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Ultrasonic vibration-assisted pelleting of wheat straw: A predictive model for energy consumption using response surface methodology

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ABSTRACT

Cellulosic biomass can be used as a feedstock for biofuel manufacturing. Pelleting of cellulosic biomass can increase its bulk density and thus improve its storability and reduce the feedstock transportation costs. Ultrasonic vibration-assisted (UV-A) pelleting can produce biomass pellets whose density is comparable to that processed by traditional pelleting methods (e.g. extruding, briquetting, and rolling). This study applied response surface methodology to the development of a predictive model for the energy consumption in UV-A pelleting of wheat straw. Effects of pelleting pressure, ultrasonic power, sieve size, and pellet weight were investigated. This study also optimized the process parameters to minimize the energy consumption in UV-A pelleting using response surface methodology. Optimal conditions to minimize the energy consumption were the following: ultrasonic power at 20%, sieve size at 4 mm, and pellet weight at 1 g, and the minimum energy consumption was 2.54 Wh.

1. Introduction

Liquid transportation fuels currently used in the United States are mainly petroleum-based [1–3]. In 2011, the US transportation sector consumed about 18.95 million barrels of petroleum per day and half of it was imported [4,5]. The dependence on foreign petroleum threatens the nation's energy security. Another issue of consuming petroleum-based transportation fuels is greenhouse gas (GHG) emissions. One-third of the total carbon dioxide emissions in the US are from the use of petroleum-based transportation fuels [6–8].

Biofuels, particularly cellulosic biofuels, can help addressing these issues. Biofuels have the potential to reduce GHG emissions by as much as 86% compared to gasoline [9]. Because biofuels are made from renewable, plant-based feedstocks, the carbon dioxide released during fuel combustion is 'recycled' by the plant as it grows [10]. Cellulosic biofuels are produced from cellulosic biomass, including agricultural and forestry residues and dedicated energy crops. Unlike other type of feedstocks (e.g. corn, sugar cane, and soybean) for biofuels, cellulosic biomass does not compete with food production for the limited agriculture land [11,12].

However, cellulosic biomass feedstocks have low bulk density, resulting in high costs in their transportation and storage. Densification of cellulosic biomass into pellets [13] can increase the bulk density from 40 to 250 kg/m^3 for cellulosic biomass materials to as high as 1200 kg/m^3 [14].

Traditional pelleting methods (e.g. extruding, briquetting, and rolling) [15] generally involve high pressure, high-temperature steam or usage of binder materials. Ultrasonic vibration-assisted (UV-A) pelleting is a new pelleting method developed by the authors [16,17]. UV-A pelleting, without using binder materials or high-temperature steam, can produce biomass pellets whose density is comparable to that processed by traditional pelleting methods [18]. Moreover, cellulosic biomass (wheat straw, corn stover, switchgrass, and sorghum stalk) processed with UV-A pelleting had more than 30% higher sugar yield (proportional to the biofuel yield) than biomass pellets processed without UV-A pelleting [17].

The literature on UV-A pelleting includes experimental investigations on pellet quality, sugar yield, pelleting temperature, charring, and energy consumption [18–25]. Energy consumption in UV-A pelleting not only contributes to the costs of cellulosic biofuel manufacturing, but also affects the energy balance and the life cycle of cellulosic biofuel manufacturing.

This paper, for the first time, developed a predictive model on the energy consumption in UV-A pelleting. The experimental data obtained were used for the optimization of the process parameters by means of response surface methodology (RSM) with a Box–Behnken experimental design. RSM is an effective statistical technique for optimizing multifactor experiments, building models, evaluating the effects of several parameters for desirable responses. The eventual objective of RSM is to determine the

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optimum operating parameters for the system, or to determine the region that satisfies the operating specifications [26]. RSM has been reported to optimize the process parameters in biofuel production [27], but this was the first effort that RSM was applied to optimizing the process parameters in order to minimize the energy consumption in UV-A pelleting.

2. Experimental procedure and conditions

2.1. Cellulosic biomass preparation

The cellulosic biomass used in this investigation was wheat straw. The wheat straw was harvested by the Deines Farm in Northwest Kansas. The wheat straw had been run through a John Deere combine (Model 9600, Deere & Company, Moline, IL, USA). The combine removed grains from straw and chaff. Wheat straw and chaff exited through the back of the combine, and had an average length of 250 mm. After being collected, wheat straw was stored indoors until this study.

