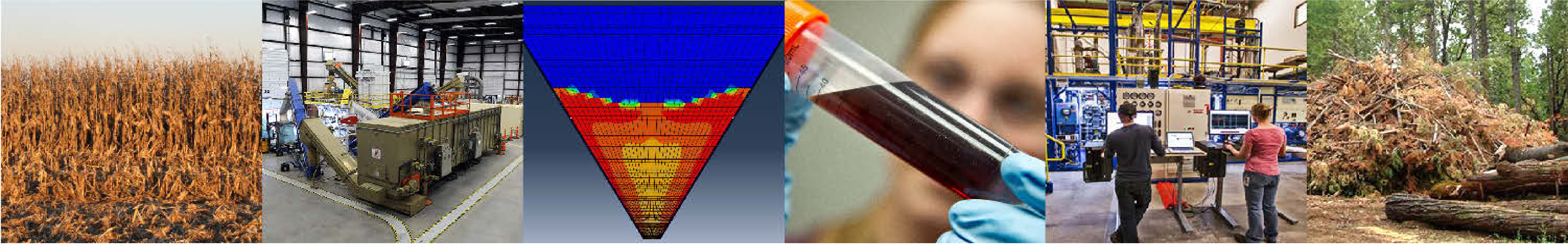


Determining Design Criteria for Feeding Biomass into a Fluidized Bed using a Feed Screw

Tim Dunning
Rosemont, Illinois
October 9, 2019

tcbiomassplus2019

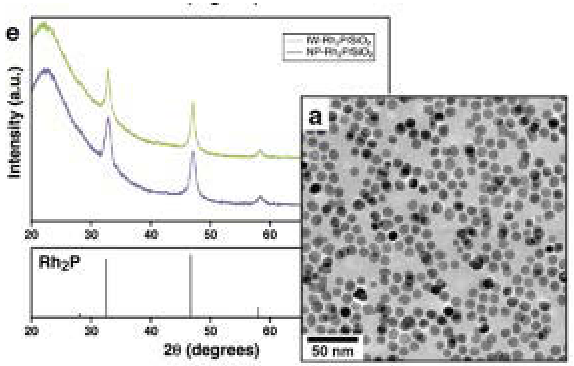
fcic
FEEDSTOCK-CONVERSION
INTERFACE CONSORTIUM

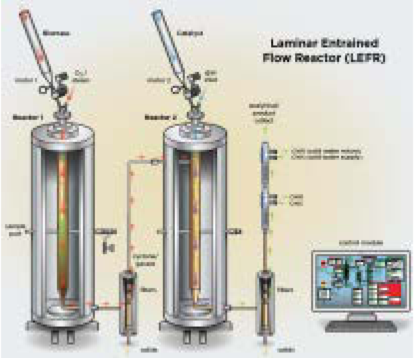
Thermochemical Conversion Research at NREL

Fundamental Science
mg-g

Catalyst Development & Testing
g-kg

Scale-up & Demonstration
100’s kg

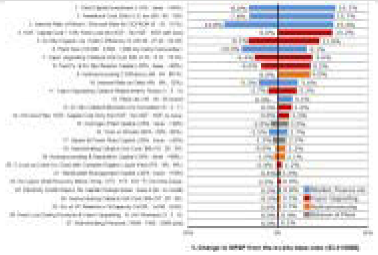




Feedstocks

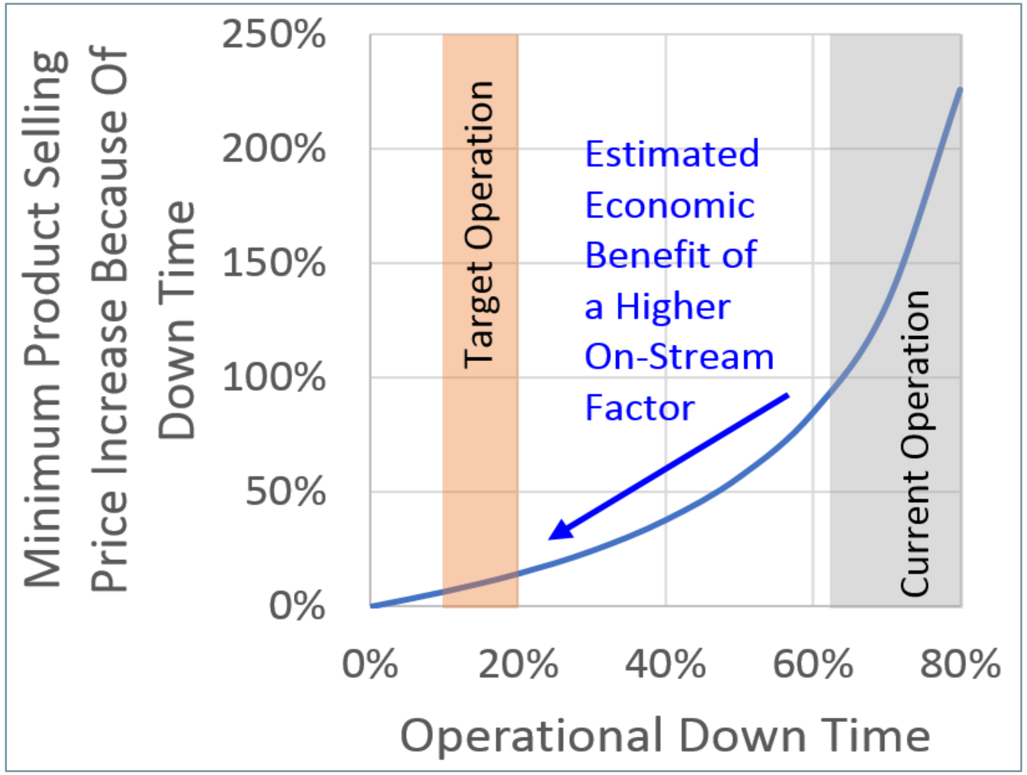
Bio-Oil Characterization

Technoeconomic Analysis



Background

- **Problem:** Most pioneer biorefineries have failed
- **Why?** Impact of 'real-world' feedstocks on unit operations is poorly understood
- **Feedstock Conversion Interface Consortium (FCIC):**
  - Consortium of 9 National Laboratories
  - Goal: Fundamental understanding of how biomass variability (chemical, physical, mechanical) manifests from field through conversion
- **Consortium Outcomes:**
  - First principles knowledge of unit op level response to feedstock variability
  - Transfer functions to bridge scales
  - Valuation of intermediate streams



