OPTIMAL DESIGN AND EVALUATION OF A RING-DIE GRANULATOR FOR STRAWS

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This research provides an optimal design of structural parameters for ring-die granulators used in the cool briquetting process. Experimental research on the briquetting rate of pellets was carried out for three kinds of crop straws with different granularities, moisture ratios, and length-diameter ratios of the die hole. Results showed that: when the swoop angle β was 45^{o} and the diameter ratio of roller to die was equal to 0.585, the equipment would have higher productivity and lower die-roller contact strength, yielding a good comprehensive briquetting effect; when the granularity was 4mm, the moisture ratio was 16% and the length-diameter ratio was 5.2, the equipment would ensure a higher briquetting rate of pellets and the lowest power consumption per ton of material, yielding the best briquetting effect. This provides references for structural design and process parameters selection of ring-die granulators.

Keywords: Straw; Briquetting rate; Granularity; Moisture ratio; Length-diameter ratio of die hole

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INTRODUCTION

Briquetting methods include “closed” compression and “open” compression (Chen et al. 2009; Li and Yu 2005). The “closed” compression involves compressing the material in a container with closure plug, and taking out the material briquetted to some density and shape, and then proceeding with new material. The “open” compression involves compressing the material in a container without closure plug while feeding new material, and pushing the compressed material to the outlet against various resistance conditions and finally yielding a product, in a continuous manner.

In the course of research on straw briquetting, domestic and foreign scholars have paid attention to “closed” briquetting and “open” hot briquetting (Miura et al. 2000; Hulme and Goodhead 2003; Singh et al. 2007). For example, scholars in West Germany and Russia focused on the research on “closed” briquetting process, while the scholars in the UK, US, Canada, and China focused on the hot briquetting process including “open” briquetting. Although these research results play a very important role in addressing the straw briquetting, they are limited to some extent because: 1) the research on “closed” compression has been to explore the briquetting mechanism, but the obtained experimental results cannot be directly put into practice due to significant difference of experimental compression conditions from actual application conditions; 2) the research on “open” compression has been focused on the hot briquetting process, but research on "open" cold briquetting has seldom been reported (Hu et al. 2009, 2010) and requires further exploration and completeness.

The "open" cold briquetting of straw involves compressing the crushed raw material to a cylinder or prism form by means of a rolled granulator at normal temperature, and cutting the product into pellets with a cutting knife (Hu 2008). In the process, no external heating is required. The briquetting mechanism is such that, under some pressure and moisture ratio conditions, the lignin of straw is softened and bonded by using the frictional heat arising from straw briquetting, and thus compacted into pellets (Obernberger and Thek 2010). The process has advantages of high adaptability of raw material, wide application of moisture ratio, low power consumption per ton of material, and high production, thus making it suitable for application in rural area where straw wastes are extensively disposed (Xie et al. 2002). Depending on structures, the rolled granulators are divided into flat-die granulators and ring-die granulators. The ring-die granulators have advantages of high production and high adaptability, becoming a hot point in current research and development (Yumak et al. 2010). But in actual applications, unreasonable structural design and improper process parameters selection of ring-die granulators cause low briquetting rate of straw pellets and unstable operation of equipment (Felfli et al. 2011; Hu 2008). Therefore, based on optimal design of ring-die granulator, the present study was carried out with experimental research on briquetting rate of straw pellets under different compression conditions in order to determine the best process condition for cold briquetting of straws, providing references for structural design and process parameters selection of commercial ring-die granulators.

OPTIMAL DESIGN OF RING-DIE GRANULATOR FOR STRAWS

Cold Briquetting Principle

The briquetting principle of a ring-die granulator is shown in Fig. 1.

