1 **Specific energy consumption and quality of wood pellets produced using**
2 **high-moisture lodgepole pine grind in a flat die pellet mill**

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ABSTRACT

In the present study a Box-behnken experimental design was used to understand the effect of the moisture content of lodgepole pine grind (33–39%, w.b.), die speed (40–60 Hz) and preheating temperature (30–90°C) on the pellet quality, and specific energy consumption. The partially dried pellets produced had high-moisture content in the range of 19 to 28% (w.b.), and were further dried to <9% (w.b.) in a mechanical oven set at 70°C for 3 hours. Dried pellets were further evaluated for pellet moisture content, unit, bulk, tapped density, and durability. Response surface models developed for the product properties have adequately described the process based on coefficient of determination values. Surface plots developed indicated higher unit, bulk, and tapped density (1050, 520, 560 kg/m³) are achievable at 33–35% (w.b.) moisture content of the lodgepole pine grind, die speed of 60 Hz and preheating temperature of 30–60°C. Higher moisture content to 39% (w.b) reduced unit, bulk, and tapped density to <912, 396, and 452 kg/m³. Higher durability values of >95% were obtained at 33-35% (w.b.) at lower preheating temperatures of 30–50°C and higher die speed of >50 Hz. At 33% (w.b.) moisture content of the lodgepole pine grind, preheating temperature of 90°C, and die speed of 60 Hz, the observed specific energy consumption was <116 kWhr/ton. Scanning electron microscope studies indicated that lignin crosslinking is the primary reason for binding of the lodgepole pine grind at high-moisture content.

Keywords: Lodgepole pine grind, high-moisture pelleting, process variables, pellet properties, specific energy consumption, response surface methodology

1. Introduction

The major limiting factors for utilization of biomass for energy applications in commercial scale are low bulk density, and its availability in a less-convenient form for feeding, handling, and transportation. Biomass, after harvesting and baling, has a density in the range of 112–160 kg/m³ (Atchison and Hettenhaus, 2004), whereas wood after harvesting and chipping has density of about 265 kg/m³ (Tumuluru et al., 2015a). According Tumuluru et al. (2016a) advanced feedstock commodity supply system concept transforms different raw biomass resources from a highly variable, aerobically unstable, low density form into a fairly uniform, aerobically stable, high density, tradable, aggregatable commodity. Densifying the biomass using compression systems such as pellet mill or briquette press, the bulk density is increased by a factor of 4-7 and makes it as a commodity type product (Tumuluru et al., 2011). The common densification systems used for increasing the density of the biomass are pellet mill, briquette press, and screw extruder (Tumuluru et al., 2011). Among the densified products produced using different densification systems, the biomass pellets produced using woody and herbaceous biomass are more commonly used for thermochemical conversion applications, such as co-firing, gasification, and pyrolysis (Tumuluru et al., 2012; Sarkar et al., 2014; Yang et al., 2014), and for biochemical conversion applications to produce liquid fuels (Ray et al., 2013). Typically wood pellets have a bulk density in the range of 700 to 750 kg/m³ (Tumuluru et al., 2010a), whereas wood briquettes have a range of 400 to 450 kg/m³ (Tumuluru et al., 2015b; Tumuluru et al., 2016a). Several advantages of densified products such as pellet are (1) biomass becomes a uniform commodity-type product, (2) properties are better for handling and transportation, (3) reduces the storage foot print, (4) no recalcitrance during biochemical conversion (Ray et al., 2013), and (5) pellets have moisture in the range of 5 to 7% (w.b.) (Tumuluru et al., 2010a) after cooling are less susceptible to biological degradation during storage.

1.1 Conventional pelleting process

Searcy et al. (2015) in their report on validation of advanced feedstock supply system indicated that the one of the major limitation in using high moisture woody and herbaceous biomass by biorefineries for biofuels production is high preprocessing (size reduction, drying and densification) costs. Various unit operations associated with the

1 conventional pelleting process include a stage-1 and stage-2 grinder, a dryer, and a pellet mill (Fig. 1). In the
2 conventional pelleting process, the high-moisture woody and herbaceous biomass, typically at 30% (w.b.), is
3 conveyed through a stage-1 grinder, which is typically a hammer mill fitted with a screen size in the range of
4 25.4-50.8 mm (Yancey et al., 2013). Next, the ground biomass is dried in rotary drier to about 10% (w.b.) and is
5 passed through a stage-2 grinder, a hammer mill fitted with a 4.8 mm screen (Yancey et al., 2013). The dried
6 ground biomass is further steam conditioned and pelleted (Yancey et al., 2013). The schematic of biomass
7 pelleting process is given in Fig. 2. The cost of pelleting is mainly dependent on the energy consumption,
8 throughput, and capital costs associated with these unit operations. Technoeconomic analysis indicated efficient
9 moisture management is critical for reducing the preprocessing costs of biomass (Tumuluru et al., 2014).
10 Sakkampang and Wongwuttanasatian (2014) in their study on glycerin-biomass briquettes indicated that drying
11 takes about 2.25 MJ/kg, whereas briquetting takes about 0.05–0.10 MJ/kg for different feedstocks (saw dust,
12 sugarcane bagasse, sugarcane leaf, and rice husk). Yancey et al. (2013) indicated that the type of the biomass has
13 an impact on the drying, and pelleting costs. In case of lodgepole biomass it takes about 350 kWhr/ton to dry
14 biomass from 30 to 10% (w.b.) moisture content and eucalyptus takes about 401 kWhr/ton, whereas pelleting
15 lodgepole pine takes about 48.94 kWhr/ton and eucalyptus takes about 125 kWhr/ton. Pirraglia et al. (2010)
16 indicated that in commercial scale wood pellet production drying requires about 70% of energy. Fig. 1 indicates
17 the energy associated with the various unit operations in wood pellet production (Yancey et al., 2013).

