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Fluid mechanics relevant to flow through pretreatment of cellulosic biomass

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HIGHLIGHTS

- Compaction of biomass, water absorption and fine particles increase pressure drop.
- Bagasse and switchgrass require more water than poplar to operate in a FT mode.
- Pretreatment pressure drop is unpredictable from measurements at room temperature.
- Water flow compressed switchgrass and bagasse above threshold initial loadings.
- Viscous compression was not observed with poplar.

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ABSTRACT

The present study investigates fluid mechanical properties of cellulosic feedstocks relevant to flow through (FT) pretreatment for biological conversion of cellulosic biomass. The results inform identifying conditions for which FT pretreatment can be implemented in a practical context. Measurements of pressure drop across packed beds, viscous compaction and water absorption are reported for milled and not milled sugarcane bagasse, switchgrass and poplar, and important factors impacting viscous flow are deduced. Using biomass knife-milled to pass through a 2 mm sieve, the observed pressure drop was highest for bagasse, intermediate for switchgrass and lowest for poplar. The highest pressure drop was associated with the presence of more fine particles, greater viscous compaction and the degree of water absorption. Using bagasse without particle size reduction, the instability of the reactor during pretreatment above 140 kg/m^3 sets an upper bound on the allowable concentration for continuous stable flow.

1 Introduction

Producing fuel from lignocellulosic biomass is of interest in the context of developing a sustainable global energy system (International Energy Agency, 2012). The main obstacle impeding production of cost-competitive cellulosic biofuels is the high cost of converting cellulosic feedstocks to reactive intermediates, termed biomass recalcitrance (Lynd et al., 1999; Himmel et al., 2007). In the case of biological conversion of cellulosic biomass to sugars, it has been widely observed that a pretreatment step is necessary in order to achieve high solubilization yields (Mosier et al., 2005; Wyman et al., 2005). There are a wide variety of pretreatment processes, generally involving elevated temperature and pressure and in some cases added chemicals (Mosier et al., 2005; Wyman et al., 2005; Yang and Wyman, 2008). Pretreatment has multiple objectives that are difficult to achieve at once including high recovery of sugars in concentrated form and high yields and rates upon subsequent hydrolysis (Dale and Ong, 2012). Pretreatment operated in a flow through (FT) mode typically achieves higher solids reactivity, higher xylan removal, less sugar degradation and substantially higher removal of lignin compared to pretreatment in non FT configurations at the same temperature and residence time (Mosier et al., 2005; Wyman et al., 2005; Yang and Wyman, 2008).

Operation of FT configurations in a practical context is challenging because the higher water usage compared to non-flow configuration dilutes the sugar streams and increases energy

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consumption (Bobleter, 1994). Several configurations have been proposed and investigated to address these concerns including “recirculation flow”, “partial flow” and “counter-current flow”(Bobleter, 1994; Liu and Wyman, 2005; Shao and Lynd, 2013). Operation of FT is also challenging because of the mechanical complexities of arranging a reactor of biomass in a flow type configuration at elevated temperature (180–220 °C) and pressure (1000–2000 kPa). Although continuous counter-current flow operation is common in the wood pulp and paper industry (Marcoccia et al., 2000) and has been reported for wheat straw pretreatment at a pilot scale (Thomsen et al., 2008), operating continuous FT pretreatment at scale is challenging and few studies have reported related fluid mechanics.

Kim et al. (2001, 2002) used an inclined screw reactor designed by NREL intended to achieve counter current flow as a result of water draining to the bottom of the reactor. The reactor was found to be suitable for large particle size softwood residues, but it was unsuitable for severely pretreated softwood, poplar sawdust and chips. For these unsuitable substrates, the abundance of fine particles and smaller average particle size allowed lower drainage rates and caused problems such as compaction, lower void volume, increased pressure drop, blocking, channeling, packing and filter clogging. Sugarcane bagasse’s mechanical properties are very prone to cause high resistance to flow (Plaza et al., 2002) making continuous FT pretreatment particularly challenging to implement.

The relevant fluid mechanics, including the pressure drop, must be better understood to address the mechanical complexities of arranging a reactor of bagasse in a flow type configuration. It has been shown that laminar flow through a packed biomass reactor follows Darcy’s law, described in Eq. (1) (Plaza et al., 2002):

$$\Delta P/Q = \mu L/KA = \mu R/A, \tag{1}$$

where ΔP (Pa) is the pressure drop across a porous media, Q (m^3/s) is the volumetric flow rate, μ (cP) is the fluid viscosity, L (m) is the porous media length, K (m^2) is the porous media permeability, R (m^{-1}) is the porous media resistance and A (m^2) is the cross-sectional area. The resistance of the media is a function of porosity, which is in turn a function of solids shape and size, compression, swelling or water absorption, temperature and pressure. Porosity, or void volume, is the fraction of free liquid. The remainder of the reactor is occupied by the solid particles. The solids contain a fraction of solid material and a fraction of pore volume containing bound water and air. The free liquid fraction decreases when the bed is compressed or when the solids swell or absorb water, resulting in a smaller void fraction available for flow and thus a higher resistance to flow. The specific resistance of a porous media can be determined from the graph of media resistance against the mass of solids per unit area.

