PELLETIZATION EXPERIMENTS ON BIOMASS RAW MATERIAL PRE-OPTIMIZATION SYSTEMS

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To further investigate the effects of temperature on biomass densification and roller-type pelletization machines during production, this study developed a pre-optimization system to heat the raw materials. A two-factor experimental study was conducted using flat die pelletizers and pine wood chips at temperatures of 30 °C, 50 °C, 70 °C, 90 °C, and 110 °C, and raw material moisture content levels of 8%, 11%, 14%, and 17%. The experimental results demonstrated that the interactions between temperature and raw material moisture content significantly influence the production rate, the pelletization success rate, and the power consumption. The optimal parameter combination was 70 °C and a raw material moisture content of 14%. The corresponding production rate, pelletization success rate, and power consumption were 295.2 kg/h, 100%, and 0.061kWh/kg, respectively. After implementing the new system, the production rate and pelletization success rate increased by 20.59% and 1.9%, respectively, whereas the power consumption decreased by 19%.This paper is illustrated that temperature can effectively improve pellets quality and reduce power consumption In the granulation process by experiments, and the optimum heating temperature could be adjusted according to the moisture content of the raw material during actual production.

Keywords: Temperature; Pelletization; Moisture content; Interaction

1. Introduction

Biomass compaction is described that the dried and crushed biomass raw materials undergo a process of mechanical and plastic deformation exposed under a certain of temperature, humidity, and pressure, which was then compressed into a kind of solid fuel with regular shape, high density and high combustion value for the convenient transportation and storage. [1, 2]. Biomass densification technology has changed the traditional methods of biomass energy utilization by converting loose biomass into dense molded fuels, which is currently one of the most effective and relatively popular technologies of large-scale biomass energy utilization [3, 4].

Recently, researchers have conducted relevant studies based on the

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characteristics of different biomass raw materials and pelletizers. It is pointed out that mold temperature is the main factor affecting pellet production rate, but mold temperature is not controllable, so further research and development of densification technology with raw material heat treatment are needed [5]. The single-pore pellet mills are employed to carry out hot pressing tests, and it is discovered that rice straw and wood chips mixed in a 1:1 ratio gives pellets better physical properties; meanwhile temperature variations influence the particle binding mechanism and enable pressure reduction [6]. Through studying densification of willow branches and wheat straw, it is discovered that the effects of temperature on pellet quality are greater than those of pressure; and proposed that future research should focus on standardization of pelletization, especially the upper and lower limits of the raw material moisture content [7]. From the research on residues from olive tree processing, it is concluded that temperature is the most critical factor to the mechanical properties of pellets; and that high temperature, low moisture content, and relatively small grain size produce the best-quality pellets, while pressure imposes almost no effect [8]. A temperature control system customized for ring-shaped molds is employed to carry out experiments on mixed sawdust. Independent tests were done across various conditions, such as mold temperature, moisture content, and steam treatment [9]. Under the collective effects of mold temperature and other factors, higher mold temperature can result in better pellet quality and reduced power consumption.

When densification experiments are carried out on cow feces, it was discovered that the power consumption due to compression increases with the moisture content of raw materials sieved through 30-mm mesh sieves, when the moisture content is in the range of 15% to 20% [10]. However, when the moisture content is 20% to 25%, the power consumption due to compression reduces as the moisture content increases. For raw materials sieved through 50-mm mesh sieves, the power consumption due to compression decreases with the moisture content. Aquatic plants are prepared with different moisture contents and compressed with cylindrical and square molds [11]. The optimal moisture content, pressure, and temperature were determined to be 7-10%, 31.4 MPa, and 85-105 °C, respectively. It is conducted uniaxial densification experiments on spruce sawdust using a hydraulic piston machine at room temperature, and it is pointed out that moisture content is a limiting parameter for briquette quality [12]. The wood chips used for pelletization must fulfill certain moisture content conditions. The acceptable moisture content range for spruce sawdust is 11-16%, and the optimal value is 13%. It is considered pre-compression as a way to boost the production of reed pellets, and multivariable linear regression models are utilized to perform experimental design on factors like moisture content and density of the raw material, steam addition volume, and mold temperature to obtain the optimal combination of parameters for high-quality pellet production [13].