18 (Insert Figure 2)

19 One way to reduce the high drying costs in pellet production process is to pellet biomass at high
20 moistures and then dry the high-moisture pellets using low capital and low temperature drying methods like grain
21 or belt dryer. Studies on pelleting corn stover, ammonia fiber explosion pretreated corn stover, and municipal
22 solid waste at high-moisture content of about >20% (w.b.) in a flat die and ring die pellet mill indicated that good
23 quality pellets, in terms of density and durability, can be produced (Tumuluru, 2014 & 2015; Bonner et al., 2016).
24 The high-moisture pelleting process (Fig. 3) replaces rotary dryer in the front end with a grain or belt dryer at the
25 back end of pelleting. Steam conditioning of biomass in conventional process is replaced with short preheating

step in the high-moisture pelleting process. Some of the moisture in the biomass is lost due to frictional heat developed in the die due to compression and extrusion. According to Tumuluru (2014, 2015) and Tumuluru et al. (2016b) the biomass moisture content reduces by about 5–10% (w.b.) based on the process conditions selected. The high-moisture pellets can be dried more efficiently using grain or belt dryers, which operate at a lower temperature of <90°C. Techno-economic analysis of conducted by Lamers et al. (2015) indicated that in high-moisture pelleting the energy consumption decreases by about 40% compared to the conventional method. Based on their study one of the main reasons for reduction of energy is due to replacing the rotary dryer with grain dryer. The requirement of ultra-high air temperature in rotary dryers keep the drying cost higher when compared to crossflow or mixed flow grain dryers. Grain dryers, which are used to dry the agricultural products, are operated between 32–90°C, where the drying temperature is selected based on the material that is dried (Hellevang, 2013).

(Insert Figure 3)

1.2 Pelleting process variables

The wood pellet physical properties (density and durability) are dependent on the process variables, including biomass feedstock process variables (moisture content, particle size, and composition), and pellet mill process variables, such as die speed, length-to-diameter ratio of pellet die, pellet die diameter, preheating temperature, and steam conditioning. These variables will influence not only the quality but also the specific energy consumption of the pelleting process. Moisture content of the biomass lowers the glass-transition temperature, promotes solid-bridge formation, and increases the contact surface area (Tumuluru et al., 2011). Significant research has conducted pelleting studies on woody and herbaceous biomass at different moisture contents (Stelte, 2011). In some of the recent studies on pelleting of municipal solid waste, compost, corn stover and ammonia fibre explosion pretreated corn stover, and woody biomass, higher biomass moisture content of >25% (w.b.) has been used (Tumuluru, 2014; Poddar et al., 2014; Zafari and Kianmehr, 2013; Hoover et al., 2014). Steam conditioning and preheating of the biomass helps to activate some of the biomass binding components such as lignin, starch, protein, and water soluble carbohydrates, which assist in producing good durable pellets. Smith et al. (1977) indicated increasing the preheating temperature of the die to 110°C results in reduction in density. Tumuluru

(2015) observed similar results, where increasing the moisture content of the ground corn stover and preheating temperature decreased the density due to expansion of the pellet as it extrudes the die. Higher preheating temperatures $>90^{\circ}\text{C}$ are suitable for biomasses that have higher protein and starch content, developing starch gelatinization and protein denaturation resulting in forming protein starch complexes. The die dimensions (diameter and length) affect several components, such as the amount of material that can be pelleted, the quality of the pelleted material, and the energy required for compression and extrusion.

1.3 Pellet physical properties and specific energy consumption

Physical properties of raw biomass and pellets are important to design processing, storage, and handling equipment used in biorefineries. Moisture content, density (unit, bulk and tapped), and durability are key quality attributes for fuel pellets. Moisture content of the pellets is important for safe storage and efficient transportation. Higher moisture content ($>15\%$, w.b.) in the pellets can lead to spoilage during storage due to microbial decomposition, whereas very low moisture of $<3\%$ results in low durability and leads to producing more pellet crumbles, which generate more fines during storage and transportation (Tumuluru et al., 2010a). Both scenarios will result in loss of revenue for the pellet manufacturers. Unit, bulk, and tapped densities are important for storage and transportation. For long-distance transportation, pellets with higher packing density are preferred. Expansion ratio is important index that is measured for extrudates prepared from high-moisture biomasses. It is the ratio of diameter of the pellet extruded to diameter of the die. There is an inverse relationship between the expansion ratio to density of the extruded pellet (Tumuluru, 2015). Durability indicates the integrity of the pellets during storage and transportation. In addition, it can be defined as the ability of the pellets to withstand the abrasive, impact, and frictional resistances during handling, storage, and transportation. The higher the durability of pellets, the greater is the resistance of the pellets to impact and shear forces. Higher pellet durability is desirable as it helps the pellets to retain their size and shape without any breakage during the storage and transportation.

According to Reed et al. (1980) specific energy consumption of the pelleting process depends on pellet mill process variables (length to diameter ratio of the die, die diameter, rotational speed of the die, and feed rate),

processing parameters (temperature and pressure), biomass constituents (moisture content, particle size, and distribution), and chemical composition (starch, protein, lignin fat, waxes, and other lignocellulosic components). In general, low-moisture materials need smaller die diameters and lower rotational speeds, whereas for wet and sticky biomass, bigger pellet dies and higher die speeds are desirable. Biomass composition contributes significantly to the quality of densified materials (Tumuluru 2015). The natural binding of biomass particles during pelleting is due to presence of biomass components during, such as protein, starch, and lignin.

Biomass has micro (organics and inorganics) and macromolecular (cellulose, hemicellulose, and lignin) composition. During pelleting the process heat developed in the die and pressure bring changes in biomass composition, such as protein, starch, and lignin, which help in natural binding of biomass particles. Also, the presence of moisture and heat during pelleting makes some of the water soluble carbohydrates act as binder. Among the lignocellulosic biomass woody biomass are higher lignin (about 25–30%) and agricultural straws and crop residues has lowest (14–17%). Commercial binders are generally used in pelleting if the biomass has lower binding components. Typically for pelleting, woody biomass binders are not needed as they are high in lignin content. During pelleting, glass transition temperatures of biomass components, such as lignin, waxes, protein, and starch, change due to temperature and pressure experienced by the biomass, thus making these biomass components take an active part in the binding of biomass particles. Natural and commercial binders, such as starch and lignosulphonate or bentonites, are used when biomasses have lower binding components and to reduce the pelleting energy. Adding 2 and 4% corn starch binder to high-moisture corn stover grind resulted in reduction of specific energy consumption by about 30–40% and increased the durability of the pellets to >99% (Tumuluru et al., 2016b). The specific energy reduction by approximately 30-40% using binder can outweigh the cost of the binder, which is used in small quantities and in turn can have a significant impact on the cost of pellet production process. In addition, corn starch is less costly compared to other commercial pellet binders. Also, the same authors have suggested starch wastes from food processing industries can also be used for pellet production process. Scanning electron microscope is commonly used to understand the structural changes and composition modifications due to temperature and pressure experienced by the biomass during pelleting (Tumuluru 2014).

This results in some of the biomass components, such as protein and starch to become plasticized and lignin to soften.