*Adapted from biomass-to-gasoline conceptual design**

**NREL/TP-5100-62402, PNNL-23822, 1-189*

Biomass Transformations During High Temperature Feeding

What we know:

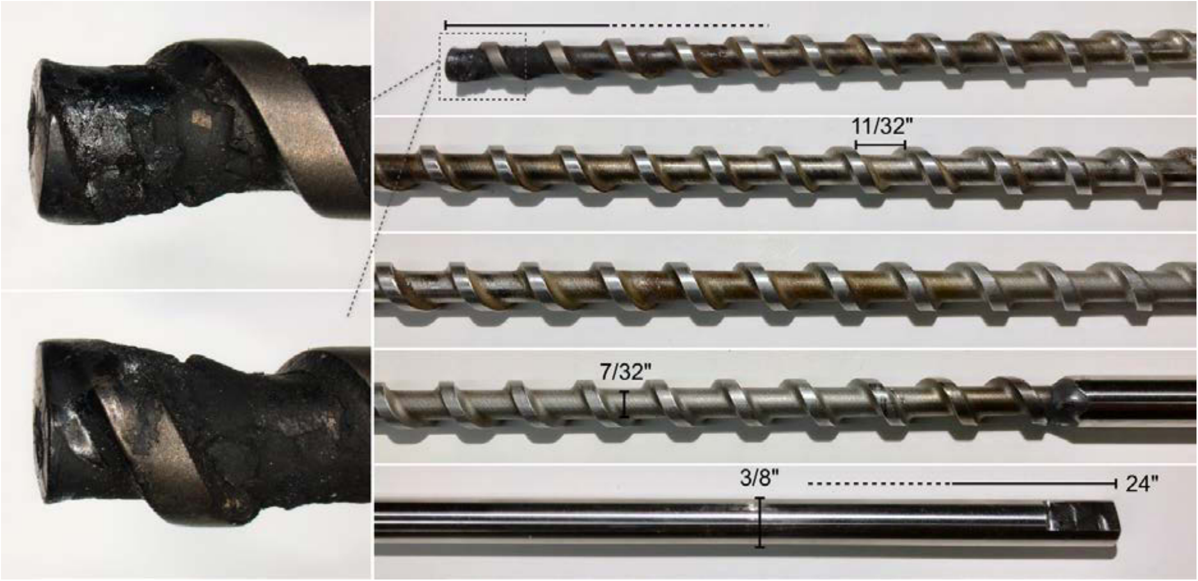
- Particle attributes and bulk behaviors change over temperature gradient
- Current feeder design does not account for temperature gradient
- Screw feeders are frequently problematic when feeding high temperature fluidized beds

What we will explore:

- Fundamentals of particle agglomeration across thermal gradients
- Feeder design in relation to temperature gradient

Why:

- Inform and validate heat and mass transfer models
- Determine Critical Material Attributes (CMA’s) for feedstocks
- Develop engineering guidelines for successful feeder design



Bryon Donohoe 2019

Feedstock Properties Affecting Feeder Design

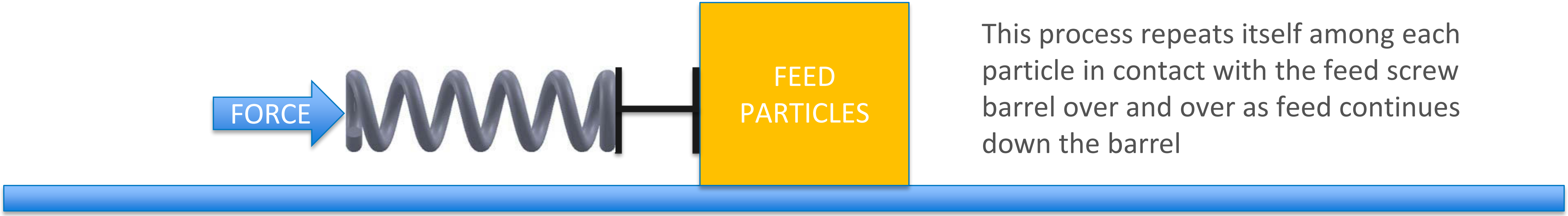
- Mean Particle Size
- Maximum Particle Size
- Shape
- Shape Factor
- Bulk Density
- Bulk Material Lump Size
- Compressibility
- Moisture Content

Scope of Current Work

- Loblolly Pine – Whole Tree
- Hammermilled
- Passed through a ¼” screen
- Screw Feeder
- Temperature – Ambient → 600˚C
- Pressure – Ambient → 60 kPa

Stick-Slip Principle

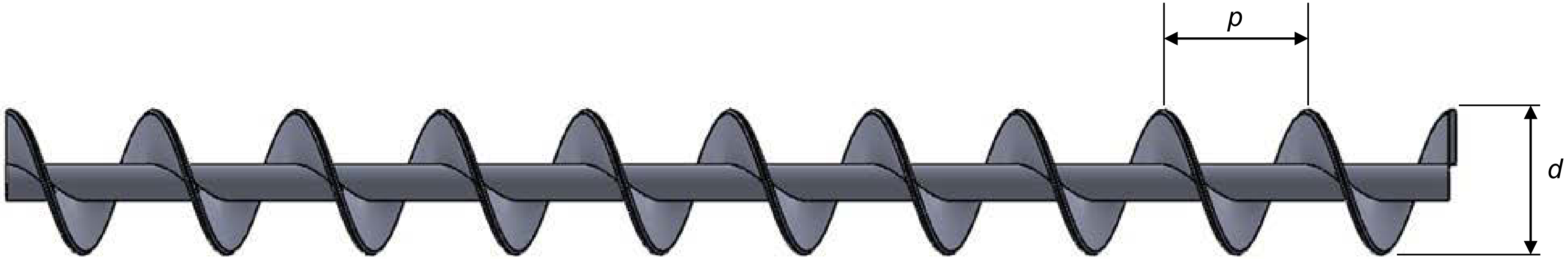
- Feed screw exerts force on feed particle
- Feed particle resists movement due to static friction with feed screw barrel
- Force builds until friction is overcome, moving particle until frictional force exceeds force exerted by feed screw
- Particle stops until feed screw force overcomes static frictional force