These studies often considered heating temperature and raw material moisture content as important factors. When temperature conditions are examined, compression tests using single-pore pellet mills are often performed to investigate the effects of temperature on pellet quality. Hence, it is necessary to conduct research, which accounts for production equipment based on the actual conditions in China. Based on the current prevalent use of roller-type pelletizers in China [14], this study utilized a flat die pelletizer as the densification experimental equipment and mostly wood chips as raw materials, the main constituents of which are cellulose, hemicellulose, and lignin [15]. Among the various factors influencing pellet properties, such as type, ground grain size and moisture content of raw materials, heating temperature, and binders heating temperature and raw material moisture content were selected as the main contributing factors in this study [16]. Since wood chips contain comparatively more lignin, when temperature increases, lignin gradually softens and causes binding of grains [17, 18]. Therefore, pellet quality can be enhanced without further addition of binders. This also reduces power consumption in palletization. Because heating affects the mold life span and the heating efficiency is low, raw materials are instead heated in this study. The energy consumed due to heating is considered, and the optimal heating temperature can be selected through experiments to effectively lower the total power consumption.

To further examine the effects of temperature on pellet quality, production rate, and power consumption during production, a raw material pre-optimization system was developed to heat the raw materials before they enter the pelletizer in this study. Two-factor experiments including temperature and moisture content were conducted by using pine wood chips to explore the optimal combination of heating temperature and moisture content to ensure we can get the product with best quality, maximum yield and minimum energy consumption during the production.

2. Materials and Methods

2.1 Test Materials

Raw materials used in this study are pine wood chip residues from wood processing plants. They are chip-shaped with a grain size of 3 mm. Based on the actual production using a flat die pelletizer, pelletization is basically impossible, when the raw material moisture content exceeds 20%. Based on the experience of other researchers, the raw material moisture content can be controlled to be within 20% during experiments [19, 20]. After the raw materials were stored under natural conditions for one month, their original moisture content was measured (6.32% mean). Subsequently, they were dried and water was added to prepare test specimens with moisture contents of 8%, 11%, 14%, and 17%. Each specimen weighed 150 kg and was sealed.

2.2 Experimental Equipment

The experimental equipment is as shown in Figure 1. The ZLMG300 roller-type flat die pelletizer (with a nameplate capacity of 22 kW; length and diameter of compression channels of 26 mm and 6 mm, respectively; cone depth of 3 mm; and compression ratio of 3.83) manufactured by Anyang Jim Kenengyuan Machinery Co., Ltd. in China was used. During operation, the mold plate was stationary and the roller rotated to squeeze raw materials into the mold plate. Raw materials were transported from the feeder to the conditioner, where the raw material pre-optimization system is installed. Induction heating coils were wound around the underside of the outer wall of the system. Four temperature transducers were set up to measure the heating temperature of the system. The control system allowed the heating temperature to be set (300 °C maximum). When the temperature reached the set value, the system switched to a mode to keep the specimen warm.

