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Intermittent pressurized operation of steam explosion pretreatment system

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ABSTRACT

An acid catalyzed steam explosion pretreatment system was developed to process wood chips for biomass conversion. The degree of mixing in the pressurizing process was found to be a crucial factor to saccharification efficiency. With a low load fill (100 l, half load) in the pressurized vessel, ribbon blender provided enough mixing power for wood chips. The temperature difference in the reactor was found to be less than 15 °C, the total saccharification efficiency can be up to 63%. At high load fill condition (200 l, full load), the temperature difference under regular mixing was found to be quite large (20 °C) with a low saccharification efficiency of 38%. To increase the temperature uniformity, an intermittent pressure pulsation method was used. The pressure pulses helped the vertical mixing and a total saccharification efficiency up to 65% can be reached in the improved pretreatment process.

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1. Introduction

Lignocellulosic materials, such as agricultural or wood residues, are potential resources for production of biofuels and other valuable chemicals. Lignocellulosic materials are of particular interests because the usage of these materials does not have to compete against food production. To convert lignocellulosic materials into sugar related products, it is necessary to destruct the structures of the biomass so that cellulose can be more accessible in the enzymatic hydrolysis process. This structural destruction process, which is generally referred to as pretreatment, is fairly difficult and plays an important part in the lignocellulose-to-ethanol process.

Among many known pretreatment strategies, dilute-acid hydrolysis with steam explosion has been widely adopted in pilot scale equipment and is considered to be a feasible method for industrial applications [1–5]. Besides operational easiness, the addition of mineral acids usually results in more efficient hemicelluloses hydrolysis in steam pretreatment and the subsequent enzymatic digestion in the biomass conversion. With these advantages, acid-catalyzed steam explosion process is regarded as a plausible commercial process for biomass conversion. [6] Wood chips are traditionally used as burning solid fuel for space heating. The lumber industries in Europe and southeast Asia have been producing a large quantity of logging residues, and it is expected that the shares of stumps and roundwood will keep increasing in the foreseeable future. These large amount of wood chips from these areas thus provide an attractive and stable lignocellulosic material source for biofuels and other useful biomass chemicals. Hence, a detailed understanding of wood chip hydrolysis in a pilotscale continuous pretreatment system will be helpful to enable logging waste recycling *via* biomass conversion. In general, biomass is traditionally processed *via* a batch processing method; however, if ethanol production from wood chips is to be successful in the marketplace, a platform for its large-scale processing must be developed. Although many researchers have studied dilute-acid hydrolysis or steam explosion pretreatment in a pilot-scale continuous pretreatment system [7–14], less attention has been paid to wood chips in a pretreatment system. INER has developed pretreatment systems for different scales on the basis of previous dilute-acid hydrolysis experiments that were performed at the lab-scale (400 g/batch), the bench-scale (10 kg/batch) and at a pilot plant (1 ton/day) harboring a cellulosic ethanol-testing platform [15–17]. Out of these in-house technologies, the pilotscale continuous pretreatment system uses the acid-catalyzed steam explosion process to pretreat feedstocks such as wood chips.

In this study, a thorough analysis is performed to optimize the acid-catalyzed steam explosion process for wood chips in the pilot-scale pretreatment system. Effects of pressurization conditions, temperature distributions, residence time, and feedstock amounts on the pretreatment efficiency of the feedstock were carefully examined. The pretreatment efficiency will be evaluated by estimating the xylose yield after pretreatment and the glucose yield from

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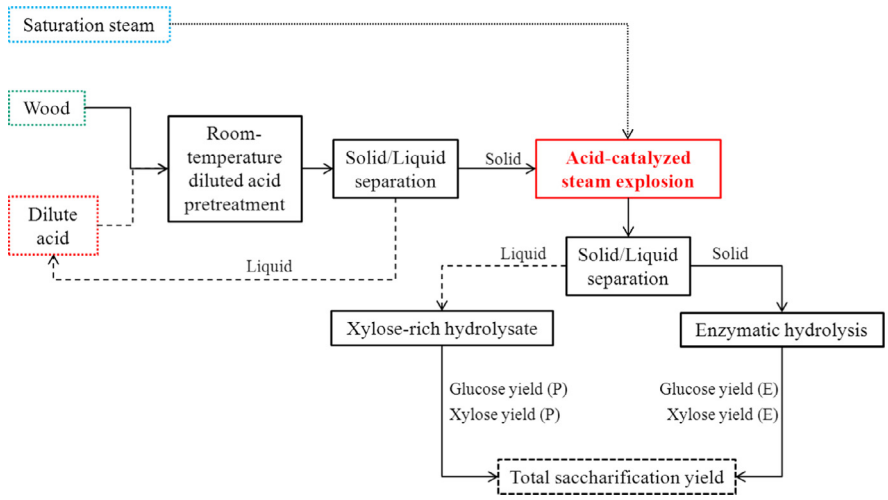

Fig. 1. Schematic diagram of the pretreatment system.

the subsequent enzymatic hydrolysis. Moreover, the operation stabilities and the corresponding performance will also be reported.