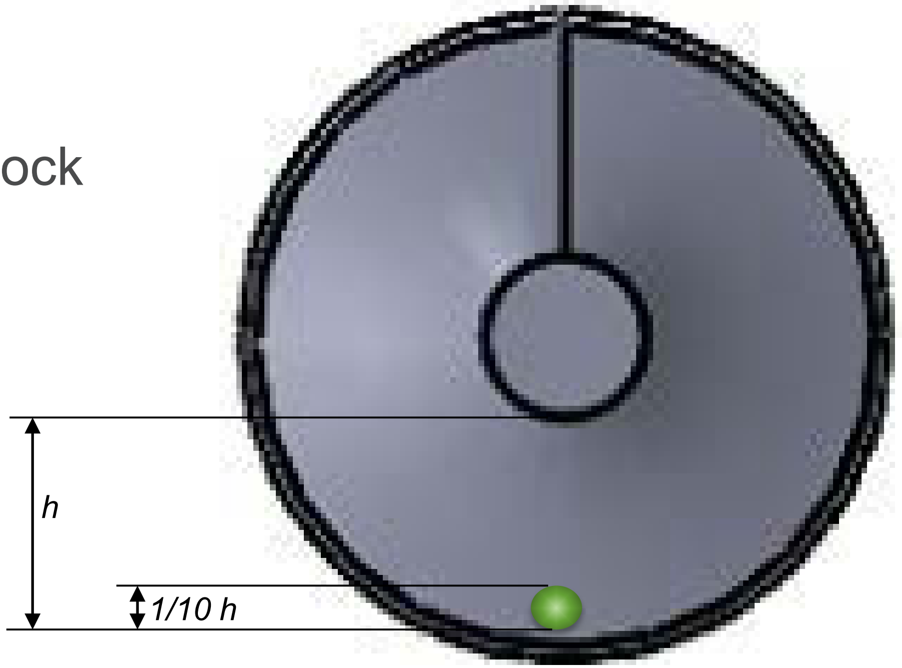
This process repeats itself among each particle in contact with the feed screw barrel over and over as feed continues down the barrel

While traveling across the temperature gradient approaching the feeder, the frictional coefficient likely changes

Feed Screw Mechanics



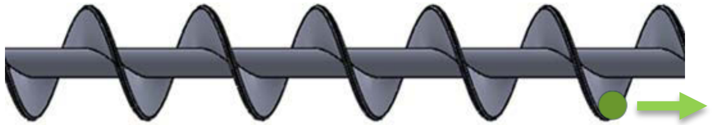
- Rotational Speed – Generally less than 80 RPM
- Size and shape of screw flight – Based on flowability of feedstock
- Feed particle size-Less than 1/10 of flight height
- Angle of friction on the screw face
- Pitch Ratio- $Q=p/d$
- Pitch ratio generally .25-1
- Optimum Flow- $Q_{optimum} = .75Q_{max}$

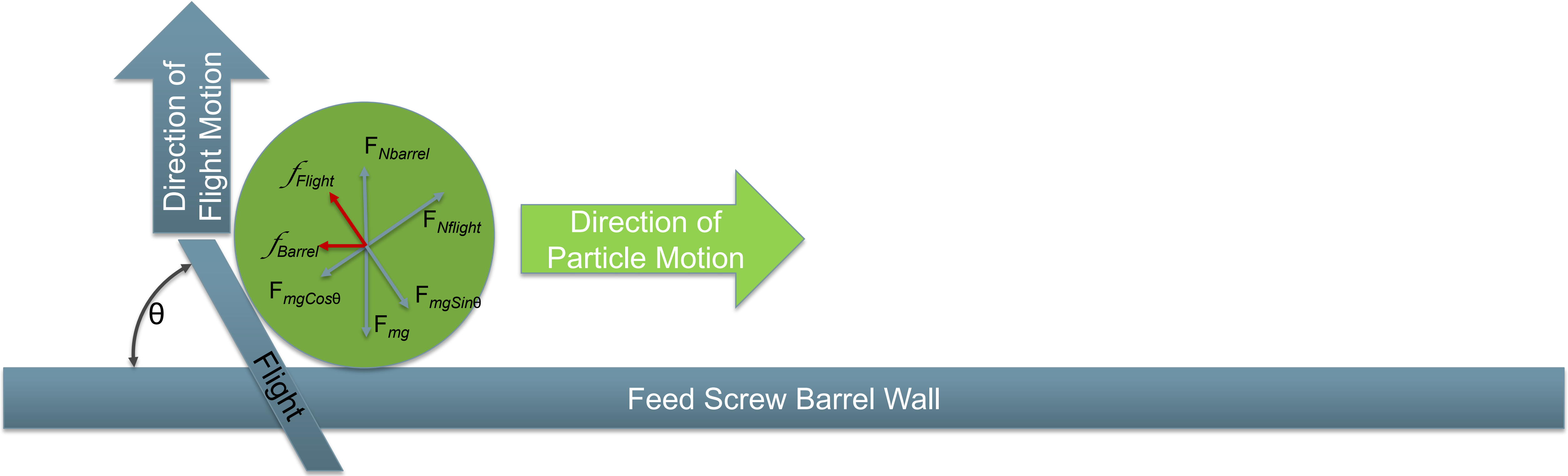


Haaker et al, 1994; Yu, 1997

Basic Forces at Feed Screw Barrel Interface

- Screw Feeder is essentially an inclined plane
- Frictional forces must be minimized for smooth operation
- Flight must have enough energy to overcome $f_{Flight/Particle}+f_{Barrel/Particle}$





