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INFLUENCE OF DIE TEMPERATURE AND MOISTURE CONTENT ON THE DENSIFICATION OF BAMBOO POWDER USING DIE HEATING METHOD

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ABSTRACT

Residues of agriculture and forestry are usually exploited as feedstock within pellet production for energy producing applications. Some variables such as moisture content and die temperature strongly influence this process. Bamboo powder was used as the experimental material to produce high quality pellet fuel in this paper. A series of experiments involving pellet production were conducted in different die temperatures and at different moisture contents by a newly-developed pellet extruder using a die heating production method. Unit density and densification pressure were tested with four levels of moisture contents (5, 10, 15 and 20%) at five levels of temperatures (40, 80, 120, 160 and 200°C). The surface quality of the pellets was investigated 6 months after the pellets had been produced. The optimum moisture content is around 10% and a suitable die temperature is 160°C to 200°C when producing bamboo pellets.

KEYWORDS: Biomass, bamboo powder, bamboo pellet, densification pressure, unit density.

INTRODUCTION

World-wide biomass serves as the third-largest energy source behind coal and oil (Bapat et al. 1997). The use of this renewable and environmentally friendly resource of raw material can significantly reduce net carbon emissions. To some extent, biomass provides a good substitute for fossil fuels (Wei et al. 2012). China has an abundance of forestry and agricultural residue resources that can be used to produce biomass feedstock and fuel for energy applications (Xianmiao et al. 2013). However, the low bulk density of biomass limits its direct application because employing this raw material will lead to problems in storage, transportation and use (Eranki et al. 2011, Tumuluru et al. 2010). Various densification methods have been applied to overcome these shortcomings to increase the bulk density of biomass fuels (Tumuluru et al. 2011).

Bamboo forests area are the largest in the world and provides the abundant biomass resources; 39 genera and more than 500 species of bamboo grow in China according to the fourth forest resource survey (Yang 2012). Bamboo, like woody or agricultural biomass, is mainly composed of hemicelluloses, cellulose, and lignin. It is often used for making buildings, tools, furniture and instruments (Dou et al. 2011). However, its anatomical structure results in a low use ratio when processing the material. Harvested bamboo produces a large amount of residues, specifically bamboo powder. When bamboo is processed, 60% - 70% of bamboo become residues such as chips and powder (Chei et al. 201, Gu et al. 2016). Usually some of these residues are used as boiler fuels, and other parts are dumped and burned in the wild. The disposal method in rural areas not only results in serious environmental issues, but also wastes potential as energy resources for an energy sector. Bamboo residues can be used as a clean fuel which hardly produce SO_2 in the burn process (Zeng et al. 2009, Scurlock et al. 2000). After comparing the structure of cells and chemical composition between wood and bamboo, Jiang pointed out the feasibility that bamboo could produce biomass pellets (Jiang et al. 1999). The densified biomass fuel is formed under high pressure, the density of which is much greater than the raw material (Liu 2011). After a series of analysis about bamboo pellets, Liu et al. (2012) and Yang et al. (2013) found it was a kind of biomass solid fuel with commercial value. Use of pellets was shown to have a temperature cooling effect due to carbon sequestration in soil and biomass (Porsö et al. 2016). Therefore, we formed some potentially wasted bamboo powder into bamboo pellets for use in energy applications and investigated the effects of different variables for the densification process and the surface quality of the bamboo pellets.

Previous studies have shown that moisture content, particle size, temperature, material type and densification pressure all affect the quality and density of pellets. Li and Liu (2000) recommended an optimum moisture content of ~8% to produce high-density charcoal briquettes. They also recommended a moisture content of 5-12% to produce high quality logs in terms of density and long-time storage properties for products made from hardwood, softwood, and bark. Liu concluded that the density and durability of bamboo pellets were inversely proportional to the particle size, because smaller particles have a greater surface area in contact during densification (Liu et al. 2013). Smith in their study of briquetting wheat straw, found that the degree of compaction and dimensional stability increased as the temperature increased from 60 to 140°C (Smith et al. 1977). For olive tree pruning residues, Carone et al. (2011) also concluded that temperature was the most important variable influencing the mechanical properties of pellets, followed by the initial moisture content and particle size of the raw material. Miao investigated the amount of energy consumed during the compression of herbaceous feedstock in relation to particle physical properties, preheating, and binding agents. They found that the parameters of preheating temperature, particle size, and moisture content played a significant role in improving the energy efficiency of the process and pellet density (Miao et al. 2012). Nalladurai, and Morey (2009) verified that increasing the strength and durability of pellets would increase pellet density and the specific consumption of energy during pelletisation. Densification pressure is an important factor affecting energy consumption. The greater the densification pressure is, the greater the energy consumption is needed for the densification process. However, very few studies have analysed the effect of temperature and moisture content on densification pressure. Therefore, this article used die heating method to study the laws of it. In the study, bamboo powder was used as the experimental material, and a single pellet extruder, which had a heating tape wrapped on the cylindrical open end die, was developed to conduct tests. A series of experiments was carried out involving the production of pellets using bamboo powder to prove that temperature and moisture content have an effect on the densification pressure and the feasibility of producing bamboo pellets under various conditions, the densification process was observed. The effects of different moisture contents and die temperatures on densification pressure, unit density and surface quality of pellets were also investigated. In particular, the present study (i) assessed the effects of moisture content and temperature on unit density and average densification pressure; (ii) conducted initial work on understanding the influence of moisture content and temperature on the surface quality of bamboo pellets.