1.4 Objective

Numerous studies were conducted by researchers to understand the effect of process variables (biomass moisture content and particle size) and densification system variables (die rotational speed, preheating temperature, die diameter, length-to-diameter ratio of the die, and steam conditioning) on the quality of the densified products such as pellet and briquettes (Holm et al., 2006; Tabil and Sokhansanj, 1996; Msani et al., 2006; Li and Liu, 2000; Tumuluru et al., 2010b; Ndiema et al., 2002; Tumuluru et al., 2015b&c; Zafari et al., 2013; Tumuluru, 2014; Poddar et al., 2014; Hoover et al., 2014; Pace, 2015; Kaliyan and Morey, 2009; Stelte, 2011; Winter, 1981; Yancey et al., 2013; Zhang and Gua, 2014; Mani et al., 2004; Mani et al., 2002; Al-Widyan et al., 2002; Tumuluru, 2015). To understand the effect of moisture content of the biomass on the quality (density and durability) of the pellets or briquettes, these researchers has adjusted the moisture content of the ground raw (both woody and herbaceous) and chemically pre-treated biomasses over a wide range (10–45%, w.b.) by adding additional moisture.

Aim of the research is to see the technical feasibility of pelleting lodgepole pine (LPP) grind biomass at higher moisture content of $\geq 33\%$ (w.b.). In the present study 4.8-mm dried ground woody biomass is pelleted by adjusting the moisture content between 33 and 39% (w.b), die speed of 40–60 Hz, and preheating temperatures of 30–90°C. Experiments were conducted based on Box-behnken experimental design. The pellets produced at different experimental conditions were evaluated for quality attributes, such as pellet moisture content, unit, bulk and tapped density, expansion ratio, and durability. Also, the power data was recorded for each experimental run to calculate the specific energy consumption of the process. Response surface models and plots were developed using the experimental data to understand the interactive effect of process variable on the pellet quality and specific energy consumption.

2. Materials and methods

2.1 Biomass

Lodgepole pine was harvested from Fremont County, Idaho – Island Park Area. The wood chips were first ground in stage-1 grinder (Vermmer HG 200 grinder) fitted with a 30.8-mm screen. The ground material was dried in a rotary drum dryer to 10% (w.b.) moisture content. The dried material was further ground using Bliss Hammer mill (Bliss Eliminator Hammer mill, Model E-4424-TF, manufactured by Bliss Industries, Ponca City, Oklahoma, USA) fitted with a 4.8-mm screen. The ground samples were measured for moisture content and are further stored in air-tight containers.

2.2 Laboratory scale pellet mill

Tumuluru (2014, 2015), Hoover et al. (2014) and Tumuluru et al. (2016b) have discussed in detail the ECO-10 pellet mill configuration used in the present research (Fig. 4). The pellet mill was equipped with a 10-HP, 460-volt, 3-phase motor. The pellet mill was also provided with a hopper for holding the biomass and a screw feeder for feeding it into the pellet mill. The hopper and screw feeder are provided with flexible tape heaters, temperature controllers, and thermocouples to preheat the biomass to desired temperatures. The pellet mill die and feeder are equipped with a variable frequency drive to control the rotational speed die and regulate the feed rate to the pellet mill. A horizontal pellet cooler was furnished to cool the warm pellets coming out of the pellet die. Pellet mill motor RPM is 1750 at 60 Hz and with an 88.9-mm-diameter motor pulley. The diameter of the pulley provided for the pellet mill die is 444.5 mm. The revolutions per minute (rpm) calculated for the pellet mill die using Equation (1) is 350 at 60 Hz.

$$D_1 N_1 = D_2 N_2 \quad (1)$$

Where D_1 is the diameter of the motor pulley, N_1 is the rpm of the pellet mill motor, D_2 is the diameter of the pellet mill pulley, and N_2 is the rpm of the pellet mill die. Power meter was provided to the pellet mill to record the power consumption during pelleting.

(Insert Figure 4)

2.3 *Experimental conditions*

The process variables tested in the present study are moisture content of the lodgepole pine grind (33–39%, w.b.), die rotational speed (40–60 Hz), and preheating temperature (30–90°C). All pelleting experiments were conducted using 4.8-mm screen size grind LPP material using an 8-mm pellet mill die. Box and behnken design was used to generate the experimental data for the physical properties of the pellets produced and energy consumption. The lower and upper limits and coded levels of the process variables are given in Table 1.

(Insert Table 1)

2.4 *High-moisture pelleting process (HMPP)*

The process flow diagram for making pellets using moisture adjusted 4.8-mm lodgepole pine (LPP) grind is given Fig. 5. About 2 kg of ground LPP with calculated amounts of water was mixed in a ribbon blender (Model: RB 500, Colorado Mill Equipment, Canon City, Colorado, USA), to adjust the moisture content to desired levels based on the experimental design (Table 1). The moisture-adjusted LPP grind biomass is stored in cooler set at 4°C to allow moisture to equilibrate so that it attains stable moisture level. In the present study, lower storage temperature was selected to prevent any material degradation during storage due to high moisture in the biomass. On the day of pelleting, the material is left at room temperature for couple of hours to allow the biomass reach the room temperature. This material was loaded into the feeder hopper of the pellet mill where it was preheated at different temperatures (30, 60, and 90°C) for very short durations (about 2 to 3 min). The preheated biomass was continuously fed further into the pellet mill using the screw feeder (Tumuluru 2014, 2015) and Tumuluru et al. (2016b). The high-moisture pellets produced were further cooled using the horizontal cooler. The moisture content of the high-moisture pellets was measured after cooling to determine how much moisture was lost during compression and extrusion process in a pellet mill and cooling. As the moisture content of the cooled pellets were found to be high, the pellets were dried in a mechanical oven at 70°C for about 3–4 hours to reduce the moisture content to about 7–9% (w.b.) (Tumuluru, 2015). These dried LPP pellets were immediately analyzed for physical properties, including pellet diameter, unit, bulk, and tapped density, and durability based on standard procedures.

(Insert Figure 5)

2.5 Procedures for pellet properties measurement

American Society of Agricultural and Biological Engineers (ASABE) (2007) Standards S269.4 were used to measure the pellet moisture content, density, and durability. A small quantity of high-moisture pellet sample (about 25 grams) was dried in a mechanical oven at 105°C for 24 hours to measure the moisture content of the pellet sample. Moisture measurements were performed in triplicates on both high-moisture and dried pellets.

Unit density of the dried pellet was measured by measuring the length, diameter, and weight of individual pellets. Ten dried pellets from the sample were selected randomly. The two ends of dried single pellet were smoothed with sand paper. Pellet length and diameter were measured using Vernier Calipers (Fig. 6). The mass of the pellet was measured on a balance with 0.001 g precision. Unit density is measured by dividing mass of an individual pellet by its volume. The reported values are an average of 10 measurements.

