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Improved bulk density of bamboo pellets as biomass for energy production

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ABSTRACT

To the best of our knowledge, there is the lack of sufficient information concerning bamboo pellets. In the preliminary research, bamboo pellets showed a low bulk density which could not meet requirement of Pellet Fuels Institute Standard Specification for Residential/Commercial Densified (*PFI*). To improve its bulk density, pellets were manufactured using mixtures of bamboo and pine particles and the properties were investigated. It was found that adding pine particles to bamboo particles was an effective way to improve bulk density of bamboo pellets. When adding 40% pine particles to bamboo particles, bulk density of pellets increased from 0.54 g/cm^3 to 0.60 g/cm^3, meeting grade requirement of *PFI* utility. Furthermore, length, diameter and inorganic ash of pellets were also improved. Fine contents of pellets decreased from premium grade to utility grade according to *PFI* standard. Net calorific value also slightly decreased but it could meet the requirement of *DIN 51731* (>17,500 J/g). The effect of this interaction on bulk density, inorganic ash, Net calorific value, combustion rate and heat release rate were significant. The results from this research will be very helpful to develop bamboo pellets and provide guidelines for further research.

1. Introduction

Biomass is widely recognized as a renewable and sustainable energy source around the world. Biomass particles can be compacted to cylindrical pellets, the main type of solid fuels [1]. Some advantages of biomass pellets include the higher bulk and energy density, the better flow and storage property and the lower material wastage [2]. Recently, biomass pellets are well suitable for home heating in China. Wood resources or wood wastes are considered as the most dominant raw materials for biomass pellets except for agricultural residues. Agricultural and forestry residues represented the major fuel sources for potential bio-energy projects in many developing countries [3]. Magelli et al. investigated the fuel consumptions and emissions of wood pellets in British Columbia [4]. Rhen et al. analyzed the effect of the compositions in woods pellets on combustion characteristics. It was found that bark pellets had up to a 50% longer char combustion time than stem pellets [5]. Ohman et al. analyzed slagging tendencies of wood pellets during combustion in residential pellet burners [6]. Li et al. investigated pelletization of torrefied sawdust from a fluidized bed reactor to quantify the energy consumption and pellet properties. They found that torrefied sawdust had a higher energy consumption at the same compression temperature, compared to untreated sawdust [7]. Lam et al. investigated energy input and quality of pellets made from steam-exploded Douglas Fir. It was found that the steam-treated wood required more energy to compact into pellets and had a higher breaking strength than untreated wood [8].

The market demands for biomass pellets have largely increased during recent years. Market demands of biomass pellets are about fifty million ton in China now. One of the greatest barriers is deficient in biomass resources. Bamboo is a main type of biomass materials and has been widely cultivated in China. The total areas of bamboo have been more than five million hectares and that of moso bamboo (*Phyllostachys heterocycla)* have been more than three million hectares [9]. They have great potentials as bio-energy resources of the future due to fast growth. To the best of our knowledge, there is the lack of sufficient information concerning bamboo pellets. Liu et al. analyzed the moisture of bamboo for pellets [10] and investigated the effect of carbonization temperature and residue time on properties of bamboo pellets [11]. In the preliminary research, bamboo pellets were also successfully

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manufactured using the pellet mill. A low bulk density of bamboo pellets was observed, which could not meet requirement of *PFI* standard.

It is well known that mixing different types of biomass materials is an effective way to improve the properties of pellets. To improve the bulk density of bamboo pellets, pine particles, a main type of wood wastes in China, were added to bamboo particles with different mass ratios in the manufacturing process of bamboo pellets. Pellet properties were determined based on *PFI* standard. The objective of this research is to investigate the effect of mixing bamboo and pine particles on pellet properties. Furthermore, the results from this research will also be very helpful to select an effective way to improve properties of bamboo pellets and provide guidelines for further research.

2. Materials and methods

2.1. Materials

Moso bamboo (4 years old) was taken from a bamboo plantation located in Louisiana, US. Its initial moisture content was about 6.1%. Bamboo materials were cut off to sample size with 40 mm (longitudinal) by 3–8 mm (radial) by 20–30 mm (tangential). Pine particles were directly taken from the USDA Forest Service Forest Products Laboratory (FPL), came from American Wood Fibers of Schofield, WI. Its initial moisture content was about 5.1%.