MATERIALS AND METHOD

Materials

The bamboo powder used in this study was obtained from a bamboo product factory in Fujian Province, south eastern China. This factory mainly produces tea sets and home furniture using moso bamboo and produces bamboo powder as a residue that is discarded during the manufacturing process. Prior to the experiments bamboo particles were separated using a series of nominal sieve openings of 1.00, 0.50, 0.23, 0.18, 0.15, 0.075 mm. Next, different sizes of bamboo powder were weighed by a digital balance and the mass ratio of different size particles and the whole was calculated (see the Tab. 1). The most of the particles were distributed in the range of 0.075 to 0.15 mm.

Tab. 1: Size distribution of bamboo powder particles.

Sieving opening	1.00-0.50	0.50-0.23	0.23-0.18	0.18-0.15	0.15-0.075
Percentage (%)	6.20	6.47	7.47	2.80	77.06

Bulk density measurements were performed according to a method used by Mani (Mani et al. 2006). A glass cylinder with a volume of 1 L was used (see the Fig. 1). A mass of bamboo powder was weighed using a digital balance and the volume was calculated by reading the scale of the glass cylinder. The weight of five bamboo powder samples was averaged to calculate bulk density and the result was 0.248 $g \cdot cm^{-3}$.

Fig. 1: Illustration of a bulk density test of the bamboo powder.

Preparation of materials

The bamboo powder was dried in a lab drier at 105°C for 24 h, the weight of the bamboo powder before and after drying was measured respectively, and then the initial moisture content (Mi) was calculated by Eq. 1, which was ~5%. Then, the desired moisture content of each sample was adjusted by adding a predetermined amount of water into the powder according to the Eq. 2. Next, the raw materials with different moisture contents were sealed in individual plastic bags at ambient temperature for 3 days before the experiment to allow moisture to become more uniformly distributed. In this way, we obtained raw materials with a moisture content of 5%, 10%, 15% and 20%.

$$M_i = \frac{m_1 - m_0}{m_1} \times 100 \quad (\%) \tag{1}$$

where: M_i - the initial moisture content,
m_1 - the weight before drying,
m_2 - the weight after drying.

$$M_c = \frac{m + m_1 - m_0}{m + m_1} \times 100 \quad (\%) \tag{2}$$

where: M_c - the desired moisture content,
m - the weight of predetermined amount of water.

Experimental equipment

For this study, the researchers designed a newly-developed pellet extruder for pelletisation that was manufactured and assembled in the lab of Beijing Forestry University (see the Fig. 2).

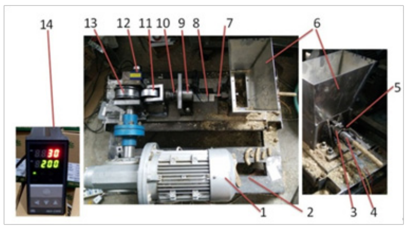

Fig. 2: Mechanical structure of the newly-developed pellet extruder.

1. Reducer, 2. Frame, 3. Heating tape, 4. Cylinder die, 5. Thermocouple, 6. Hopper, 7. Piston, 8. Pressure sensor, 9. Sliding bearing, 10. Spring, 11. Rolling bearing, 12. Displacement sensor, 13. Eccentric wheel, 14. Temperature controller and monitor.