(Insert Figure 6)

Bulk density and durability of dried pellets produced was determined based on ASABE Standard S269.4 (2007). A cylindrical container with an H/D (155 mm/120 mm) ratio of 1.29 was used in this study. The dried pellet samples were poured into the cylindrical container. The excess material was removed by striking a straight edge across the top and then the container is weighed again. In the case of tapped density, the loosely filled container was tapped on the laboratory bench five times and is filled again with biomass and weighed. Bulk and tapped density was calculated by dividing the weight of the pellets over the container volume. The reported values are an average of four measurements.

Expansion ratio of the pellets is the ratio of diameter of the pellet to diameter of the die. It is calculated using Equation (2). Schematic of the expansion of the pellet during compression and extrusion in a pellet die is indicated in Fig. 7.

$$\text{Expansion ratio (ER)} = \frac{D^2}{d^2} \quad (2)$$

Where D is the diameter of the pellet (mm) and d is the diameter of the die (mm). The reported values are an average of 10 measurements.

(Insert Figure 7)

Durability of pellets was determined by tumbling the pellet sample at 50 rpm for 10 min, in a dust-tight enclosure. About 500 grams of pellets produced were sieved and placed in each compartment of the tumbler. After tumbling for 10 minutes, the sample is removed and sieved using 6.7-mm screen (ASABE 2007). Pellet durability is calculated using Equation (3). The data presented is an average of three measurements.

$$\text{Durability} = \frac{\text{Mass of pellets after tumbling}}{\text{Mass of pellets before tumbling}} \times 100 \quad (3)$$

Scanning electron microscope of the pellets was taken using JEOL JCM-5000 NeoScope in a high-vacuum mode (JEOL; Arvada, Colorado, USA). The LPP pellet samples were dried to low-moisture contents (w.b.) in a laboratory oven set at 40°C for 24 h. Micrographs were taken for the pelleted samples to understand the structural changes in the biomass (Ray et al., 2013, Tumuluru, 2014).

APT power monitor meter connected to the pellet mill to records the power in kilowatts. The power data was logged into the computer using LabVIEW software. Specific energy consumption was calculated by subtracting the no-load kW from the full-load power. The no-load power at different die rotational speeds (40, 50, and 60 Hz) was recorded by running the pellet mill empty. Specific energy for pelleting was calculated for steady-state pellet production where the initial pellet mill start up time was avoided.

$$\text{Specific energy consumption} = \frac{(\text{Full load power (kW)} - \text{No load power (kW)}) * \text{time (hr)}}{\text{weight of biomass processed (kg)}} = \frac{\text{kWhr}}{\text{kg}} \quad (4)$$

2.6 Data analysis

Experimental data collected based on Box-behnken experimental design was used to develop the second-order response model Equation (5). Where x_i and x_j are the coded independent variables, y is the dependent variable, b_0 , b_i , b_j are equation constants, n is the number of independent variables, and ϵ is an unobservable error. Response

surface models were further used to develop the surface plots to understand interaction effect of the process variables (moisture content of the LPP grind (x_1), die speed (x_2), and preheating temperature (x_3) on the quality attributes (pellet moisture content, unit, bulk and tapped density, durability, expansion ratio) and specific energy consumption. Analysis of variance (ANOVA) was conducted to understand the significance of the linear, quadratic and interactive terms. Experimental data collected based on Box-behnken is further analyzed using Statistica software, version 9.1 (StatSoft Inc., 2010).

$$y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n b_{ii} x_i^2 + \sum_{i=1}^n \sum_{j=1}^n b_{ij} x_i x_j + \varepsilon \quad (5)$$

3. Results and discussion

3.1 Experimental results

The initial moisture content of the lodgepole pine (LPP) grind samples was about 7.54% (w.b.). The bulk density of the samples at this moisture content was about 240 kg/m³. Table 2 indicates the experimental data generated for the different process conditions using Box-behnken design. Fig. 8 shows the LPP pellets produced at different process conditions.

(Insert Table 2)

(Insert Fig. 7)

The moisture content of the high-moisture pellets produced was in the range of 19 to 28% for the different process conditions tested. Pelleting the LPP grind biomass at both 33 and 39% (w.b.) resulted in decrease of the moisture of the biomass by about 8–11% (w.b.) after pelleting and cooling. These findings have corroborated with earlier published literature on high-moisture pelleting of corn stover (Tumuluru 2014, 2015; Tumuluru et al., 2016b).

Unit and bulk density of the pellets is lower at a higher LPP grind moisture content of 39% (w.b.) and a preheating temperature of 90°C. Also lower die speed of 40 Hz resulted in lowering the density values of the

pellets produced. The observed lower unit, bulk, and tapped density values were <900 , <410 , and $<476 \text{ kg/m}^3$. At moisture content of 33–36% (w.b.) and a die speed of 50–60 Hz (the maximum unit), bulk and tapped density observed was >950 , >510 , and $>559 \text{ kg/m}^3$.

Lower durability values $<95\%$ were observed at lower die speed of 40 Hz and at different moisture content (33, 36, and 39%, w.b.) of the LPP grind. Durability values of $>95\%$ were observed at die speed >50 Hz, higher preheating temperature of 90°C , and lower-to-medium moisture content (33–35%, w.b.) of the LPP grind.

Diameter of the pellet produced was in the range of 8.02 to 8.05 mm when the moisture content of the LPP grind is $<36\%$, (w.b.). Highest expansion ratio of 1.12 was observed at moisture content of 39% (w.b), die speed of 40 Hz, and preheating temperature of $>60^\circ\text{C}$.

In the case of specific energy consumption, higher moisture content of 39% (w.b.) of the LPP grind and lower die speed of 40 Hz resulted in higher specific energy consumption values of $>180 \text{ kWhr/ton}$. Lowering the ground LPP biomass moisture content to 33% and increasing the die speed to 60 Hz and preheating temperature to 90°C lowered the specific energy consumption values to $<110 \text{ kWhr/ton}$.

Analysis of variance (ANOVA) of the experimental data indicated that pellet moisture content was influenced by biomass moisture content of ground LPP at $P < 0.001$. The unit, bulk, and tapped density were influence by the moisture content of the LPP grind and die speed at $P < 0.01$ and $P < 0.05$. Durability was influenced by the moisture content of the ground LPP at $P < 0.05$, whereas the die speed was the most significant variables at $P < 0.05$ influencing the specific energy consumption.