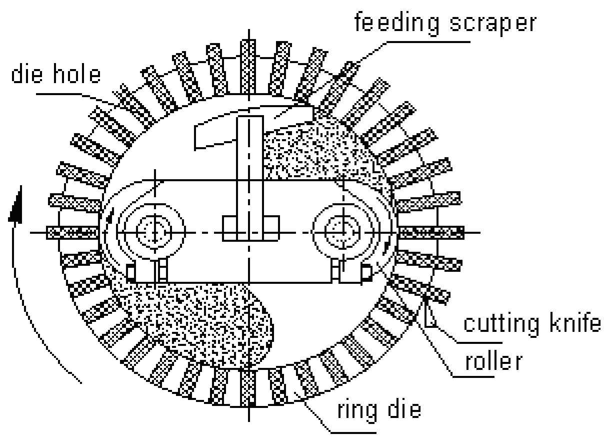

Fig. 1. Theoretical chart of ring die pellet mill

In Fig. 1, the raw material is drawn between ring die and roller by the feeding scraper. The ring die is driven by the main shaft of equipment, and rotates the roller by means of friction. Then the raw material is gradually compressed into the holes of the ring die by relatively rotating roller and ring die, and the product is extruded from the hole and cut into some length of pellets by the cutting knife according to the length acquired.

In the briquetting process of pellets, different regions of material in the briquette-ting area cause different compression force to be applied by roller, and the briquetting area is divided into feeding zone, compressing zone, compacting zone, and briquetting zone (Hu 2008), as shown in Fig. 2. In Fig. 2, σ means the roller compacting force ($kg•m•s^{-2}$), and Φ means the swoop volume (m^3).

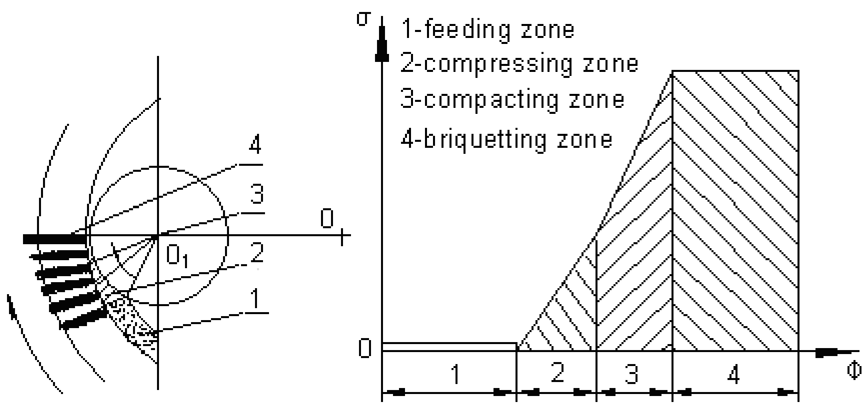

Fig. 2. Compressing force in different region of the raw material

In the feeding zone, the raw material is naturally loose and almost not applied with mechanical force, but it is closely attached to the internal ring of ring die due to centrifugal force arising from rotation of the ring die. In the compressing zone, the raw material is compressed by relatively rotating ring die and roller, and thus subjected to relative movement to reduce pore space. With acceleration of forward movement speed of the raw material, the compression force gradually increases, and the pore space becomes smaller, but the material is essentially not deformed. In the compacting zone, with reduced clearance between the ring die and roller, with dramatically increased compression force, and increased contact area and bonding force between pellets, the material is inlaid in each other and compressed into the die hole, yielding elastic-plastic deformation. In the briquetting zone, the die hole is filled with compacted pellets, and with the action of continuously pushed new material, the straw pellets move to the outlet, yielding stress relaxation. From the four stages above, if the raw material is briquetted to pellets, two conditions must be satisfied (Li and Yu 2005): 1) the raw material shall be drawn into die hole by ring die and roller, and 2) the compression force applied to material by the roller shall be greater than the total friction force of pellets in a die hole.

Structural Parameters Design of Ring-die Granulator for Straws

Determination of die & roller size

The size of the die & roller assembly is one of the most important parameters for a ring-die granulator, and proper design of die & roller size will play an important role in stable operation of the equipment. In this paper, proper selection of die & roller size is provided according to geometric relationship of structural parameters.

