

## Vibration-assisted Compaction of Biomass

Pei Wu,\* Yanhua Ma, Yanhong Chen, Yong Zhang, and Huiyuan Wang

The biomass extrusion process for making biomass briquettes or logs normally requires large amounts of energy to overcome the springback of the material and friction with the die surface. Also, the products readily expand and disintegrate because of the retention of internal stresses. In this study, tests on vibration-assisted compaction of biomass were performed as a method to reduce the energy requirement and to improve product quality. An experimental set-up was designed and manufactured by which vibration-assisted compaction was exerted on a die surface. Tests on compaction to form upgraded biomass logs with and without the assistance of vibration were conducted and compared. The results showed that the vibration applied on a die surface can reduce the compression energy requirements and improve product quality.

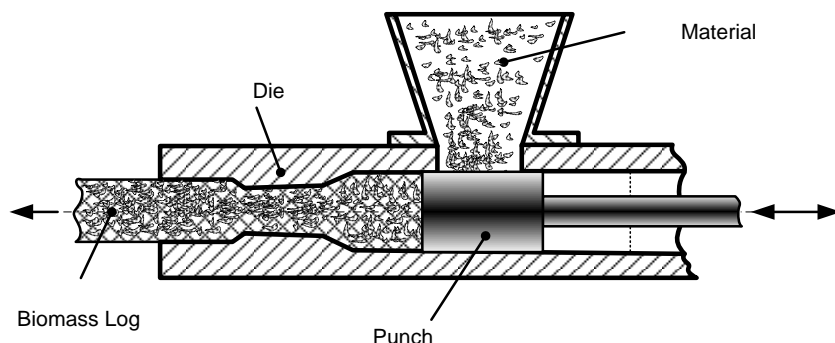
*Keywords: Biomass; Vibration-assisted; Compaction; Energy requirement*

*Contact information: College of Mechanical & Electrical Engineering, Inner Mongolia Agricultural University, Huhhot, 010018, P. R. China; \*Corresponding author: jdwupei@163.com*

### INTRODUCTION

Large amounts of biowaste materials, such as wheat stalks, rice husks, and sawdust, are produced each year in China (Jian and Liu 2013). It is very difficult to handle, transport, store, and utilize this biomass in its original form because of its low bulk density, irregular shape, and size. Therefore, the costs and difficulties in handling and storage of loose biomass are major obstacles in using it as feedstock for bio-based products and fuels. One solution to these problems is to densify it into briquettes, pellets, or logs, which improves the handling properties and reduces the cost of transportation and storage (Chen *et al.* 2009; Mani *et al.* 2006; Sultana and Kumar 2012).

As an example, in a conventional biomass extrusion process for making biomass logs, raw material is fed and compressed by a screw or a piston through a cylindrical die or other shapes, as shown in Fig. 1.



**Fig. 1.** Conventional biomass extrusion process

This process requires large amounts of energy to compress material and to overcome its springback and friction between the material and the die surface; thus, the extruder commonly has problems associated with high energy consumption, low productivity, and heavy wear of the die (Granada *et al.* 2002; Singh *et al.* 2007; Li and Liu 2000). In addition, the products have a tendency to expand again and disintegrate because of the retention of internal stress.

To increase the throughput and reduce the energy consumption, some producers preheat the material to form biomass briquettes or pellets. The goal of such preheating of biomass is usually to activate the inherent binders for making permanent bonding and lower the compression force needed (Skoch *et al.* 1981; Winowiski 1985; Gilpin *et al.* 2002).

Although heating is favorable, some studies have found that the temperature should not be too high; otherwise the heating will decompose or carbonize the material and anneal the die and thus cause failure of upgrading the biomass, as well as reducing the die life (Grover and Mishra 1996; Zhang *et al.* 1999).

