Advanced Powder Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Advanced Powder Technology

journal homepage: www.elsevier.com/locate/apt

Original Research Paper

Energy-efficient milling method for woody biomass

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ARTICLE INFO

Article history:
Received 13 January 2017
Received in revised form 24 March 2017
Accepted 6 April 2017
Available online xxxx

Keywords:
Size reduction
Milling
Steam explosion
Wood chip

ABSTRACT

Size reduction is essential to utilize biomass in many applications. Production of fine particles from biomass chips is usually performed using milling machines that consume large amount of energy. Steam explosion (SE) is a promising method for reducing the size of biomass using less energy consumption because it utilizes thermal energy. In this study, we focused on the possibility of the SE method to produce fine particles with a size below 1 mm from wood chips. Sakura (*Prunus* spp., hardwood) and Japanese cedar (Cryptomeria japonica, softwood) chips with a size of 5–10 mm were used in this study. The effects of SE conditions – such as temperature and residence time – and of the biomass type on the biomass size reduction were investigated in detail. The energy consumption of SE was also calculated and compared with that of the conventional mill. We found that SE is an energy-efficient method for biomass milling.

1. Introduction

Size reduction is an essential step to properly utilize biomass. The reduction in particle size benefits the heat and mass transfer during pretreatment, increasing the susceptibility of biomass to hydrolysis for bioethanol production [1]. Several studies have revealed that a biomass size of below 1 mm is desirable for this application [2,3]. For energy production, the introduction of biomass as fuel for pulverized coal (PC) boilers, which comprise over 90% of the boilers in the world, also requires reduction in the biomass size to below 1 mm [4]. Biomass gasifiers, particularly entrained-flow gasifiers, even require the reduction in biomass size to below 100 μm before the gasification process [5]. Biomass particles of less than 1.5 mm are also preferable for fast pyrolysis in a fluidized bed to convert biomass into bio-oil [6].

The size reduction of woody biomass usually involves two steps. The first step is wood chipping which produces wood chips with sizes ranging from 5 to 50 mm [7]. The second step is biomass milling to further reduce the size of wood chips to smaller or finer particles (0.1–10 mm) [8]. The second step typically consumes substantially higher energy than the first step. In the present study, we focused on the biomass milling particularly on wood chips to produce fine particles (<1 mm). Biomass milling for wood chips is usually performed by mechanical mills such as knife [8,9], hammer [10,11], or vibration mills [12]. Zhang et al. [8] reported that the energy consumption to mill poplar wood chips (5–12 mm) by knife mill through a 1-mm sieve screen was 1.6 kW h/kg. Using the same milling method, Miao et al. [9] also reported that the energy consumption for willow chips was 0.65 kW h/kg. Esteban et al. [10] presented a crushing system suitable for forest biomass with 95% product passing a 1-mm mesh using 2 hammer mills, and the energy consumption was 0.12–0.15 kW h/kg. However, the wood chips used in this study were small, i.e., below 4 mm. The possibility of a vibration mill to pulverize biomass was studied by Kobayashi et al. [12], and they found that the total energy consumption was 0.8 kW h/kg for the pulverization of wood chips (22 mm, moisture content = 11%) to wood powder (150 μm). Assuming that the conversion efficiency from thermal energy to electricity is 40% (coal-fired power plants), the typical mechanical energy consumption for milling wood chips to fine particles lies between 5.8 and 14.4 MJ/kg, which accounts for 30–76% of the high heat value of common wood chips (19 MJ/kg). Thus, a reduction in energy usage for size reduction is indispensable for efficient utilization of woody biomass.

A promising method for biomass size reduction that directly uses thermal energy, instead of mechanical or electric energy, is steam explosion (SE). This method consists of two steps, namely, the steaming (auto-hydrolysis) step under

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http://dx.doi.org/10.1016/j.apt.2017.04.005
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Please cite this article in press as: D.E. Priyanto et al., Energy-efficient milling method for woody biomass, Advanced Powder Technology (2017), http://dx.doi.org/10.1016/j.apt.2017.04.005

Nomenclature

c_b	specific heat capacity of the dry biomass, kJ/(kg·°C)
c_w	specific heat capacity of water, kJ/(kg·°C)
E_{evap}	heat of evaporation, kJ/kg
E_{mill}	energy for size reduction, kJ/kg
Δh	enthalpy difference, kJ/kg
m_b	mass of the dry biomass, kg
m_s	total amount of steam, kg
m_w	mass of water, kg
R_0	Severity factor, –
t	time, min
T	temperature, °C
ΔT	temperature difference, °C
V	reactor volume occupied by the biomass, m^3
v	the specific volume of the saturated steam, m^3/kg
γ	yield of the product after SE, %

high-temperature–high-pressure conditions and the sudden depressurization (explosion) step, which causes an adiabatic expansion of steam inside the pores of the biomass tissue. This method has been primarily applied in bioethanol [13–15] and biomethane [16,17] production. Recently, this concept has been applied in pellet [18,19] and biofuel production from microalgae [20]. However, according to the best of our knowledge, studies that seek to possibility of SE for biomass milling to produce fine particles have been rare.