Response surface models (RSM) developed using the experimental data are given in Table 3. Based on the coefficient to determination values the models have adequately described the process with respect to the process variables. Analysis of the model coefficients indicated that linear and quadratic terms (x_1 and x_1^2) of the moisture content of the LPP grind was highest for pellet moisture content, unit, bulk and tapped density, durability and specific energy consumption. However, in the case of expansion, the ratio linear term (x_1) of the die speed and the quadratic term (x_1^2) of the moisture content of the LPP grind have the highest coefficient value. In

the case of interactive terms, moisture content of the LPP grind and die speed (x_1x_2) have the highest impact on the pellet moisture content, unit, bulk and tapped density, durability, and specific energy consumption. However, the interactive terms of the die speed and preheating temperatures (x_2x_3) have higher coefficient values for the expansion ratio. These models were further used to draw the surface plots to understand the interaction effect of the process variables on the quality (pellet moisture content, unit, bulk and tapped density, durability, expansion ratio) and the specific energy consumption. Using the response surface models surface plots were developed for the different process conditions studied. In this paper, the plots for the statistical significant process variables were presented to understand the interaction effect of these process variables on the quality attributes (pellet moisture content, unit and bulk density, expansion ratio and durability) and specific energy consumption.

(Insert Table 3)

3.2 Pellet moisture content (% w.b.)

Results from the present study indicated that moisture content of the lodgepole pine (LPP) grind was reduced by about 8–13% (w.b.) after pelleting and cooling. The resulting pellets had moisture contents in the range of about 20 to 28% (w.b.). At a LPP grind moisture content of 33% (w.b.), die speed of 40 Hz, and preheating temperature of 110°C, the LPP pellet moisture content observed was 23–25% (w.b.). By increasing the die speed to 60 Hz, the change in pellet moisture content was marginal. At a higher LPP grind moisture content of 39% (w.b.) and preheating temperature of 110°C, the pellet moisture observed was about 28–30% (w.b.). The surface plot (Fig. 9) drawn for pellet moisture content, with respect to moisture content of the LPP grind and preheating temperature. Plot indicated that higher preheating temperature and lower moisture of the LPP grind reduced LPP pellet moisture. There is about 8–13% (w.b.) reduction in pellet moisture content for the different conditions tested. The reduction is mainly due to frictional heat developed in the die, preheating temperatures, and further cooling, which results in most of the surface moisture being lost and in partially dried pellets. The moisture loss finding during pelleting has corroborated with the earlier observations on high-moisture corn stover pelleting, where about 8–10% (w.b.) biomass moisture reduction was observed (Tumuluru 2014 & 2015; Tumuluru et al., 2016b). The author also reasoned that frictional heat developed in the die and pressure of extrusion results in moisture

flash-off as the pellets extrude out of the die. In general, moisture evaporation from surface is more rapid compared to moisture diffusion from the granules of the biomass. This might be one of the reasons for higher moisture loss observed during the high-moisture pelleting process. This type of partially dried product (typically called half product) needed to be further dried to lower moisture using slow air-drying methods. Rapid air-drying methods can lead to the formation of hard skin (case hardening), which leaves moisture in the center, thus leading to microbial degradation of the product during storage.

(Insert Figure 9)

3.3 Unit bulk and tapped density (kg/m³)

The highest unit density recorded was about 1,050 kg/m³ at a lower biomass moisture content of 33% (w.b.) with higher die speeds of 60 Hz, whereas bulk density values were about 550–560 kg/m³. The changes in unit and bulk density with respect to preheating, die speed, and moisture content of the LPP grind are significant. Lower to medium moisture content of the LPP grind and higher die rotational speed maximized these properties. Commercial wood pellets have unit and bulk density in the range of 1100 to 1300 kg/m³, and 700-800 kg/m³ (Tumuluru, et al., 2010a; Tumuluru et al., 2011). Surface plots (Figs. 10-12) drawn for moisture content of the LPP grind and die speed indicated that higher unit density >1020 kg/m³, bulk density >540, and tapped density >600 kg/m³ were observed when the moisture content of the LPP grind was 33% (w.b.) at 60 Hz die speed. Increasing the moisture content of the LPP grind to 39% (w.b.) and reducing the die speed to 40 Hz significantly reduced the unit, bulk, and tapped densities to <876, <388, and <452 kg/m³. These results have corroborated with our earlier studies on pelleting of high-moisture corn stover (Tumuluru, 2014, 2015), where higher moisture content (38%, w.b.) of corn stover and lower die speed reduced the unit, bulk, and tapped density values of the corn stover pellets. Preheating temperature also influenced the unit, bulk, and tapped density. Increasing the preheating temperature to 90°C and moisture content of the LPP grind to 39% (w.b) and decreasing the die speed of 40 Hz decreased the unit, bulk, and tapped density values (surface plots not shown). Many researchers (Hall and Hall 1968; Zhang and Guo 2014; Mani et al., 2002; Tumuluru et al., 2015b &C; Tumuluru, 2014 and 2015) have indicated that high moisture of the biomass and temperature and pressure associated with the pelleting and

briquetting process results in lateral and diametrical expansion of the product. This expansion consequently results in reduced density. Tumuluru (2015) indicated that bulk density is directly related to diametrical expansion of the pellet. Biomass composition is also an important variable that influences the bulk density of the extruded pellets. Biomasses with higher amounts of protein can results in more durable and denser pellets. In cases of lignocellulosic biomasses, the binding during pelleting is mainly due to lignin mobility. Higher moisture content of the LPP grind as used in the present study might have resulted in the mobility of lignin molecules (reduce the glass transition temperature) and might have helped in binding of biomass particles. The lower density values observed at high-moisture content of ground biomass can be improved by adding protein-based binders. Tumuluru et al. (2013) and Shankar and Bandyopadhyay (2004) in their studies on extrusion of fish and rice flour indicated that when protein is extruded at temperature of 100°C, undergoes denaturation and increases the hardness of the extrudates.

(Insert Figures 10–12)

3.4 Expansion ratio

Expansion ratio is defined as ratio of pellet diameter to die diameter. In general, food and feed when extruded at low moisture result in a minimal expansion ratio (Shankar and Bandyopadhyay, 2005; Oke et al., 2013; Filli et al., 2013). Typically, the pellets made at biomass moisture content of 10–12% (w.b.) have lower expansion ratio values (≤ 1.0). In the present study, LPP pellets made at a higher moisture content of $\geq 33\%$ (w.b.) resulted in expansion ratio values of >1.0 . At 33% (w.b.) of the moisture content of the LPP grind and die speed of 40 Hz, the expansion ratio values observed were >1.06 , whereas increasing the moisture content to 39% (w.b.) increased the expansion ratio to 1.12. Another important variable that influenced the expansion ratio was preheating temperature. Fig. 13 is the surface plot drawn for preheating temperature to moisture content of the LPP grind. At 33% (w.b.) moisture content of the grind and a 30°C preheating temperature, the expansion ratio was about 1.03. However, increasing both the preheating temperature to 90°C and the moisture content of the LPP grinds to 39% (w.b.) increased the expansion ratio to >1.09 . The additional two surface plots (not shown) were drawn for die speed and moisture content of the LPP grind, and for die speed and preheating temperature; both surface plots

indicated the same trend, where expansion ratio values were maximized at a lower die speed, a higher preheating and higher moisture content of the LPP grind. The main reason for a higher expansion ratio at a higher moisture content of the LPP grind and higher preheating temperature can be attributed to moisture flash-off as the pellet extrudes out of the die. This can be due to material under high pressure and temperature when expelled through a constricted die expands when it comes in contact with ambient pressure and temperature and cool rapidly through water flash-off (Fellows, 2009).