Bamboo and pine materials were milled into particles using a wood particle mill at FPL, respectively. Bamboo and pine particles (particle size of less than 2.0 mm) were uniformly mixed with different mass ratios (100% bamboo/0% pine, 80% bamboo/20% pine, 60% bamboo/40% pine, 40% bamboo/60% pine, 20% bamboo/80% pine and 0% bamboo/100% pine). About ten g mixtures in each mass ratio were randomly weighed using a precision digital balance (0.0001 Resolution). They were dried at temperature 105 °C until the mass stabilized and then the final mass was recorded. Moisture content of mixtures was calculated according to mass loss of samples. Then five kg of mixtures in each mass ratio were conditioned by adding predetermined amounts of distilled water to the samples [12]. They were transferred to separate Ziploc bags and sealed tightly. Finally, they were placed into a conditioning room with temperature 27 °C, humidity 65% for 48 h to enable moisture uniform distribution. The final moisture content of mixtures in each mass ratio were 15.97%, 15.86%, 15.96%, 15.83%, 15.91% and 15.75%, respectively.

2.2. Pellet formation

Biomass pellets were manufactured using laboratory pellet mill (L-175), made by the Amandus Kahl Co. of Hamburg, Germany. Pellet mill parameters were set to a rotary speed of 235 rpm and pellet diameter of 6.0 mm. Particles mixtures were continuously fed into the pellet mill and compacted into pellets. The temperature of pellets was about 70 °C after exiting die due to particle friction. Pellets were kept in the laboratory more than a week with temperature 27 °C, humidity 50% to stabilize their properties.

2.3. Property test

Pellet properties were determined according to *PFI* standard.

2.3.1. Pellet dimensions

Pellets are cylindrical in shape. In order to determine dimensions and unit mass, fifteen pellets were randomly selected in each mass ratio. Length (L) and diameter (D) of each pellet were measured using a digital vernier caliper (0.01 Resolution). Mass of each pellet (m) was also weighed using a precision digital balance (0.0001 Resolution).

2.3.2. Particle density

Particle density (ρ_p) of pellet was calculated according to the following equations.

$$V_p = \pi \Big/ 4D^2L \tag{1}$$

$$\rho_p = m_p/V_p \tag{2}$$

where, V_p is the volume of individual pellet (cm^3), D is the diameter of individual pellet (mm), L is the length of individual pellet (mm), ρ_p is the density of individual pellet (g/cm^3), and m_p is the mass of individual pellet (g).

2.3.3. Bulk density

Bulk density (ρ_b) was determined in accordance with *ASTM 873* standard (Test Method for Bulk Density of Densified particulate Biomass Fuels).

2.3.4. Fine contents

Fine contents (P_f) were determined in accordance with *PFI* standard.

2.3.5. Inorganic ash

Inorganic ash (I_a) of pellets was determined in accordance with *D 1102-84* Standard (Test Method for Ash in Wood).

2.3.6. Net calorific value

Net calorific value (N_c) of pellets was determined in accordance with *ASTM E 711* Standard (Test Method for gross calorific Value of Refuse-Derived fuel by the Bomb Calorimeter).

2.3.7. Combustion rate and heat release rate

Combustion time was recorded according to the *PARR 1266 Bomb Calorimeter* during determining net calorific value. Based on the mass of the pellets and combustion time, the combustion rate (C_r) was calculated by using following equation.

$$C_r = m/t \tag{3}$$

where, Cr is the average combustion rate, (g/s); m is the mass of pellets, (g); t is combustion time, (s).

By knowing the net calorific value and combustion rate, heat release rate (Hr) could be calculated by using the following equation.

$$H_r = N_c \times C_r \tag{4}$$

where, H_r is the heat release rate, (J/s); N_c is the net calorific value, (J/g); and Cr was the average combustion rate, (g/s).

2.3.8. Proximate and ultimate analysis

Volatile matters were determined in according with GB/T 212-2008. C, H and N were determined in according with GB/T 476-2008. S was determined in according with GB/T 217-2007. Heave metals (Na, Mg, Al, Si, K, Ca, Ti, Fe, Zn) were determined according to standard analysis methods using inductively couple plasma mass spectrometry (ICP-MS).

2.3.9. Synergistic analysis

To investigate whether synergistic interactions occurred between bamboo particles and pine particles during pelleting, the

Table 1
The properties of different pellet types.

Pellet types	L (mm)	D (mm)	ρ_b (g/cm^3)	ρ_p (g/cm^3)	P_f (%)	I_a (%)	N_c (J/g)	C_r (g/s)	H_r (J/s)
100%bamboo/0%pine	13.89 ± 0.33	6.02 ± 0.002	0.54 ± 0.005	1.25 ± 0.009	0.37 ± 0.01	1.64 ± 0.01	18495 ± 71	0.188 ± 0.009	3494 ± 247
80%bamboo/20%pine	12.81 ± 0.69	5.95 ± 0.001	0.58 ± 0.007	1.01 ± 0.007	0.59 ± 0.06	1.52 ± 0.09	18472 ± 63	0.181 ± 0.010	3434 ± 204
60%bamboo/40%pine	12.82 ± 0.30	5.97 ± 0.005	0.60 ± 0.003	0.99 ± 0.009	0.64 ± 0.07	1.28 ± 0.06	18335 ± 42	0.176 ± 0.003	3269 ± 185
40%bamboo/60%pine	13.03 ± 0.50	5.96 ± 0.001	0.62 ± 0.008	1.03 ± 0.005	0.67 ± 0.06	1.26 ± 0.12	18271 ± 37	0.174 ± 0.001	3186 ± 115
20%bamboo/80%pine	13.70 ± 0.44	5.97 ± 0.001	0.65 ± 0.005	1.05 ± 0.006	0.88 ± 0.10	1.03 ± 0.09	18136 ± 94	0.168 ± 0.005	3092 ± 159
0%bamboo/100%pine	13.25 ± 0.70	5.90 ± 0.004	0.68 ± 0.004	1.30 ± 0.007	0.07 ± 0.03	0.83 ± 0.01	18298 ± 84	0.156 ± 0.004	2887 ± 113

