Improving the Conventional Pelletization Process to Save Energy during Biomass Densification

Zhongjia Chen, Guosheng Yu,* Xiangyue Yuan, Qingyu Wang, and Jiangmin Kan

A pellet mill is currently the most frequently used method for producing pellets using either a ring die or a flat die. In the densification process, a great amount of energy is required to avoid spring-back and to overcome the friction between the material and the channel surface of the die. However, extra energy is unnecessarily consumed because of friction between the roller and densified material and the pressure between the roller and die, where there are no opening channels. The aim of this work was to attempt to eliminate a portion of the frictional and compaction energy consumption based on an improved method of densification using a ring die. An upgraded pellet mill was designed and manufactured with rams on its roller. When the die and the roller rotate in a fixed transmission ratio, the rams precisely press raw material into opening channels on the die. Experimental tests on its feasibility were carried out. The results showed that the pellet mill, with this improvement, worked without wear on the surface of either the ring die or the roller; furthermore, the density and mechanical durability of pellets were the same as those produced using the traditional method.

Keywords: Biomass; Densification; Pelletization process; Energy consumption; Upgraded ring die mill

Contact information: School of Technology, Beijing Forestry University, Beijing, China, 100083;
** Corresponding author: sgyzh@bjfu.edu.cn*

INTRODUCTION

Biomass is the third most widely used energy source in the world. It is free of sulfur, renewable, and can significantly reduce net carbon emissions. However, its low bulk density limits its utilization. The bulk density is normally under 100 kg/m^3 (Adapa *et al*. 2002; Larsson *et al*. 2008) for agricultural residues and under 400 kg/m^3 (Sokhansanj and Fenton 2006) for forest residues. If the low bulk density biomass is not densified, its transportation cost will be very high and this kind of transportation is not efficient, because the distances between biomass production sites to industrial and residential locations are usually very long. For the convenience of logistics and utilization, biomass materials can be densified into briquettes, pellets, or logs (Zhang *et al*. 1999; Sultana and Kumar 2012).

In general, there are several densification processes, which include baling, pelletization, extrusion, and briquetting (Tumuluru *et al.* 2010; Zhang *et al*. 2014). These operations are carried out using a bailer, pelletizer, screw press, piston press, or roller press. Pelletization and briquetting are the two most commonly used processes for densification (Stelte *et al.* 2012; Zhang *et al*. 2014).

A briquette extruder is used for making biomass briquettes or logs (Zhang *et al.* 1999; Wu *et al*. 2014). Raw material is put into a hopper and is dropped in front of a piston by gravity or by a screw. With the reciprocating motion of the piston, the briquette is squeezed out through an open end die intermittently, as shown in Fig. 1.

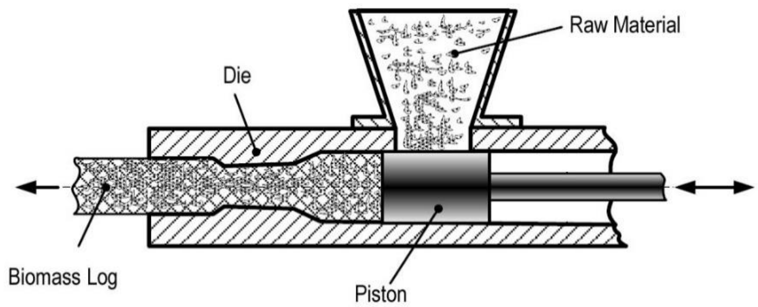


Fig. 1. Working process of briquette extruder

Compared to a briquetting machine, a ring die mill is more commonly used in China because of its high productivity (Zhao *et al.* 2007; Zhang *et al*. 2014). Both the machine and the pellet production technology are mature, and the productivity is higher compared with other biomass machines (Zhang *et al*. 2014). The ring die mill in general has a ring die with cylindrical opening channels and rotational roller(s) that will press the raw material into and through the channels, as shown in Fig. 2. The friction between the channel surface of the die and the raw material builds up the pressure, and this pressure is the key factor in the densification. The densification process requires large amounts of energy to press material into the opening channel to overcome spring-back and friction on the surface between material and cylindrical channels. As the roller passes over the channel under various pressures, a small layer of the pellet will be squeezed out of the channel. The pelletization process is considered continuous (Zhang *et al*. 2014), because the roller rotates at a high speed.