(Insert Figure 13)

3.5 Durability (%)

Durability values are measured to understand the strength of the pellets to withstand impact and shear resistances during storage, handling, and transportation (Tumuluru et al., 2010a). The needed durability value for pellets is based on the distance it has to be transported. Pellets that have to be transported to longer distances need to have higher durability values of >97.5%, whereas for short distance transportation lower durability values of <95% and <90% may be sufficient. Pellet Fuel Institute (PFI), USA has graded the pellets into premium, standard, and utility based on the durability and density values (Tumuluru et al., 2010a). According to European standard (CEN) for international transport the expected durability values are >97.5. Lower durability pellets break during storage and transportation and create fines that can result safety issues, such as spontaneous combustion and higher off-gas emissions, and also can result in revenue loss for the pellet producers (Tumuluru et al., 2010a). The surface plot in Fig. 14, drawn for the durability values, indicated that at a moisture content of the LPP grind in the range of 33 to 35% (w.b.) and preheating temperatures of 30–60°C, the durability values of the pellets were >95%. Increasing the moisture content of the LPP grind to >37% (w.b.) significantly reduced the durability values to <93.6%. Many researchers have observed that increasing the preheating temperature and reducing the moisture of the biomass can increase the durability values of the densified products, such as pellets and briquettes (Tumuluru, 2014 and 2015; Koullas and Koukios, 1987; Zhang and Guo, 2014). Typically, higher temperatures and moisture contents associated with the pelleting process activate some of the biomass components, such as lignin (glass transition), protein (denaturation), and starch (gelatinization), which acts as natural binders to bind the biomass grinds.

(Insert Figure 14)

3.6 *Specific energy consumption (kWhr/ton)*

The process variables such as moisture content of the ground biomass, die dimensions, biomass composition, feeding rate, and die rotational speed have a great impact on the pelleting energy consumption (Tumuluru et al., 2011). A surface plot (Fig. 15) for the specific energy consumption was drawn for preheating temperature and die speed. It is clear from the plot that increasing the die speed to 60 Hz and the preheating temperature to 90°C reduced the specific energy consumption to <116 kWhr/ton. At 39% (w.b.) moisture content of the LPP grind, die speed of 40 Hz, and preheating temperature of <70°C the specific energy consumption increased to about 225 kWhr/ton (figure not shown). At 39% (w.b.) moisture content of the LPP grind, to produce good pellets with fewer fines, the feeding rate was lowered. However, lowering the feeding rate at higher moisture content resulted in a reduced throughput and increased the specific energy consumption. One way to increase the throughput of the pellet mill at higher biomass moisture contents can be the addition of binders to help improve the pellet properties, throughput and reduce specific energy consumption. Recent studies by Tumuluru et al. (2016b) on the pelleting of high-moisture corn stover using a cornstarch binder (2 and 4% by weight) resulted in increasing the throughput and lowering the specific energy consumption by 20–40%. The surface plot drawn between the die speed and the preheating temperature for specific energy consumption indicated that lower die speed and higher preheating temperature increased the specific energy consumption values to >200 kWhr/ton, whereas higher die speed and higher preheating temperatures reduced the specific energy consumption values to <116 kWhr/ton.

(Insert Figure 15)

3.7 *Scanning electron microscope*

The scanning electron microscope photograph was used to understand the structural changes in the LPP pellets produced at 33 and 39% (w.b.) moisture content of LPP grind (Fig. 16 a & b). Lignin distribution is clearly visible in both the photographs. Crosslinking and agglomerating the lignin due to lowering the glass transition temperature at higher moisture content of the LPP grind might be one of the reasons for lignin distribution. In

general, higher moisture content in the biomass results in higher mobility of the lignin molecules. Also temperature and pressure associated in the pelleting process helps lignin to take active part in the cross linking with the other biomass components. Furthermore, in Fig. 16 (a & b) it indicates a network of holes after solidification at ambient temperature that might explain the expansion of the LPP pellet as it extrudes the die. The sudden drop of pressure and vaporization of superheated entrapped water results in porous and fibrous product. The number of holes observed are higher at a moisture content of 39% (w.b.) compared to 33% (w.b.). Also, when pellet extrudes out of the die, lignin embedded in the hemicellulose matrix quickly solidifies and retains a partially open-celled structure. The temperature and pressure associated with pelleting might have resulted in getting the fiber strands cemented with lignin material, which could lead to cross-linking.

(Insert Figure 16 (a & b))

3.8 Comparison of pellets physical properties with international pellet quality standards

Table 4 indicates the comparison of the physical properties of the pellets produced with respect to European wood pellet standards. It is clear from Table 4 that the pellet produced using lower moisture or conventional pelleting process met the highest durability and bulk density standards ($>97.5\%$ and $>700 \text{ kg/m}^3$), established by pellet fuel institute and CEN (European standard). In the case of pellets produced by the high-moisture pelleting process, there are process conditions such as the LPP grind moisture content (33-36% (w.b.)), die speed of 50-60 Hz and preheating temperature of 60–90°C that can help to meet the different durability standard ($>95\%$ and $>90\%$) established by PFI and CEN. According to CEN it is recommended to state the bulk density values when trading in volume basis, whereas PFI has established the values needed to meet the different grades. For utility grade, the bulk density values established should be in the range of 576 to 736 kg/m^3 . Some of the process conditions (moisture content of the LPP grind (33%, w.b.); die speed of 50–60 Hz and preheating temperature of 60–90°C) resulted in bulk density in the range of 552–562 kg/m^3 . These values are very close to lower limits of bulk density value established by PFI for utility grade pellets. These bulk density values can be influenced by changing the length-to-diameter ratio (L/D). The pellet diameter and length produced using this process has met the CEN standards established. However, in the case of PFI standards the diameter of the pellet did not match due to using

an 8-mm die in this current study, but this diameter standard can be met using a 6-mm die in the flat pellet mill. This study has helped to produce pellets with various densities and durability's that can be suitable for short-distance transportation scenarios. The pellets that need to be transported for shorter distances do not need to meet the highest standard established for international transport. Also, the current transportation cost savings by using pellets produced by the conventional process does not totally offset the costs associated with the conventional pelleting process (size reduction, drying, and densification) with all transportation distances. The high-moisture pelleting process that was tested in this present study can reduce the pelleting cost and can make pelleting of woody and herbaceous biomass a viable option for different transportation distances. Also, the cost can be tipped more toward pelleting if additional advantages are quantified, such as handling and storage benefits. Additionally, as the pellets pack the same weight in less than 1/4th of the volume, it reduces the storage footprint and the storage cost. Compared to high-moisture bales, pellets are low in moisture and can be stored for longer durations without any microbial degradation and spontaneous combustion issues.