In other work, the compression process was optimized by studying the factors affecting the biomass densification process, such as moisture content as well as particle size of material, extruding pressure, and critical sizes of die (O'Dogherty and Weeley 1982; Fabrode and O'Callaghan 1989; Meng 1994; Peng *et al.* 2012). Due to the interactions of these factors and their different effects under different conditions, such as the constituents of material, types of machine *etc.*, one can conclude that there is no universal optimum densification variables; rather, favorable values of independent variables need to be determined using an optimization procedure for each case (Kaliyan and Morey 2009).

Zhao and Zhao (2013) presented a general designing scheme of the vibration compactor for discrete materials beginning with energy saving and low cost. The device mainly consists of a compression roller, backspin rolls, as well as an eccentric shaft, which is driven by a motor to generate vibration exciting force. The material entering from the feeding inlet is compacted between the compression roller and the backspin rolls under the actions of both extrusion force and vibration.

Though the design has been shown to be able to improve the compaction of the material, it is not possible to form upgraded briquette or pallets with the device, since no die is employed. Also several researchers studied the densification for granular material packing and extrusion of polyethylene under vibration, but the characteristics of the materials processed in these cases are different from those encountered in biomass densification (Kim and Pyun 1995; Lesaffrea *et al.* 2000; Gao *et al.* 2007). Therefore, results of the cited studies cannot be used with confidence to predict whether or not vibration-assisted compaction can be successfully employed when dealing with biomass.

The objective of this paper was to study the feasibility and effects of applying vibration as a supplemental effect aimed at lowering the energy requirement and improving the product quality in densification of the biomass. This research is based on the principle that vibration can reduce the friction between material and die surfaces, thus increasing the flow capacity of the material. In principle, such a treatment has potential to relieve or improve the uniformity of internal stresses to thus lower the springback effect, thereby minimizing disintegration of the product.

## MATERIALS AND METHODS

### Materials

*Caragana korshinskii* Kom, used as the experimental material, is produced in the region of Ordos (37°35'N-106°42'E) in Inner Mongolia of China. It has been planted in a large scale in the Gobi desert area of northwestern China in recent years in order to resist the generation of dust by wind. The *C. korshinskii* is of a drought-enduring plant that has a special biological characteristic in that it must be cut once every 3 to 5 years to rejuvenate and maintain healthy growth (called stumping and rejuvenating); therefore, the resource is abundant. In this study, the cut *C. korshinskii*, dried naturally for one month, was milled into a fibrous form using a 9R-28 feed crumbling machine (Plant of Inner Mongolia Agricultural University, Huhhot, China) with sieve size of 4 mm (as shown in Fig. 2). The milled raw material with an initial bulk density of 210 kg m<sup>-3</sup> and moisture content around 6.5% is shown in Fig. 3. The particles of the milled raw material ranged in size from 0 to 2 mm, 0 to 4 mm, and 0 to 6 mm and were prepared according to the oscillating screen method using different sieve apertures (British Standards 2005b). To obtain different moisture contents, water was added to the milled raw material and mixed thoroughly. After preparation, the material was bagged and stored for 48 h at room temperature (Fig. 4). The moisture content of the milled raw material was determined according to the British Standards (2004) technical specification.