In the present study, we investigated the effect of SE conditions on the biomass chip size reduction in detail. Samples of Japanese hardwood and softwood were subjected to SE, and the solid products were analyzed to determine the particle size distribution and their chemical properties. Reduction in the biomass chip size to below 1 mm (fine particles) is the focus of this study with the objective of exploring the possibility of applying this method to biomass milling, particularly for pulverized-fuel boilers. We also compared the energy consumption of the SE method with the conventional mechanical mill.

2. Experimental method

2.1. Raw materials

Sakura (*Prunus* spp., hardwood) chips and Japanese cedar (softwood) chips with sizes ranging from 5 to 10 mm and moisture content of below 10% were used in this experiment.

2.2. Steam explosion

2.2.1. Experimental procedure

The SE apparatus mainly consists of three components; steam generator, high-pressure vessel, and collecting vessel (Fig. 1). Initially, samples were fed into the reactor which has been preheated to the designated temperature (Table 1). The volume of the sample fed into the reactor (with 1-L capacity) was set to 700 mL (approximately 170 g) during each experiment. The reactor was then heated up to the required temperature by supplying high-pressure saturated steam and then kept for a set period of time. In most experiments, the reactor pressure was equal to the pressure of the saturated steam. Subsequently, instantaneous decompression was created with the release of the reactor pressure through a valve. The solid product was then collected from the vessel and kept in a plastic bag for further analysis.

After treatment, the solid product particles were separated according to their size as shown in Fig. 2. We performed the separation process twice. The first of these processes is wet separation achieved by mixing the solid product with 1-L of distilled water and then by filtering by using a 1-mm sieve. This step separated most of the particles with a size of below 1 mm from the rest. Both sets were then dried in a drying oven at 110 °C for 2–3 days. The particles with a size of below 1 mm from the first filtering were weighed. However, a possibility exists that some fine particles are not entirely separated from the solid product during the wet separation. Therefore, those with size above 1 mm were then subjected to second separation.

After the drying process, those with sizes above 1 mm were milled using ball mill (Fritsch Mini Mill II) at 120 rpm for 10 min. We chose the ball mill because it did not significantly affect the size reduction of raw chips under the same milling condition as that of the steam-exploded solid. Therefore, the effect of the ball mill probably can be neglected. After milling, the second separation was conducted by placing the milled particles on top of a stack of sieves (4760, 2380, and 1190 μm). This stack of sieves was placed on a sieve shaker (IIDA shieve shaker) and was subjected to vibration for 10 min. The material retained by each sieve was weighed to determine the particle size distribution. The particles that passed through the 1190-μm sieve were regarded as solid

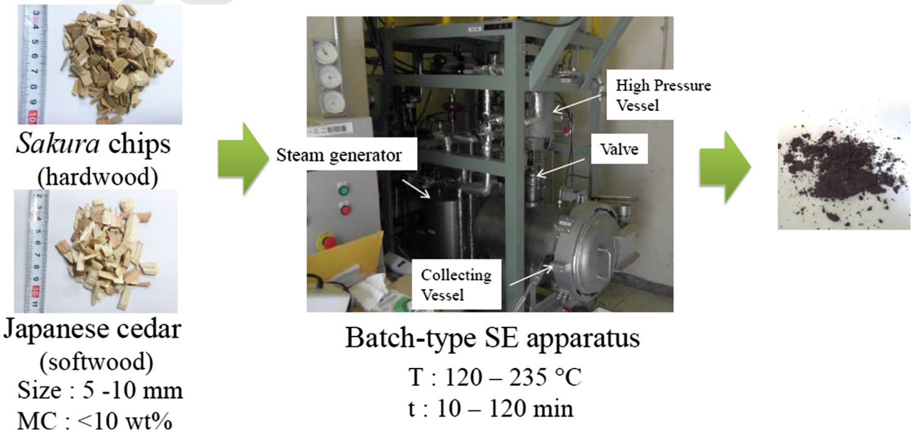

Fig. 1. SE apparatus.

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