(Insert Table 4)

Tumuluru et al. (2011) indicated that densification of biomass is critical to improving the handling and conveying efficiencies throughout the supply system and biorefinery infeed. Currently, biorefineries are experiencing challenges in storage, feeding, handling, and transportation ground raw biomass. Also variable moisture (high and low moisture) and less convenient form of biomass aggravate these limitations. Some of the common problem associated with the raw biomass are bridging of the particles that lead to uneven discharge from the silos and jamming of the conveyors, which result in inconsistent feeding to reactors. These issues are greatly dependent on the feedstock moisture content and particle size. Also, high-moisture woody and herbaceous biomasses are not considered by biorefineries for fuels production mainly due to high preprocessing costs (Searcy et al., 2015). Pellets produced using the high-moisture pelleting process compared to raw ground biomass can help overcome the cost and quality issues as they have a uniform size and shape characteristics and low-moisture content. Pellets can also be stored more efficiently (storage foot print reduces by about 2-4 times compared to

baled herbaceous biomass or wood chips), with low moisture in the pellets helping to reduce the spontaneous combustion issues that are typically seen in bales and wood chips storage.

4. Conclusions

Drying of woody biomass is the major energy consumer in wood pellet production process (takes about 70% of the total energy). Pelleting woody biomass at high-moisture content of $\geq 33\%$ (w.b.) helps to reduce the drying cost and, in turn, the total pellet production cost. At a 33% (w.b.) moisture content of the LPP grind, the die speed of about 60 Hz and preheating temperature of about (90°C) pellets with a density of 544 kg/m³ and durability of 95.69% were produced at a specific energy consumption of <116 kWhr/ton. Increasing the moisture content of the LPP grind to >36% (w.b.) and preheating temperatures to >60°C significantly decreased the unit, bulk, and tapped density. Moisture content of the LPP grind in the range of 33 to 35% and higher die speeds >50 Hz maximized durability of the pellets, whereas at the same moisture content increasing the die speed to 60 Hz and preheating temperature to 90°C reduced the specific energy consumption. At higher preheating temperatures of 90°C, some of the woody biomass components (lignin, protein, water soluble carbohydrates, waxes and fatty acids) may have been activated, which results in stronger binding and better flow of material in the die, leading to higher density and durability and lowering the specific energy consumption. Scanning electron microscope studies indicated that lignin mobility resulted in binding at high-moisture content and moisture flash-off during pelleting produced a network of holes, which resulted in a porous product.

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Figures

Fig. 1 - Energy consumption of various unit operations in conventional pelleting process.

Fig.2 - Schematic of the pelleting process (FAO, 1980).

Fig. 3 - Schematic of a high moisture pelleting process (adapted from Lamers et al., 2015).

Fig. 4 - Flat-die pellet mill developed at Idaho National Laboratory (adapted from Tumuluru, 2014; Hoover et al., 2014).

Fig. 5– Process flow diagram for making pellets using high moisture lodgepole pine grind.

Fig. 6 - Diametrical and longitudinal section of the pellet used in unit density measurement.

Fig. 7 - Schematic showing expansion of the high moisture pellet during compression and extrusion in a flat die pellet mill

Fig. 8 - Pellets produced at different process conditions using high moisture lodgepole grind.

Fig. 9 - Effect of preheating temperature and moisture content of lodgepole pine (LPP) grind on pellet moisture content.

Fig. 10 - Effect of preheating temperature and moisture content of lodgepole pine (LPP) grind on unit density.

Fig. 11- Effect of preheating temperature and moisture content of lodgepole pine (LPP) grind on bulk density.

Fig. 12 - Effect of die speed and moisture content of lodgepole pine (LPP) grind on tapped density.

Fig. 13 - Effect of preheating temperature and moisture content of lodgepole pine (LPP) grind on expansion ratio.

Fig. 14 - Effect of preheating temperature and moisture content of lodgepole pine (LPP) grind on durability.

Fig. 15 - Effect of die speed and preheating temperature on specific energy consumption.

Conditions: 33% moisture content, 30 °C pre-heating temperature, 60 Hz die speed

Conditions: 39% moisture content, 60 °C pre-heating temperature, 40 Hz die speed

Fig. 16 (a & b) – Scanning electron microscope photograph of pellets made from high moisture lodgepole pine (LPP) grind.

Tables

Table 1 - Experimental conditions tested for pelleting high moisture lodgepole pine grind.

Pelleting process variables	Experimental limits		
	Coded levels		
	-1	0	+1
Moisture content of lodgepole pine grind (% , w.b.) (x_1)	33	36	39
Die speed (Hz) (x_2)	40	50	60
Preheating temperature (°C) (x_3)	30	60	90

Table 2 – Pelleting experimental data collected based on Box-behnken design.

