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Motion simulation analysis and experimental study of a ring mold pelletizer

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ABSTRACT In this paper, a three-dimensional model of a ring mold pelletizer was established based on the Pro/Engineer software, and the model was transferred into ADAMS software through Mech/Pro which is a dedicated interface software. The ADAMS software was used to run simulations. The analysis showed that the machine's working state was good. Corn stover was used as material, for experimental manufacturing of fuel pellet using the ring mold pelletizer. A single-factor experiment was designed to analyze the effect of each experimental factor, namely, moisture content and material particle size on pellet durability by drop test. The test results showed that the durability of the fuel pellet made by the prototype machine was up to standard. Using virtual prototype technology to simulate the working state of the ring mold pellet pelletizer resulted in high accuracy.

Keywords: Biomass, Pellet, Fuel, Pro/Engineer, ADAMS, Virtual design, Durability

INTRODUCTION

Biomass fuel pellet has a great potential for development. The emissions from biomass pellet combustion with respect to SO_2, NO_X, and other pollutants is far below the emission standards for air pollutants (Wang, 2007; Qiu, 2013; Rabaçal, 2013). Pelleting using the ring mold pelletizer does not require external heating and additives or binders. It relies on the frictional heat, resulting in the softening of the biomass particles, and extrusion molding, resulting in the compaction of particles to a certain density and shape. It is an ideal forming process for biomass pellet production (Kim, 2004). Equipment design involves a long research and development cycle and a high testing cost. This reality restricts the application and development of ring mold pelletizer technology (Sun, 2009). This work involves the design of a ring mold pelletizer by modeling using the Pro/Engineer 3D software. The ADAMS software was used for movement simulation analysis of high wear and pressure parts of the pelletizer.

WORKING PRINCIPLE AND MOLDING PROCESS

The ring mold pelletizer is composed of a power unit, a deceleration unit and body unit. The motor provides power to drive the rotating ring mold. The deceleration unit connected the motor with the shaft and the coupling; it has a reducer to control speed and increase the torque. The body unit includes a screw conveyor, rollers, a ring mold, a roller plate and accessory parts. During rotation, extrusion pressure is generated between the ring mold and rollers, so that the biomass feed is shaped into a densified product (pellet).

To form pellets, molding of the biomass starts in the feed zone, followed by the deformation zone and then it goes into the extrusion zone. The formation process is shown in Figure 1. In the feed zone, the biomass is not affected by external mechanical forces, but it is subjected to the centrifugal force produced by high-speed rotation of the ring mold conveying the biomass to the deformation zone. In the deformation zone, with the rotation of ring mold and rollers, the material enters the nip. By the pressing action of rollers (as the pressing force increases by the decrease of degree of α), the gap between the biomass particles is gradually reduced, thereby compressing the biomass particles, and resulting in deformation and density increase. In the extrusion zone, the gap between the mold and rollers becomes smaller. The extrusion pressure increases rapidly, the biomass particles are pressed into the ring mold die. In the extrusion zone, the biomass in the ring mold die is subjected to axial extrusion pressure to overcome the frictional pressure in the die wall to extrude the formed pellet out of the die.

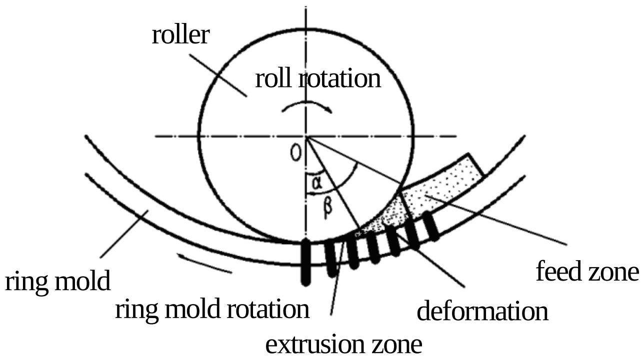


Figure 1. Pellet formation process of particles

3D SOLID MODELING

Design parameters The transmission ratios of the two stage cylindrical gear reducer were $i_1 = 4.6$, $i_2 = 3.5$, respectively. Belt drive ratio was $i_3 = 2$. Table 1 shows the design specifications of the motor used in the pelletizer.