**Fig. 2.** The 9R-28 feed crumbling machine



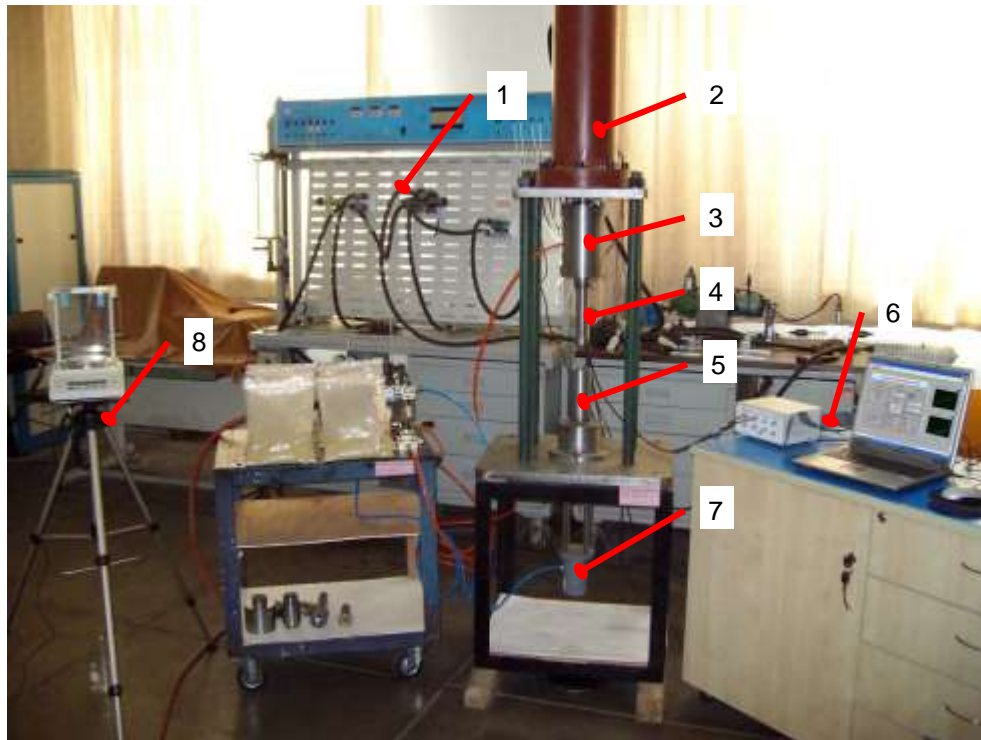
**Fig. 3.** The milled raw material



**Fig. 4.** The bagged test material

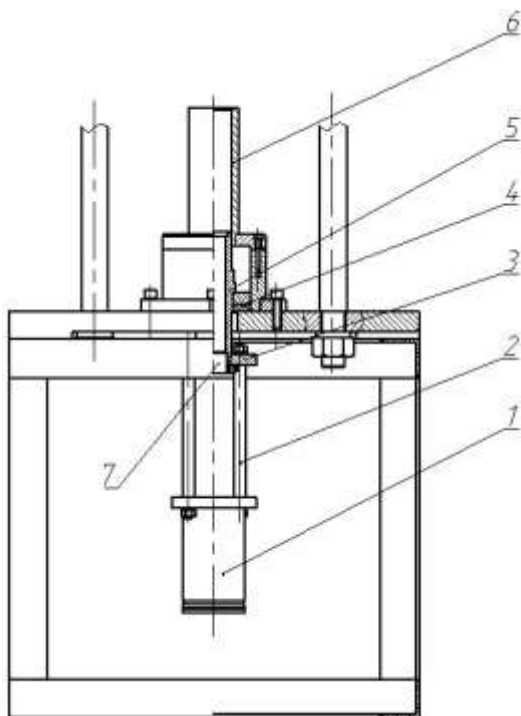
### Methods

The experimental set-up for this study is shown in Fig. 5. A cylindrical die with a channel diameter of 30 mm and die length to diameter ratio of 5.2 was used to prepare the biomass logs (100 mm in length) from the raw materials. A punch connected to a piston was driven by a hydraulic system with maximum pressure limit of 11 MPa; thus the maximum pressure the punch could exert on the material during the compaction process was approximately 139 MPa.



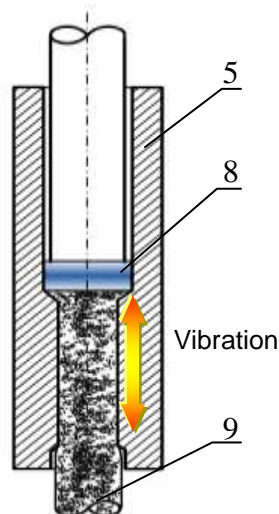
**Fig. 5.** Photograph of the experimental set-up. 1, hydraulic power system; 2, hydraulic cylinder; 3, pneumatic vibration exciter; 4, punch; 5, die; 6, data acquisition system; 7, pneumatic vibration exciter; and 8, electronic balance

The vibration used to supplement the compaction process was introduced using an air-operated vibration exciter (Model QJQ3-63; Shanghai YaHong Auto-Controlling Equipment Co., Ltd.; Shanghai, China) with an excitation force of 1.7 kN and frequency range of 10 to 40 Hz. The vibration exciter, connected to the die via connecting bars and a ring flange, excited the die so that it vibrated in an axial direction (Fig. 6).