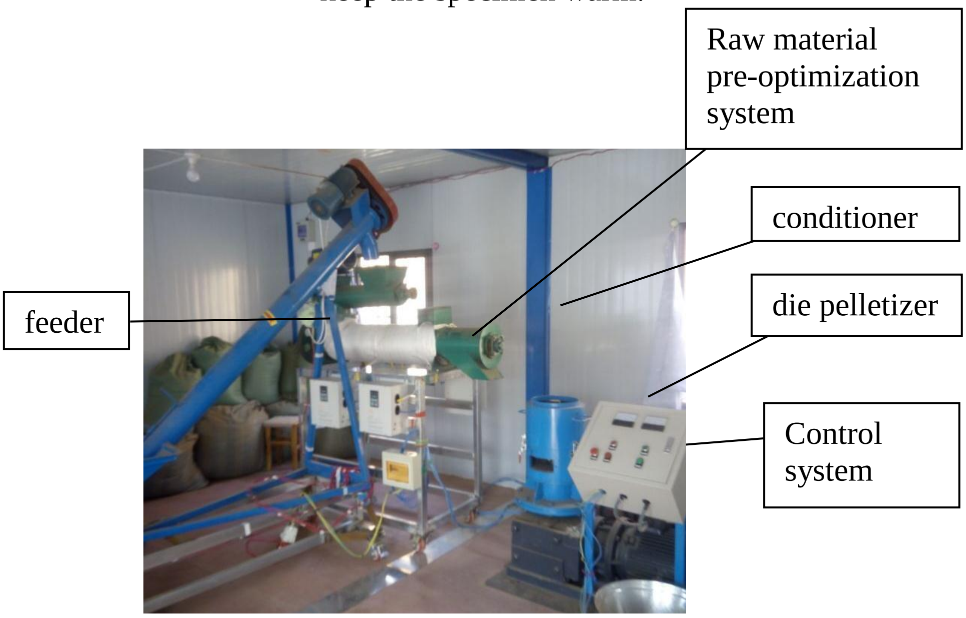

Fig1 Experimental equipment

2.3 Test Methods

The test was divided into an adjustment stage and a measurement stage. For each test, raw materials prepared with a certain moisture content were transported from the feeder to the conditioner for pre-heating and then to the pelletizer. At this time, the test entered the adjustment stage. As pellet production became steady, the test entered the measurement stage. Samples produced within two minutes from this moment were collected in a 30-L stainless steel container. They were cooled in situ and then weighed to determine the production rate as well as the pelletization success rate. After that, the samples were put into sample bags and sealed. The total work done by pre-optimized system and the whole equipment was recorded continuously by data recorder during the experiment.

2.4 Test Indicators

2.4.1 Work

The work done by heating raw materials with pre-optimized system was recorded continuously by three-phase smart power measuring apparatus, which was defined as heating work (WR) .The work done by the entire pelletization system (including the raw material pre-optimization system) is denoted as W_Z and was continuously measured by a power meter (DW-6093, by Lutron Electronic Enterprise Co., Ltd., Taiwan). Deducting the work done by the pre-optimization system from that of the entire system gives the work done during the entire pelletization process, which is defined to be W_J, and $W_J = W_Z – W_R$.

2.4.2 Production rate

Two minutes after the entire system operated normally and steadily, the pellets produced were collected using a 30-L stainless steel container. Then, their weight was measured and converted into the production rate P_r (kg/h).

2.4.3 Pelletization Success Rate

In order to obtain representative samples, a soil divider was used to split the pellet samples, and a standard 4-mm mesh sieve was used to screen the samples manually. The ratio of the mass of the pellets remaining in the sieve after screening to the total mass before screening production rate the pelletization success rate is B_r (%).

2.4.4 Power Consumption

The raw material pre-optimization system will increase the power consumption of the pelletization equipment. Hence, in this study, the total power consumption C_z refers to the power consumption of the whole production system, including the pre-optimization system, while the net power consumption C_j is the power consumption of the production equipment after the pre-optimization system power consumption is removed. To account for the pelletization success rate, test indicators also include the effective total power consumption C_{zb} and the effective net power consumption C_{jb}, where $C_{zb} = C_z \times B_r$ and $C_{jb} = C_j \times B_r$, respectively.

2.5 Experimental Design

A two-factor experimental design was employed in this study. Experiments on the optimization of pine wood chip pelletization through pre-heating was carried out at different temperatures set by the raw material pre-optimization system (30 °C, 50 °C, 70 °C, 90 °C, and 110 °C, where 30 °C is the temperature at which the pre-optimization system is not in use and acts as the control) under different moisture content conditions (8%, 11%, 14%, and 17%). The experiment for each combination was repeated five times. With the help of the IBM SPSS Statistics software [23], analysis of variance (ANOVA) and multiple comparisons on experimental data were performed. The optimum range of the raw material pre-optimized system temperature and the raw material moisture content were determined by analyzing the relations of moisture content and raw material pre-optimization system temperature versus work, output (production rate) and successful pelletization rate by the means of orthogonal test.

3. Results and Discussion

3.1 Effects on Work

The ANOVA results for the experimental data revealed that the work of heating is significantly affected by temperature ($p = 0.009$), moisture content ($p < 0.001$), and their interactions ($p < 0.001$). As illustrated in Figure 2(a), as temperature rises, work of heating gradually increases. At 30 °C, 50 °C, and 110 °C, moisture content does not significantly impact work of heating. At 70 °C, the raw material moisture content of 14% leads to the greatest work of heating. This is probably because at a moisture content of 14%, water and other substances in the raw material, such as lignin, are optimally mixed. At 70 °C, the raw material absorbs heat more easily for softening and binding (the subsequent test results also verify this assumption). As temperature continues to increase and reaches 90 °C, raw materials of different moisture content show different degrees of softening and work of heating. At 110 °C, water in raw materials basically evaporates and disappears. Thus, moisture content does not remarkably influence work of heating.