Direction of Flight Motion

$F_{Nbarrel}$

f_{Flight}

$F_{Nflight}$

f_{Barrel}

$F_{mgCos\theta}$

$F_{mgSin\theta}$

F_{mg}

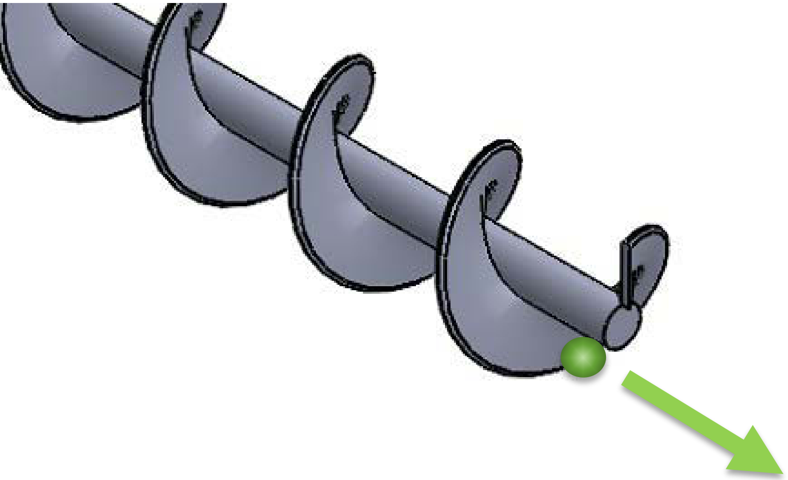
θ

Flight

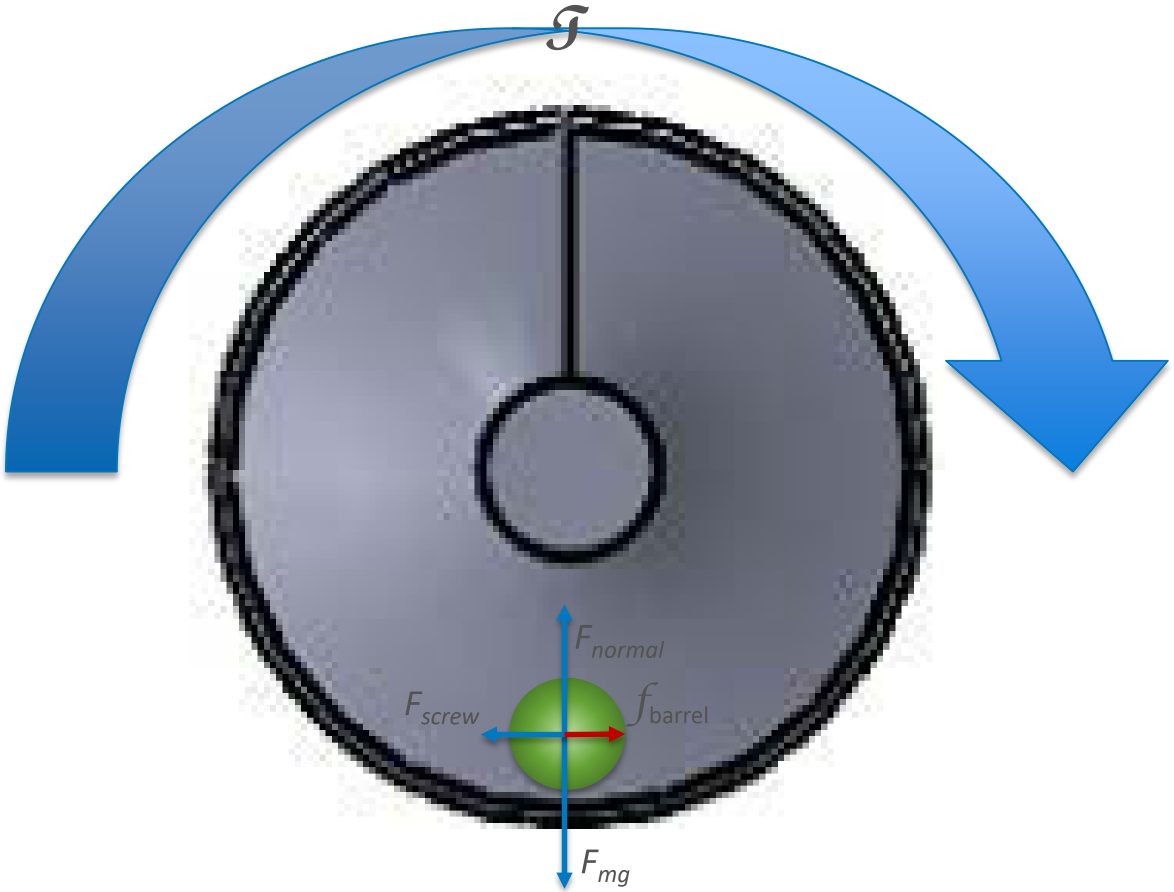
Direction of Particle Motion

Feed Screw Barrel Wall

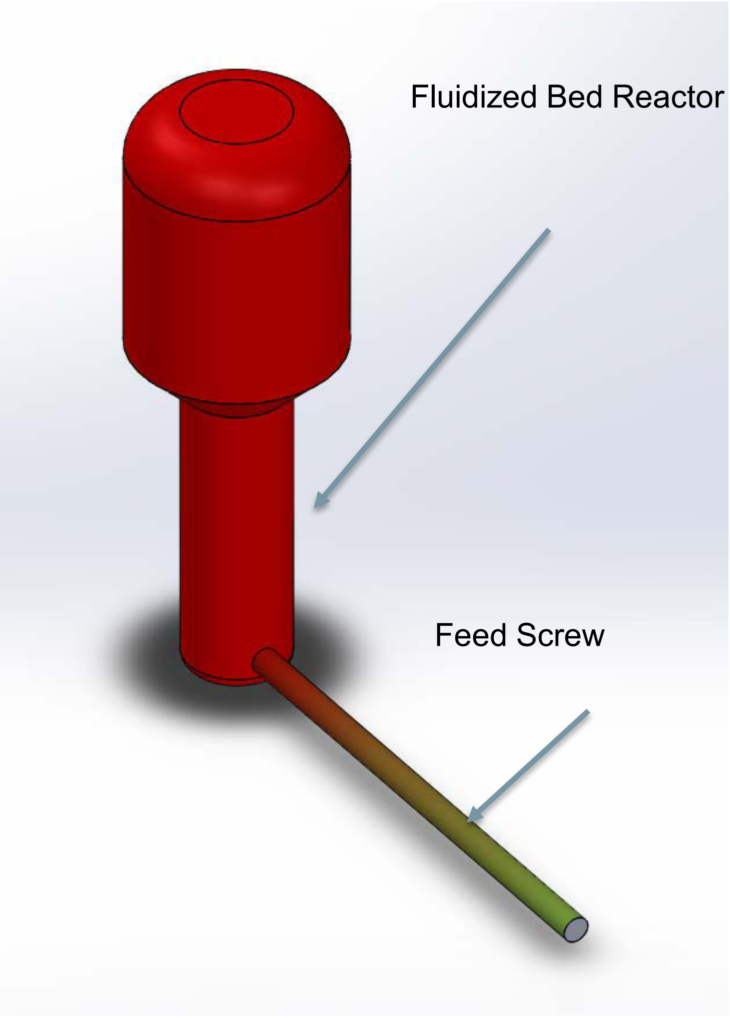
Rotational Forces



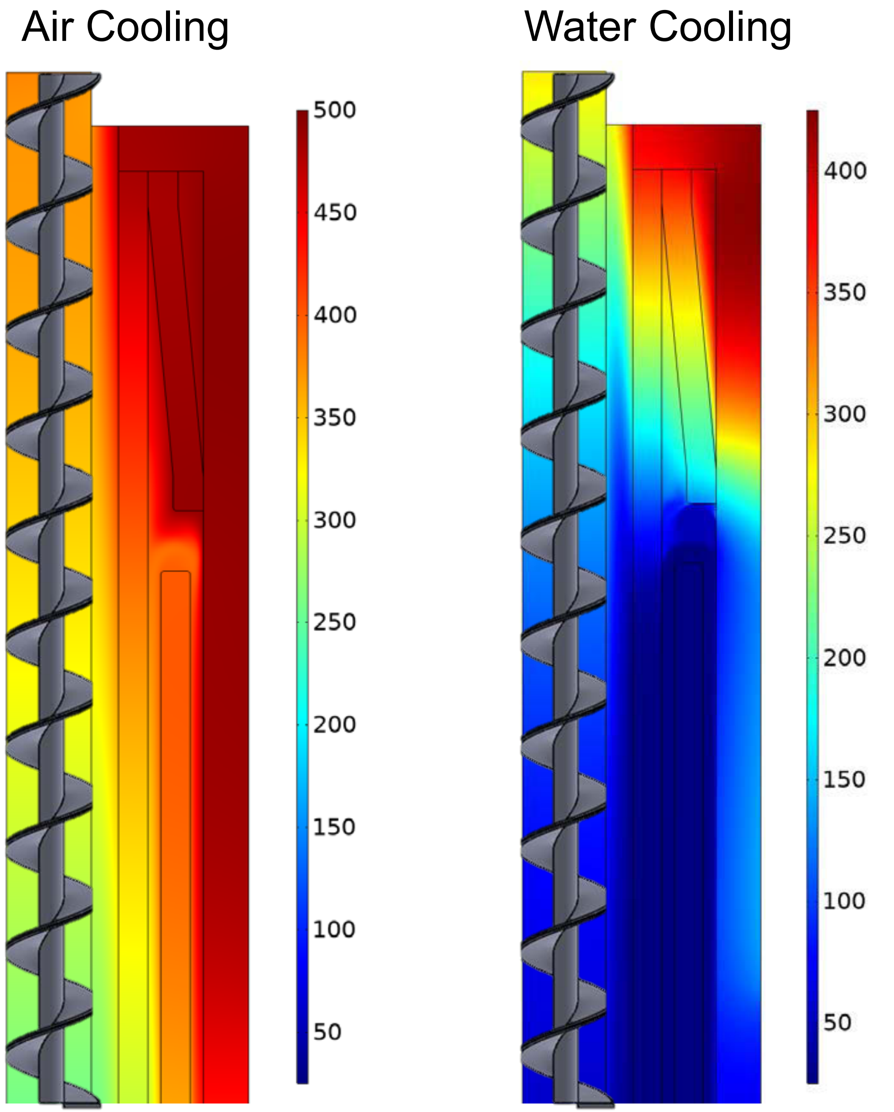
