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Ignition and volatilization behavior of dust from loblolly pine wood

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ABSTRACT

Generation of dust particles typically occurs when biomass feedstocks are preprocessed in preparation for conversion to energy, fuels and chemicals. This paper investigated the ignition risk of dust from loblolly pine wood by quantifying (including moisture content and grinding screen size effects on) the amount of dust in ground wood chips, dust physical and chemical properties, hot surface ignition temperature, critical volatilization and exothermic temperatures, volatile release activation energy and exothermic energy. Experimental results showed that up to 22% (on mass basis) of the ground chips can be in dust form and that about 7% dust will be produced from the typical conditions used to grind wood chips (moisture content of about 15% and hammer mill screen size of 3.18 mm). The fine dust fraction (dust particles passing through 90 μm sieve) had higher ignition risk compared to medium (between 90 and 180 μm) and coarse (between 180 and 420 μm) dust fractions. Up to 5113 kJ/kg of exothermic energy was released during the ignition of the fine dust sample. The results from this study will be useful in the modeling of behavior and design of equipment and systems to minimize risk of dust-causing ignition, fire and explosion in biomass processing plants.

1. Introduction

About 86% of the energy consumed in the United States in 2013 was obtained from petroleum, coal and natural gas (www.eia.doe.gov). These are fossil-based energy sources that are limited in supply and have adverse impacts on the environment. For example, the burning of these fossil fuels was responsible for 79% of the U.S. greenhouse gases (e.g. carbon dioxide, methane, water vapor, fluorocarbons, ozone and nitrous oxide) emitted in 2011 [1]. In addition, the increased emissions of these greenhouse gases over the past decades are generally considered to be a major cause of the global warming trends and the increase in frequency of extreme weather conditions [1].

Energy from renewable sources (e.g. hydropower, wind, solar, geothermal and bioenergy) has the potential to reduce our reliance on fossil fuels with bioenergy being the only renewable resource that can supply the carbon required to manufacture transportation fuels, chemicals and products. Bioenergy is energy obtained from plants and animals (often called biomass) such as dedicated energy crops, agricultural crops and trees, food, feed and fiber residues, aquatic plants, forestry and wood residues, industrial and municipal wastes, processing byproducts and non-fossil organic material [2]. According to a report by the U.S. Department of Energy [3], the United States can produce by 2030 over one billion tons of biomass that can potentially replace at least 30% of the current petroleum consumption.

After harvesting and/or gathering all of these vast quantity of biomass feedstocks, they will have to be handled, processed and transported with bulk material unit operation equipment (e.g. hammer mills, conveyors, cyclones, dryers and classifiers) before they are fed into the throat of biorefinery plants that will convert them into energy, fuels, products and chemicals. However, these pieces of equipment generate dusts when they are used to process other bulk materials such as coal, grains and feed, food, chemicals, pharmaceutical powders, metals and plastics [4–7]. According to National Fire Protection Association [8], dust is any finely divided solid with a diameter of 420 μm or less. The two main hazards that can result from the presence of dust in processing plants are a) health problems (respiratory, skin and eye effects) due to dust inhalation, and contact with eyes and skin; and (b) fire/explosion. Other problems that dust can cause in processing plants include abrasion damage to equipment, impaired visibility, unpleasant odors, material loss and community relation problems [9].

About 330 million t of the projected billion tons of biomass is expected to come from forest biomass and residues. The southern U.S. is the primary wood basket for the country because it currently supplies about 60% of the U.S. total timber harvest volume [10]. Loblolly pine wood is one of the predominant wood specie grown in this region [11]. With the relocation of the U.S. pulp and paper manufacturing industry to overseas countries, a significant amount of wood fiber is therefore available as feedstocks for the production of energy, fuels, chemicals and products [12].

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This study focuses on ignition of dust from loblolly pine wood because the ignition of dust is a prerequisite for and the main causes of dust causing fire and explosion in processing plants [13,14]. Therefore the overall goal of this study is to understand the ignition behavior of dust from loblolly pine wood by quantifying the effects of (a) moisture content (5%, 15% and 25%) and hammer mill screen size (1.20 mm, 3.18 mm and 6.35 mm) on the amount of dust generated during the grinding of loblolly pine chips; and (b) dust particle size on the physical, chemical, and ignition properties of loblolly pine wood dust. Some ignition related properties of bulk material dust include hot surface ignition temperature (which is the temperature at which a hot surface will ignite the dust that is settled on the surface), amount and rate of volatile released in air atmospheres (which affects the rate at which the fire spreads to other parts of the plants), and the amount of exothermic heat released during ignition [6,15]. The physical and chemical properties are needed in modeling the ignition and explosion behavior of dust–air mixture [16–18].