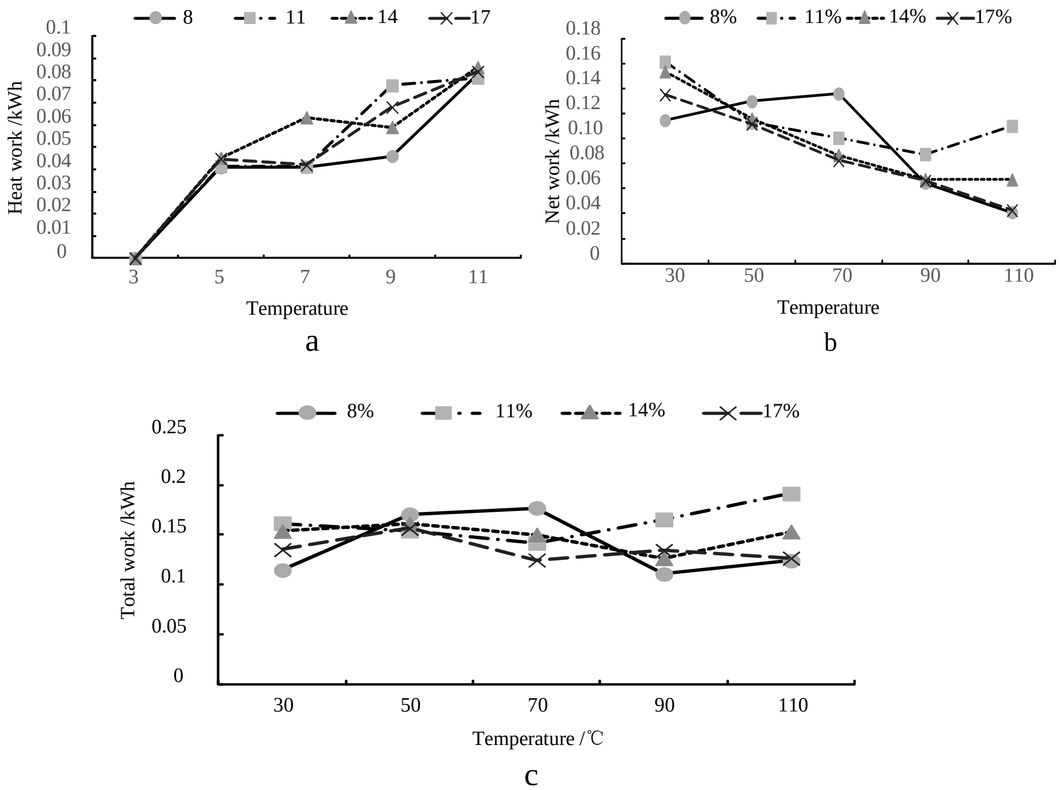

Fig.2 Effect of temperature and moisture content on work

The net work done is significantly affected by temperature, moisture content, and their interactions ($p < 0.001$ for all parameters). Figure 2(b) shows that, for raw materials with 11%, 14%, and 17% moisture content, the net work required for pelletization gradually decreases with moisture content as temperature increases. This is because water acts as a lubricant, and reduces the friction between wood chips. As temperature rises, lignin gradually softens and gains higher mobility. Therefore, raw materials can enter the pores of the equipment more easily, and the work done by the rollers is reduced. When temperature is higher than 90 °C, a large amount of water vapor is present between raw material grains [8], which is hindering the grains from entering the pores, to a certain degree. Thus, the net work slightly increases. As illustrated in Figure 2(b), the net work at a moisture content of 11% increases more remarkably, compared to those at 14% and 17%. When the raw material moisture content is 8%, the obstruction due to water vapor is greater at 30 °C to 70 °C. Hence, the net work progressively increases and attains its maximum at 70 °C. At 70 °C to 110 °C, water evaporation becomes increasingly complete. Raw materials become dry and brittle, which are gradually carbonized. The friction is reduced, and the pelletization success rate substantially drops (Figure 3,4). As a result, the net work declines.