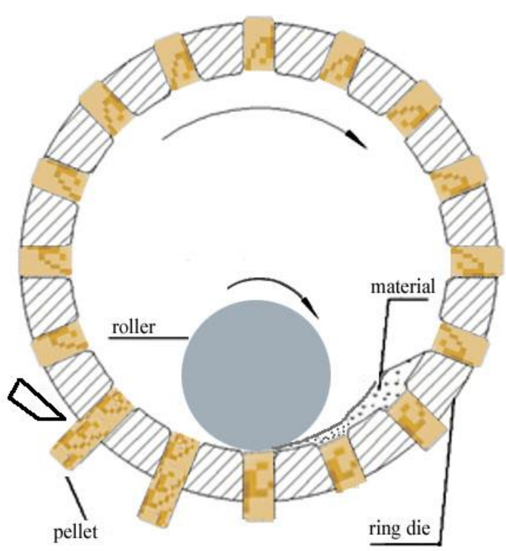


Fig. 2. Working process of ring die mill

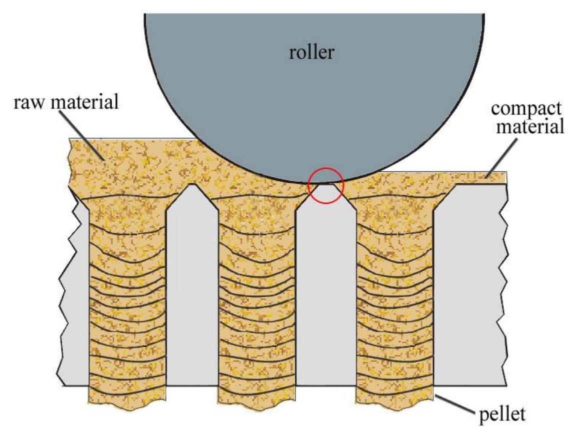


Fig. 3. Compression of particles

In addition to the essential energy required to compress material, extra energy is wasted by the compaction of raw material at locations where there is no channel, and by the friction among the roller, compact material, and ring die, as shown in the red circle in Fig. 3. Research shows that the friction generates heat and helps the raw material to melt and flow easily (Nielsen *et al*. 2009). However, extra energy consumption not only generates heat, but it also leads to wear and deformation on both the roller and the ring die, no matter how hard the steel parts are that are used, as shown in Figs. 4 and 5.

Fig. 4. Roller failure with wear

Fig. 5. Ring die failure with wear and deformation

The present research aims to develop an improved ring die mill and demonstrate its feasibility. The combination of the briquetting machine and the conventional ring die mill makes the intermittent extrusion of the briquetting machine become continuous, and the wear on the roller and on the ring die is eliminated. Briefly speaking, there are fixed position rams installed on the roller and fixed position opening channels set up on the ring die. When the ring die and the roller rotate in a fixed transmission ratio, the rams precisely press raw material into opening channels on the die. The main purpose of this alteration is to reduce extra energy consumption and component wear and deformation.

EXPERIMENTAL

Materials Preparation

The experimental material was *Caragana microphylla* Lam. – a drought-resistant plant that grows in the city of Horqin, in a sandy soil of Tong Liao, Inner Mongolia, China (Fig. 6). There were 7.99 million hectares brush resources such as *C. microphylla* in Inner Mongolia in 2014 (Publicity Office 2014). It needs to be cut every three to five years for rejuvenation and can be used as biomass fuel if handled properly.