theoretical value of pellet properties was calculated based on measured value of pure bamboo and pine pellets.

$$Y_{calculated} = X_{bamboo} \times Y_{bamboo} + X_{pine} \times Y_{pine} \quad (5)$$

where, $Y_{calculated}$ is the theoretical value of pellet properties, X_{bamboo} is the percentage of bamboo particles in the mixtures, Y_{bamboo} is the measured value of the properties of bamboo pellets, X_{pine} is the percentage of pine particles in the mixtures, and Y_{pine} is the measured value of the properties of pine pellets.

To further investigate the effect of the interaction of pine and bamboo particles on pellet properties, the percent change of the difference (PCD) between measured and calculated values was calculated [13]:

$$PCD(\%) = (Y_{Measured} - Y_{Calculated})/Y_{Calculated} \times 100\% \quad (6)$$

where, $Y_{Measured}$ is the measured value of pellet properties, and $Y_{calculated}$ is the theoretical value of pellet properties.

3. Results and discussion

3.1. Pellet properties

Table 1 showed the mean values of the properties of pellets with different mass ratios. Length slightly varied between 13.89 mm and 12.80 mm. Diameter varied between 5.9 mm and 6.0 mm. The dimension change of pellets is due to characteristic differences of bamboo and pine materials. It was confirmed that bamboo owned a greater stiffness than wood, resulting in easier destruction of the natural binding between particles in the pelletization process [10]. The dimensions of all pellets met the grade requirement of *PFI* premium (Length greater than 38.1 mm ≤ 1.0%, Diameter between 5.84 mm and 7.25 mm).

Pellet density is an important quality indicator to evaluate substantial storage facilities, spaces and handing systems. Transport, handling and storage efficiencies are affected by the bulk density of pellets. Higher bulk density leads to greater transport efficiency and lower storage space. Bulk density of pellets increased with increase in pine contents of mixtures. The values were 0.54 g/cm^3, 0.58 g/cm^3, 0.60 g/cm^3 0.62 g/cm^3, 0.65 g/cm^3 and 0.68 g/cm^3 for pellets with mass ratios of 100% bamboo/0% pine, 80% bamboo/20% pine, 60% bamboo/40% pine, 40% bamboo/60% pine, 20% bamboo/80% pine and 0% bamboo/100% pine, respectively. Particle density of pellets from mixtures was lower compared with pure bamboo or pine pellets. Bulk density of bamboo pellets could not meet the requirement of *PFI* utility (0.60 g/cm^3–0.74 g/cm^3). But it was improved through adding pine particles to bamboo particles. Bulk density of pellets with mixing ratio of 60% bamboo/40% pine could meet grade requirement of *PFI* utility (≥0.60 g/cm^3).

Fine contents are also an important factor connected with handling and transportation. Pine pellets (0.07%) had the lower fine contents than bamboo pellets (0.37%). Fine contents of both pellets could meet the grade requirement of *PFI* premium (≤0.5%). Fine contents of pellets from mixtures decreased compared to pure bamboo or pine pellets. The value was 0.59%, 0.64%, 0.67% and 0.88% for pellets with mass ratios of 80% bamboo/20% pine, 60% bamboo/40% pine, 40% bamboo/60% pine and 20% bamboo/80% pine, respectively. Fine contents of pellets from mixtures also decreased from premium grade (≤0.5%) to utility grade (≤1.0%) according to *PFI* standard.

Inorganic ash of pine pellets (0.83%) was lower than that of bamboo pellets (1.64%). Inorganic ash of pellets from mixtures also decreased with increase in pine contents of mixtures. It was confirmed that inorganic ash of biomass pellets depended on the composition of mineral constituents in the source fuel [14]. The main ash-forming elements of biomass materials included Na, Mg, Si, Al, Fe, Ca, Na, K, Zn and Ti [15]. The difference in inorganic ash of pellets was mainly due to these element variations of bamboo and pine, showed in Table 2. The main types of elements were similar in the ash of bamboo and pine pellets such as Na, Si, K, Ca. Bamboo had more Si (358.14 mg/kg), K (4032.58 mg/kg) and less Na (242.83 mg/kg), Ca (956.03 mg/kg). Inorganic ash of pellets decreased with increase in pine contents of mixtures, meeting the grade requirement of *FPI* premium (≤8.0%).