- Friction with the barrel and gravitational forces must exceed friction with screw for feed to travel length of screw
- Largest Particle size/Clump size should not exceed



Modeling of Thermal Gradient within a Screw Feeder



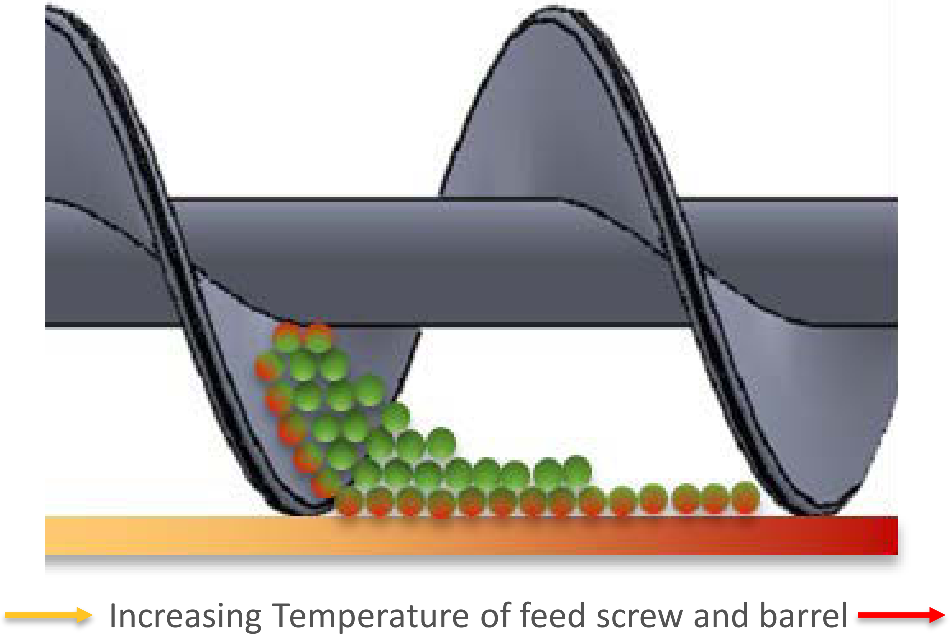
- Biomass is an insulator, negligible for heat transfer
- Active cooling of feed screw dramatically changes temperature profile within screw
- Temperature within the feed screw is high enough for thermal reactions to occur