The cut brush was transported to a laboratory in Beijing and dried naturally for 1 week in the summer. The material was milled into small fibrous pieces using a crumbling machine (Model GXP-400; Beijing Forestry University; Beijing, China), as shown in Figs. 7 and 8. The milled raw material was separated into two piles using a sieve aperture of 2 mm. The pile with particle sizes under 2 mm was used in the experiment. The moisture content of the milled raw material was measured using the following drying method. Ten grams of milled raw material was put into an electronic drier at a constant temperature of 100 °C for 48 h; then, samples were weighed using an electronic balance with a precision of 0.01 g every 2 h until the mass did not change. The moisture content was calculated to be approximately 10% by dividing the mass loss by the initial total mass.



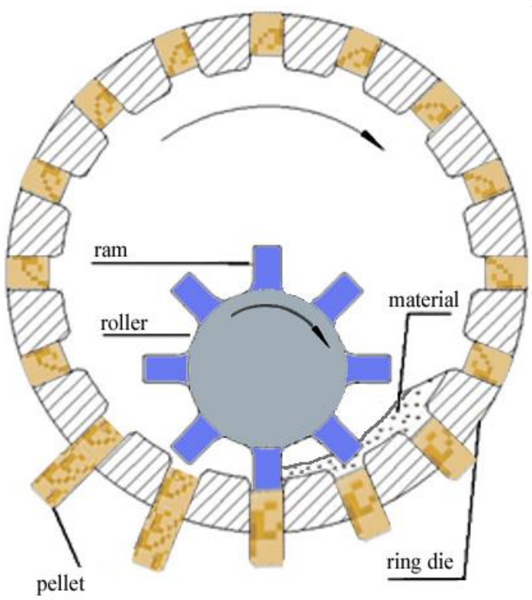
Fig. 6. The sandy area with *Caragana microphylla*

Fig. 7. The GXP-400 crumbling machine

Fig. 8. The milled raw material

Pellet Production

The upgraded pellet mill was designed according to the patent held by our research team (Yu *et al.* 2013) and manufactured and assembled in the machine workshop of Beijing Forestry University. Its working principle is shown in Fig. 9. In addition to a ring die and a roller like conventional pellet mills, the roller also has many rams on it. The pelletization process only takes place in the cylindrical opening channels on the ring die using the pressure of the rams.



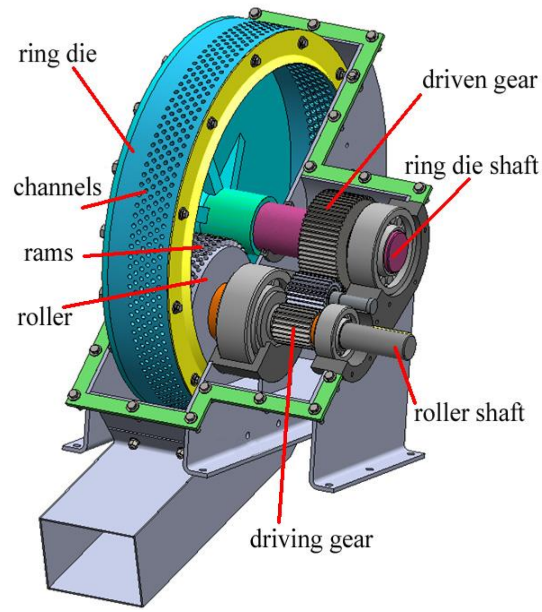


Fig. 9. Principle of improved ring die mill

Fig. 10. Mechanical stucture of improved ring die mill

The structure of the upgraded pellet mill is shown in Fig. 10. The roller shaft drives the roller. A driving gear, equipped on the roller shaft, drives a driven gear to rotate *via* an idle gear. The driven gear is fixed to the ring die shaft assembled with the ring die. When the driving gear forces the driven gear to rotate in a certain ratio, the roller and the ring die rotates synchronously. Both positions of rams on the roller and the opening channels on the ring die are designed precisely to mesh well with each other as the above two gears revolve. In this way the raw material was compacted by the ram only on the spot of the opening channel to avoid compaction and friction on the roller and the ring die. The distance between the roller and the ring die of the upgraded pellet mill is much larger than that of the conventional mill, which helps to eliminate the extra pressure and friction between the roller and the compact material. The inner diameter of the ring die is 660 mm, and the outer diameter of the ring die is 760 mm. The diameter of the opening channel is 8.5 mm; thus, the ratio of the length to the diameter of the opening channel is 5.88.