So the spindle speed is given as

$$n_s = n_m / i_1 i_2 i_3 = 1460/(4.6 \times 3.5 \times 2) = 45.4 \text{ r·min}^{-1} \quad (1)$$

Table 1. Design specification of the motor

Model and Manufacturer	Rated power (kW)	Rotational speed（r·min^{-1}）	Efficiency (%)
Y160L-4 Shanghai Shenyue Electrical Co., Ltd. Daxi, Wenling, Zhejiang, China	15	1460	88.5

Design of the main parts Ring mold: The material selected for the ring mold was high chromium alloy steel forgings. The tensile strength was ≥ 980 MPa. After heat treatment, the surface hardness was up to that 58-62HRC steel. The hole was straight, for simple processing and is applicable to a wide range of materials. The arrangement of the die was equilateral triangle (Figure 2), ensuring the intensity of ring mold and reducing the breakage of parts.

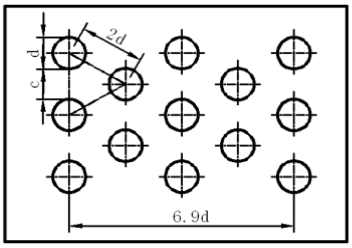


Figure 2. Arrangement of mold die holes in the ring mold

The inner diameter of the ring mold is:

$$D = \frac{60v}{\pi n_s} \quad (2)$$

Where D =inner diameter of ring mold (mm); v =line speed of ring mold, the machine selected, v =850 mm/s.

Thickness of ring mold should consider not only the die effective length and intensity (die wall compressive stress), but also the die diameter and material characteristics. The thicker the mold, the deeper is the die and the smaller is the aperture ratio, resulting in greater die wall resistance. The widely used thickness of the ring mold is 32-127 mm (Huo, 2010). Table 2 shows the design specifications of the ring mold.

Table 2. Design specifications of the ring mold

Inner diameter (mm)	Thickness(mm)	Aperture (mm)	Type	Arrangement
360	30	8	straight	equilateral triangle

Rollers: Failure of the ring mold is mainly attributed to bending fatigue stress which is caused by alternating loads on the cross section of the ring mold. This fatigue damage is caused by the stress amplitude and stress ratio under alternating loads. The fatigue failure accelerated when the stress amplitude or the stress ratio increased (Huo, 2010). The stress amplitude and the stress ratio were all related to the number of rollers. Our research determined that the reasonable number of rollers was 4 (Gao, 2012).

The roller adopted a groove surface structure (Figure 3 a). The ring mold diameter D was twice longer than the roller's diameter d. Considering the adjustment of gap and other factors, this relationship is shown in equation (3) (Sun, 2009):

$$d = (0.3 \sim 0.5)D \tag{3}$$

The roller diameter affects the production efficiency and the intake angle of biomass particles being pelleted. Thus, the roller diameter should be as large as possible. In order to convey the particles more easily from the feed zone to the extrusion zone, the ring mold and the rollers should maintain a certain clearance. Rollers were installed into the ring mold, and were adjusted to slightly contact each other to cause rotation of the rollers. Table 3 shows design specifications of rollers for the ring mold pelletizer.

Table 3. Design specifications of rollers for the ring mold pelletizer

Diameter of roller (mm)	Depth of groove (mm)	Roll thickness (mm)	Tolerance clearance (mm)
120	4	90	0.1

Modeling the ring mold pelletizer To establish each of the main working parts of the ring mold pelletizer involved creating each feature surface by the way of stretching, rotating, scanning, mixing, shelling and other methods(David, 2000; Gecevska,2006; Vinodh, 2009). The 3D models of the main working parts are shown in Figure 3.

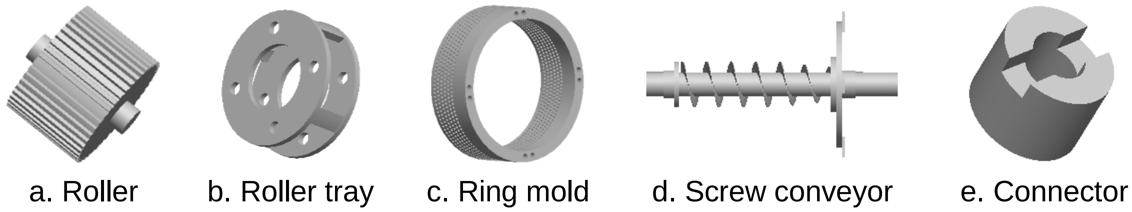


Figure 3. 3D models of the main working parts of ring mold pelletizer

The assembly modeling module of Pro/Engineer software was used to complete the virtual assembly. According to the assembly movement and connection of the main working parts, the corresponding relationship and the connection type of setting was selected. Assembly of each part separately was completed first. This was followed by finishing the whole assembly. Lastly, an interference check was performed to ensure that there were no interferences of the whole assembly. The whole model of ring mold pelletizer is shown in Figure 4.