**Fig. 6a.** Schematic of the experimental set-up.

1, Vibration exciter; 2, Connecting bar; 3, Ring flange; 4, Elastic cushion; 5, Die; 6, Feeder; 7, Outlet; 8, Punch; and 9, Biomass log



**Fig. 6b.** More detail about the die

To compare the effects of supplemental vibration on the densification of biomass, a TS-2 pressure sensor (Nominal pressure 15 MPa), connected to the oil inlet pipe of the hydraulic system, was employed to measure the hydraulic pressure in the cylinder, and a BESTNEW BM-300 mm variable-resistance displacement sensor ( $\text{LIN} \pm 0.05\%$ , 5 k $\Omega$ ) was used to measure the displacement of the punch. The two signals were detected simultaneously by a NI6062 data acquisition board, which was interfaced with a laptop computer running LabVIEW 7.1 software (National Instruments, USA).

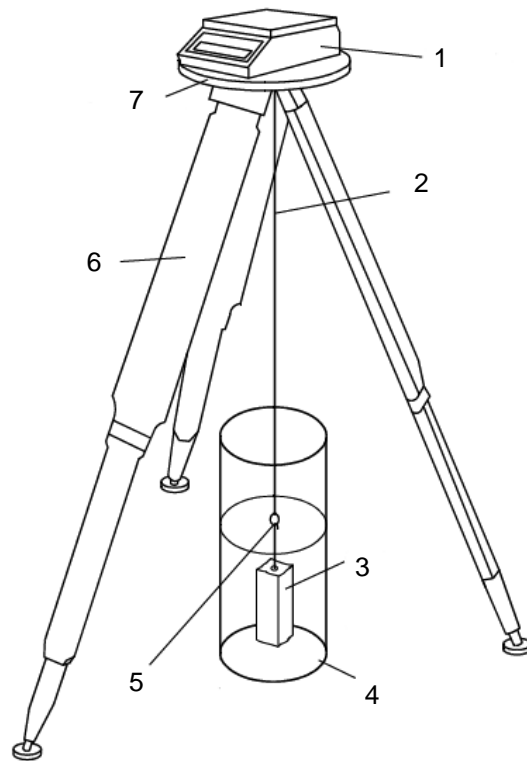
There are many factors affecting the compaction of biomass. Considering that the main purpose of this study was to test the feasibility and effects of supplementary or assistive vibration on compaction, the tests with and without assistive vibration were performed and compared under the same test conditions. Before performing the assistive vibration tests, pre-tests were conducted to find a set of appropriate parameters for the current experimental conditions. These were conventional compression tests under normal temperature and without using binder and heat. Table 1 shows the resulting parameters for all subsequent tests.

**Table 1.** Test Parameters

Biomaterials in moisture content (%)	Extruding pressure (MPa)	Particle size in length (mm)	Feeding charge (g)
24	101	4	80

The material was fed into the top of the die. Because it is a continuous process, some material was fed and then compressed until biomass log began to extrude while establishing the normal pressure. Then, in a continuous series, the tests with and without assistive axial vibration on the die were performed. Three replicate tests were carried out for each condition, and their data averaged. The feed quantity of material was the same for each test. During the tests, hydraulic pressure in the chamber of cylinder and displacement of punch were measured and recorded by the LabVIEW data acquisition system.