Particle size is one of the major properties that affect the ignition properties of dust because the total surface area of a material increases with decrease in particle size. Therefore, during ignition, more oxygen from the atmosphere is available to react with the particles. The result is that smaller particles tend to react/volatilize at a faster rate [19–21]. Jain et al. [22] reported that the ignition temperature of boron powder in oxygen atmosphere increased (510–525 °C) with particle size (10 μm to 300 μm diameter). Sweis [23] determined that the hot surface ignition temperatures of 75.3 μm and 212.3 μm diameter oil shale dust was 640 °C and 680 °C respectively. Pilao et al. [24] found that the maximum volatile generation for cork dust occurs in the temperature range of 380 °C to 450 °C. Liu et al. [25] reported that volatile generation for coal dust started at 300 °C and about 83% of the original mass was volatilized by the time the coal dust was heated to 600 °C. Ramirez et al. [6] determined the onset of rapid exothermic reaction for corn and wheat dusts to be 242 and 252 °C respectively. Lu et al. [15] studied the ignition characteristics of dust obtained from crystalline benzoyl peroxides and reported that the heat released during the decomposition reactions of 98%, 75% and 50% crystalline benzoyl peroxide dusts were 1048, 957 and 771 kJ/kg respectively.

The physical and chemical properties of biomass feedstocks are also dependent on particle size. For example, Miranda et al. [26] fractionated Norway spruce into six sizes (vary from particles passing through 180 μm sieve and particles passing through 2.00 mm sieve). The authors found that for both samples, the ash content increased with decrease in particle size. Ash contents of the finest fraction (particles less than 180 μm) and the coarsest fraction (retained on 1.00 and passing through 2.00 mm sieve) were 5.3% and 3.2% respectively. Bridgeman et al. [27] fractionated ground samples of switchgrass and reed canary grass into two fractions ≤90 μm and 90–600 μm fractions and found that the fine fractions of the two grasses had significantly higher ash contents, and lower carbon contents compared to the coarse fractions. Littlefield et al. [28] reported that the carbon and ash contents of the fine fraction of pecan shells were 42.4% and 3.0% respectively while the corresponding values for the coarse fraction were 46.1% and 2.5%. The bulk density, particle density, cohesion and flowability of the fractions were also found by the authors to be significantly different.

2. Methodology

2.1. Dust generation

Clean loblolly pine wood chips were obtained from a forest plantation in the southern part of the state of Alabama, U.S. The initial moisture content of the chips was determined to be 53.2% (w.b.). To adjust the moisture contents of the chips to levels desired in objective 1, the chips were dried at 45 °C (Model 2 Zone, Excalibur Dehydrators, Sacramento, CA) until the mass of sample reduced to that equivalent to the desired moisture level. Using the ASTM standard E871-82 [29], the actual moisture contents of the wood chips were measured to be 4.7%, 14.7% and 23.6% (w.b.). This involved placing of 10 g of sample in a forced convection oven (temperature of 105 °C) for 24 h. The samples at the three moisture levels were kept in a sealed container until they were ground with a hammer mill (Model No. 10HBLPK, Sheldon Manufacturing, Tiffin, OH) that was fitted with the desired screen size (1.20 mm, 3.18 mm or 6.35 mm screen). The dust portion in the ground material was obtained by passing the ground material through the 420 μm screen of a vibratory shaker (Model No K30-2-8S, Kason, Millburn, NJ). The amount of dust generated (M_{du}) due to grinding of the chips was estimated as follows (Eq. (1)).

$$M_{du} = 100\frac{M_i - M_p}{M_i} \quad (1)$$

where M_i is the initial mass of ground sample, and M_p is the mass of ground sample that passed through the 420 μm screen. The moisture contents of the samples after grinding were also measured.

To conduct experiments for the second objective, dust from clean loblolly pine chips were obtained using the methodologies outlined above except that the chips were dried to 10% moisture content level and ground through 1.20 mm screen. The dust sample was then fractionated (Model RX-20, W.S. Tyler Industrial Group, Mentor OH) into three fractions as follows:

a. Coarse fraction: dust particles passing through 420 μm and retained on 180 μm screens.
b. Medium fraction: dust particles passing through 180 μm and retained on 90 μm screen.
c. Fine fraction: dust particles passing through 90 μm screen.

The physical, chemical and ignition properties of these fractions (including that of the unfractionated dust sample) were then quantified as described below.

2.2. Particle size distribution

Particle size and particle size distribution of the three dust fractions were measured by a digital image analysis system (Model Camsizer, Retsch Technology, Haan, Germany). About 100 g of dust sample was loaded onto the hopper of the instrument. The sample was then conveyed and dropped via a vibratory feeder onto the measurement field of the two cameras in the equipment. The size of particles was recorded and analyzed by the software provided by the equipment manufacturer. Geometric mean diameter of the samples was then computed from the particle size distribution obtained from the software of the equipment using the procedure outline in ASABE Standard S319.4 [30].

2.3. Bulk density and particle density

Bulk density was determined by a bulk density measuring apparatus [28]. This method involves pouring the bulk solid into a container (volume of 1137 mm^3) from a funnel. The material was leveled across the top of the surface of the container and weighed. Bulk density was calculated from the ratio of the mass of sample that filled the container to the volume of the container.

A gas comparison pycnometer (Model AccuPyc 1330, Micromeritics Instrument Corp., Norcross, Ga) was used to determine the particle density. In the pycnometer, helium under pressure was allowed to flow from a previously known reference volume into a cell containing a sample of the material. By applying the ideal gas law to the pressure change from the reference cell to the sample cell, the pycnometer calculates the volume of the material in the sample cell. Particle density was calculated as the ratio of the mass of material in the sample cell to the volume measured by the pycnometer. A digital balance with 0.001 g precision (Model AR3130, Ohaus Corp, Pinebrook, NJ) was used to measure sample mass.