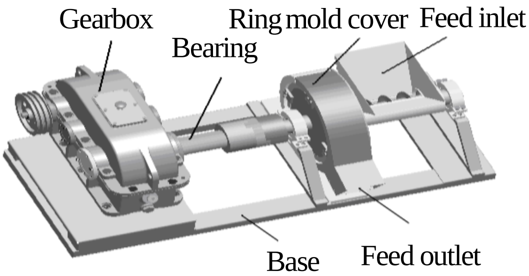


Figure 4. Whole model of ring mold pelletizer

SIMULATION ANALYSIS

Determination of the interaction force F **:** The motor provided the energy for the ring mold to rotate through the motion bearing ring through a rigid connection between the ring mold and the motor. In one minute, the energy, W' which was provided by the motor is given in equation (4):

$$W' = P \times 60 \tag{4}$$

Where P =motor power (kW).

In one minute, the energy required for the ring mold rotation is given in equation (5):

$$E = Me_h \varphi = Me \times 2\pi n \tag{5}$$

Where Me_h =rotating force moment (J); φ =turning angle of the ring mold in one minute (rad); n =Speed of the ring mold (r/min).

The rotating force moment of the ring mold is given in equation (6):

$$Me_h = \frac{60P \times 1000}{2\pi n} = 9550\frac{P}{n} \tag{6}$$

The driving force Q to enable the rollers' rotation was the sum of the friction force acting on the surface of the rollers and the friction force produced by the extrusion of materials on the rotating ring mold. The friction force Q' between the materials and the ring mold is equal to the value of Q. By analysis of moments, the ring mold stress can be obtained from equation (7):

$$\sum M = 0, \quad Me_h - 4Q'R = 0 \tag{7}$$

Where R =ring mold radius(mm).

According to equations (6) and (7), and knowing that $Q' = Q$, the equation for Q could be written as:

$$Q = 2388\frac{P}{nR} \tag{8}$$

Meanwhile, the friction force Q between the materials and the rollers is caused by the pressing force F' between the rollers and the materials (which was equal to the pressing force F between the ring mold and the materials, and F is the force between the rollers and the ring mold, F' is equal to F), Q could be written as:

$$Q = \upsilon F' \tag{9}$$

Where υ =Frictional coefficient between the materials and the pressure rollers, which is 0.35 to 0.40 (David, 2000; Gecevska, 2006; Vinodh, 2009).

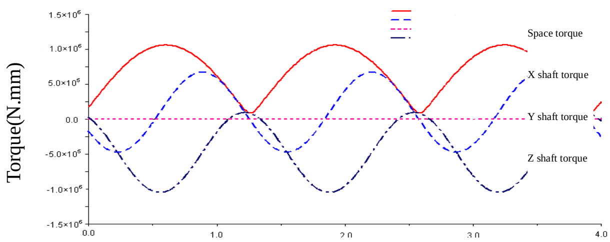
Keeping in mind that $F' = F$, then F could be written as:

$$F = 2388\frac{P}{n\upsilon R} \tag{10}$$

So, F is equal to 9.8 kN.

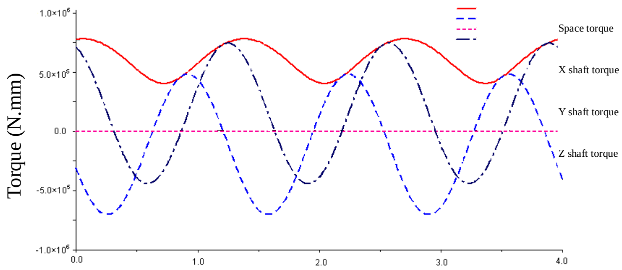
***Transferring the model into ADAMS*:** Mechanism/Pro is the interface module which connected the 3D solid modeling software Pro/Engineer and the dynamics simulation analysis software ADAMS (Wu, 2008; Zhu, 2008; PTC, 2004). This utility model has the advantage of seamless connection. The assembled model can be transferred into ADAMS and dynamic simulation would be done by means of the ADAMS solver.

Simulation analysis: Simulation analysis using ADAMS/Solver was carried out with input parameters involving the angular velocity of the ring mold's rotation and the spatial Force F between the rollers and the ring mold (Zhang, 2007; Xue,2007; Sinou,2010; Stubkier,2014). The results of simulation analysis on the torques involved as function of the number of rollers generated by the ADAMS/Postprocessor module are shown in the Figure 5. It shows that the ring mold turns 3.03 laps in 4 seconds and is consistent with the actual law of rotation. The maximum space torques acting on the screw conveyor are 1.06×10^6 N.mm, 7.80×10^5 N.mm and 6.75×10^5 N.mm, for four, three and two rollers, respectively. The largest torque resulted from the biggest friction torque from the case of the 4-roller design. The production efficiency of 4-roller design is about 1.33 times to that of the 3-roller design and 2 times to that of the 2-roller design. However, the electrical power used to drive the 4-roller design is about 1.36 times to the 3-roller and 1.57 times to the 2-roller designs. The maximum spatial force acting on the screw conveyor in the case of 3-roller design is 1.3 times to that of the 4-roller design; The maximum spatial force F is the main factor that leads to the strength damage of the ring mold (Gao, 2012). According to the efficiency, power consumption and the strength safety of the ring mold, the optimal number of rollers is 4.