The density of the upgraded biomass logs was measured within 2 min of extrusion and based on a technical specification that assumes that the logs underwent springback following ejection and that the most rapid expansion occurred within the first 2 min (British Standards 2005a). For this measuring principle, the density was determined by measuring both mass and volume of the biomass briquette. The volume is measured by determining buoyancy in a liquid. This procedure follows from the physical principle that the buoyancy of a body is equal to the weight of the displaced volume of a liquid. The apparent loss in weight between a measurement in air and a subsequent measurement in liquid marks its buoyancy. The weight was measured using a balance, as shown in Fig. 7. The volume of the sample body is calculated *via* the density of the applied liquid.



**Fig. 7.** Schematic for the device measuring buoyancy. 1, electric balance; 2, thin steel wire; 3, sample; 4, container; 5, connecting ring; 6, tripod; and 7, plate

Water from the tap was used as the liquid for measuring the volume of the sample. In order to prevent absorption of the water into the specimen, it was coated by submerging it in liquid paraffin. Considering the specimen densities to be below or near the density of water, a cylindrical stainless weight was positioned onto the sample in a way that made the briquette completely and rapidly become immersed into the water. Then the weight of the cylindrical stainless weight was subtracted when calculating the buoyancy.

## RESULTS AND DISCUSSION

Graphs of pressure and displacement versus time based on the raw data were generated in Origin 7.5 software (OriginLab). Figure 8a shows the curves for conventional compression of biomass without assisted vibration, with a moisture content of the material of 24%. It is clearly shown that the compression process can be divided into five stages: AB (pre-compression stage), due to the low bulk density of material, the required pressure is low and increases slowly, and the displacement of the punch is great, moving at nearly a constant speed as determined by the hydraulic flow in cylinder; BC (compression stage), the material is further compressed, the density of material increases and viscoelastic deformation occurs, with the increase of density and material coming into the narrow section of the die; the required pressure increases rapidly but the punch displacement is small; CD (shape-preserving stage), the pressure builds up, reaches the maximum and maintains for a time to overcome the maximum static friction, while the displacement increases slightly (almost unchanged); DE (extrusion stage), the biomass log begins to squeeze out, indicating that the pressure has reached the maximum static friction force between material and die surface, and the static friction turns into kinetic friction, so the pressure decreases and displacement increases, then the punch reaches the end of the die (EF), so the pressure increases sharply (Fig. 6b.); and FG (punch-return stage), in which the punch returns and the cycle of compression is completed.

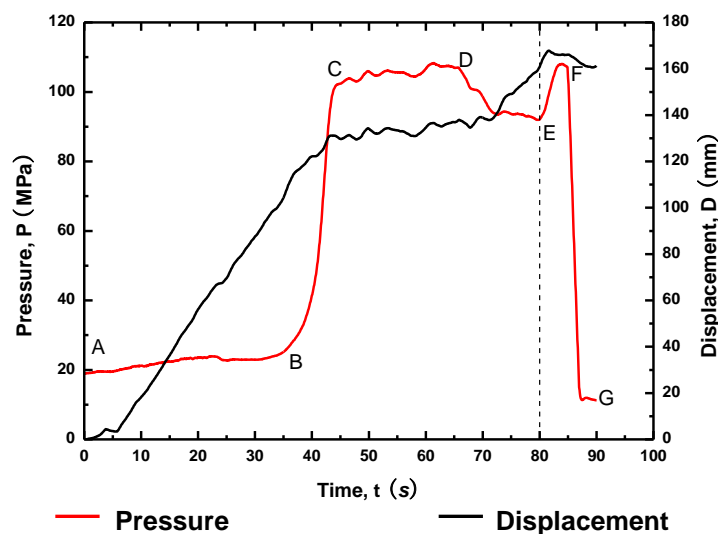
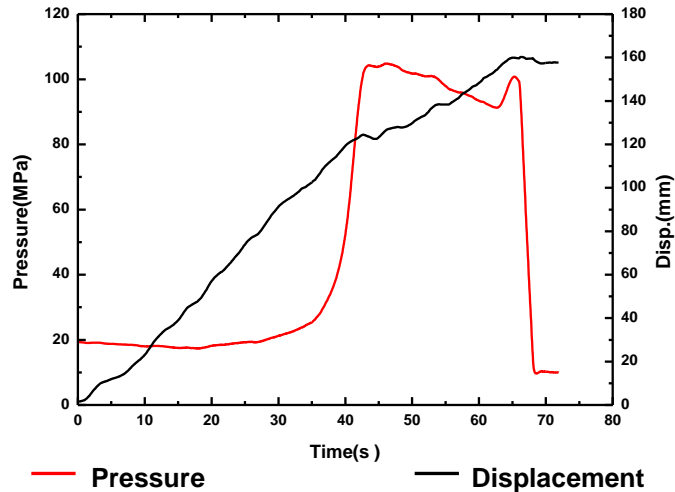