The experimental set-up for this research is shown in Fig. 11. A 26-kW diesel engine (Model ZN485Q; Changchai Co. Ltd; Changzhou, China) was used as a power source with specified rotation of 2,400 rpm and with a maximum torque of 120 N·m at the 1800 rpm. The engine drove the rotation of the ring die mill *via* a gearbox (Model NJ130; Yuejin-gearbox Co. Ltd; Nanjing, China). A torque sensor (Model XLN; Beijing Dadetianyun Co. Ltd; Beijing, China) was connected to the gearbox with the ring die to test the required torque and the rotation speed in the densification process. A data acquisition system including hardware and software running on a laptop (developed by the same company that manufactured the torque sensor) was employed to acquire the torque signal and the rotation speed data simultaneously.

According to previous studies (Tumuluru *et al*. 2010), moisture, particle size, temperature, and material type all affect the densification force, pellet quality, and density. Because the main aim of this study was to prove the feasibility of improving the pellet mill and testing the quality of the pellets, experiments in the idle state (no raw material) and working state (compaction of raw material) were performed to test the torque and the rotational speed.

The raw material was uniformly fed into the hopper at ambient temperature. The rotational speed of the roller was set at 170 rpm by adjusting an accelerator lever. The experiment was conducted for 10 min.

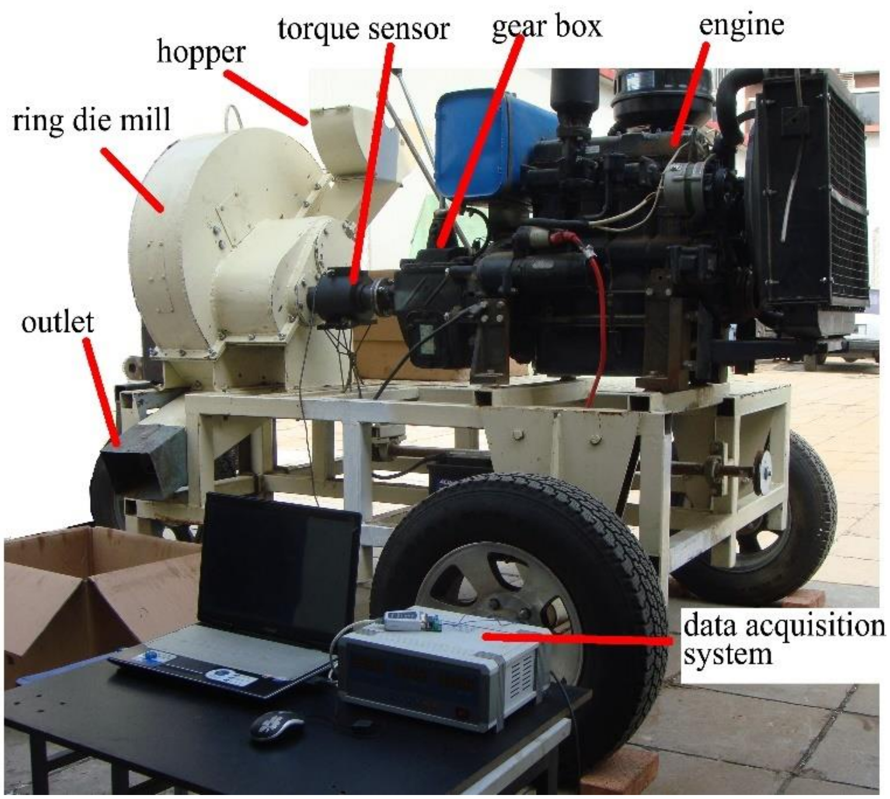


Fig. 11. Experimental set-up

Pellet Density Test

The density of the pellets was calculated by measuring the length and the diameter of the pellet using an electronic caliper and by measuring the mass of the pellet using an electronic balance with a precision of 0.01 g. To achieve precise volume, the edges of the pellets were smoothed. Pellet density was calculated by dividing the individual mass by its volume and calculated from its length and diameter (Abedin 2012). Ten randomly selected samples were measured, and their properties were recorded.