2. Material and methods

2.1. Biomass materials

Wood chips with a dimension of ~1 cm × 1 cm and 2–3 mm thick were collected from a private lumber mill in Malaysia. The wood chips were taken directly to the acid pretreatment without washed.

2.2. Pretreatment system

The pretreatment system (Fig. 1) consisted of a feedstock receiving hopper with a weighmetric screw feeder, a horizontal reactor (presteamer) with a long residence time for the presteaming, and for the acid impregnation of the biomass, a vertical high pressure steam explosion reactor, a receiving flash tank and a solid liquid separator. The unique design of the pretreatment system includes a piston pressure feeding device, special mechanical equipment and a modified outlet device for steam explosion. The vertical high-pressure reactors (Fig. 2) are heated to the desired temperature by the direct injection of 16 kg/cm^2 saturated steam. The flow meters, equipped with automatic temperature or pressure compensation, maintained the desired temperature and pressure. The acid mixing and preheating times of wood chips are controlled by the screw speed of the horizontal reactor. Additionally, the feeding rate of the screw feeder and diaphragm pump can be used to regulate the solid–liquid ratio of wood chips and dilute sulfuric acid solution. An advanced Distributed Control System (DCS) has been used in the pilot-scale continuous pretreatment system. It provides continuous and automatic operation during the pretreatment process. The throughput can vary from 100 to 200 kg of dry material per hour, depending on the bulk density of the raw material and processing conditions.

2.3. Pretreatment process

The acid-catalyzed steam explosion processes used in this pretreatment system are shown in Fig. 1. The wood chips were first transferred to the hopper by a pneumatic conveyor system, and presoaked with dilute sulfuric acid in a large agitating tank. After soaking, the wet wood chips were compressed by a pneumatic compressor to remove the excess acid solution, which can be reused. Then, the wet wood chips were transferred to the vertical high-pressure reactor for acid-catalyzed steam explosion. The resultant slurry was then transferred to the solid–liquid separator. The xylose-rich hydrolysate and the cellulose-rich residues were obtained. In this study, the throughput was 100 ± 20 kg of wood chips per hour, and the total feed amount was 1000 ± 50 kg for each test condition. The wood chips were mixed with dilute sulfuric acid solution to an initial solid loading of about 4–5% (w/w) and preheated as they passed through the pressurized reactor at a temperature of 120–130 °C. The test conditions of the acid-catalyzed steam explosion process varied in temperature from 160 to 190 °C, residence time varied from 2 to 4 min and acid concentrations in the acid supply tank is 1.0 wt%. These operating parameter settings, such as sulfuric acid mixing, steam explosion residence time and acid concentrations, were used based on previous experiences for straws [15,16]. In particular, the steam was supplied at a higher pressure of 16 kg/cm^2 with a three-inlet reaction design (Fig. 2) to increase the steam feed rates so that the reaction can be complete within a 3-min residence time. Samples were analyzed for the sugar concentrations in the hydrolysates. Four samples were taken for each test condition. The pH, concentration, percentage of oligomers in the hydrolysate, carbohydrate content of the pretreated residues and the total enzymatic hydrolysis for each test run were the average value of the four samples.

2.4. Enzymatic hydrolysis

The unwashed and washed pretreated residues (about 1 g dry weight) were transferred to a 250 ml shake flask, and the pH was adjusted to 4.8–5 by adding 50 mM acetate buffer at a 2% (w/v) solid loading. The digestion of the cellulose was conducted at a cellulose (Novozyme celtic CTec3) activity level of 15 FPU/g cellulose. The enzymatic digestion was carried out at 50 °C and 100 rpm for 72 h. In this study, the pretreatment efficiency is estimated by combining total xylose and glucose conversion yields after both the pretreatment and enzymatic hydrolysis processes. The definition of the total saccharification yield (overall monosugar yield) is the sum of the monomeric xylose and glucose saccharification yields. The xylose/glucose saccharification yields are calculated by the following equations:

Xylose saccharification yield (%)

= [(Xylose (g) released in pretreatment and enzymatic hydrolysis)/(Total xylose and glucose (g) in the feedstock)] × 100

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