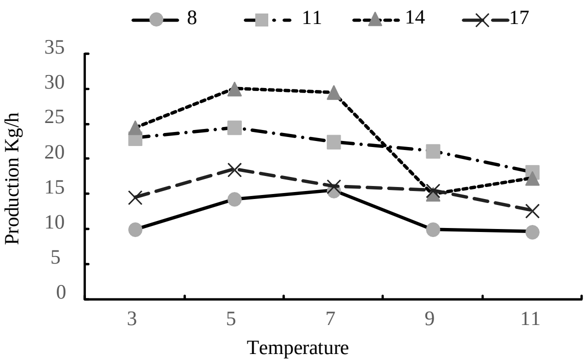

Fig.3 Effect of temperature and moisture content on production

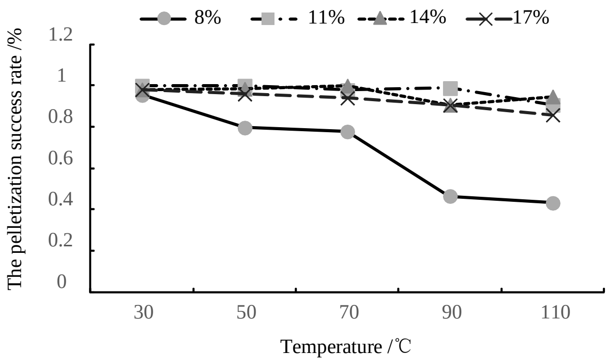

Fig.4 Effect of temperature and moisture content on ratio of briquetting

The total work is significantly influenced by temperature, moisture content, and their interactions ($p < 0.001$ for all parameters). From Figure2©, at 30 °C to 90 °C, the total work does not change much with moisture content. At 110 °C, since the decrease in the net work becomes steady and the work of heating increases rapidly, the total work increases.

3.2 Effects on Production rate and Pelletization Success Rate

The ANOVA results indicate that the production rate is significantly affected by temperature, moisture content, and their interactions ($p < 0.001$ for all parameters). When the raw material moisture content is within the range of 8% to 14%, the production rate increases with moisture content. Nevertheless, when the moisture content reaches 17%, the production rate substantially decreases, as shown in Figure 3. Therefore, overly high or low moisture content is not conducive to production rate improvement. The optimal moisture content range has to be determined. From Figure 3, when the raw material moisture content is 11% to 17%, the production rate is at its maximum at 50 °C. When the moisture content is 8%, the production rate attains its maximum at 70 °C. This suggests that an increase in moisture content reduces the optimal temperature of the raw material pre-optimization system.

Since the effects of the interactions between temperature and moisture content are significant, in order to obtain the optimal combination of these two parameters for the highest production rate, ANOVA and multiple comparisons were carried out using their interactions as one factor. The results are listed in Table 1. Treatment group 7 (moisture content 14%, temperature 50 °C) and group 11 (15%, 70 °C) give the highest production rate. There are no obvious differences between these two treatment groups, but they are considerably different from other groups.

The pelletization success rate is significantly influenced by temperature, moisture content, and their interactions ($p < 0.001$ for all parameters). As shown in Figure 4, the pelletization success rate is relatively high without significant variations except, when the moisture content is 8%. When the moisture content is 8%, as temperature rises, raw materials are gradually dried and carbonized, and they become brittle and are easily fractured. Binding becomes relatively hard, seriously influencing pelletization. Therefore, as temperature increases, the pelletization success rate reduces considerably, when the raw material moisture content is 8%. Thus, to ensure pelletization performance, pine wood chips with moisture content lower than 8% should not be used when employing the pre-optimization system. Because the impacts due to the interactions between temperature and moisture content are significant, multiple comparisons were conducted. From Table 1, treatment group 7 (moisture content 14%, temperature 50 °C) gives a pelletization success rate of 98.84%, while group 11 (14%, 70 °C) has a rate of 100%. Treatment group 6 (11%, 50 °C) has a success rate of 100%, but a lower production rate.