The relationship between die & roller size and material thickness is shown in Fig. 3,

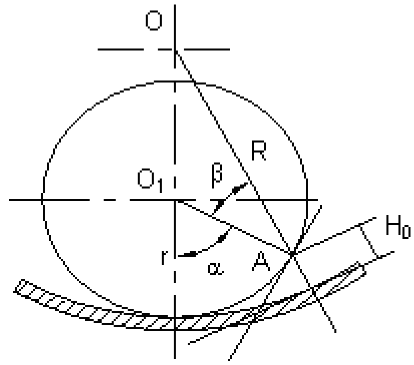

Fig. 3. Relationship between the material thickness and die & roller size

$$OA = \sqrt{(R-r)^2 - (r\sin\beta)^2} + r\cos\beta \tag{1}$$

$$H_0 = R\text{-}OA = R[1 - \sqrt{(1-\lambda)^2 - (\lambda\sin\beta)^2} - \lambda\cos\beta] \tag{2}$$

$$\frac{H_0}{R} = [1 - \sqrt{(1-\lambda)^2 - (\lambda\sin\beta)^2} - \lambda\cos\beta] \tag{3}$$

$$\lambda = \frac{r}{R} \tag{4}$$

where, H_0 means the material thickness the roller can swoop on (m); β means the swoop angle (°); and λ means the diameter ratio of roller to die, i.e. the ratio of roller radius (r) to the die radius (R).

With β respectively being 10°, 20°, 30°, 40°, 50°, and 60°, Equation (3) was used to calculate the maximum λ, with the results shown in Table 1.

Table 1. Max of λ under Different Swoop Angles

β	10°	20°	30°	40°	50°	60°
λmax	0.852	0.745	0.667	0.609	0.566	0.536
H_0/R	0.1609	0.2998	0.4224	0.5335	0.6360	0.7321

The data listed in Tab. 1 were used to draw the curve of swoop β versus λ_{max} and H_0/R, as shown in Fig. 4.

From Fig. 4 it is apparent that H_0/R follows a linear relationship with β, and increases obviously with the increase of β; but in contrast, λ_{max} shows a nonlinear relationship with β, and is reduced by less and less value with the increase of β.

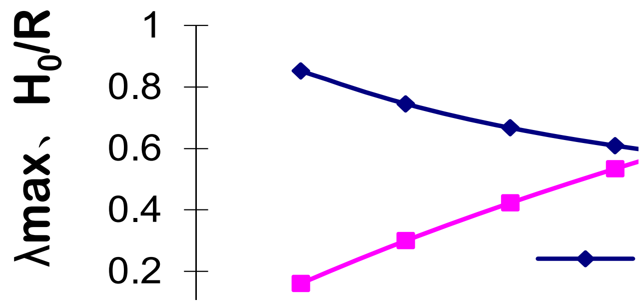

Fig. 4. Curves between β, λ_{max} and H_0/R

It is also shown that, when the two curves meet and the swoop angle β is about 45^0, the equipment ensures both a higher H_0/R which means stronger swooping capability for material and higher productivity, and a lower λ_{max}, which means smaller die-roller contact strength and easier increment of service life of ring die. It is noted that, when the raw materials of straws are different, the value of β is different; the research by Hu et al. (2010) shows that the types of raw materials have a small influence on briquetting, and thus the difference of β in relation to different straws is small and negligible.

Substitution of β=45^0 into the Equation (3) yields λ_{max}=0.585. That is to say, when the swoop angle β is 45^0 and the diameter ratio of roller to die is 0.585, the equipment will maintain a good briquetting effect.

Determination of productivity

From Fig. 3, in one revolution of the ring die, the material amount compressed into a die hole by a single roller is determined by the material layer thickness. With numerical calculation, the compressed material volume (V) is obtained as follows (Xie et al. 2002),

$$V=\pi[R^2-(R-H)^2]b\varepsilon=\pi(R^2-OA^2)b\varepsilon \tag{5}$$

$$\varepsilon=\frac{\pi r_0^{\,2}N}{2\pi Rb}=\frac{r_0^{\,2}N}{2Rb} \tag{6}$$

where b means the axial size of roller (m), ε means the extent of opening of the die (%), and N means the number of die holes.