Net calorific value is the amount of energy per unit mass released upon complete combustion. Net calorific value of bamboo pellets (18,495 J/g) was higher than that of pine pellets (18,298 J/g). The different compositions of bamboo and pine led to the variations of net calorific value. C, H and O are the main components of biomass

Table 2
Ash-forming elements of moso bamboo and pine pellets (mg/kg).

Biomass types	Na	Mg	Al	Si	K	Ca	Ti	Fe	Zn
Bamboo	242.83 ± 1.91	229.46 ± 2.99	35.09 ± 0.23	358.14 ± 0.12	4032.58 ± 8.24	965.03 ± 3.74	18.07 ± 0.67	111.93 ± 1.21	20.88 ± 1.54
Pine	827.15 ± 2.93	234.98 ± 2.72	48.89 ± 0.71	250.75 ± 2.38	1261.39 ± 5.64	1160.94 ± 3.64	6.74 ± 1.03	192.60 ± 2.37	25.28 ± 1.47

Table 3
Chemical composition of moso bamboo and pine (%).

Species	C	H	N	S	O (diff.)
Pine	49.40 ± 2.12	4.60 ± 0.92	1.43 ± 0.09	0.02 ± 0.003	45.82 ± 1.54
Moso bamboo	49.71 ± 1.89	6.36 ± 1.13	0.18 ± 0.002	0.04 ± 0.001	42.50 ± 2.27

Table 4
Analysis of variance.

Properties	Variance	SS	df	MS	F Value	P-value	F Crit
Length (mm)	Interior-group	10.42	5	2.08	1.91	0.10	2.38
	Inter-group	58.93	54	1.09			
	Total	69.36	59				
Diameter (mm)	Interior-group	0.07	5	0.01	7.83	1.34E-05	2.38
	Inter-group	0.10	54	0.002			
	Total	0.17	59				
Particle density (g/cm^3)	Interior-group	0.12	5	0.02	136.52	2.311E-29	2.38
	Inter-group	0.01	54	0.0002			
	Total	0.13	59				
Bulk density (g/cm^3)	Interior-group	0.90	5	0.18	47.27	1.583E-18	2.38
	Inter-group	0.21	54	0.004			
	Total	1.11	59				
Inorganic ash (%)	Interior-group	2.29	5	0.45	3.12	0.025	2.62
	Inter-group	3.52	24	0.14			
	Total	5.82	29				
Net calorific value (J/g)	Interior-group	1256937.6	5	251387.52	3.18	0.024	2.62
	Inter-group	1896653.9	24	79027.24			
	Total	3153591.5	29				
Combustion rate (g/s)	Interior-group	0.0030	5	0.0006	2.59	0.052	2.62
	Inter-group	0.0056	24	0.00023			
	Total	0.0086	29				
Heat release rate (J/s)	Interior-group	1256937.6	5	251387.52	3.18	0.024	2.62
	Inter-group	1896653.9	24	79027.247			
	Total	3153591.5	29				

Note: SS = Sum of squares, df = Degree of freedom, MS = Mean square.

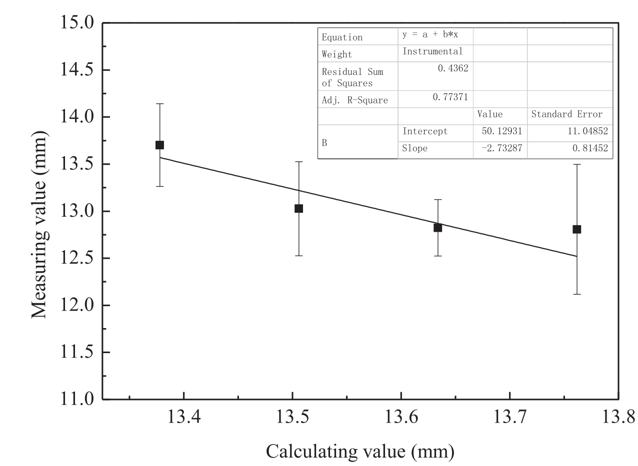

Fig. 1. Measuring and calculating length of pellets with different mass ratios.

materials. Tillman found a linear relationship between net calorific value and carbon contents [16]. Table 3 showed that carbon contents of bamboo were higher than that of pine, resulting in its higher net calorific value. It was also confirmed that net calorific value of pellets slightly decreased with increase in pine contents of mixtures. Net calorific value of all pellets could meet the minimum requirement for making commercial pellets of *DIN 51731 (*>17,500 J/g*)* [17].