Fig. 8a. Curves for conventional compression of biomass without supplementary vibration

Figure 8b shows the compression curves of biomass at a moisture content of 24% with assistive axial vibration of the die. A very short shape-preserving stage is present, at which the pressure reached the maximum but the displacement was very small, which indicates that the supplemental vibration helped to overcome the maximum static friction and therefore extrude the material faster.



**Fig. 8b.** Compression curves of biomass with assistive axial vibration on die

Figure 8c provides a comparison of pressures between conventional compression and compression with assistive axial vibration. It can be seen that there was no obvious difference at the first two stages (AB and BC), indicating that the vibrational assistance had no significant effect on the pre-compression and compression phases. However, at the shape-preserving and extrusion stages, the time period of compression with assistive vibration was much shorter (by nearly 10 s) than that without assistive vibration and the pressure was lower. The energy requirement during compression was the production of pressure, flow rate, and time, that is,

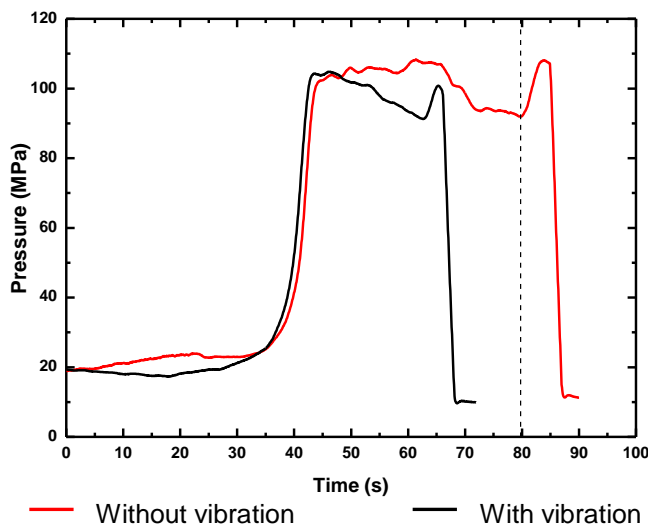
$$W = PQ t \quad (1)$$

where  $W$  is the energy required for the compression (J),  $P$  is the pressure of the hydraulic system (Pa),  $Q$  is the flow rate of the hydraulic system ( $\text{m}^3/\text{s}$ ), and  $t$  is the elapsed time.

At the shape-preserving stage, the pressure reached the maximum and the flow was the rated flow of the hydraulic pump (4 L/min), so the power requirement was determined by the time period of compression. As shown, a savings in power could be obtained with assistive vibration under the present parameters. Also productivity will be higher since the entire compression process is shorter. According to the above formula, the hydraulic energy required for the compression with vibration at the shape-preserving stage was 2.67kJ, but without the vibration it was 12.27 kJ, nearly 4.6 times of energy saving. At this stage, the density of a biomass log comes to the maximum but the displacement of punch nearly equals to zero. The function of the compression pressure is only to overcome the biomass springback and to match the static friction force acting between the biomass and the die surface. When the vibration is introduced, as in the case of a metal vibration aging treatment, the vibratory exciting force will promote the internal



stress of the biomass to become released or more uniform, lowering the springback. Also it will reduce the friction between the biomass log and the die surface and cause the static friction to be converted to a dynamic friction force at an earlier stage. That is the reason why the shape-preserving period is shorter and the compression pressure required is lower compared to the case without assistive vibration.



