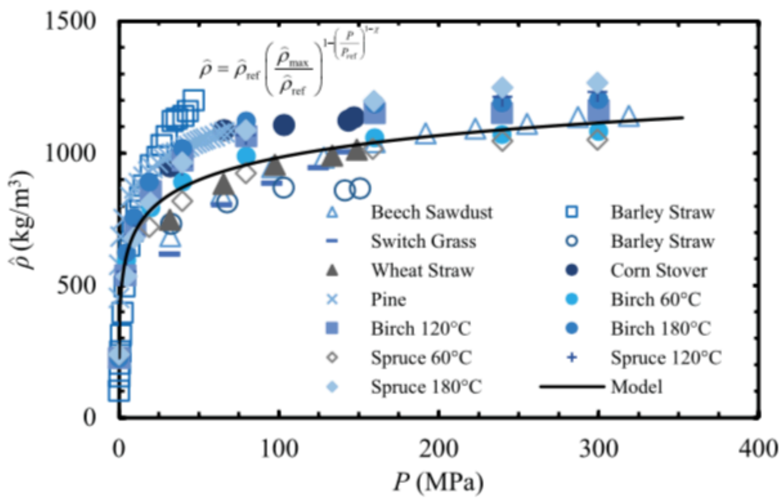
Numerical Model

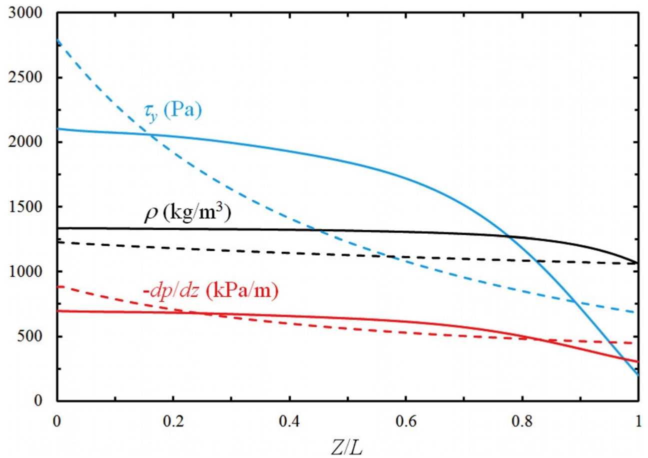
Compressible Bingham Fluid

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

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

Duncan et al. *Journal of Rheology* 62 (2018) 801-815





Governing equations

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

$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \underline{u} = 0$$

Continuity

$$\frac{\partial}{\partial t}(\rho \underline{u}) + \nabla \cdot \rho \underline{u}\underline{u} = -\nabla P + \nabla \cdot \underline{\underline{\tau}}$$

Conservation of momentum

$$\underline{\underline{\tau}} = \mu_{\text{Bingham}} \left(2\underline{\underline{D}} - \frac{2}{3} \nabla \cdot \underline{u} \underline{\underline{I}} \right)$$

Stress tensor for Bingham fluid

$$\underline{\underline{D}} = \frac{1}{2} \left(\nabla \underline{u} + (\nabla \underline{u})^T \right)$$

Rate of strain tensor

Transport/rheology models

$$\mu_{\text{Bingham}} = \min(\mu_{\max}, \mu_p + \tau_y/\dot{\gamma})$$

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.)

Parameter	Value	Unit
ρ_{ref}	395	kg/m^3
$\tau_{y,ref}$	3E+5	Pa
μ_{max}	1E+5	Pa.s
μ_p	1E+3	Pa.s
b	6.2	-

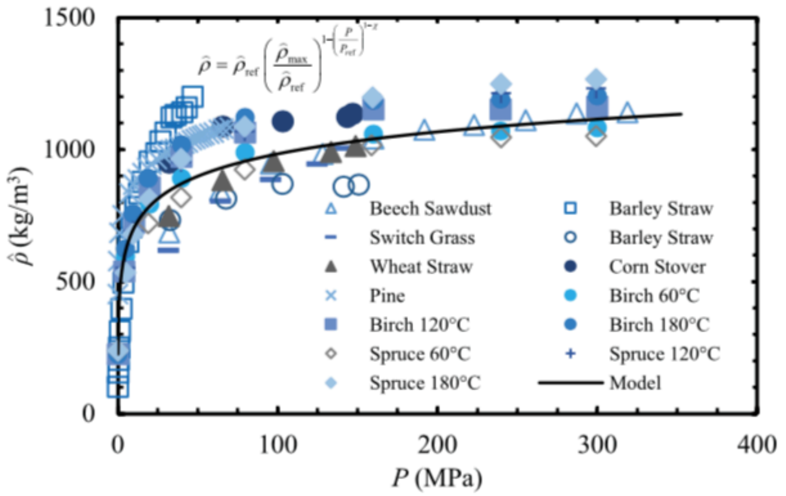
Collaborators (Akbari et al.) from University of Toledo measured yield stress parameters for the feedstock

Equation of State

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

Pressure-dependent density equation (Duncan et al.)