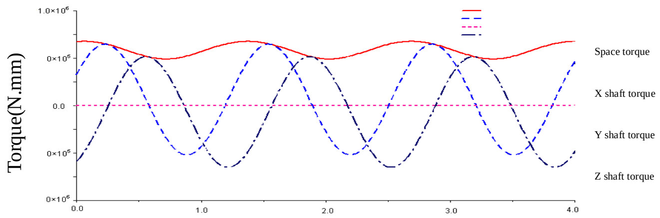
Time (s)

a. Four rollers



Time (s)

b. Three rollers



Time (s)

c. Two rollers

Figure 5. The torques in the screw conveyor as a function of the number of rollers in the design

PROTOTYPE OF THE RING MOLD PELLETIZER

An actual prototype of the ring mold pelletizer was fabricated to evaluate the design and simulate its working state. The ring mold pelletizer was driven by a 15 kW power three-phase asynchronous electric motor. Using a reducer to reduce the rotating speed of ring mold and increase the transmitting torque. Transmission ratio of the reducer is 28. Figure 6 shows a photograph of ring mold pelletizer prototype.

a. Gearbox

b. Body unit

Figure 6. Ring mold pelletizer sample

MATERIALS AND METHODS

Corn stover samples Corn stover without cobs was obtained from an experimental farm in Shenyang Agricultural University in October 2010. The initial moisture content of ground corn stover was 8.8% in percent wet basis (w.b.), and it became 8.1% (w.b.) after it was stored for 6 months in the laboratory.

Sample preparation The corn stover was cut to a length of 500 mm. The cut samples were further ground using a crop straw crusher (Serial no.3ZX C-700A, Huike Machinery Plant of Qufu City, Shuyuan, Qufu, Shandong, China) having 24 rotors, attached to a shaft powered by a 18.5 kW electric motor. A 6 mm screen size was used for grinding the manually cut corn stover.

Using Ro-Tap sieve shaker (W. S. Tyler Inc., Mentor, OH, USA) and Tyler sieves to get 5 different series size of samples, every kind sample is 600g. Sieve opening sizes are 5.600, 4.750, 3.350, 2.360 and 1.400 mm. For each shaking test, 100 g materials was used to shake 10 min depending on the ASAE Standard S319 (ASABE, 2006). Then, the mass retained on each sieve was weighed.

The moisture content of corn stover after it was harvested, stored and cut was determined using ASAE S358 (ASAE, 2006), where 25 g of material was oven-dried at 103°C for 24 h. The moisture content of corn stover crushed with screen size of 6 mm was determined using AACC Standard 44-15A (AACC, 2005), where 3 g of material was oven-dried at 130°C for 90 min. All of the moisture content tests were performed in triplicates. Spraying water to adjust the moisture content of corn stover samples to 10%, 20%, 30%, 40% and 50% (w. b.) were carried. After moisture adjustment, samples were conditioned in air-tight plastic bags at 20°C for 2, 3, 4, 5 and 6 h, respectively. The mass of water added to the sample to achieve a moisture content of w (w.b.) from a sample with initial moisture content of 8.1% (w.b.) is given in equation (11):

$$m_w = \frac{w - 0.081}{1 - w} \times m_{8.1} \tag{11}$$

Where w =material moisture content after moisture adjustment (%, w.b.); $m_{8.1}$ =mass of sample with moisture content of 8.1% (w. b.) (g).

Corn stover samples with five different particle size intervals (4.75 to 5.60 mm, 3.35 to 4.75 mm, 2.36 to 3.35 mm, 1.40 to 2.36 mm and 0 to 1.40 mm), at 10%, 20%,30%, 40% and 50% (w. b) moisture content, and 2, 3, 4, 5 and 6 h of moisture conditioning time were.

Durability determination According to the European standard (CEN/TS 15210-1, 2005), 100 g fuel particles were subjected to free-fall to a hard surface from 1.8 m height. Each test was repeated 10 times. The mass (g) of unbroken fuel pellets m_1 was taken after falling, and the durability DS was calculated using the following:

$$DS = \frac{m_1}{m_0} \times 100\% \tag{12}$$

Where m_0 =initial total mass of the fuel pellets (g).

