Parameter determination of the non-local granular fluidity model for wood chips by comparison to well-defined experimental flow systems

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The unique role of biomass

While the growing need for sustainable electric power can be met by other renewable sources...
The unique role of biomass

While the growing need for sustainable electric power can be met by other renewable sources... biomass is our primary renewable source of carbon-based fuels and chemicals.
Terrestrial biomass utilization

**Biomass Feedstock**

- **Lignocellulosic**
  - Woody (trees)
  - Herbaceous (grass)
  - Waste (agri, municipal)

- **Sugar/Starch**
  - Corn
  - Sugar cane

- **Plant oils**

**Utilization**

- Paper
- Heat & Power
- Liquid Fuel
  - Ethanol
  - Diesel/gasoline blends
- Food
Terrestrial biomass utilization

### Biomass Feedstock

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### Utilization

**Paper**
- Pulp and paper proc.

**Heat & Power**
- Combustion, gasification
- Digestion + bioconv, pyrolysis

**Liquid Fuel**
- Ethanol
- Diesel/gasoline blends

**Food**
- Low-cost commodity feedstocks
- Storage and transport of large volumes

*Storage and transport of large volumes*
Terrestrial biomass feedstocks

- Non-spherical particles
  - “Chips” (plates, rods)
  - Fibers (flexible)
- Heterogeneous (size, shape, and composition)
- Low density
- Compressible
- Moisture content: 10-50%

*Short term goal:* model feed-handling operations of simple biomass (wood chips with narrow size range)
Mathematical models of dense granular materials

**Discrete element method (DEM)**
- Interactions between individual particles computed and all particles tracked
- State-of-the-art for flows of granular materials
- Limited by computational cost to a few million particles

**Continuum models**
- Mohr-Coulomb
- Drucker-Prager-Cap
  - Originally used in solid-mechanics frameworks (probing structural failure)
  - Recent work to implement for dynamic flow (FEM simulations)
- Inertial (“μ-I”) rheology
  - Shear and pressure-dependent friction coefficient
  - Implemented in a fluid mechanics framework
- Non-local granular fluidity
  - Extension of inertial rheology
  - Aims to capture “nonlocal” phenomena
- Nonlocal Hypoplasticity, NorSand, Others?
Inertial ("μ-I") rheology

Implemented as a generalized Newtonian fluid\(^1,2\)

- Navier-Stokes equations
- Inertial rheology viscosity: depends on strain rate and pressure
- Shown to reproduce bulk-flow phenomena, e.g., Beverloo scaling in flow from a silo
- Ill-posed for some parameter values (due to pressure term in viscosity)?\(^3\)

\[
\nabla \cdot \mathbf{u} = 0
\]

\[
\rho_B \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \rho_B g - \nabla p + \nabla \cdot (2\eta \mathbf{D})
\]

\[
\eta = \frac{\mu(l)p}{\dot{\gamma}}
\]

\[
\mu(l) = \mu_s + \frac{\Delta \mu}{1 + l_0/l}, \quad l = \frac{d\dot{\gamma}}{\sqrt{p/\rho_p}}
\]

DEM (left) and Inertial rheology (right)\(^2\)

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Nonlocal granular fluidity (NLGF)

Extension of inertial rheology\(^4,^5\)

- "Fluidity", \(g(x)\), with an evolution equation: propagation of flow that depends on particle length scale

- Previously evaluated in steady-state flows and simple geometries (no dynamic simulations)
  - Shown to reproduce nonlocal phenomena, e.g., stop height of flow on an incline

- Pressure-viscosity-shear instability?