Heat Transfer to Biomass in Screw Feeder

- Feed screw / Barrel are conductors with gradient from ambient to ~500°C
- Biomass is essentially an insulator (k ≈> 0.2 W/m*k)
- Steel is conductor (k ≈< 10 W/m*k)
- Heating of biomass in feeder is not uniform

Proposed heating mechanism of biomass in a feed screw

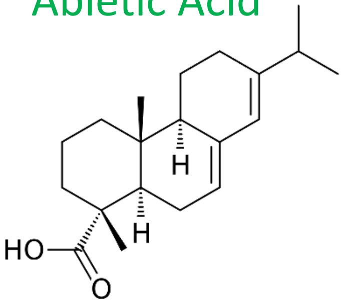


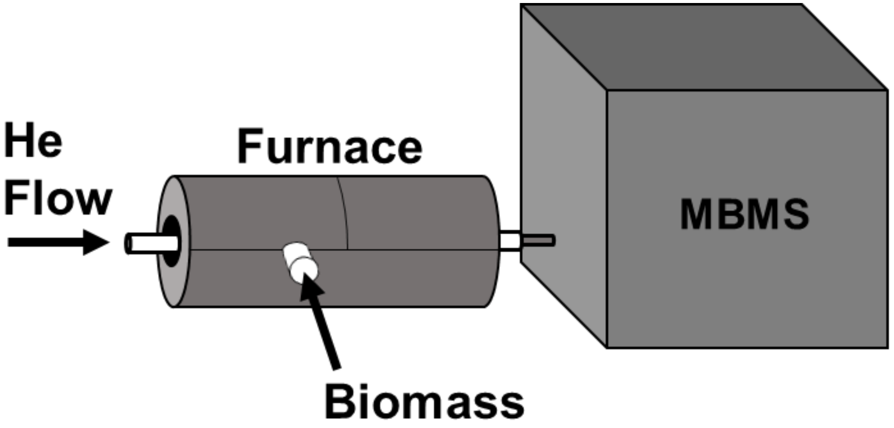
- Based on Tadmor's Melting Model
- Implies Volatilization and condensation of compounds within the feed screw as biomass mixes
- Biomass in contact with screw and barrel heated far more than biomass between flights
- Biomass directly in front of flight will carry more heat than biomass directly behind flight

Volatiles – Release of Resins at Low Temperature

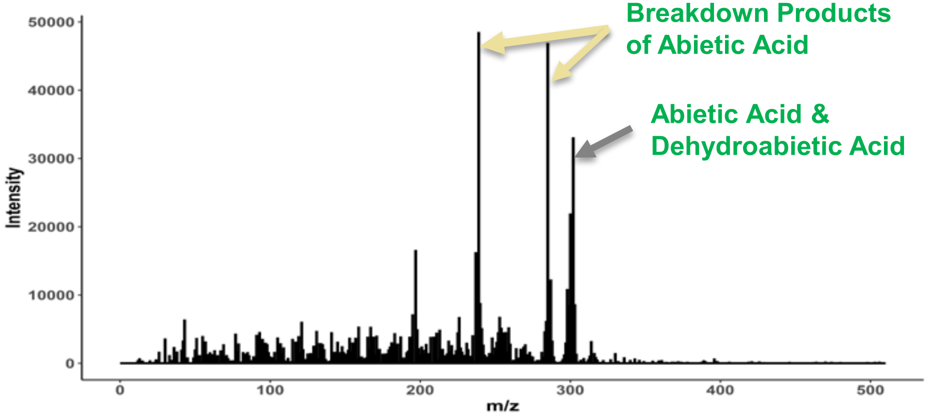
- Pine sap shown to volatilize at 200°C
- Early Volatiles may add stickiness in screw feeder

