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Ultrasonic vibration-assisted pelleting for cellulosic biofuels manufacturing: A study on in-pellet temperatures

Yongjun Tang [a], Weilong Cong [b, c, *], Jun Xu [a], Pengfei Zhang [c], Defu Liu [c]

[a] College of Electromechanical Engineering, Guangdong University of Technology, Guangzhou, Guangdong 510006, China
[b] Department of Industrial Engineering, Texas Tech University, Lubbock, TX 79409, USA
[c] Department of Industrial and Manufacturing Systems Engineering, Kansas State University, Manhattan, KS 66506, USA

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ABSTRACT

Cellulosic biofuels have been proposed to replace part of traditional liquid transportation fuels. Cellulosic biomass is the feedstock in cellulosic biofuel manufacturing. Costs associated with collection and transportation of cellulosic biomass account for more than 80 percent of the feedstock cost [1]. By processing cellulosic biomass into pellets, energy density and handling efficiency of cellulosic feedstock can be improved, resulting in reduction of transportation and handling costs. Ultrasonic vibration-assisted (UV-A) pelleting is one of important pelleting process which can make high quality pellets efficiently. The literature on UV-A pelleting covers studies about effects of input process parameters on pellet density, durability, sugar yield, charring, and pelleting force, but has little information about pelleting temperature. This paper presents an experimental investigation on effects of input variables on pelleting temperature. The pelleting temperatures at the different locations of a pellet were measured during pelleting using metal wire-typed thermocouples. Several pelleting parameters were varied to study their effects on pelleting temperature. Results obtained will be helpful in understanding why pelleting parameters affect pellet quality (density and durability), charring, and sugar yield.

1. Introduction

The U.S. demand for transportation liquid fuel will rise from about 14 million barrels per day in 2007 to 16.18 million barrels per day in 2030 [2]. Petroleum-based liquid fuels are currently the most-commonly used for transportation. However, according to the report of Hirsch and his colleagues [3], the maximum production of crude oil will be reached and the production of crude oil will decline. This situation will “adversely affect global economics”. If no action is taken immediately, the oil problem will be “long-term and pervasive” [3]. In addition, there is a worldwide concern on emission of HC, CO, NO_x, SO_x and particulate materials from burning of petroleum [4,5]. Therefore, finding alternative sources for transportation liquid fuel is urgent.

Biofuels, including bioethanol and biodiesel, are recognized as the third largest renewable energy resource and are alternative sources for petroleum-based transportation liquid fuels [6–8]. Unlike petroleum-based liquid fuels, biofuels are fuels produced from renewable resources which are biomass or other biological materials [9–11]. The advantages of biofuels include renewability, GHG reduction, and pollutants avoidance [12].

Bioethanol and biodiesel are currently being manufactured and used in some countries. The feedstocks mainly include sugarcane, corn, and rapeseed oil. The use of these edible crops to produce fuel arouses the problem of food crisis [13]. It is desired to find out non-food crops for biofuels manufacturing. Cellulosic biomass is more suitable.

The major steps for manufacturing of biofuels from cellulosic biomass include harvest and collection, transportation and handling, storage, pretreatment, and biofuel conversion. There still exist technical barriers hindering large-scale and cost-effective manufacturing of cellulosic biofuels [14,15]. One main barrier is related to the low-density of raw cellulosic materials, causing high transportation and storage costs [16,17] which can constitute 35% or more of total production costs of cellulosic biofuels [18,19]. Specifically, the logistics associated with moving low-density biomass from the land to central biorefinery plants can make up more than 50% of those feedstock costs [16]. It is reported that the major portion of feedstock cost is biomass collection and transportation, accounting for more than 80% of feedstock cost due to the dispersed agriculture structure [1]. Pelleting can significantly

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* Corresponding author. Department of Industrial Engineering, Texas Tech University, Lubbock, TX 79409, USA. Tel.: +1 806 834 6178.
E-mail address: weilong.cong@ttu.edu (W. Cong).

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increase density of cellulosic biomass [20,21], decreasing the cost of biofuel manufacturing.

Conventional pelleting methods (for example, using a screw extruder, a briquetting press, or a rolling machine) [22,23] generally require high-temperature steam, high pressure, and binder materials, making it difficult to realize cost-effective pelleting on or near the field where cellulosic biomass is available. Also, most publications on pelleting deal with biomass pellets used as either feed or fuels (not as feedstocks for conversion to liquid biofuels) [24]. Ultrasonic vibration-assisted (UV-A) pelleting, without using binder materials or high-temperature steam, can produce biomass pellets whose density is comparable to that processed by conventional pelleting methods [25,26]. Moreover, biomass (switch grass) processed with UV-A pelleting has increased sugar yield (ethanol yield) by more than 20% compared with non-pelleted biomass or biomass pellets processed without ultrasonic vibration [27].

Temperature of biomass plays an important role in pelleting process [23,28,29]. Hall [30] found that the higher the temperature, the lower the force needed to provide a given degree of compaction. According to Faborode [31], increasing operating temperature increased the density and durability of the pellets. Dam et al. [32] found that when biomass was heated, lignin in the biomass become soft and sometimes melted and exhibited thermosetting properties. The temperature of biomass during UV-A pelleting is desired to investigate. Such knowledge can help explain some experimentally determined relationships between pelleting parameters and pellet quality and sugar yield in UV-A pelleting.