Substituting Equations (1) and (6) into Equation (5) yields:

$$V=\frac{\pi}{2}r_0^{\,2}RN\left\{1-[\sqrt{(1-\lambda)^2-\lambda^2\sin^2\beta}+\lambda\cos\beta]^2\right\} \tag{7}$$

If the number of rollers in the equipment is set to Z, the speed of the die is n, and the initial density of material is ρ_o, then the productivity of the equipment is:

$$Q=\frac{\pi}{2}r_0^{\,2}RN\rho_0 nZ\left\{1-[\sqrt{(1-\lambda)^2-\lambda^2\sin^2\beta}+\lambda\cos\beta]^2\right\} \tag{8}$$

From Equation (8), when the roller-to-die diameter ratio λ and the swoop angle β increase, the productivity Q will increase accordingly. But in Fig. 4, the roller-to-die diameter ratio λ and the swoop angle β show a reverse trend, and thus the equipment will only yield higher productivity when λ= 0.585 and β=45^0.

Determination of ring-die strength

In the cold briquetting process, the bearing capability of ring die is vital. To research the extent to which the ring die is influenced during its operation, it is necessary to analyze the bending stress and contact stress resulting from the roller.

To facilitate the analysis of bending stress and contact stress, the following assumptions were made (Hu 2008):

(1) Actions of reinforcement ring and die hole of the ring die are neglected;
(2) Influence of materials is neglected;
(3) The ring die is approximated to a thin-wall cylinder with uniform section;
(4) Internal contact of roller and ring die is approximated.

Regarding bending strength, the bending moment in any section of ring die is shown in Fig. 5.

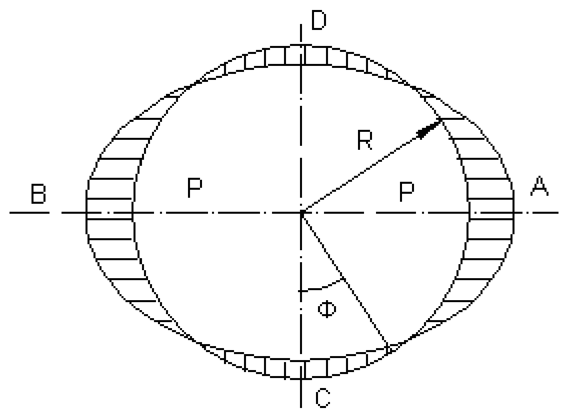

Fig. 5. Chart of bending moment on the ring die

From Fig. 5, the bending moment in any section of ring die can be calculated as:

$$M\varphi = PR\left(\frac{1}{\pi} - \frac{1}{2}\cos\varphi\right) \tag{9}$$

when $\varphi = \frac{\pi}{2}$ and $\frac{3\pi}{2}$ (at Points A and B), the maximum bending moment occurs:

$$M_{\max} = \frac{1}{\pi}PR \tag{10}$$

When φ=0 and π (at Points C and D), the minimum bending moment occurs:

$$M_{\min} = PR\left(\frac{1}{\pi} - \frac{1}{2}\right) \tag{11}$$

The maximum and minimum bending stresses of the ring die are,

$$\sigma_{\max}=\frac{1}{\pi}\frac{PR}{W} \tag{12}$$

$$\sigma_{\min}=\frac{PR}{W}\left(\frac{1}{\pi}-\frac{1}{2}\right) \tag{13}$$

$$W=\frac{1}{6}Bh^2 \tag{14}$$

where M means the bending moment (kg•m^2•s^{-2}), P means interaction force between ring die and roller (kg•m•s^{-2}), R means the radius of ring die (m), W means the modulus of axial section of ring die (m^3), B means the width of ring die (m), and h means the thickness of the ring die (m).

From Equations (12) and (14), the maximum bending stress of ring die is related to R and Bh^2, and thus when designing the structure of ring die, the value of R shall be minimized and the value of Bh^2 shall be maximized to increase the bending resistance and productivity of ring die.

In the cold briquetting process, local elastic deformation and strong local contact stress occur in the contact surface of ring die (Deng et al. 2004). With the assumptions of neglected material influence and approximated internal contact between roller and ring die, the contact stress σ_j can be represented by the following equations (Hu 2008),

$$\sigma_j=0.418\sqrt{\frac{\mathrm{PE}}{br'}} \tag{15}$$

$$E=\frac{2E_1E_2}{E_1+E_2} \tag{16}$$

$$r'=\frac{Rr}{R-r} \tag{17}$$

where E means the equivalent elastic modulus, and E_1 and E_2, respectively, mean the elastic moduli of ring die and roller; b means effective compression length of ring die (m); r' means equivalent curvature radius; and R and r respectively mean the radii of ring die and roller (m).