RESULTS AND DISCUSSION

Influence of moisture content on pellet durability Figure 7 shows that with the increase in material moisture content, the durability of fuel pellets increased initially, and then decreased. The durability of pellets almost did not change when the testing time was 48h, 72 h or 96 h. The durability was the highest when the moisture content was 20%.

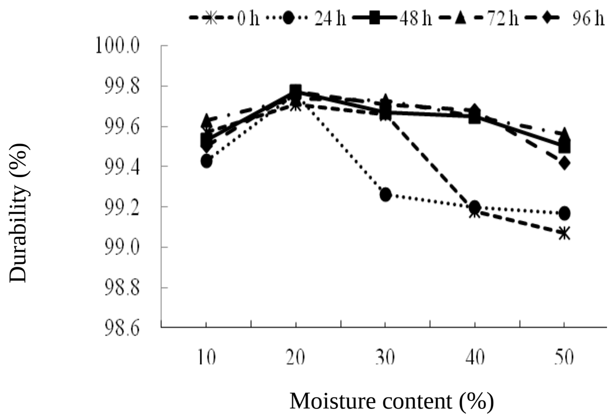


Figure 7. Effect of moisture content on the durability of pellets at testing times of 0, 24, 48, 72, and 96 h.

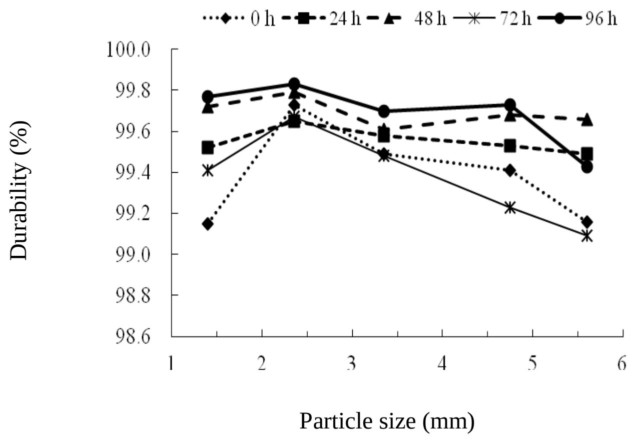


Figure 8. Effect of particle size on the durability of pellets at testing times of 0, 24, 48, 72, and 96 h.

Influence of particle size on pellet durability Figure 8 shows that the durability of pellets was almost the same when the testing time was 48h and 96h. The durability appeared to be the biggest value when the particle size was 2.5mm. Overall, the durability of pellets was 99% or higher, and the results were according to standards.

Influence of conditioning time on pellet durability Figure 9 shows that the influence of conditioning time to the durability was obvious in each testing times; the durability had a maximum value when the conditioning time was 4 h.

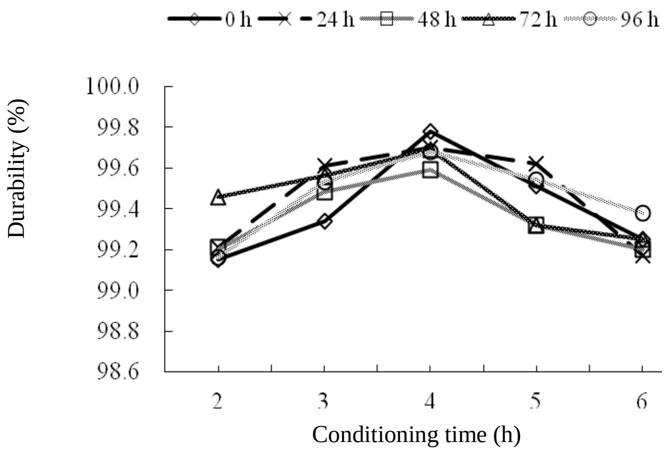


Figure 9. Effect of conditioning time on the durability of pellets at testing times of 0, 24, 48, 72, and 96 h.

CONCLUSION

Pro/Engineer software was used to create a 3D solid model of ring mold pelletizer and ADAMS software was used for simulation to determine the space torque between the screw conveyer and the ring mold. The simulation results validated that four rollers were more reasonable than the 3- or 2-roller design. Pellets formed in the ring mold pelletizer using corn stover had acceptable durability according to standards. Particle size and moisture content significantly affected the pellet durability of corn stover. Pellet durability of corn stover increased initially, and then decreased with increasing the particle size, moisture content and conditioning time.

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