Parameter	Value	Unit
ρ_{ref}	188	kg/m^3
ρ_{max}	2290	kg/m^3
P_{ref}	1	atm
χ	1.146	-



CFD implementation

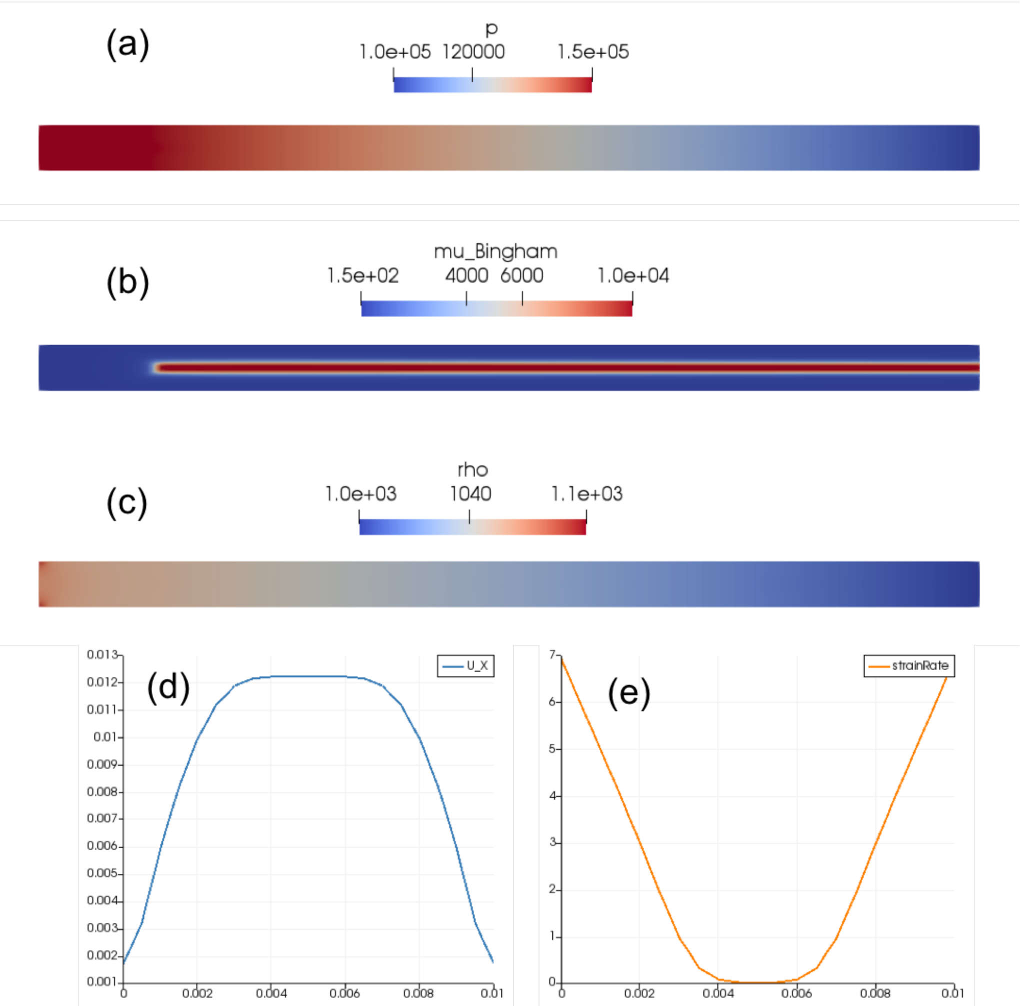
- Used OpenFOAM framework
- Implemented a new thermophysical model for biomass equation of state
- Modified the transient compressible *rhoPimpleFoam* solver to include the new constitutive model in the momentum equation with density dependent yield stress
- Screw feeder geometry CAD STL files were used 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

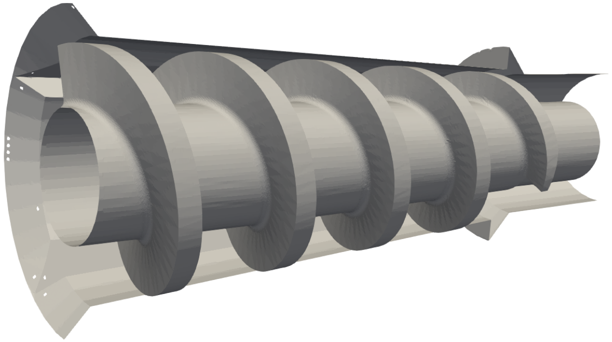
- High strain rate --- low viscosity (wall)
- Low strain rate --- high viscosity (middle)