3.3 Effects on Power Consumption

Temperature, moisture content, and their interaction significantly impact the net power consumption ($p < 0.001$ for all parameters). From Figure 5(a), as temperature rises, the net power consumption drops, when the moisture content is 8% and 17%. When the moisture content is 11% and 14%, the net power consumption shows a U-shaped variation curve, and attains its minimum at 70 °C.

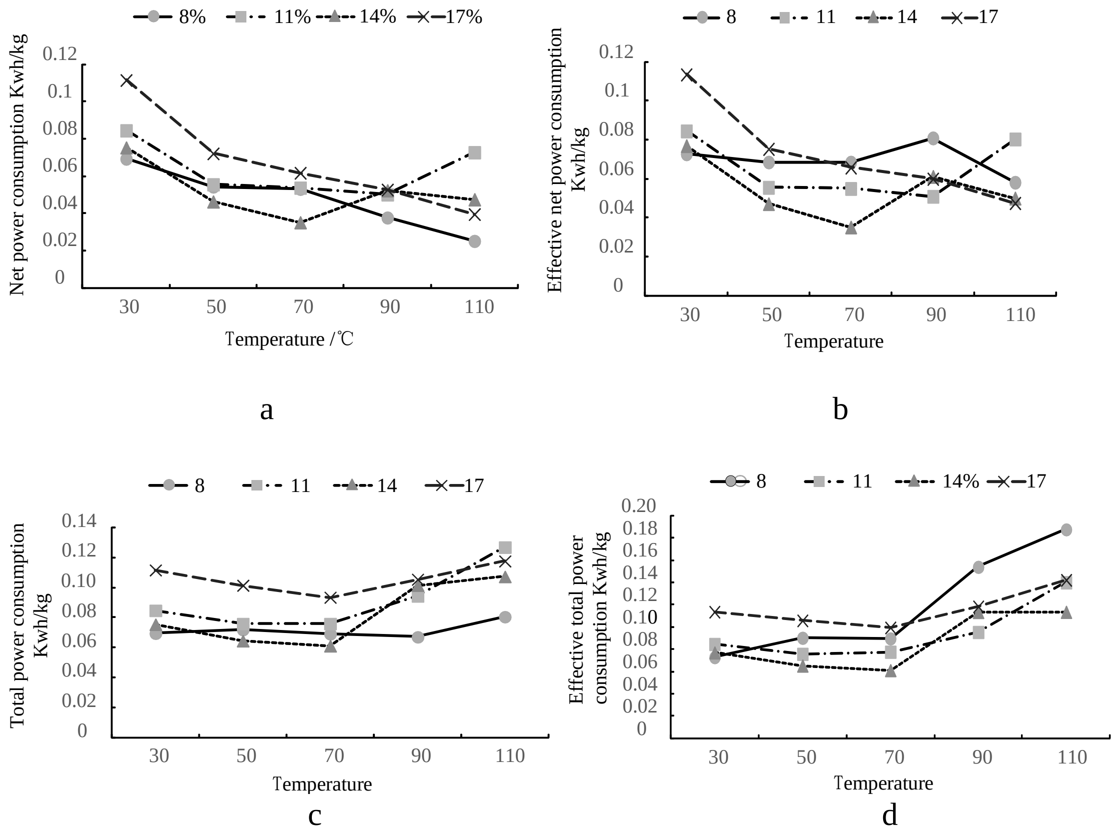

Fig.5 Effect of temperature and moisture content on power consumption

Temperature, moisture content, and their interaction impose significant influences on the effective net power consumption ($p < 0.001$ for all parameters). From Figure 5(b), since the production rate and the pelletization success rate are relatively low when the raw material moisture content is 8%, the effective net power consumption is relatively high overall. The effective net power consumption and the net power consumption show no obvious variations under other moisture content values. When the moisture content is 14%, the effective net power consumption is generally lower, indicating that there is an optimal value for the raw material moisture content. Values lower or higher than the optimum lead to higher power consumption. This differs from some studies, which concluded that power consumption is negatively correlated with moisture content [21.22].