Abietic Acid





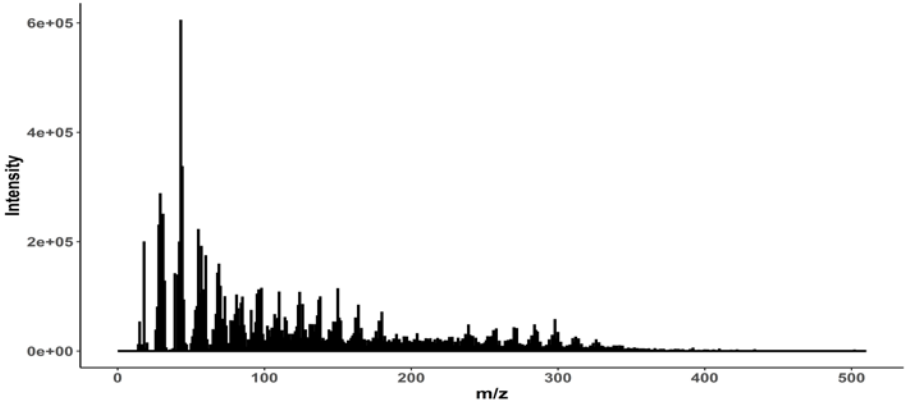
Whole Tree Pine 200°C



Breakdown Products of Abietic Acid

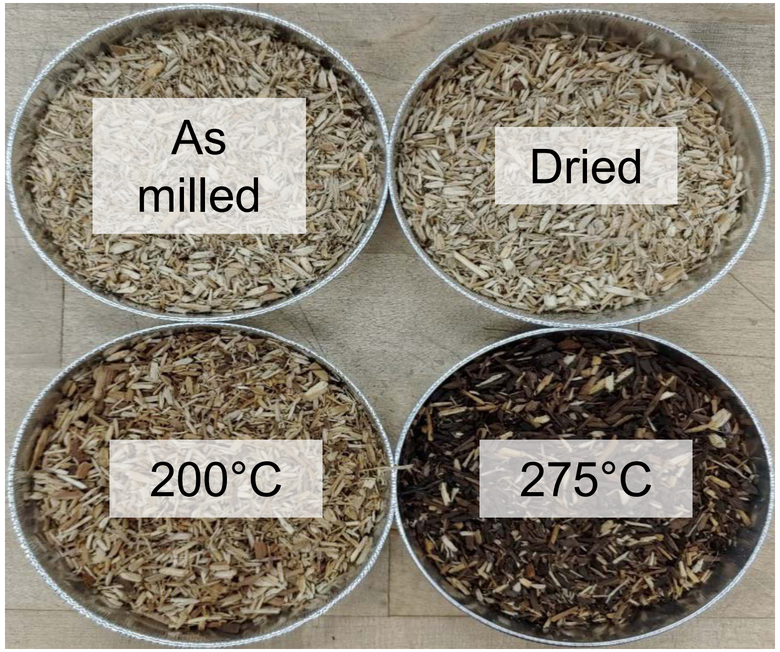
Abietic Acid & Dehydroabietic Acid

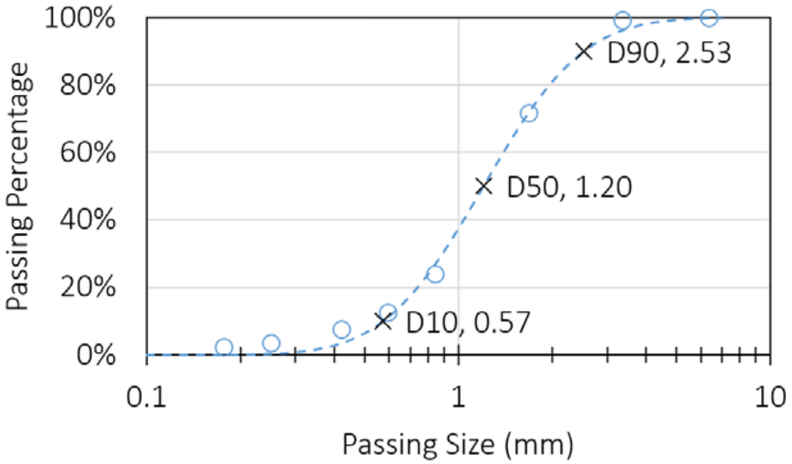
Whole Tree Pine 500°C



Biomass Feedstock - Loblolly Pine

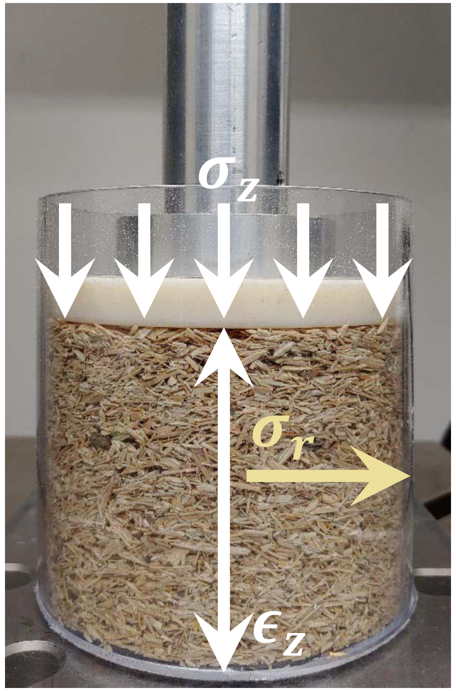
- Loblolly pine from Southern Georgia
  - Full parent/progeny sample metadata available in INL’s Biomass Feedstock Library
  - GUID #1326b6e1-bfb6-8048-8284-b6fc888c28f7
- Ground as-received field chips
  - Schutte Buffalo hammermill
    - 3600 RPM with ¼” screen
- Presented results are duplicate tests from two analytical splits, n = 4
- 29.0% raw moisture content
- Dried at 60° C
- Thermally treated with conductive ramp up to 200° C and 275° C