Bamboo pellets had a faster combustion rate (0.188 g/s) and heat release rate (3494 J/s) than that of pine pellets. Biomass materials underwent heating up, drying, devolatilization and finally the combustion of the volatiles and char during combustion process. Bamboo had the higher contents of volatile matters (81.87%) than pine (80.34%), indicating that it was easier to be ignited and be burned. Combustion rates and heat release rates of pellets decreased with increase in pine contents of mixtures.

The other important characteristics related to the combustion of biomass materials are pollutant emissions. These emissions are

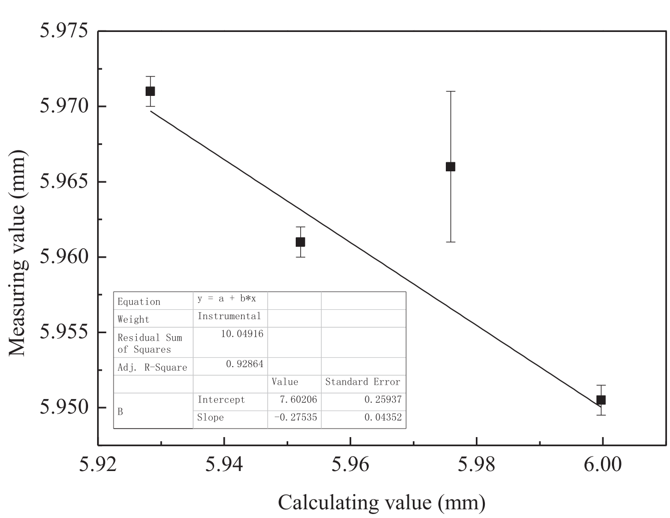

Fig. 2. Measuring and calculating diameter of pellets with different mass ratios.

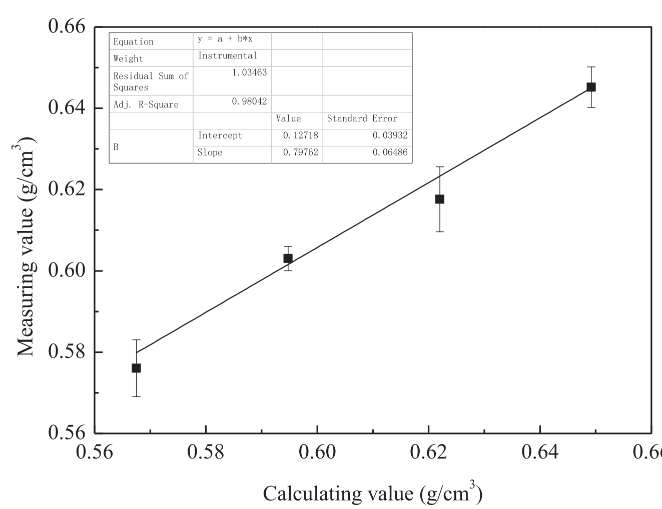

Fig. 3. Measuring and calculating bulk density of pellets with different mass ratios.

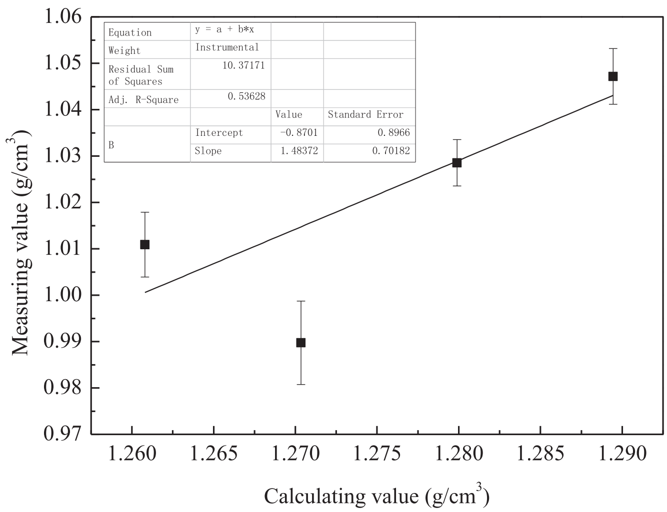

Fig. 4. Measuring and calculating particle density of pellets with different mass ratios.