Both the total power consumption and the effective total power consumption are affected significantly by temperature, moisture content, and interactions between the two ($p < 0.001$ for all parameters). As shown in Figure 5(c), at 70 °C, the total power consumption is the lowest under all moisture content conditions. When the raw material moisture content is 14%, the total power consumption is the lowest compared to other moisture content values. From Figure 5(d), variations in the effective total power consumption and the total power consumption are basically the same. Due to the influences of the pelletization success rate and the production rate, when the raw material moisture content is 8%, the effective total power consumption increases. This follows that the optimal moisture content is 14%, which results in the smallest effective total consumption.

Since moisture content and temperature interactions significantly influence the total power consumption, multiple comparisons were performed (Table 1). Treatment group 11 (moisture content 14%, temperature 70 °C) has the smallest total power consumption. Meanwhile, the total power consumption of treatment group 7 (14%, 50 °C) is higher than that of group 11, but the difference is not considerable.

Table 1

The comparison of experimental index under different temperature and moisture

No	Temperature /℃	Moisture content /%	Production rate kg/h	Pelletization success rate /%	Total power consumption Kwh/kg	Effective total power consumption Kwh/kg
1	30	8	99.6 i	95.5 ab	0.0694 abc	0.0728abc
2	30	11	229.2 bc	100 a	0.0846 cd	0.0846abcd
3	30	14	244.8 b	98.14 a	0.0754 abc	0.0770abcd
4	30	17	145.2 gh	98.18 a	0.1116 f	0.1136cdef
5	50	8	142.8 gh	79.68 c	0.0718 abc	0.0902abcd
6	50	11	244.8 b	100 a	0.0758 abc	0.0758abcd
7	50	14	300 a	98.48 a	0.0644 ab	0.0652ab
8	50	17	184.8 d	95.98 ab	0.1014 ef	0.1058bcdef
9	70	8	154.8 fgh	77.8 c	0.069 abc	0.0896abcd
10	70	11	224.4 bc	97.88 a	0.0758 abc	0.0776abcd
11	70	14	295.2 a	100 a	0.061 a	0.0610a
12	70	17	160.8 efg	94.08 ab	0.0934 de	0.0994abcde
13	90	8	99.6 i	46.58 d	0.067 abc	0.154g
14	90	11	211.2 c	98.82 a	0.0942 de	0.0954abcd
15	90	14	150 fgh	90.76 ab	0.1014 ef	0.1134cdef
16	90	17	154.8 fgh	90.62 ab	0.1054 ef	0.1184def
17	110	8	96 i	43.22 d	0.0804 bcd	0.1876h
18	110	11	181.2 de	90.7 ab	0.1268 g	0.1400fg
19	110	14	172.5 def	94.75 ab	0.1073 ef	0.1135cdef
20	110	17	129.6 h	87.06 b	0.1176 fg	0.1362efg

Different letters within the same column indicate significant ($P<0.05$).

In summary, for the biomass raw material pore-optimization system, the optimal temperature is 70 °C. When the moisture content is 14%, the pelletization production rate and the pellet quality are the highest while the power consumption is the lowest. The overall production efficiency is optimized. Since different raw materials have different contents of substances such as lignin, further experiments on the system should be conducted using different raw materials in order to make it more widely applicable.

4. Conclusions

The study found that the interaction of temperature and moisture content effect on production rate, the pelletization success rate and power consumption was significant. There is an optimal combination of temperature and moisture content, which is different depending on the type of material. The results demonstrated that, as temperature rises, the net work done by the pelletizer for pelletization significantly decreases. The total work shows no distinct variations at 30 °C to 90 °C. The optimal temperature for the pine wood chip pre-optimization system is 70 °C and the optimal moisture content is 14%. The resulting production rate, the pelletization success rate, and the total power consumption are 295.2 kg/h (20.59% increase), 100% (19% increase), and 0.061 kWh/kg (19% decrease). Compared to the original technology, the raw material pre-optimization system increase the resulting production rate by 20.59% , increase the pelletization success rate by 1.9%, and decease the total power consumption by 19%. The appropriate temperature range is 50-70 °C, when the raw material pre-optimization system is applied in actual production. Therefore, the raw material pre-optimization system can be applied to the actual production. Due to the different lignin content of different materials, the system can also be tested for different materials in the future to improve the application range.