Durability Test

Durability, defined as the ability of pellets to withstand destructive loads and force during transport, is the most important physical quality of a pellet (Tabil and Sokhansanj 1996). Durability is considered high with values above 80%, medium with values between 70% and 80%, and low with values below 70% (Colley *et al*. 2006). Low pellet durability not only affects the pellet usage, but also increases the risk of fire explosion during pellet handling and storage (Abedin 2012). Determination of pellet durability was carried out according to Chinese Agriculture Industry Standard NYT 1881.8 (2010). According to the standard, a 1-kg sample of pellets was tumbled at 40 rpm for 12.5 min in an enclosed tumbling can tester (Model KER-2400, Beijing Jingjing Co., Ltd, Beijing, China). After tumbling, the sample was sieved using a sieve aperture of 3.5 mm, and mechanical durability was calculated by dividing the whole pellet mass by the initial total mass.

RESULTS AND DISCUSSION

A graph of the torque and the rotational speed *versus* time in the pelletization process was plotted using the data collected by the data acquisition system on the laptop. Although the experiment was conducted for 10 min, the results from the 20^{th} s to the 10^{th} min were similar. Therefore, Fig. 12 only shows the beginning 64 s of the experiment for compaction torque and rotation speed at the roller speed of 170 rpm. It is clearly shown that the working process can be divided into three stages.

At idle stage (AB), the upgraded mill started to rotate at a velocity of 170 rpm and prepared to work. At this stage, the raw material was not fed into the machine, and the required torque to maintain idle rotation was about 150 N·m.

At pre-compress stage (BC), the milled raw material rotated together with the ring die due to the static friction, and it came into the working gap between the ring die and the roller. Then the rams on the roller began to press the material into the opening channels on the ring die; and gradually the pressure was built up by the friction between the material and the channels; then more material was pressed into the channels and the pellet density increased, and the required torque was increasing sharply to about 200 N·m, until the pellets were extruded out of the channels. In this stage, the rotational speed decreased from 170 to 155 rpm.

At steadily extrude stage (CD), the rotational speed fluctuated in the range from 155 to 160 rpm. Although the torque curve fluctuated strongly with time, it reached a relatively stable range from 180 to 220 N·m to overcome the friction on the surface between each cylindrical opening channel and compact pellet inside while the pellets were extruding out. This stage lasted to the end of the experiment

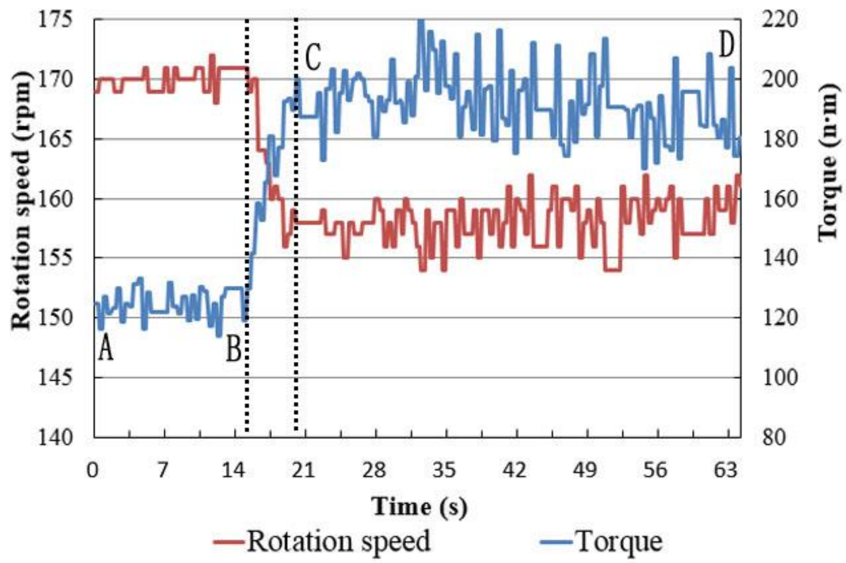


Fig. 12. Torque and rotation *versus* time at the roller speed of 170 rpm

Figures 13 and 14 show the state of the roller and ring die surfaces after a period of work (approximately 50-h run-in period). Wear and deformation were not found on the rams, the roller, or the ring die, which showed no evidence of excessive friction and compaction between the roller and the ring die.