Wheat straw was processed by a knife mill (Model SM 2000, Retsch, Inc., Haan, Germany). Fig. 1 shows the milling chamber of the knife mill. The knife mill used a 240-V, 2.2-kW electric motor with a fixed rotation speed (1,720 round/min). Three cutting blades (95 mm long and 35 mm wide) were mounted on the rotor. Four shear bars were mounted on the inside wall of the milling chamber. There was a 3-mm gap between a cutting blade and a shear bar. Wheat straw was cut between the cutting blades and the shear bars. Three sieves with different sieve sizes (2, 4, and 8 mm) were used to control wheat straw particle size. It is noted that these three sieves were used to produce wheat straw particles with three size levels. Sieve size (2, 4, or 8 mm) only represented the three size levels, but not the actual size in any dimension (length, width, or thickness) of a particle. Wheat straw particles would fall through the openings on the sieve installed until they were cut small enough. Wheat straw particles after milling were kept in Ziploc® bags until being used for further experiments.

Biomass moisture content (*MC*) was measured by following the National Renewable Energy Laboratory procedure (NREL/TP-510-42621) [28]. About 2.5 g of biomass was placed in an aluminum weighing dish and dried in an oven at 105 °C for 24 h. The loss in weight of the biomass after oven drying was recorded. Moisture content was calculated as follows:

$$\text{Moisture content } (MC)\ (\%) = \frac{\text{Loss in weight}}{\text{Weight of biomass before drying}} \times 100\% \quad (1)$$

Fig. 1. Milling chamber of knife mill.

The moisture content of the wheat straw particles in this study was 7%. After knowing the moisture content, biomass dry weight could be calculated as follows:

$$\text{Dry weight(g)} = (1 - MC) \times \text{weight of biomass with moisture} \quad (2)$$

Biomass weight reported in this study is dry weight.

2.2. Experimental setup and procedure

Fig. 2 shows a schematic illustration of the experimental set-up for UV-A pelleting. UV-A pelleting experiments were performed on a modified ultrasonic machine (Model AP-1000, Sonic-Mill, Albuquerque, NM, USA). The machine included a power supply (which converts 60 Hz electrical power into 20,000 Hz electrical power), a converter (which converts high frequency electrical energy into mechanical vibration), and a titanium tool. The tip of the tool was a solid cylinder with a flat end (17.4 mm in diameter).

Before one pelleting test, the weight of the wheat straw particles was measured by an electronic scale. This weight was referred to as the pellet weight. Then wheat straw particles were loaded into an aluminum mold. The mold was consisted of three parts. The upper two parts formed a cylindrical cavity (18.6 mm in inner diameter) and the bottom part was a square disk, serving as a base. They were assembled together with pins.

The pneumatic cylinder was driven by the compressed air provided by a 1.2 kW, 12.5 L. air compressor (Sears, Roebuck and Co., Hoffman Estates, IL, USA). The air pressure in the pneumatic cylinder was controlled by a pressure regulator. A higher air pressure in the cylinder led to a higher pressure applied on the biomass in the mold by the tool.

In each pelleting test, the pelleting duration was 120 s. After 120 s, the tool was retracted and the mold was disassembled to unload the pellet. A finished UV-A pellet is shown in Fig. 3.

2.3. Measurement of energy consumption

Energy consumption in this study was referred to as the electrical energy consumed by the power supply in the UV-A pelleting set-up. A Fluke 189 multimeter and a Fluke 200 AC current clamp (Fluke Corp., Everett, WA, USA) were used to measure the electric current, as shown in Fig. 2. The power line to the power supply has three wires: black, red, and green[1] wires. The current clamp was clamped on the black wire to measure the current. The data was collected using the Fluke View Forms software (Fluke Corp., Everett, WA, USA). The sampling rate was two readings per second. After the tool touched the biomass in the mold, the power supply was switched on and the software started collecting the current data. After 120 s, the software stopped collecting data and power supply was switched off.

The software recorded the average current (I_{AVE}). The voltage (V) was 120 V. The energy consumed during the 120 s of pelleting duration can be calculated using the following equation [29]:

$$E = \frac{V \times I_{AVE} \times 120}{3600}\,(\text{Wh}) \quad (3)$$

2.4. Design of experiments using response surface methodology (RSM)

According to the results of experimental investigations conducted previously [19], the appropriate parameters for obtaining

[1] For interpretation of color in Fig. 2, the reader is referred to the web version of this article.