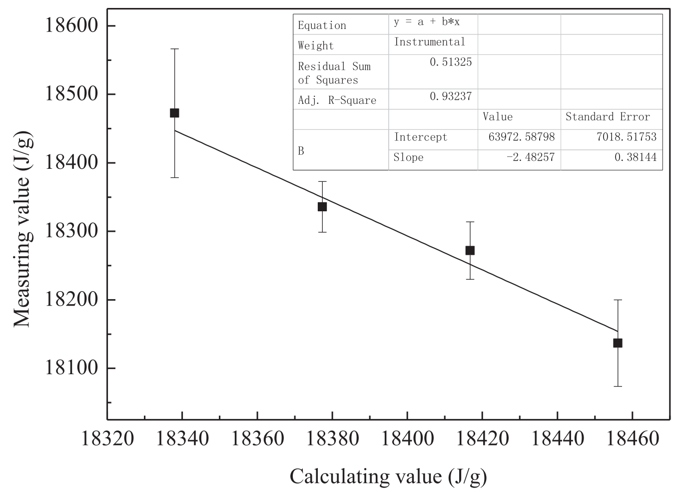

Fig. 7. Measuring and calculating net calorific value of pellets with different mass ratios.

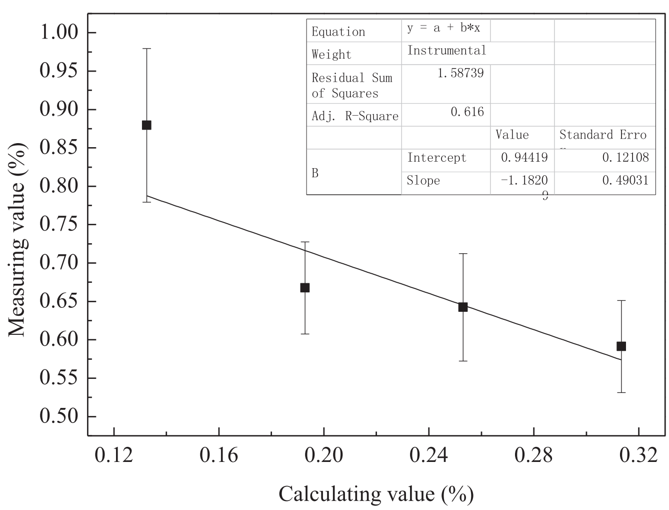

Fig. 5. Measuring and calculating fine contents of pellets with different mass ratios.

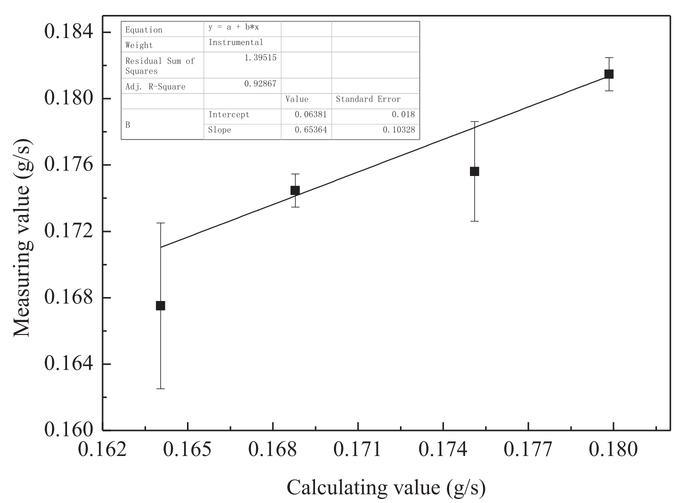

Fig. 8. Measuring and calculating combustion rate of pellets with different mass ratios.

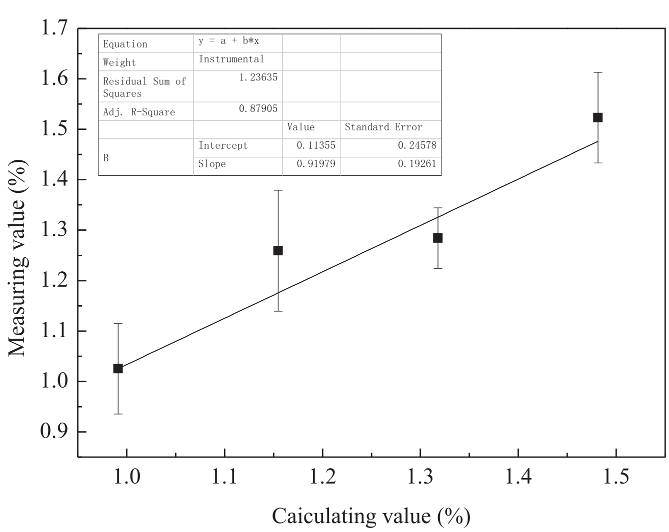

Fig. 6. Measuring and calculating inorganic ash of pellets with different mass ratios.