As shown in the Fig. 2, a reducer provided a power source with a specified rotation of 50 rpm, and it drove the rotation of the eccentric whose linear eccentricity was 15 mm. When the eccentric rotated, it drove the rolling bearing that was set up on one side of a piston 16 mm in diameter to reciprocate along with the sliding bearing in the axis of the piston. The piston reached to the end position when the eccentric and the rolling bearing contact points reached the farthest point from the axis of the eccentric. Then, without the energy from the eccentric, the return spring began to work to push the piston back into position at the other end. A cylinder die of 16 mm inside diameter and 72 mm in length was installed in the end of the piston. The length-diameter ratio of the cylinder die was 4.5. The cylinder die was wrapped by a heating tape with a thermocouple, used to preheat the cylinder die to a certain temperature by controlling and monitoring the temperature. A pressure sensor was connected to the piston and the rolling bearing to test the force required in the densification process. In addition, a displacement sensor was fixed on the frame to test the displacement with the reciprocating motion of the rolling bearing. A data acquisition system was designed to acquire the data from the pressure and displacement sensors simultaneously. Thus, the derived data of the pressure and the displacement had a one to one correspondence.

Average densification pressure and pellet unit density test

Bamboo powder was fed into the hopper, stirred by a screw set up at the bottom of the hopper to ensure uniform feed occurred in front of the piston. Each experiment with different temperatures and different moisture contents was conducted for 2 minutes. The temperature was controlled at 40°C, 80°C, 120°C, 160°C and 200°C and the moisture content was adjusted to 5%, 10%, 15% and 20%, as needed. During the experiment, pressure values were acquired in each single pouch by a pressure sensor. There was a maximum pressure in every single pouch, and the average densification pressure refers to the average number of all the maximum pressure values in each 2-minute experiment. Each experiment in the same condition was repeated three times, and then the average densification pressure was calculated.

The density of the pellets was calculated by measuring the length and the diameter of each pellet using an electronic calibre and by measuring the mass of the pellet using an electronic balance (Model SF-400A, Suofei electronic balance factory, Jiangsu, China) with a precision of 0.01 g. The edges of the pellets were smoothed to achieve a precise volume prior to testing. Pellet unit density was calculated by dividing the mass of each pellet by its volume (Abedin 2012). During the experiment, pellets produced in each 2-min test were sealed in individual zip lock bags and kept in the laboratory.

RESULTS AND DISCUSSION

Effects of die temperature and moisture content on average densification pressure

In this study, we discovered a strange phenomenon occurred when the moisture content was 5%. The bamboo particles squeezed out by the piston from the die were still in powder form within the temperature range of 40°C to 200°C. This was probably because water acts as a film type binder with hydrogen bonding by increasing the contact area of the particles (Jiang et al. 2014), and without enough water particles could not be bound together. Thus the low moisture content may have led to bamboo particles that were squeezed out by the piston from the die that were still in a powder form. In addition, pellets could not be squeezed out from the pellet extruder with 10% moisture content at 40°C. Therefore, we mainly analysed and discussed the experimental results of only the alternative conditions when pellets were properly formed.

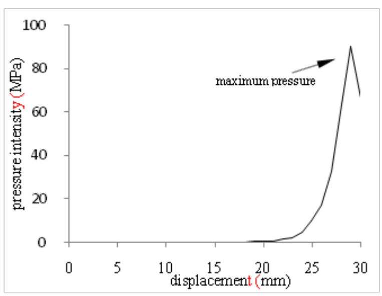

Fig. 3: The curve representing changing of pressure intensity in relation to displacement in a pouch.

The Fig. 3 shows the changing trend of pressure intensity with displacement. From this figure we can conclude that the pressure increased slowly when displacement increased from 0 mm to 25 mm. However, when displacement increased from 25 mm to 30 mm, the pressure increased significantly, and then peaked when displacement reached 30 mm. The experimental data and calculation analysis of average densification pressure and unit density are shown in the Tab. 2.

Tab. 2: The experimental data and calculation analysis.