**Fig. 8c.** Comparison of pressures with and without assistive axial vibration

Although the entire compression process and time of material through the die were shorter with assistive vibration than conventional compression, the density of products was similar and the quality of products improved.

Table 2 provides a comparison of compression density and relaxation ratio of products obtained with and without assistive vibration. As mentioned above, the compression density of the product was measured within 2 min of extrusion, while relaxation density and density after springback or stress relaxation was measured after the product had been left at room temperature for one week. Thus, the relaxation ratio was determined with compression density divided by relaxation density. It can be seen that both compression density and relaxation ratio with assistive vibration were not significantly different compared with that without assistive vibration, indicating that the vibration had no apparent effect on product density under same compression conditions.

**Table 2.** Comparison of Relaxation Ratio of Solidified Biomass Fuel under Three Conditions

Conditions	Compression density ( $\text{g}\cdot\text{cm}^{-3}$ )	Relaxation density ( $\text{g}\cdot\text{cm}^{-3}$ )	Relaxation ratio
No vibration	0.966	0.577	1.673
With vibration	1.011	0.579	1.746

Figure 9 shows a comparison of the surface quality of products produced with the same materials (*e.g.*, moisture content 24%, particle size 4 mm in length, charge quantity 80 g) that were stored at room temperature for a week prior to analysis. The surfaces of products created under assistive vibration were clean and smooth with no disintegration, while the surface of the product created without vibration contained cracks, illustrating

that vibration improved the product quality. This may be due to the fact that the vibration relieved some internal stresses and helped fibres or flattened particles fill and interlock with each other to form interlocking bonds. Internal stress is an important factor affecting the product quality, as it causes springback and disintegration of the product.



**Fig. 9.** Comparison of surface quality of products

## CONCLUSIONS

1. A compression cycle of *C. korshinskii* for producing solid biomass logs can be divided into five stages: pre-compression stage, compression stage, shape-preserving stage, extrusion stage, and punch-return stage.
2. From the tests on vibration-assisted compaction of *C. korshinskii*, it was found that the energy requirement was lower compared to that of the compression without assistive vibration because the vibration in the axial direction on the die reduced the biomass springback and the friction between the material and the die surface. The vibration only has an apparent effect at the shape-preserving stage of a compression cycle, it lowers the springback of the biomass and promotes an early transition from static friction to dynamic friction compared to the case without assistive vibration.
3. It was also found that the assistive vibration has no apparent effect on product density under the same compression conditions, but improves the product quality since the vibration relieves some internal stresses and helps fibres or flattened particles fill and interlock each other to form interlocking bonds.

## ACKNOWLEDGMENTS

This research was funded by the National Natural Science Foundation of China (Grant No. 51165029) and by the Inner Mongolia Natural Science Foundation of China (Grant No. 2010MS0707, Grant No. 2011MS0705).

## REFERENCES CITED

British Standards (2004). "Solid biofuels - Methods for the determination of moisture content oven dry method - Part 2: Total moisture-Simplified method," *DD CEN/TS 14774-2*.