Fig. 13. The surface of the roller after work

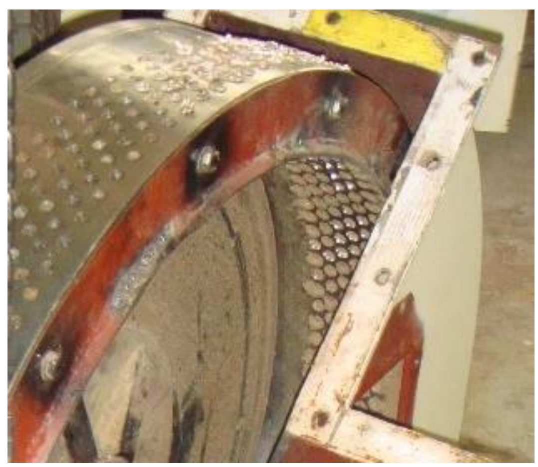


Fig. 14. The surface of the ring die after work

Figure 15 shows the pellets produced by the upgraded mill. They all showed a smooth outer surface with varying lengths. Table 1 shows the measured pellet density data: the density was approximately 1.0 g/cm^3. Normally the density values of pellets ranges from 0.8 to 1.3 g/cm^3 when produced by a conventional mill (Pang *et al*. 2012, Zhang *et al*. 2008); therefore, the pellets produced by this improved method are qualified, and it can be expected that higher density of pellets will be achieved by increasing the ratio of the length to the diameter of the opening channel using this improved densification method. Table 2 shows the mechanical durability tested three times; all the values were above 92%.

Fig. 15. Densified pellets

Table 1. Density of 10 Randomly Selected Pellets

Pellet No.	Diameter (mm)	Length (mm)	Mass (g)	Density (g/cm^3)
1	8.60	29.50	1.90	1.11
2	8.60	14.80	0.96	1.12
3	8.55	20.54	1.29	1.09
4	8.73	17.52	1.03	0.98
5	8.82	19.58	1.16	0.97
6	8.88	17.40	1.02	0.95
7	8.89	24.08	1.59	1.06
8	8.51	20.66	1.20	1.02
9	8.58	16.30	1.00	1.06
10	8.59	9.81	0.55	0.97

Table 2. Mechanical Durability of Pellets in Three Tests

Sample No.	Durability (%)
1	92.1
2	94.7
3	93.5

CONCLUSIONS

1. An upgraded pellet mill with rams on the roller was designed and manufactured. The roller and the ring die rotate in a fixed ratio to ensure that the rams press the raw material directly into the open channel on the ring die.
2. Milled *Caragana microphylla* Lam with a diameter of under 2 mm and with an ambient moisture content of approximately 10% was fed into the mill and was densified by the rams on the rotating roller. The result showed that the upgraded pellet mill meshed well and could produce pellets.
3. After a period of trials working, there were no obvious signs of wear or deformations on the surface of the rams, the roller, and the ring die.

4. Pellets were produced by the upgraded mill. Their densities were approximately 1 g/cm^3, and mechanical durability values were all above 92%.

ACKNOWLEDGMENTS

The authors are grateful for the support of "The Fundamental Research Funds for the Central Universities" (No. TD2013-4) and "The National Science & Technology Pillar Program during the Twelfth Five-year Plan Period" (No. 2012BAD30B00). And we also sincerely thank Joshua Green for revision work.

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Article submitted: June 15, 2015; Peer review completed: July 20, 2015; Revised version received: August 3, 2015; Accepted: August 10, 2015; Published: August 14, 2015.
DOI: 10.15376/biores.10.4.6576-6585