\[ \nabla \cdot \mathbf{u} = 0 \]

\[ \rho_B \left( \frac{\partial \mathbf{u}}{\partial t} + \mathbf{u} \cdot \nabla \mathbf{u} \right) = \rho_B g - \nabla p + \nabla \cdot (2 \eta \mathbf{D}) \]

\[ \eta = \frac{p}{g}, \quad \mu = \frac{\dot{\gamma}}{g} \]

\[ t_0 \frac{dg}{dt} = A^2 d^2 \nabla^2 g - \Delta \mu \left( \frac{\mu_s - \mu}{\mu_2 - \mu} \right) g \]

\[ - \frac{\Delta \mu}{l_0} \sqrt{\frac{\rho_p d^2}{p} \mu g^2} \]


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parameter
repeated or derived parameter
field variable
\[ t_0 \frac{dg}{dt} = A^2 d^2 \nabla^2 g - \Delta \mu \left( \frac{\mu_s - \mu}{\mu_2 - \mu} \right) g \]

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- **Parameter**
- **Repeated or derived parameter**
- **Field variable**

- Material properties (e.g., pine chips)

\[ \rho_B, \quad \rho_p, \quad d \]
NLGF model parameters

\[ t_0 \frac{dg}{dt} = A^2 d^2 \nabla^2 g - \Delta \mu \left( \frac{\mu_s - \mu}{\mu_2 - \mu} \right) g - \frac{\Delta \mu}{I_0} \sqrt{\frac{\rho_p d^2}{\rho}} \mu g^2 \]

- 3 parameters shared with inertial-rheology model:
  \( \mu_s, \mu_2, I_0, (\Delta \mu = \mu_2 + \mu_s) \)
  Can be determined directly from inclined-plane flow experiments.

- Material properties (e.g., pine chips)
  \( \rho_B, \rho_p, d \)

- Parameter
- Repeated or derived parameter
- Field variable

Material properties (e.g., pine chips)
NLGF model parameters

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- 3 parameters shared with *inertial-rheology* model:
  
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  Can be determined directly from inclined-plane flow experiments.

- 2 new parameters:
  
  \[ A, \quad t_0 \]

  Can be determined by matching model results to flow experiments.

- Material properties (e.g., pine chips)

  \[ \rho_B, \quad \rho_p, \quad d \]

- Parameter
- Repeated or derived parameter
- Field variable
$t_0 \frac{dg}{dt} = A^2 d^2 \nabla^2 g - \Delta \mu \left( \frac{\mu_s - \mu}{\mu_2 - \mu} \right) g$

$- \frac{\Delta \mu}{l_0} \sqrt{\frac{\rho_p d^2}{\rho \mu g^2}}$

- 3 parameters shared with *inertial-rheology* model:
  - $\mu_s$, $\mu_2$, $l_0$, $(\Delta \mu = \mu_2 + \mu_s)$
  - Can be determined directly from inclined-plane flow experiments.

- 2 new parameters:
  - $A$, $t_0$
  - Can be determined by matching model results to flow experiments.

- Material properties (e.g., pine chips)
  - $\rho_B$, $\rho_p$, $d$

- Limits needed on values for fluidity, friction coefficient, and pressure to prevent divide by zero:
  - $g_{\text{min}} = 10^{-6}$, $\mu_{\text{max}} = 0.98 \mu_2$, $p_{\text{min}} = 10 \text{ Pa}$
CFD implementation

- Open-source CFD software OpenFOAM
- Incompressible Volume-of-fluid (VOF) method
- Implemented custom rheology model for NLGF
  - Viscosity model with pressure
  - Evolution equation for fluidity
- Simple meshes were developed directly (blockMesh)
  - At least 10k cells (for 2D geometries)
- Boundary conditions for fluidity? Both fixed and zero gradient suggested in literature. Small fixed value is logical for zero slip:
  $$g(x = \partial \Omega, t) = g_{\text{min}}$$
- Initial condition:
  $$g(x, t = 0) = 10$$
Materials

Hammer-milled loblolly pine to pass through 1/4 in screen:

\[ \rho_p = 500 \text{ kg/m}^3 \]
\[ \rho_B = 236 \text{ kg/m}^3 \]
\[ d_{50} = 0.8 \text{ mm} \]
Hammer-milled **loblolly pine** to pass through 1/4 in screen:

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Some simulations used properties of **glass beads** to compare to literature results:

\[ \rho_p = 2500 \text{ kg/m}^3 \]

\[ \rho_B = 1500 \text{ kg/m}^3 \]

\[ d = 1 \text{ mm} \]
Experimental methods: Inclined plane

- Storage-box filled with material
- Laser-scanner used to measure material position and velocity on ramp
- Gate opened to sufficient height to initiate flow, 75 – 200 mm
- Flow observed and front velocity measured
- Gate closed when $\sim \frac{1}{2}$ of material has exited
- Stop-height profile measured
Experimental methods: Ring-shear tester

- Schulz Ring-Shear Tester (RST-01)
- Mohr-circle analysis of shear stresses vs. compressive stresses
- Standard measurement of cohesion and internal friction

Inclined-plane, experimental results

animations/29'5deg_14in_open.mp4
Inclined-plane, experimental results

animations/29'5deg_14in_open.mp4
Inclined-plane, experimental results (cont’d)

**Glass beads**

\[ \frac{h_{\text{stop}}(\theta)}{d} = \frac{L_0}{d \left( \frac{\mu_2 - \mu_s}{\tan(\theta) - \mu_s} - 1 \right)} \]

\[ L_0/d \sim 2 \text{ for glass beads} \]


**Milled pine**

\[ h_{\text{stop}}/d \]

\[ \mu_i = \tan \theta_i \]

\[ L_0/d = 50 \]

\[ \beta \propto \langle v \rangle/h \sim 0.1, \text{ glass beads} \]
Inclined-plane simulations

- Biomass parameters for $\rho_B$, $\rho_p$, $d$, $\mu_s$, $\mu_2$, and $I_0$
- Presumed values for $A$ and $t_0$
- $\theta = 27^\circ$

animations/biomass_fullCov_crop_short.mp4

animations/biomass_baffle_crop.mp4
Inclined-plane simulations

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![Graph showing relationship between $h_{stop}$ and $d$ at different inclination angles with experimental, model fit, and simulation data points.](image)
Experimental results, biomass
Ring-shear tester

Experimental results, biomass

Simulations, qualitative results
Flows from a silo

- Simple 2D rectangular silo with a centered bottom outlet
- Flow is steady between startup and formation of hollow center
- Static piles remain in the corners of the silo
- Flow profiles obtained for different outlet widths (L) and particle diameters (d)
Flows from a silo, Beverloo scaling

- The steady flow rate correlates with $L/d$
- 2D equations:
  \[ Q = Cg^{1/2}(L - kd)^{3/2} \]
  \[ \hat{Q}^{2/3} = C^{2/3} (\hat{L} - k) \]
  \[ \hat{Q} = g^{-1/2}d^{-3/2}Q, \quad \hat{L} = L/d \]
- Our simulation results confirm Beverloo scaling when changing either $L$ or $d$
Flow onto a pile

- Another classic test of granular behavior
- Qualitatively correct results with pile angle between static and dynamic friction angles (21° and 33°)
Flow from a hopper (3D)

- 3D conical hopper flow successfully performed using HPC
- 1.5 m tall, $\theta = 40^\circ$
- 220,000 cell mesh
- Simulation took 3 h on 32 cpus
Summary and future work

- *Dynamic* NLGF model successfully implemented in a general CFD software package

- Preliminary parameter determination for milled softwood
  - Stop height on inclined ramps
  - Ring shear testing

- Other classic flow phenomena reproduced qualitatively
  - Beverloo scaling in flows from silos
  - Pile formation
  - Hopper discharge

- Industrial-scale 3D simulation of hopper discharge

**Future work**

- Euler-Euler solver
  - Improved pressure evaluation and numerical stability
  - Variable density
  - Air passage

- Bulk solid compression?
Thank you

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