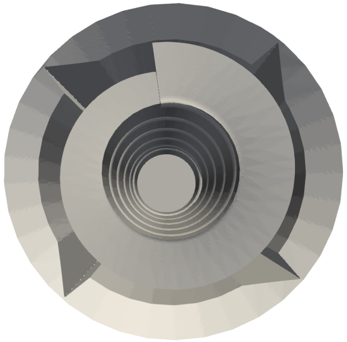


Screw Feeder Simulation Results

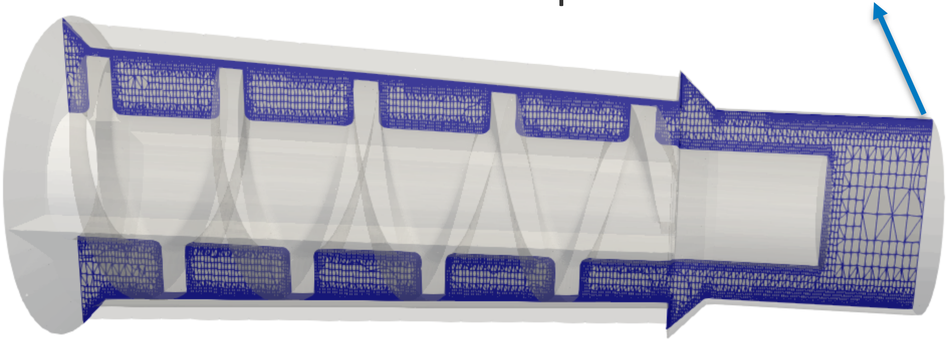
Mesh and Boundary

- 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

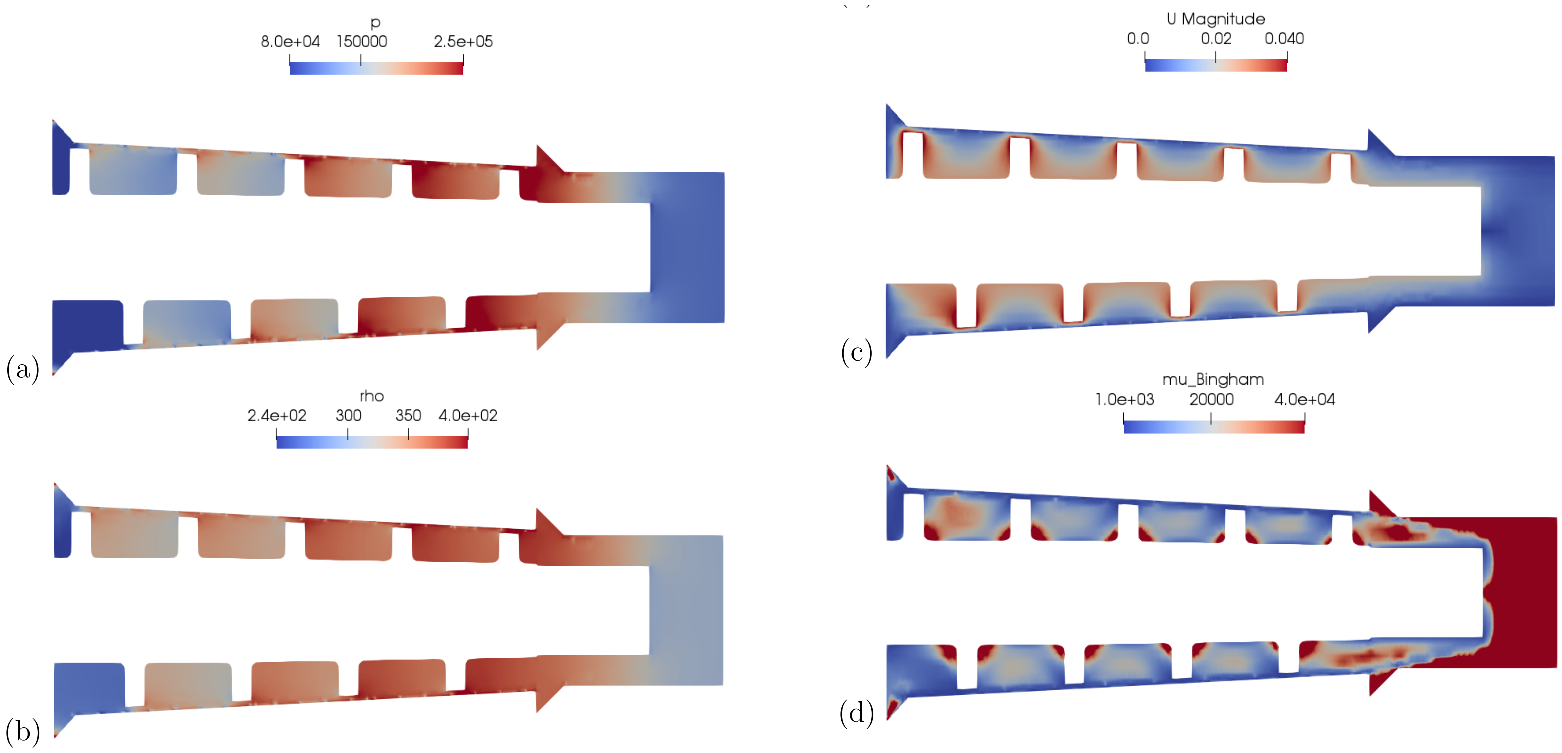




Outlet boundary is moved further out to have a 1 atm uncompressed free flow

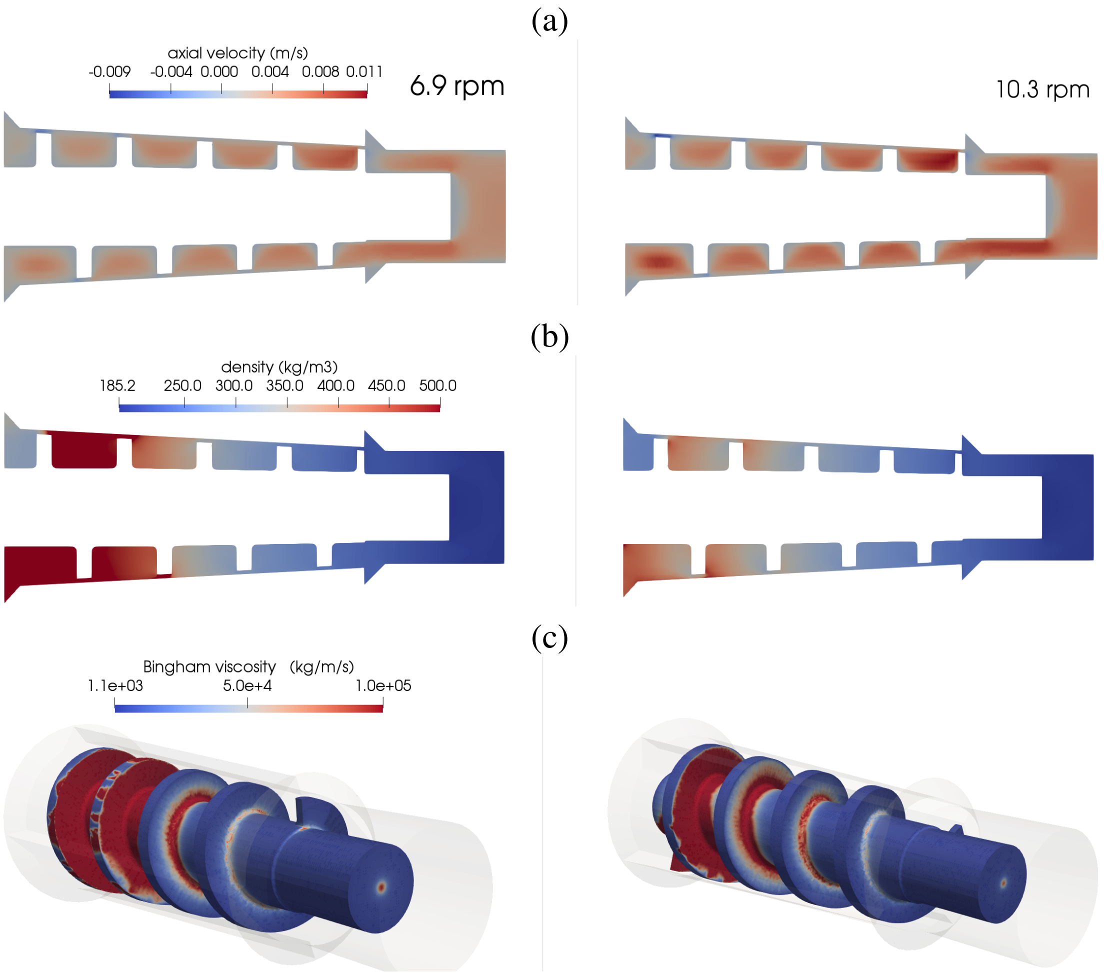


Flow Field Results



Low rpm vs. high rpm

- 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



Torque Validation

Axial torque is calculated on the screw wall surface, from both viscous shear stress and pressure.

Screw speed (rpm)	Feed rate (kg/h)	Fill fraction	Measured screw torque (Nm)	Simulation torque (Nm)
10.3	16.6	53%	290	265
6.9	16.6	80%	488	464

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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