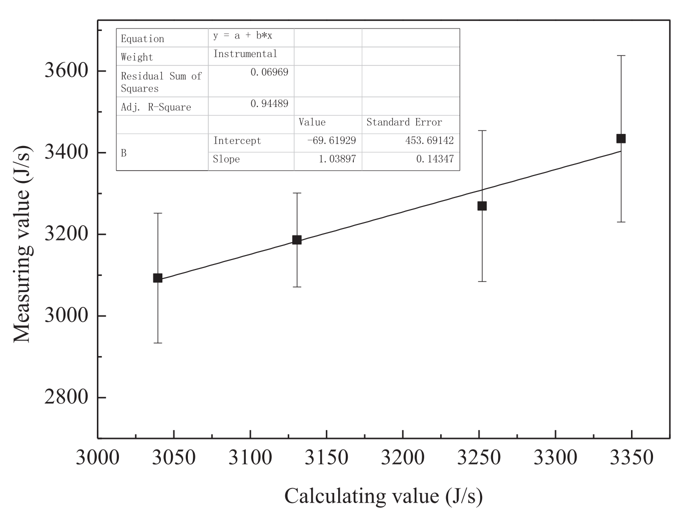

Fig. 9. Measuring and calculating heat releasing rate of pellets with different mass ratios.

Table 5
The deviation between calculated and measured values of properties for different pellets.

Pellet types	Property PCD of pellets with different types (%)								
	L (mm)	D (mm)	ρ_b (g/cm^3)	ρ_p (g/cm^3)	P_f (%)	I_a (%)	N_c (J/g)	Cr (g/s)	Hr (J/s)
80%bamboo/20%pine	−6.94	−0.82	1.50	−19.82	88.72	2.80	−1.73	0.90	2.73
60%bamboo/40%pine	−5.95	−0.17	1.39	−22.09	153.82	−2.56	−0.79	0.29	0.54
40%bamboo/60%pine	−3.55	0.15	−0.71	−19.64	246.27	9.05	1.95	3.36	1.78
20%bamboo/80%pine	2.42	0.72	−0.63	−18.79	563.48	3.42	0.73	2.11	1.75

affected by the contents of S and N, resulting in the formation of gaseous pollutants such as SO_2, NOx or N_2O, etc. Table 3 showed that bamboo had the lower N contents and the higher S contents compared to pine. It was found that the N and S contents of bamboo and pine were obviously lower than that of coal. Taking care of the environment, bamboo and pine materials with the low contents of S and N were not contributed to acid rain and destruction of the ozone layer.

Statistical analysis of variance results (Table 4) showed that the effects of mixing ratios of bamboo and pine particles on pellet diameter, bulk density, particle density, fine contents, inorganic ash, net calorific value and heat release rate of pellets were significantly different at $p = 0.05$.

3.2. Analysis of synergistic interaction

In this research, some properties of pellets with different mass ratios of bamboo and pine particles were determined based on *PFI* standard. Adding pine particles and bamboo particles was helpful to improve pellet properties. Bulk density of pellets could meet the grade requirement of *PFI* utility when adding 40% pine particles to bamboo particles. Furthermore, length, diameter and inorganic ash of pellets were also improved. It was also observed that fine contents and net calorific value of pellets slightly decreased.

To investigate whether the interactions occurred between bamboo particles and pine particles during pelleting, the theoretical value of pellet properties was calculated based on the measured value of pure bamboo and pine pellets. Figs. 1–9 showed the line relationship between measured value and calculated value of pellet properties with different mass ratios. It was confirmed that there was the interaction of bamboo particles and pine particles to improve bulk density during pelleting, due to higher R-Square value of 0.98. The effect of interaction between bamboo particles and pine particles on combustion properties of pellets was also significant. The R-Square value for the inorganic ash was 0.89, net calorific value was 0.97, combustion rate was 0.93 and heat release rate was 0.94. There are five binding types during pelleting, such as attractive forces between solid particles, interfacial forces, capillary pressure, adhesive and cohesive forces, mechanical interlocking behavior and formation of solid bridges [18]. Stelte et al. found that chemical composition had a significant influence on the bonding quality between biomass particles [19]. Hemicelluloses and lignin are essentially amorphous polymers in the biomass components. The glass transition of these amorphous polymers using moisture and temperature is very helpful to make durable particle–particle bonding. The glass transition of amorphous polymers in bamboo and pine is similar and the temperature of glass transition is different, resulting in the variation of pellet properties. There is the waxy layer on the surface of bamboo, like straw. The subsequent flow of the waxes at lower temperature inhibits adhesion between particles in fuel pellet production, resulting in the formation of weak boundary layers. This is also responsible for the low mechanical strength of bamboo pellets. It was confirmed that bamboo owned a greater stiffness, resulting d in easier destruction of the natural binding between particles in the pellets [10]. These negative factors of bamboo materials were weakened when adding pine particles to bamboo particles during pelleting.

To further investigate the interaction of bamboo and pine particles, the percent change of the difference (PCD) for pellet properties was calculated. Table 5 showed that PCD values of pellet length, diameter and fine contents increased and that of bulk density of pellets decreased with increase in pine contents of mixtures, indicating increased interactions occurred when more pine particles were added to bamboo particles during pelleting. Different PCD values of combustion properties of pellets also showed the interaction of bamboo and pine particles.

