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Overview of DOE Flowability Measurement and Modeling Project at Forest Concepts and Penn State University

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ABSTRACT. New and improved laboratory equipment to measure biomass physical, mechanical, and flowability properties are being developed to prototype stage within this project. Improved analytical models and simulation tools are being developed to improve the design of biomass handling unit operations such as hoppers, chutes, feeders, and the like. The objective of the project is to contribute to the design and operation of reliable, cost effective, continuous feeding of biomass feedstocks into a reactor of an integrated biorefinery.

Keywords. Biomass, Feedstock, Biomass Flow, Flowability, Integrated Biorefinery, Cubical Triaxial Tester, Constitutive Flow Model

Introduction

In 2018, Forest Concepts was awarded a competitive contract by the U.S. Department of Energy, Bioenergy Technologies Office to develop improved methods to model biomass flowability (Funding Opportunity Announcement (FOA) Number: DE-FOA-0001689). The FOA specifically sought applications focusing on the development of dynamic, novel, real-time analytical models that would contribute to the design of reliable, cost effective, continuous feeding of biomass feedstocks (assuming the feedstock is already available within the plant boundary) into the reactor. Modeling efforts should focus primarily on feedstock characterization, particle size distribution, flow behavior and rheological properties within the feedstock handling unit operations and how the solid material will flow within the reactor unit operations. Modeling efforts must account for the effect of temperature and pressure on feedstock handling. Forest Concepts was one of four awardees resulting from the solicitation.

Project Team

The project team includes a small group to ensure focus, enable low-cost project management, and to facilitate communication. Cooperators include Forest Concepts, LLC (FC), The Pennsylvania State University (PSU), and Amaron Energy (AE). The team is led by Forest Concepts, a biomass feedstock technology developer that has received more than 30 US Patents and published more than 50 manuscripts and technical papers related to biomass utilization and bio-based products. In addition to its R&D group, Forest Concepts is a significant processor and producer of biomass feedstocks through its production division. Dr. Jim Dooley from Forest Concepts has published on feedstock flowability metrics (Dooley, Lanning et al. 2011, Dooley, Lanning et al. 2011) and has recently authored a technical journal article summarizing flowability work going on around the world (Dooley 2017). Mr. Chris Lanning, P.E., is the project lead at Forest Concepts.

Penn State has a long history in biomaterials physical properties research. Penn State is the major academic partner in this proposal. Penn State's PI is Dr. Virendra Puri built upon the legacy of Mohsenin with his work on particulate materials flow modeling and measurement. Dr. Puri invented new and improved methods and equipment for measurement of particle flowability parameters (US Patent 6,003,382). Over the past thirty-plus years, Dr. Puri has greatly advanced the modeling of compression, flowability, and storage for biomaterials (D'Alfonso, Kamath et al. 1997, Mittal, Zikatanov et al. 2001, Mittal and Puri 2002, Mittal, Zikatanov et al. 2003, Jun, Puri et al. 2004). Dr. Puri's 30-year tenure has resulted in sophisticated models and simulations that hold great promise as building blocks for feedstock handling engineering tool kits. Dr. Hojae Yi is the project lead at Penn State.

Amaron Energy, led by Dr. Ralph Coates and located in Salt Lake City, is an industrial partner in the project. Amaron has been developing truly mobile fast pyrolysis systems for use with forest residuals, pinyon-juniper forest restoration debris, and other woody biomass. After several major field trial upsets, Forest Concepts worked with Amaron and their feedstock suppliers to reprocess chipped forest and wildfire protection biomass into highly flowable feedstocks (Dooley 2014). Jeff Caldwell is the project lead at Amaron Energy.