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REFERENCES

[1] *Bhattacharya S C, Leon M A, Rahman M M, et al.* A study on improved biomass briquetting. Energy for Sustainable Development 6(2), 67-71. 2002

[2] *Yuan Zhenhong, Wu Chuangzhi, Ma Longteng,* Principles and technologies of bioenergy utilization. Chemical Industry Press, Beijing. 2004

[3] *Jing Yuanzhuo, Dong Yuping, Gai Chao, et al.* Researsh development and prospects of biomass briquetting technology. Engineering Sciences (02), 72-77. 2011

[4] *Liu Yanchun, Zhang Yingnan, Liu Ming, et al.* Review on solidification technology of biomass. World Forestry Research 21(4), 41-47. 2008

[5] *Larsson S H, Rudolfsson M, Nordwaeger M, et al.* Effects of moisture content, torrefaction temperature, and die temperature in pilot scale pelletizing of torrefied Norway spruce. Applied Energy 102, 827-832. 2013

[6] *Tu Deyu, Li Anxin, He Guisheng.* Hot pressing forming experiment of the rice straw and sawdust mixed material. Transactions of the Chinese Society of Agricultural Engineering (Transactions of the CSAE) 31(20), 205-211. 2015

[7] *Gilbert P, Ryu C, Sharifi V N, et al.* Effect of process parameters on pelletisation of herbaceous crops. Fuel 88(8), 1491-1497. 2009.

[8] *Carone M T, Pantaleo A, Pellerano A.* Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of Olea europaea L. Biomass and Bioenergy 35(1), 402-410. 2011

[9] *Segerstrom M, Larsson S H.* Clarifying sub-processes in continuous ring die pelletizing through die temperature control. Fuel Processing Technology 123, 122-126. 2014

[10] *Ghadernejad K, Kianmehr M H, Arabhosseini A,* Effect of moisture content and particle size on energy consumption for dairy cattle manure pellets. Central European Journal of Experimental Biology 1(2), 62-68. 2012

[11] *Yumak H, Ucar T, Seyidbekiroglu N.* Briquetting soda weed (Salsola tragus) to be used as a rural fuel source. Biomass and Bioenergy 34(5), 630-636. 2010

[12] *Matú M, An P K, Beniak J, et al.* Effects of initial moisture content on the production and quality properties of solid biofuel. Acta Polytechnica 55(5), 335-341. 2015

[13] *Sylvia H. Larsson, Mikael Thyrel, Paul Geladi, et al .* High quality biofuel pellet production from pre-compacted low density raw materials. Bioresource Technology 99, 7176–7182. 2008

[14] *Wang M, Song W, Jinji W, et al.* Research Progress of Biomass Fuel Composite Molding Technology. Agricultural Science & Technology 17(1), 175-177. 2016

[15] *Sitkei G,* Mechanics of agricultural materials (Developments in Agricultural Engineering). Elsevier Science Ltd, Amsterdam. 1986

[16] *Mazzu A,* Study, design and prototyping of an animal traction cam based press for biomass densification. Mechanism and Machine Theory 42(6), 652-667. 2007

[17] *Delmer D,* CELLULOSE BIOSYNTHESIS: Exciting Times for A Difficult Field of Study. Annual Review of Plant Biology 50(1), 245-276. 1999

[18] *Jiang Tingda,* Lignin. Chemical Industry Press, Beijing. 2010

[19] *Samuelsson R, Larsson S H, Thyrel M, et al.* Moisture content and storage time influence the binding mechanisms in biofuel wood pellets. Applied Energy 99,109-115. 2012

[20] *Hui Caijuan, Yu Guosheng,* A Study on the Influencing Factors of Biomass Forming with High Pressure of General Concicitions of Bio-matericals Solidification Fuel. Forestry Machinery & Woodworking Equipment 11(33), 10-14. 2005

[21] *Larsson SH,* Kinematic wall friction properties of reed canary grass powder at high and low normal stresses. Powder Technol 198, 108-113. 2010

[22] *Nielsen N P, Gardner D J, Poulsen T, et al.* Importance of temperature, moisture content, and species for the conversion process of wood residues into fuel pellets. Wood and Fiber Science 41(4), 414-425. 2009

[23] *Xu Xianghong, He Mingzhu*, Experiment design and application of Design-Expert, SPSS software. Science Press, Beijing. 2010