Test number	Die temperature (°C)	Moisture content (%)	Average pressure (MPa)	Test number	Die temperature (°C)	Moisture content (%)	Unit density (g·cm-3)
1	40	10		1	40	10	
2	40	15	104.76	2	40	15	1.13
3	40	20	43.19	3	40	20	0.90
4	80	10	171.44	4	80	10	1.20
5	80	15	80.63	5	80	15	1.03
6	80	20	29.46	6	80	20	0.79
7	120	10	145.36	7	120	10	1.13
8	120	15	58.08	8	120	15	1.01
9	120	20	32.01	9	120	20	0.83
10	160	10	118.18	10	160	10	1.11
11	160	15	59.89	11	160	15	0.98
12	160	20	27.78	12	160	20	0.80
13	200	10	134.21	13	200	10	1.10
14	200	15	48.36	14	200	15	0.90
15	200	20	26.52	15	200	20	0.75
K1	147.950	569.190		K1	2.030	4.540	
K2	281.530	351.720		K2	3.020	5.050	
K3	235.450	158.960		K3	2.970	4.070	
K4	205.850			K4	2.890		
K5	209.090			K5	2.750		
k1	73.975	142.298		k1	1.015	1.135	
k2	93.843	70.344		k2	1.001	1.010	
k3	78.483	31.792		k3	0.990	0.814	
k4	68.617			k4	0.963		
k5	69.697			k5	0.917		
R	25.223	110.506		R	0.433	0.321	

According to the experimental data in the Tab. 2, the line chart of the relationship between die temperature and the average densification pressure and the unit density was drawn at different levels of moisture contents as shown in the Figs. 4 and 5. The following conclusions can be drawn from the Fig. 4. When the moisture content was 10% or 15%, the average densification pressure gradually decreased with an increase at die temperature. However, when the moisture content was 20%, all of the average densification pressures were small at any experimental die temperature. The average densification pressure at 40°C is higher than at other temperatures, and it was almost equal at 80°C, 160°C, and 200°C. It is shown that the die temperature had an influence on the average densification pressure at the level of 10% and 15% moisture content and the effect was not obvious at the level of 20% moisture content by using die heating method.

This drop in pressure was caused by the glass transition temperature of the lignin, cellulose and hemicellulose in the bamboo powder. As these materials softened, they could be used not only as binders to improve the binding ability of the particles, but also acted as lubricants reduced the densification pressure which increased throughout during pelletisation.

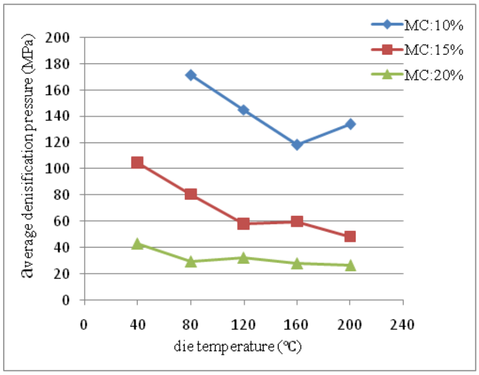

Fig. 4: Effects of die temperature and moisture content on average pressure placed on bamboo pellets.

As can be easily deduced from the Fig. 4, moisture content had strong influence on the average densification. We can conclude that when under the same die temperature, a higher moisture content results in a smaller average densification pressure. With increasing moisture content, the average densification pressure dropped significantly at the same die temperature. For example, with the die temperature was 80°C, the average densification pressure decreased sharply from more than 160 MPa with 10% moisture content to 80 MPa with 15% moisture content, and then decreased to less than 30 MPa with 20% moisture content. That is, a 5% increase in moisture content produced a 50% decrease in the average densification pressure. The main reason may be that water acted as a lubricant improving the throughout of the pellets.

According to the above results, the bamboo particles squeezed out by the piston from the die were still in a powder form when the moisture content was 5% and the value of R in the Tab. 2. One can easily conclude that the most important factor for the average pressure was moisture content when producing pellets by die heating method, followed by die temperature.

By fitting the experiment data of the average densification pressure, die temperature and moisture content with multiple linear regression analysis, the analysis results were shown in the Tabs. 3 and 4. According to the analysis results of the Tab. 4, all of the value of P is less than 0.05 under the significant level of selection 0.05. It is considered that both die temperature and moisture content have a significant effect on the average densification pressure. And the value of coefficients of intercept, die temperature and moisture content also are shown in the Tab. 4, we can conclude that there is the regression equation (Eq. 3) between die temperature, moisture content and average pressure, and the value of R^2 is 0.9573 according to the Tab. 3.

$$Z = 279.37 - 0.223X - 11.349Y \tag{3}$$

where: Z - the value of average pressure,
X - the value of die temperature,
Y - the value of moisture content.

Tab. 3: Regression statistics of the value of the average pressure.

Regression statistics	
Multiple R	0.957305413
R square	0.916433653
Adjusted R square	0.901239772
Standard error	15.39890708
Observation value	14

Tab. 4: Remarkable analysis of die temperature and moisture content to the average pressure.