The literature on UV-A pelleting includes experimental investigations on effects of input variables on pelleting parameters on pellet quality, pelleting temperature, and sugar yield [27,33,34]. However, Feng et al.'s investigation only focused on the temperatures measurement on the side (not the inside) of the pellet [34]. The heat was generated by ultrasound which was transmitted from the end surface of the tool to the inside of biomass pellet. To better understand the ultrasound transmission in the biomass pellet and pellet qualities, the temperatures at different locations of the biomass pellets are needed to be investigated. The purpose of this paper is to provide such information.

This paper presents an experimental investigation on effects of input variables (pelleting duration, ultrasonic power, pelleting pressure, pellet weight, and moisture content of cellulosic biomass) on pelleting temperature. The pelleting temperatures at different location of the pellet were measured during pelleting using embedded metal wire-typed thermocouples method. Several pelleting parameters (pelleting duration, ultrasonic power, pelleting pressure, pellet weight, and moisture content of cellulosic biomass) were varied to study their effects on pelleting temperature. Results obtained will be helpful in understanding how pelleting parameters affect pellet quality, such as, durability. The result on durability will also be reported and compared with the results on pelleting temperature.

2. Experimental conditions and procedure

Before UV-A pelleting experiments conducting, biomass material was milled into powder using a cutting mill. All the tests were performed on a modified ultrasonic machine (Model AP-1000, Sonic-Mill, Albuquerque, NM, USA). Temperatures at four locations of a pellet were measured by the metal wire-type thermocouples.

2.1. Biomass material

The cellulosic biomass used in this study was wheat straw collected in late June of 2010 at Deines Farms in Western Kansas. The wheat straw had been run through a John Deere 9600 combine. The wheat straw and chaff exited through the back of the combine. The straw chopper on the combine was disconnected to allow the straw to be baled. The longest pieces of wheat straw were 28 cm long. The wheat straw was collected and stored indoors until this study was conducted.

Before pelleting, wheat straw was milled into powder using a cutting mill (SM 2000, Retsch, Germany). The particle size of biomass powder was controlled by a 2 mm sieve in the cutting mill. The mill used a three-phase, 240 V, and 3 horsepower electric motor. The mill had a fixed rotation speed (1720 rpm).

Moisture content (MC) of biomass powder represents the amount of moisture (water) contained in a certain amount of biomass powder. The measurement and adjustment procedures were followed by the ASABE standard S358.2 [42]. It was calculated by the ratio of the weight of moisture in a sample of biomass powder to the total weight of the sample. The initial moisture content of biomass powder was measured using the following procedure. A sample of biomass powder was measured on a scale to obtain its weight. Then it was heated in an oven at 130 °C for 24 h to evaporate the moisture. After heating, the weight of the dry sample was measured again. The weight of moisture was equal to the difference between the weight of the sample before heating and that after heating. The initial moisture content was calculated as the ratio of the weight of moisture inside the sample divided by the total weight of the sample before heating. After measuring the initial moisture content of biomass powder, a certain amount of distilled water was sprayed on the biomass powder to adjust the moisture content to the desired level. In order to study effects of moisture content on pellet temperature, four moisture content levels (5%, 10%, 15%, and 20%) were used in this study.

2.2. Experimental setup

Ultrasonic vibration-assisted (UV-A) pelleting system (Fig. 1) included ultrasonic system, pneumatic system, and data acquisition system. 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 converted 50 Hz line electricity into 20,000 Hz high frequency electrical energy), and a converter (which converted high frequency electrical energy into ultrasonic vibration). An aluminum mold with a cylindrical cavity at its center was used to hold wheat straw powder. The round tool had a solid flat end. The diameter of the tool end (17.4 mm) was slightly smaller than that of the mold cavity (18.6 mm). The pneumatic system provided the pelleting force. A 101.6 mm (4 in) double acting pneumatic cylinder was mounted on the top of the converter. An aluminum protecting tube was installed in between the cylinder and converter to protect the converter. The pneumatic cylinder was driven by compressed air provided by a 1.6 HP air compressor (Sears, Roebuck and Co., Hoffman Estates, IL, USA), and its movement was controlled by a two-position, five-way manual valve. The pressure of the air pumped into the cylinder was controlled by a pressure regulator. It determined the pelleting pressure.

Pelleting duration was the period of time from the beginning to the end of a pelleting test, during which the tool was in contact with the wheat straw powder inside the mold. Pelleting duration was called pelleting time in some paper [25,35,37]. Pelleting time refers to the time between the beginning of a pelleting test till a point in time of interest. Pelleting time could be any value between 0 and pelleting duration in this paper. A higher pelleting pressure means a higher pressure applied through the tool on wheat straw in the mold. Four levels of pelleting pressure (compressed air pressure) were used in the experiments: 20, 30, 40 and 50 psi (138, 206, 275 and 344 kPa). The amplitude of tool vibration was controlled by the percentage of ultrasonic power. A higher ultrasonic power