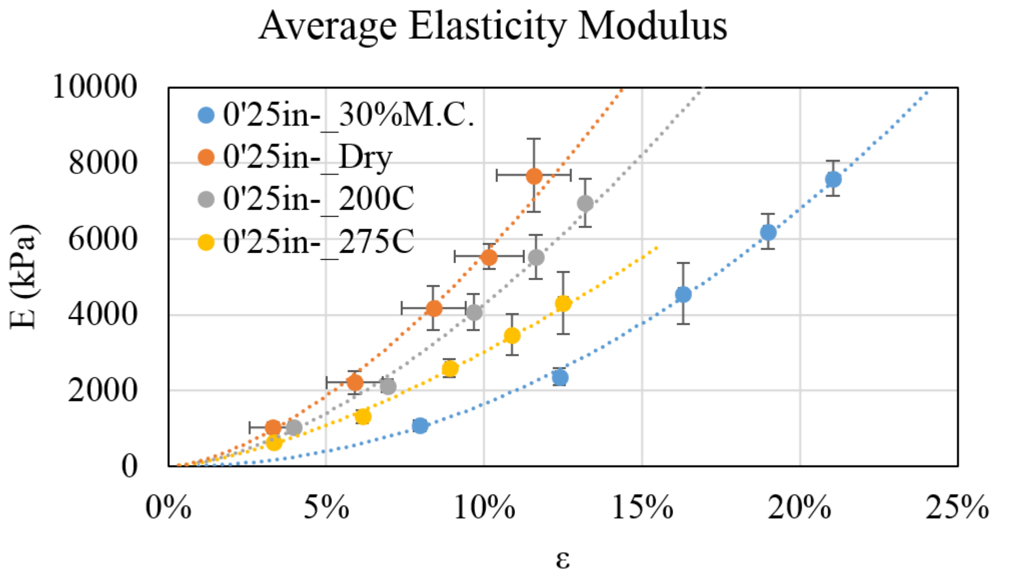
Cyclic Oedometer Testing

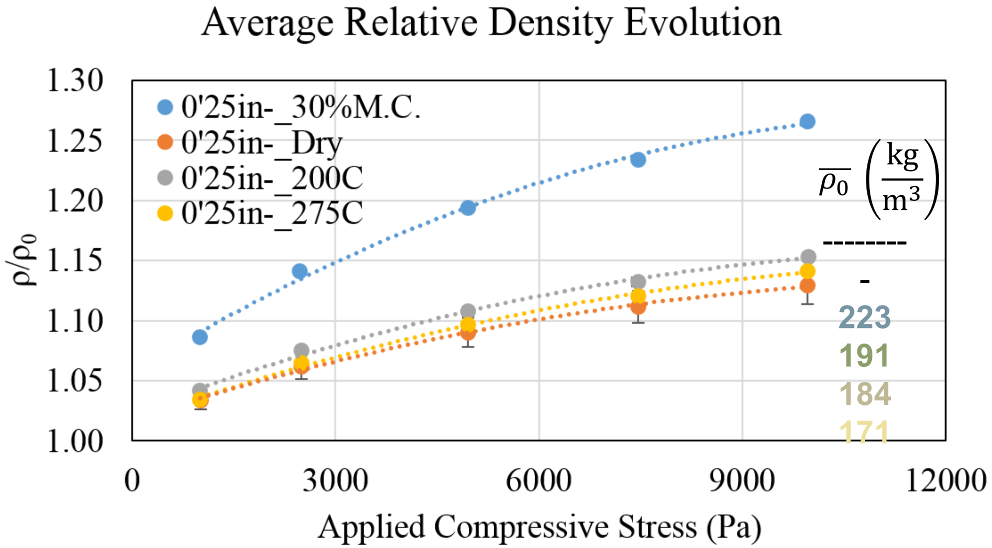
- Dry and wet pine materials have very different elastic response
- As pine is thermally degrades:
  - The elastic-strain behavior approaches that of wet pine
  - The bulk grains experience similar strain, but and are more easily consolidated
  - Partial particle fragmentation and altered surface friction and structure damage
- Flow testing with dry feedstock does not capture the complex story



$$d\sigma_z = M d\epsilon_z = \left(K + \frac{4}{3}G\right) d\epsilon_z$$

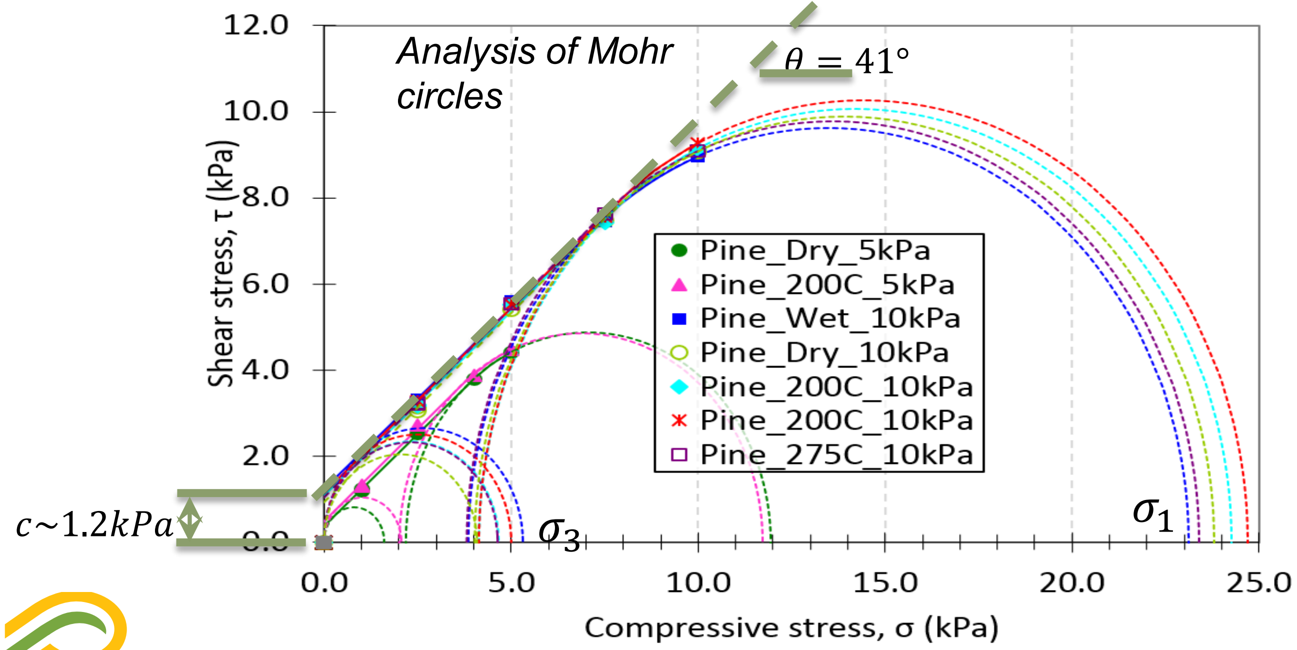
$$= \frac{1-\nu}{\nu} d\sigma_r \sim 24 d\sigma_r$$





Schulze Ring Shear Testing

- Bulk sample internal friction and cohesion are similar across the material/treatments
- Mohr-Coulomb yield envelops and criterion are insufficient to describe differences in bulk failure observed from flow testing
- Internal friction for the samples is approximately 41˚
- Cohesion is 1.2kPa at 10kPa preshear, dropping to 0.4kPa at 5kPa preshear
- Bulk internal friction is invariant to preshear. Cohesion increases with increasing preshear



Analysis of Mohr circles

Future Work

- MBMS testing of additional woody feedstocks
- MBMS testing of anatomical fractions
- Time scaling release of volatiles
- Friction testing of feedstocks in temperature regimes
- Controlled heated feed screw testing
- Materials testing

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Questions?

Thank you for your time