	Coefficients	Standard error	t Stat	P-value
Intercept	279.373206300	20.22713606000	13.811802400	2.708E-0800
Die temperature	-0.222854587	0.00766883930	-2.905936333	0.014292539
Moisture content	-11.344819050	1.041156147000	-10.896366580	3.1153E-070

Effects of die temperature and moisture content on the unit density of bamboo pellets

The effects of die temperature at different levels of moisture contents on unit density are shown in the Fig. 5. In our study, the overall unit density exhibited a small declining trend when the temperature increased with the same moisture content, the Fig. 5 illustrates this phenomenon. Unit density decreased from 1.197 at 80°C to 1.133 g·cm^{-3} at 200°C with the moisture content of 10%, from 1.133 at 40°C to 0.901 g·cm^{-3} at 200°C with the moisture content of 15%, and from 0.897 at 40 °C to 0.753 g·cm^{-3} at 200°C with the moisture content of 20%. With an increase in temperature, lignin reached its glass transition temperature, and acted as a binder to improve the binding ability of particles resulting in a slight drop in unit density.

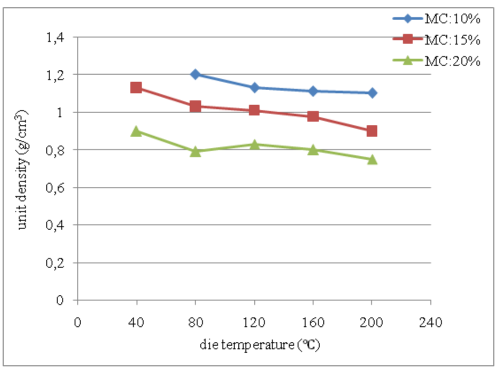

Fig. 5: Effects of die temperature and moisture content on the unit density of bamboo pellets.

From the Fig. 5, it can be concluded that when the moisture content increased from 10% to 20 %, the unit density decreased obviously at the same die temperature. For example, the unit density was 1.197 g·cm^{-3}, 1.034 g·cm^{-3} and 0.786 g·cm^{-3} with 10%, 15 % and 20% moisture content at 80°C, respectively. This illustrates that the unit density is inversely proportional to the moisture content at the same die temperature. The unit density decreased because moisture trapped within the particles may prevent complete flattening and the release of natural binders from the particles because of the incompressibility of water (Nalladurai and Vance 2009). The hydrogen bonds between polymers of particles may also be replaced by bonds to water molecules, resulting in the formation of a film of water between particles. Water film lubricates the mixture allowing the particles to slide relative to each other, causing a reduction in density. By comparing the value of R in the Tab. 2, it can be found that a die temperature had a stronger influence on a unit density than its moisture content.

The experiment data of the unit density, the average densification pressure and the moisture content were analysed by the multiple linear regression analysis. The analysis results were shown in the Tabs. 5 and 6. According to the analysis results of the Tab. 6, all of the value of P is less than 0.05 under the significant level of selection 0.05. It is considered that both the die temperature and the moisture content have a significant effect on the average densification pressure. And the value of the coefficients of intercept, the die temperature and the moisture content also was shown in the Tab. 6, we can conclude that there are the regression equation (Eq. 4) between the die temperature, the moisture content and the average pressure, and the value of R^2 is 0.9684 according to the Tab. 4.

$$Z = 1.711 - 0.001X - 0.038Y \tag{4}$$

where: Z - the value of the unit density,
X - the value of the die temperature,
Y - the value of the moisture content.

Tab. 5: Regression statistics of the value of the unit density.

Regression statistics	
Multiple R	0.968366466
R Square	0.937733612
Adjusted R Square	0.926412451
Standard error	0.045386797
Observation value	14

Tab. 6: Remarkable analysis of the die temperature and the moisture content to the unit density.

	Coefficients	Standard error	t Stat	P-value
Intercept	1.710625397	0.059617537	28.693325470	1.08191E-11
Die temperature	-0.001051349	0.000226032	-4.651336068	0.000703552
Moisture content	-0.038476190	0.003068708	-112.538239560	7.40069E-08

Pellet surface quality affected by moisture content and die temperature

Pellet quality has an important influence on the storage and transportation as well safety degree. The pellets may be transported and stored risk free for a long time after being produced. Therefore, we mainly investigated the surface quality of the pellets after they were produced.

