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Effects of biomass particle size on steam explosion pretreatment performance for improving the enzyme digestibility of corn stover

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ABSTRACT

Size reduction is an essential process for corn stover biomass utilization. Effects of biomass particle size on the efficiency of pretreatment and enzymatic hydrolysis are systematically investigated in the present study. Sugar recoveries and conversions of the biomass with particle sizes at 2.5, 2.0, 1.5, 1.0 and 0.5 cm were compared. The highest sugar recovery reached 99.6% for glucan and 67.0% for xylan at the particle size of 1.0 and 0.5 cm, respectively, but the highest sugar conversion (100% for glucan and 83% for xylan) was observed at the particle size of 2.5 cm. The enzymatic hydrolysis rate and conversion of pretreated biomass obviously increased with increasing biomass particle size. With increase of biomass particle size, the specific surface area of pretreated biomass significantly increased and the crystallinity index of pretreated biomass apparently decreased. In studied extent of particle sizes, the utilization of larger biomass particles would be desirable to achieve the high pretreatment efficiency and hence improve subsequent enzymatic hydrolysis performance compared with the smaller ones.

1. Introduction

Energy security and environmental concerns have increased the interests in alternative, nonpetroleum-based sources of energy. Lignocellulose-based renewable energy, such as cellulosic ethanol, will potentially play an important role in mitigating the dependence on fossil oil and reducing CO_2 emission (Alvira et al., 2010; Zhong et al., 2010). However, the inefficient feedstock conversion process represents hurdles for large-scale deployment of biomass-to-biofuel technologies. Corn stover (CS) is considered as potential feedstock for bioethanol production due to its high glucan and xylan contents and abundant amount in China (about 300 million tons per year) (Zhong et al., 2010). Owing to structural recalcitrance of lignocellulosic biomass, pretreatment is a crucial step for breaking down the lignin–carbohydrate-complex (LCC) structure and disrupting the crystalline structure of cellulose, which enhance cellulose accessibility to enzymes in saccharification (Alvira et al., 2010; Mosier et al., 2005; Wyman et al., 2005). Steam explosion is one of the most widely employed physicochemical pretreatments. After auto-hydrolysis and explosive depressurization stages, particle size distribution, chemical composition and micro-structure of the biomass feedstock are altered (Mosier et al., 2005). In addition, steam explosion pretreatment not only provides high sugar yield and little amount of byproducts, but also offers low capital investment with nearly no hazardous process chemicals and conditions applied (Avellar and Glasser, 1998).

Size reduction of biomass before pretreatment is an energy-intensive and expensive process, but it is necessary for cellulose bioconversion (Zhu et al., 2009). Biomass particle size obviously impacts the design of handling, transportation and conversion facilities (Obernberger and Thek, 2004). Suitable biomass particle size will significantly improve the efficiency of pretreatment due to the high efficient mass and heat transfer. During steam explosion pretreatment, heat transfer issue may result in overcooking the surface part of the larger biomass particles and incomplete pretreatment of the interior part (Ladisch, 1989; Brownell et al., 1986). For smaller biomass particles, hemicellulose may be prone to degrade into byproducts due to the intense degree of heat. Therefore, optimizing biomass particle size is crucial in terms of achieving high sugar conversion and low production cost (Zhu et al., 2009; Ballesteros et al., 2000). However, to the best of our knowledge, there is no systematic research on evaluating the effects of corn

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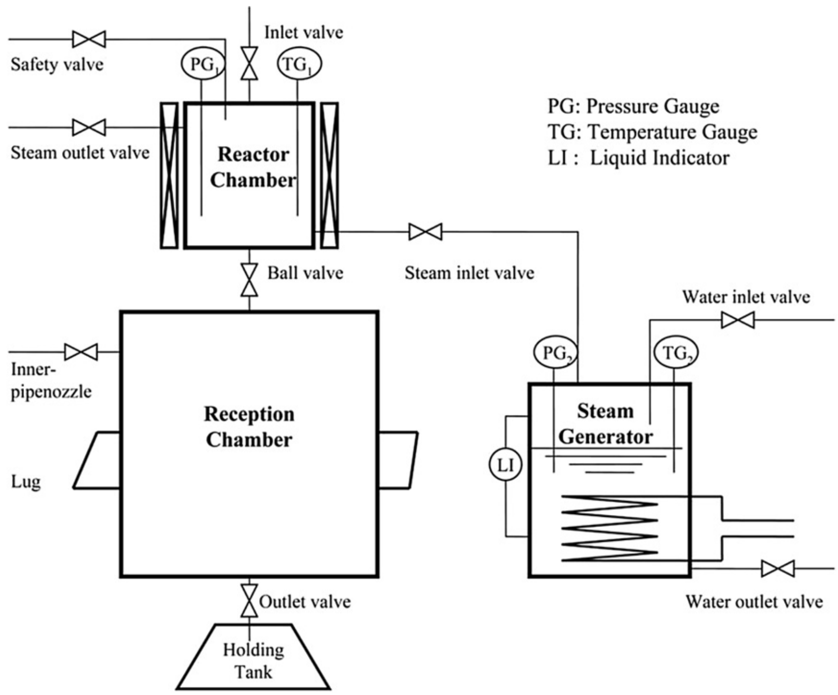