In order to assess the feasibility of operating pretreatment in a FT mode at scale for sugarcane bagasse, the present study measures key fluid mechanical properties.

2. Methods

2.1. Material

Biomass description, analysis and handling were performed as described previously (Archambault-Leger et al., 2012). Switchgrass harvested in November was provided by the Great Lakes Bioenergy Research Center (BER DE-FC02-07ER64494). Sugarcane bagasse was harvested in the fall and kindly provided by Louisiana State University. The biomass glucan, xylan/mannan/galactan (XMG), arabinan and Klason lignin composition is shown in Table 1.

2.2. Pressure drop apparatus and experiments

An apparatus, illustrated in Fig. 1, was designed and built to study the fluid mechanics of water flow through biomass packed beds at reaction temperature (160–220 °C) and pressure (1000–2000 kPa). The apparatus was a 66 cm long stainless steel pipe with an internal diameter of 4.9 cm flanged on both ends to stainless steel manifold blocks, and featured a threaded water inlet and outlet, filters to retain the biomass within the pipe, pressure and temperature monitoring and pressure relief at the inlet allowing to maintain the pressure within 35 kPa of the set pressure. All pipes and fittings were stainless steel 316L, including the 0.1 mm pore size filter placed at the outlet of the reactor to contain the solids. The outlet piping diameter was kept constant (1/2″) and the hydrolyzate only flowed downward to the collection tank to minimize the likelihood of solubilized solids recondensing and clogging the pipes upon cooling. The equipment was mounted solidly on an aluminum extrusion frame and fully enclosed in lexan sheets. The lexan enclosure was vented and the back panel was latched for easy access to the apparatus.

111 ± 1 g of bagasse or switchgrass (95 kg/m^3) or 167 ± 1 g of poplar (140 kg/m^3) were soaked for 24 h and loaded in the 1.17 L reactor. The maximum solid concentration not requiring manual compaction during loading was chosen to ensure uniform solids distribution initially. When the pipe was filled with the desired amount of biomass, the top manifold block was flanged to the pipe and the inlet and outlet pipes were screwed to the manifold blocks. The lexan panel was latched to the extrusion frame, making sure the apparatus was fully enclosed and the venting duct was operational. Water was pumped through the reactor using a diaphragm pump (Wanner Engineering, MN) at 500 mL/min and room temperature. Once the outlet liquid was devoid of air bubbles, the system was pressurized by turning the back pressure regulator at the outlet stream to 2000 kPa. With the back pressure valve set to 2000 kPa, band heaters (Thermal Corporation, AL) installed on the reactor and a circulation heater (Durex Industries Inc.) were turned on and set at the desired temperature (170–200 °C). The start of the reaction time was set arbitrarily as the time when the heaters are turned on and the heating time was observed to be about 15 min by monitoring the temperature inside the bottom and top of the reactor with a thermocouple (Omega Engineering Inc.). The pressure drop was measured throughout the experiment with differential pressure gauges (Orange Research Inc.). After 20 min at reaction temperature, the heaters were turned off. The water flow was stopped and the reactor was depressurized when the temperature at the outlet of the reactor dropped below 60 °C. Experiments were performed in duplicates.

When the pipe was at atmospheric pressure and its temperature was below 60 °C, the inlet and outlet pipes were disconnected from the manifold blocks and the top manifold block was removed. Compressed air at about 140–200 kPa was fed to the bottom manifold block to push the biomass out and to collect it. The biomass samples and collected hydrolysate were refrigerated for later analysis.

Table 1
Feedstock sugar composition before pretreatment with the standard deviation on duplicates.

	% Glucan	% XMG	% Arabinan	% Lignin
Switchgrass	37.9 ± 0.5	24.4 ± 0.3	3.0 ± 0.2	18.0 ± 0.8
Sugarcane bagasse	38.6 ± 1.1	22.1 ± 0.7	1.9 ± 0.1	20.9 ± 1.9
Poplar	37.8 ± 0.5	16.1 ± 1.3	0.9 ± 0.2	21.9 ± 0.5