Through earlier work together, Forest Concepts' engineers have an experience-backed understanding of Amaron's feedstock and biochar handling systems which use hoppers, augers, and rotary air-locks to move biomass in and out of their reactor. The project will also include a case study of the existing feedstock handling systems on Amaron's mobile pyrolyzer and proposed improvements to reduce operational issues and downtime. Amaron reports that their design objective is to have an on-stream factor of 0.9 (90% uptime) and a downtime probability on any day of less than 5%. Their current on-stream factor is approximately 0.6 and probability of a downtime event is 10-20% each operating day. Many of the issues are related to feedstock or biochar handling.

Project Goal

The overarching goal of the proposed project is to contribute to the design and operation of reliable, cost effective, continuous feeding of biomass feedstocks into various reactors typical of integrated biorefineries. The overarching goal is made up of two sub goals:

Goal 1. Develop and validate a comprehensive computational model to predict mechanical and rheological behavior of biomass flow to enable systematic and reliable design of biomass handling/conveying/feeding systems.

Goal 2. Engineer and improve laboratory protocols and equipment to generate property-driven data sets and response curves for specific biomass feedstock species and formats. New data will account for their dependence on moisture content and external conditions including temperature and pressure.

When completed, the effort will result in new and improved engineering design practices, published data sets that include relevant design data for common biomass feedstocks, greatly improved simulation and modeling software products, and new/improved laboratory equipment appropriate for measuring physical and mechanical properties of commercially relevant biomass feedstocks.

Modeling Approach

Our creation of improved design tools and technology will begin with the development of improved engineering methods and then work back to laboratory protocols/equipment to generate necessary coefficients and response curves for specific biomass feedstocks. The Penn State team will lead the development and extension of their modeling program towards providing a systematic tool to determine critical design parameters of biomass feeding system into reactors ensuring effective and reliable flow and flowrates. Key issues of biomass feeding system design can be addressed with an accurate prediction of physical and mechanical conditions of biomass feedstock and its interaction with the materials of construction of a feeding system that ensures flow initiates upon startup and stabilizes at desired throughput. To that end, we propose to adapt one or more continuum scale constitutive models that describe the pressure, moisture, and temperature-dependent strength and volume change of bulk solids as well as mechanical conditions favoring and causing continued flow of bulk solids. These constitutive models should account for high cohesiveness and biological variability of biomass feedstock. Based upon rational principles, such constitutive models will help designers accurately predict the behavior of the bulk solid at incipient-flow and sustained flow conditions. In this study, we will address two major issues in feeding biomass in the bulk solid form into the reactor, i.e. initiating and sustaining of flow in an auger or a screw feeder.

Successful application of the constitutive equations can be achieved when one chooses constitutive models that precisely represent fundamental physics of a given problem and whose parameters have well defined physical meaning and characterization protocols. From this perspective, we will adapt one or more models, such as the critical state models including modified Cam-Clay, Drucker-Prager models, their generalized time-dependent forms if needed, rheological models, and fluid mechanics models including the Stokes-flow. These models have been documented to successfully simulate flow of cohesive powders. In addition, these models can predict (a) the flow condition at compressive deformations that take place during shearing and (b) frictional interactions between bulk solid and a wall, which is thought to be the origin of jamming issues in screw feeders and augers.

Parameters of the modified Cam-Clay model, as example, include compressive index, spring-back index, critical state line slope, Young's modulus, bulk modulus, and void ratio. These parameters have well defined physical meanings, which can be related to physical properties of particulate materials including particle density, bulk density, particle size distribution, particle shape and surface roughness, chemical composition of particles, and moisture content. Similar interpretation of parameters exists for the Drucker-Prager model.

At elevated temperature, biomass is known to change its bulk behavior. We will identify appropriate temperature levels that reflect hypothesized transformative change of biomass particles in relation to their components' glass transition temperatures. Therefore, we will determine above-mentioned physical properties as well as mechanical properties of selected biomass feedstock to establish a set of design and operation parameters. Characterization of mechanical parameters will be conducted using a fundamental mechanical tester to ensure collected data represents mechanical properties free of confining and confounding effects of test instruments. Therefore, a flexible membrane cubical triaxial tester will be used to determine fundamental mechanical properties free from confining die-wall effect. In designing experiments, the pressure-states that the bulk solid experiences during storage and conveying will be considered to model the incipient and established flow of a screw feeder or an auger.