Expt. No	MC of LPP grind (x ₁)	DS (x ₂)	PHT (x ₃)	PMC (% w.b)	SD	PD (mm)	SD	UD (kg/m ³)	SD	BD (kg/m ³)	SD	TD (kg/m ³)	SD	D (%)	SD	ER	SD	SEC (kWhr/ton)-steady state
1	33	40	60	22.97	1.73	8.25	0.17	892.8	52	435.6	7.1	465.5	4.8	94.90	0.72	1.06	0.045	160.6
2	39	40	60	28.18	2.45	8.45	0.19	872.9	35	426.7	13.5	472.9	3.5	93.94	1.07	1.11	0.049	183.2
3	33	60	60	21.17	2	8.12	0.13	1011	75	533.0	3.7	592.5	1.6	96.42	0.19	1.03	0.034	103.0
4	39	60	60	25.18	4.55	8.30	0.20	938.5	25	467.0	5.5	512.1	7.4	96.35	0.41	1.08	0.053	168.4
5	33	50	30	22.05	1.79	8.12	0.08	1054	82	562.2	7.3	606.7	9.5	96.68	0.21	1.03	0.020	184.4
6	39	50	30	28.93	2.97	8.39	0.15	887.9	77	409.2	3.9	472.6	4.9	93.76	0.32	1.10	0.040	210.2
7	33	50	90	19.56	1.37	8.16	0.09	1012	48	552.4	6.2	601.7	10.3	95.17	0.73	1.04	0.024	141.5
8	39	50	90	31.52	1.22	8.32	0.21	887.9	65	368.1	13.8	422.4	5.9	93.08	0.55	1.08	0.056	145.4
9	36	40	30	22.45	0.71	8.21	0.18	989.8	61	481.5	5.6	526.4	6.2	96.5	0.32	1.05	0.046	151.6
10	36	60	30	21.65	2.54	8.41	0.26	947.9	39	519.6	10.6	567.5	3.6	95.58	1.34	1.10	0.069	157.7
11	36	40	90	25.22	1.03	8.45	0.29	945.9	21	442.1	3.1	482.6	1.6	94.83	0.77	1.12	0.080	165.5
12	36	60	90	20.94	2.88	8.33	0.22	956.4	82	488.7	8.3	544.5	3.2	95.55	0.38	1.08	0.059	118.5
13	36	50	60	23.78	1.62	8.17	0.15	990.2	53	497.3	15.5	554.8	4.9	96.24	0.21	1.04	0.040	172.7
14	36	50	60	22.38	2.71	8.20	0.15	973.0	26	468.3	6.7	538.2	5.8	96.14	0.16	1.05	0.040	165.2
15	36	50	60	22.1	0.55	8.14	0.15	1092	34	510.8	10.5	559.0	7.0	95.34	1.14	1.04	0.039	173.3

Note: MC of LPP grind: Moisture content of lodgepole pine grind (% w.b.), DS: Die speed (Hz); PHT: Preheating temperature (°C); PMC: Pellet moisture content (w.b.); PD: Pellet diameter (mm); UD: Unit density (kg/m³); BD: Bulk density (kg/m³); TD: Tapped density (kg/m³); D: Durability (%); SEC: Specific energy consumption (kWhr/ton); ER: Expansion ratio; SD: Standard deviation

Table 3 – Response surface models developed for lodgepole pine (LPP) pellet properties and specific energy consumption.

Physical property	Model	(R ²)
Bulk density (kg/m ³)	$-3804.57 + 189.4891x_1 + 40.94812x_2 + 3.36945x_3$ $- 2.36944x_1^2 - 0.15647x_2^2 + 0.0019917x_3^2$ $- 0.59658x_1x_2 - 0.10358x_1x_3$ $- 0.0082333x_2x_3$	0.84
Durability (%)	$25.31375 + 5.02583x_1 - 0.5215416x_2 - 0.0994305x_3$ $- 0.080370x_1^2 + 0.0021916x_2^2 - 0.0005675x_3^2$ $+ 0.007417x_1x_2 + 0.002305x_1x_3$ $+ 0.00136x_2x_3$	0.72
Pellet moisture content (% , w.b.)	$304.5375 - 17.4642x_1 + 1.0747x_2 - 0.4174x_3 + 0.2540x_1^2$ $- 0.0066x_2^2 + 0.0005x_3^2 - 0.0100x_1x_2$ $+ 0.0141x_1x_3 - 0.0029x_2x_3$	0.91
Unit density (kg/m ³)	$-6482.38 + 354.72x_1 + 60.60x_2 - 4.94x_3 - 4.938x_1^2$ $- 0.4530x_2^2 - 0.0149x_3^2 - 0.4446x_1x_2$ $+ 0.11756x_1x_3 + 0.04367x_2x_3$	0.66
Tapped density (kg/m ³)	$-4188.41675 + 205.19666x_1 + 46.44579x_2 + 3.509813x_3$ $- 2.46046x_1^2 - 0.17776866x_2^2 - 0.0029540x_3^2$ $- 0.7319166x_1x_2 - 0.12575x_1x_3$ $+ 0.01727x_2x_3$	0.81
SEC (kWhr/ton) - steady state	$375.96 - 31.18x_1 + 7.73x_2 + 4.21x_3 + 0.30x_1^2 - 0.193x_2^2$ $- 0.0031x_3^2 + 0.357x_1x_2 - 0.061x_1x_3$ $- 0.044x_2x_3$	0.85
Expansion ratio	$1.222 + 0.0055x_1 - 0.0217x_2 + 0.0041x_3 + 0.000145x_1^2$ $+ 0.000272x_2^2 + 0.000021x_3^2 - 0.000050x_1x_2$ $- 0.000079x_1x_3 - 0.000072x_2x_3$	0.89

Table 4 - Comparison of pellet properties made from conventional and high moisture pelleting process with European Solid Fuel Standard (CEN) and Pellet Fuel Institute (PFI).

Physical property	Normative			Informative	
	Moisture content (% w.b.)	Durability (%)	Diameter (mm)	Bulk density (kg/m ³)	Unit density (kg/m ³)
CEN standard	$M10 \leq 10\%$	$DU97.5 \geq 97.5$ $DU95.0 \geq 95.0$ $DU90.0 \geq 90.0$	$D06 \leq 6\text{mm} \pm 0.5 \text{ mm}$ $D08 \leq 8\text{mm} \pm 0.5 \text{ mm}$	Recommended to be stated if traded by volume basis	
Pellet Fuel Institute (utility standard)	≤ 10	>95	≤ 10	576-736	
Conventional wood pellets (Yancey et al., 2013; Tumuluru et al., 2010)	<8	≥ 97.5	6	700-750	1150-1200
High moisture lodgepole pine wood pellets (this study)	<8	≥ 90.0 ≥ 95.0	8	368-562	887-1092

Nomenclature

ANOVA	analysis of variance
b_0	intercept
BD	bulk density (kg m^{-3})
b_i, b_j, b_{ij}	coefficients of regression equations
D	durability (%)
DS	die speed (Hz)
ER	expansion ratio
ε	random error
HMPP	high moisture pelleting process
Hz	hertz
LPP	lodgepole pine
MC of LPP	moisture content of lodgepole grind
N	number of independent variables
P	statistical significance
PHT	preheating temperature
PMC	pellet moisture content
R^2	coefficient of determination
RSM	response surface methodology
SD	standard deviation
SEM	scanning electron microscopy
TD	tapped density (kg m^{-3})
UD	unit density (kg m^{-3})
w.b.	wet basis
x_1	moisture content of lodgepole pine grind
x_2	die speed
x_3	preheating temperature
y	dependent variable