4. Conclusions

Adding pine particles to bamboo particles was an effective way to optimize properties of bamboo pellets. When mixing mass ratios of bamboo and pine particles were more than 60%:40%, bulk density of pellets increased from 0.54 g/cm^3 to 0.60 g/cm^3, meeting the grade requirement of *PFI* utility. Furthermore, length, diameter and inorganic ash of pellets were also improved. Fine contents of pellets decreased from premium grade to utility grade according to *PFI* standard. Net calorific value also slightly decreased but it could meet the minimum requirement of *DIN 51731* (>17,500 J/g). The interaction of bamboo particles and pine particles was observed during pelleting. The effect of this interaction on bulk density, inorganic ash, Net calorific value, combustion rate and heat release rate were significant.

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References

[1] T.C. Maria, A. Pantaleo, A. Pellerano, Influence of process parameters and biomass characteristics on the durability of pellets from the pruning residues of *Olea europaea L*, Biomass Bioenergy 35 (2011) 402–410.
[2] P.K. Adapa, A.K. Singh, S.G.J. Choenau, Pellet characteristics of fractionated alfalfa grinds: hardness models, Power Handl. Process. 18 (2006) 1–6.
[3] M. Junginger, A. Faaija, R. Broek, Fuel supply strategies for large-scale bioenergy projects in developing countries. Electricity generation from agricultural and forest residues in Northeastern Thailand, Biomass Bioenergy 21 (2001) 259–275.
[4] J. Mcmullen, O. Fasina, W. Wood, Physical Characteristics of Pellets from Poultry Litter, ASABE, St. Joseph, MI, 2004. ASABE Paper No. 046005.
[5] F. Magelli, K. Boucher, H.T. Bi, S. Melin, A. Bonoli, An environmental impact assessment of exported wood pellets from Canada to Europe, Biomass Bioenergy 33 (2009) 434–441.
[6] C. Rhena, M. Ohmanb, R. Grefa, I. Wasterlund, Effect of raw material composition in woody biomass pellets on combustion characteristics, Biomass Bioenergy 31 (2007) 66–72.
[7] H. Li, X.H. Liu, R. Legros, X.T. Bi, C.J. Lim, Pelletization of torrefied sawdust and properties of torrefied pellets, Appl. Energy 93 (2012) 680–685.
[8] P.S. Lam, S. Sokhansanj, X.T. Bi, C.J. Lim, S. Melin, Energy input and quality of

pellets made from steam-exploded Douglas Fir *(Pseudotsuga menziesii)*, Energy Fuels 25 (2011) 1521–1528.
[9] Z.H. Jiang, World Bamboo and Rattan, Liaoning Science & Technology Press, China, 2002.
[10] Z.J. Liu, Z.H. Jiang, Z.Y. Cai, B.H. Fei, X.E. Liu, Moisture of bamboo for pellets, BioResources 7 (2012) 1548–1557.
[11] Z.J. Liu, Z.H. Jiang, Z.Y. Cai, B.H. Fei, X.E. Liu, Effects of carbonization conditions on properties of bamboo pellets, Renew. Energy 51 (2013) 1–6.
[12] T. Filbakk, J. Raida, N. Juha, The effect of bark content on quality parameters of Scots pine *(Pinus sylvestris L.)* pellets, Biomass Bioenergy 35 (2011) 3342–3349.
[13] Z.G. Liu, R. Balasubramanian, A comparative study of nitrogen conversion during pyrolysis of coconut fiber, its corresponding biochar and their blends with lignite, Bioresoure Technol. 151 (2014) 85–90.
[14] E.P. Dick, G.A. Ryabov, A.N. Tugov, Comparing properties of coal ash and alternative-fuel ash, Therm. Eng. 54 (2007) 231–235.
[15] J. Werkelin, D. Lindberg, D. Bostrom, Ash-forming elements in four Scandinavian wood species, part 3: combustion of five spruce samples, Biomass Bioenergy 35 (2011) 725–733.
[16] D.A. Tillman, Wood as an Energy Resource, Academic Press, New York, 1978.
[17] H.M. Faizal, Z.A. Latiff, M.A. Wahid, Study on characteristics of briquettes contain different mixing ratio of EFB fiber and mesocarp fiber, in: International Meeting on Advances in Thermo-Fluids, 2009.
[18] K.R. Nalladurai, V. Morey, Natural binders and solid bridge type binding mechanisms in briquettes and pellets made from corn stover and switch grass, Bioresoure Technol. 101 (2010) 1082–1090.
[19] W. Stelte, J.K. Holm, A.R. Sanadi, S. Barsberg, J. Ahrenfeldt, U.B. Henriksen, A study of bonding and failure mechanisms in fuel pellets from different biomass resources, Biomass Bioenergy 35 (2011) 910–918.