For model implementation of initiation of biomass flow at different temperature levels and moisture contents, an existing finite element software Abaqus™ will be used. Computational fluid dynamics software such as ANSYS Fluent will be the candidate for modeling of sustained biomass flow. If these software packages do not meet the design requirements, user-defined finite element modules will be developed and integrated into the respective software to simulate and predict biomass feeding operations. Simulation results will be validated using real applications for the conditions of incipient flow and continued flow with and without jamming. At the conclusion of this project, we will have a verified and validated quantitative tool to predict and model mechanical parameters of a biomass feedstock flow using biomass feedstock's physical properties. This knowledge will provide a framework for an efficient and reliable biomass feeding system design tree that includes storage and conveying into and out of a biorefinery reactor.

Laboratory Equipment and Methods Approach

One of key challenges of scaling-up of biomass processes is feedstock handling. The lack of a systematic tool to characterize and model biomass flow behavior results in excessive downtime due to irregular or problematic flow characteristics of the feed material. In other words, traditional flowability metrics, such as compression ratio, Hausner Index, angle of repose, etc., give qualitative indication of relative flowability among feedstocks but provide little-to-no value for the quantitative engineering design of hoppers and feeders. Therefore, there is a need to develop an engineering tool set that enables an accurate prediction of physical and mechanical conditions of biomass feedstocks and their interaction with feeding systems.

Modeling of mechanical behavior of biomass feedstock requires a deep fundamental understanding of its highly nonlinear dependence on environmental conditions. It is not possible to conduct a uniaxial mechanical test and superimpose it to construct the three-dimensional mechanical properties because biomass feedstock is in the form of particulates. Measurement of particulate materials is complicated by the confounding effect of the boundary conditions and non-linear response in orthogonal directions of the sample.

Forest Concepts is leading the development of a biomass-scale true Cubical Triaxial Tester (CTT) based on earlier work at by Puri at Penn State. A series of experiments are designed across cubical containers from 100mm to 300mm dimension to study the relationship between chamber size and boundary effects. The result of those experiments will establish the ideal dimensions for a new CTT. Instrumentation and data collection from the CTT will be processed in essentially real-time to feed into flowability engineering models.

Other laboratory devices and methods common to the powders and soil mechanics fields will also be improved for the case of biomass A new gas pycnometer is being constructed to quantify specific particle density. A wall friction tester with large coupon area will be designed.

A protocol for rehydration of dried biomass materials will be developed so mechanical and other physical properties tests can be conducted across an operational range of moisture contents. The protocol is being evaluated against samples of the same material that have been never dried.

Case Study

During the final year of the project, a case study of the existing materials handling system used by Amaron Energy will evaluate the performance of the materials characterization and modeling tools. A physical model of the Amaron hoppers, screw conveyors, feeders, and biochar handling system will be built in SolidWorks® CAD. Milled wood chip feedstocks will be characterized with the new CTT, pycnometer, and other lab tools. That data will feed into the improved flowability models to predict flows, power requirements and other measurable factors. Actual field data will then compare predicted versus actual measurements.

Concluding Comments

This and the other three DOE-funded projects constitute an initial foray into application of engineering science and modeling to solve known flowability issues in the biofuels arena. Improved tools, methods, and models resulting from each project are expected to have an immediate beneficial impact on the industry. Publications, workshops, and presentations to engineers who design, operate, and specify biomass handling facilities should reduce technical risks and process upsets in the near future.

Since this is a first-effort, there is an expectation that continuing limitations of the tools and remaining issues with modeling will be documented to guide subsequent development projects funded by the agencies and institutions supporting the biofuels industry.

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