Fig. 1. Schematic of the steam explosion pretreatment reactor system.

stover biomass particle size on pretreatment performance. In addition, in-depth understanding the effects of particle size on biomass micro-structure changes after pretreatment and their correlations with enzymatic hydrolysis performance is necessary for understanding pretreatment mechanisms.

The present study aims to identify the effect of biomass particle sizes on pretreatment and its correlation with subsequent enzymatic hydrolysis performance. The effects of biomass particle size on the sugar recoveries during pretreatment and the sugar conversions in enzymatic hydrolysis were investigated. The mass balance around the whole saccharification process was also performed. Meanwhile, the features (including crystallinity, porosity and micro-structure) of corn stover biomass with varied particle sizes were characterized. Biomass physicochemical feature analyses combined with sugar conversions and yields showed insights into the mechanisms of the effects of biomass particle size on lignocellulose bioconversion.

2. Materials and methods

2.1. Feedstock preparation and analysis

Corn stover used in the present study was harvested from the suburb of Tianjin, China. The feedstock was air-dried to the moisture content of 5–10%. For composition analysis, the feedstock was milled by knife mill (YS-08, BYZME, China), passed through a screen of 2 mm and then stored in sealed bags at 4 °C. The composition analysis was carried out according to the laboratory analysis protocol (LAP) of National Renewable Energy Laboratory (NREL), Colorado, USA (NREL, 2004). Moisture content was analyzed using a Sartorius MA 35 moisture analyzer (Sartorius, Germany). Prior to pretreatment, the feedstock was cut manually into an average size of 2.5 cm (2.5 cm L × 1.0 cm W × 1.0 cm H), 2.0 cm (2.0 cm L × 1.0 cm W × 1.0 cm H), 1.5 cm (1.5 cm L × 0.5 cm W × 0.5 cm H) and milled into an average size of 1.0 cm (1.0 cm L × 0.2 cm W × 0.2 cm H), 0.5 cm (0.5 cm L × 0.1 cm W × 0.1 cm H), respectively. Samples were sprayed with deionized water to the moisture content of 30% and then stored at room temperature until steam explosion pretreatment.

2.2. Steam explosion pretreatment (SEP)

Steam explosion pretreatment was adopted to break down the structure of the lignocellulosic matrix to facilitate the bioconversion. The pretreated reactor system consists of a reactor chamber (15 L working volume), a reception chamber (150 L working volume) and a steam generator (Fig. 1). During pretreatment, 150 g corn stover (dry basis) was top-loaded into the reactor chamber. High-pressure steam supplied by the steam generator was then filled into the reactor until the temperature reached 200 °C (1.6 MPa). After 5 min of exposure to the saturated steam, corn stover was exploded into the reception chamber by the ball-valve. The pretreatment condition (200 °C, 5 min) was optimized in our previous studies (Pang et al., 2013). After pretreatment, the pretreated biomass was separated from the liquid fraction by vacuum filtration using a Buchner funnel and then washed with 3.0 L water. Monomeric, oligomeric sugars and byproducts were determined for the liquid fractions to calculate the overall sugar recoveries.

2.3. Enzymatic hydrolysis

The NREL standard protocol (LAP-009) was followed for enzymatic hydrolysis. Commercial cellulase (Accellerase 1500, Genencor) was a generous gift from Genecor (Suzhou, China). Novozyme 188 was purchased from Sigma–Aldrich (St. Louis, MO). The cellulase activity of Accellerase 1500 is 77 FPU/mL, and the β-glucosidase activity of Novzymes188 is 250 pNPGU/mL. The pretreated biomass was hydrolyzed at a glucan loading of 1% or 6% (w/v) in a 0.05 M citrate buffer solution (pH 4.8) with an Accellerase 1500 loading of 15 or 60 FPU/g glucan and a β-glucosidase loading of 64 pNPGU/g glucan. Samples were hydrolyzed at 50 °C and 200 rpm for 168 h and then the slurry were centrifuged at 12,000 rpm for 5 min to separate solids from liquids. The solid residues were washed with a volume of water equal to 50 times the dry weight of the pretreated biomass. The liquid fractions were