- British Standards (2005a). "Solid biofuels - Methods for the determination of particle size distribution - Part 1: Oscillating screen method using sieve apertures of 3.15 mm and above," *DD CEN/TS 15149*.
- British Standards (2005b). "Solid biofuels - Methods for the determination of particle density," *DD CEN/TS 15150*.
- Chen, L., Xing, L., and Han, L. (2009). "Renewable energy from agro-residues in China: Solid biofuels and biomass briquetting technology," *Renewable and Sustainable Energy* 13(9), 2689-2695.
- Fabrode, M. O., and O'Callaghan, J. R. (1989). "A rheological model for the compression of fibrous agricultural materials," *Agric. Engng. Res.* 42 (1), 165-178.
- Gao, X. Q., Zhang, J., Chen, C., and Shen, K. Z. (2007). "Effect of vibration extrusion on high-density polyethylene," *Journal of Applied Polymer Science* 106, 552-557.
- Gilpin, A. S., Herrman, T. J., Behnke, K. C., and Fairchild, F. J. (2002). "Feed moisture, retention time, and steam as quality and energy utilization determinants in the pelleting process," *Applied Eng. Agric.* 18, 331-338.
- Granada, E., López González, L. M., Miguez, J. L., and Moran, J. (2002). "Fuel lignocellulosic briquettes, die design and products study," *Renewable Energy* 27, 561-573.
- Grover, P. D., and Mishra, S. K. (1996). "Biomass briquetting: Technology and practices," *Regional Wood Energy Development Program in Asia, Field Document No. 46. Bangkok, Thailand: Food and Agriculture Organization of the United Nations*.
- Jian, X., and Liu, S. (2013). "Research status and development prospect of densified Biofuel," *Biomass Chemical Engineering* 47(2), 54-58 (In Chinese).
- Kaliyan, N., and Morey, R. V. (2009). "Factors affecting strength and durability of densified biomass products," *Biomass and Bioenergy* 33(3), 337-359.
- Kim, H., and Pyun, M. S. (1995). "Densification of powder compacts by vibration," *Chem. Eng.* 12(4), 488-490.
- Lesaffre, C., Mineau, V., Picart, D., and Van Damme, H. (2000). "Densification under vibration of a saturated granular packing," *C. R. Acad. Sci. Paris, Série IV*, 647-653.
- Li, Y., and Liu, H. (2000). "High-pressure densification of wood residues to form an upgraded fuel," *Biomass and Bioenergy* 19(3), 177-186.
- Mani, S., Tabil, L. G., and Shahab, S. (2006). "Specific energy requirement for compaction corn stover," *Bioresource Technology* 97(12), 1420-1426.
- Meng, O. L. (1994). "The optimum design of structural parameters for the extruding apparatus of the biomass briquette," *Transactions of the CSAE* 9(1), 142-147.
- O'Dogherty, M. J., and Weeley, J. A. (1982). "The effect of die diameter mode of loading and chopping on the compression of straw to high densities in closed cylindrical dies," *Divisional Note dn/1103*, National Institute of Agriculture Engineering, Silsoe.
- Peng, J. H., Bi, H. T., Sokhansanj, S., and Lim, J. C. (2012). "A study of particle size effect on biomass torrefaction and densification," *Energy & Fuels* 26, 3826-3839.
- Singh, R. N., Bhoi, P. R., and Patel, S. R. (2007). "Modification of commercial briquetting machine to produce 35 mm diameter briquettes suitable for gasification and combustion," *Renewable Energy* 32(3), 474-479.
- Skoch, E. R., Behnke, K. C., Deyoe, C. W., and Binder, S. F. (1981). "The effect of steam-conditioning rate on the pelleting process," *Animal Feed Sci. Tech.* 6, 83-90.
- Sultana, A., and Kumar, A. (2012). "Ranking of biomass pellets by integration of economic, environmental and technical factors," *Biomass and Bioenergy* 39(S1), 344-355.

- Winowiski, T. (1985). "Optimizing pelleting temperature," *Feed Mgmt.* 36, 28-33.
- Zhang, B. L., Li, B. Q., Zhao, C. H., Xia, Z. Z., and Fu, H. T. (1999). "Test and research on HPB- I biomass briquetting machine," *Transactions of the CSAE* 15(3), 133-136.
- Zhao, Q., and Zhao, J. F. (2013). "Designs of material compactor based on vibration theory," *Advanced Materials Research* 700, 187-190.

Article submitted: February 19, 2014; Peer review completed: April 5, 2014; Revised version received and accepted: May 4, 2014; Published: May 9, 2014.