Effects of die temperature

After being stored for 6 months, all of the pellets with a 10% moisture content at any die temperature still retained their original shape and had a good surface quality (see the Fig. 6). Their surface was still smooth and the pellet rarely had fractures on the surface.

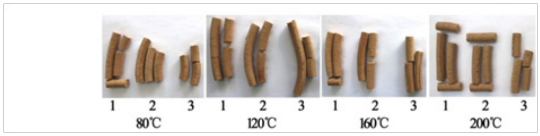

Fig. 6: Pellets samples with 10% moisture content produced at 80°C, 120°C, 160°C and 200°C.

With an increasing of die temperature, the number of fractures observed on pellets with a moisture content of 15% increased significantly (see the Fig. 7). In addition, the pellets had a small number of fractures on the surface perpendicular to the pellet's axis.

Fig. 7: Pellets samples with 15% moisture content produced at 40°C, 80°C, 120°C, 160°C and 200°C.

With a moisture content of 20% at a temperature from 40°C to 120°C almost all pellets broke into pieces after being extruded from the die (see the Fig. 8)

Fig. 8: Pellets samples with 20 % moisture content produced at 40°C, 80°C, 120°C, 160°C and 200°C.

However, at a moisture content of 20 % the particles could be pelletized when the die temperature increased to 160°C and 200°C. Although the bamboo powder can be pelletized at the 20% moisture content, the pellets had a large number of fractures on the surface. Therefore, they are not suitable for storage and transportation with the 20 % moisture content at any die temperature.

Effects of moisture content

From the Figs. 6 to 8, one can conclude that a lower moisture content was favourable for producing pellets with good surface quality. For example, all of the pellets made with 10% moisture content at temperatures from 80°C to 200°C had a very smooth surface and rarely had fractures on the surface. In contrast, pellets with 15% and 20% moisture content had many fractures on the surface. Therefore, we concluded that a relatively low moisture content also allowed particles to be pelletized into longer pellets. Thus, longer pellets were easily produced at a moisture content of 10% and 15% when compared with those having 20% moisture content. After heating, water induces a variety of physical and chemical changes such as the denaturation of proteins, thermal softening of biomass, gelatinization of starch, and consecutive recrystallization of carbohydrates (Nalladurai and Vance 2010), which may be what caused pellets to break under relatively high moisture content conditions (Jiang et al. 2014).

Mildew on surfaces of pellets

Changes occurred on the surface of some pellets after 6 months of storage in the lab. For the pellets with 10% moisture content, no change was observed from their initial form. However, pellets with moisture content of 15% and 20% became mouldy after six months of storage. More specifically, for the pellets with 15% moisture content, all the pellets formed at temperatures from 40°C to 120°C had mould growth covering the surface. However, mould did not grow on pellets formed at temperatures at 160°C and 200°C. Interestingly, for the samples with 20% moisture content, no mould grew on the surface of the pellets formed at temperatures from 40°C to 120°C. However, pellets formed at temperatures at 160°C and 200°C had more mould when compared with samples having 15% moisture content when formed (see the Fig. 9).

(a) (b) (c)

Fig. 9: Details of sample pellets with moisture content and produced at temperatures of (a) 10%, 80°C; (b) 15%, 40°C; (c) 20%. 200°C.

The reason mould formed on the pellets could be that bamboo was rich in starch, protein, fat and other nutrients; therefore, samples with high moisture content easily attracted the growth of mildew (Li et al. 2014). According to this phenomenon, one can predict that if pellets are stored for a longer period of time, perhaps all of the pellets with moisture content of 15% and 20% will grow mould on their surfaces.

CONCLUSIONS

Within this study, the pelletisation process of bamboo powder was observed to investigate the densification pressure, unit density and surface quality using a newly-developed pellet extruder by die heating method. Moisture content and temperature significantly influenced the densification pressure, unit density and surface quality. With an increase in moisture content, the average densification pressure and unit density will decrease at the same die temperature. In addition, with an increase in die temperature, the average densification pressure and unit density will decrease at the same moisture content. Bamboo pellets with a high moisture content will have many fractures on the surface, and may even break into small pieces during production. And most of the pellets with 15% and 20% moisture content at the time of production had mould growth covering the pellet surface after 6 months of storage.

According to the above results, a relatively high moisture content is not favourable for pelletisation. The optimum moisture content is around 10% and a suitable die temperature is 160°C to 200°C when producing bamboo pellets. These conditions will reduce energy consumption because of the relatively low die temperature, and will produce bamboo pellets with the highest quality.

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