Substitution of the roller-to-die diameter ratio $\lambda=r/R$ into the Equation (17) yields:

$$r'=\frac{r}{\lambda-1} \tag{18}$$

Substitution into Equation (15) yields:

$$\sigma_j = 0.418\sqrt{\frac{PE}{br}(\lambda - 1)} \tag{19}$$

From the Equation (19), when the roller radius (r) is constant, the contact stress is proportional to λ. This is to say, the greater the roller-to-die diameter ratio, the greater the contact stress and the easier the ring die is damaged. To extend the service life of ring die, λ is assigned a lower value, i.e. a greater radius of ring die is better. However, it is not to say the greater, the better (Xie et al. 2002), because oversized radius will cause poor swooping of raw material, influencing the productivity of equipment. According to the aforesaid conclusion that the roller-to-die diameter ratio has the best value, if the roller radius r is designed greater, then the die radius R must be greater correspondingly to ensure a constant λ, and thus the contact stress will be smaller and the service life of ring die will be longer.

Additionally from the Equations (15) and (16), if reducing the contact stress of ring die, it is necessary to reduce E. When E_1 and E_2 are assigned the same value, E is maximal and the contact stress of ring die is also maximal. This shows that the same material of ring die and roller should be avoided in the design.

Structural design of die hole

Proper structural design of die hole will have direct influence on the briquetting effect of straw pellets. Due to different types and properties of raw material, if the briquetting machine is designed to have strong adaptability, it is necessary to provide proper structural design of die hole. Structure of die hole provided in this paper is shown in Fig. 6.

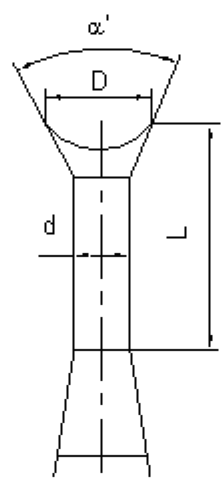

Fig. 6. Chart of the die hole

In Fig. 6, α' is the taper of tapered hole, which should conform to the following equation,

$$\mathrm{tg}\frac{\alpha'}{2} = \frac{\Delta d}{\Delta l} = \frac{d}{l} \tag{20}$$

where Δd means the increment of diameter of die hole (m), Δl means the increment of height of die hole (m), d means the diameter of die hole (m), and l means the height of die hole (m).

In Fig. 6, the structure of the die hole consists of the tapered hole, straight hole, and relief hole. The diameter of the tapered hole is designed to be greater than that of the straight hole to reduce the resistance of material against entering the tapered hole, and to facilitate the material to enter the straight hole; the taper of the tapered hole has a signify-cant influence on the briquetting pressure of equipment and power consumption per ton of material, and in this paper it is 45^{o} (Hu 2008; Xie et al. 2002). The straight hole is the effective length of the die hole, its diameter is dependent on actual production require-ments for briquettes, and its height determines the pressure maintenance time of briqu-ettes: the longer the pressure maintenance time, the harder the briquettes and the better the strength and quality of the briquettes. The relief hole is designed to reduce the resis-tance of raw material against passing the die hole, and the raw material with rated load is then briquetted under pressure relief to reduce the elastic deformation of briquettes.

EXPERIMENTAL RESEARCH ON COLD BRIQUETTING OF STRAWS

In the cold briquetting process, once the structural size of equipment is deter-mined, the selection of briquetting process parameters becomes the technical key to the cold briquetting. Main factors having influence on briquetting effect include types of materials, granularity, moisture ratio, and length-diameter ratio of the die hole (ratio of effective length of die hole to hole diameter). The briquetting rate is one of the most important indicators to evaluate the briquetting effect. Therefore in this paper, different types of raw materials of straws were chosen to determine the best briquetting process parameters by experimental research on the briquetting rate in different compression conditions.

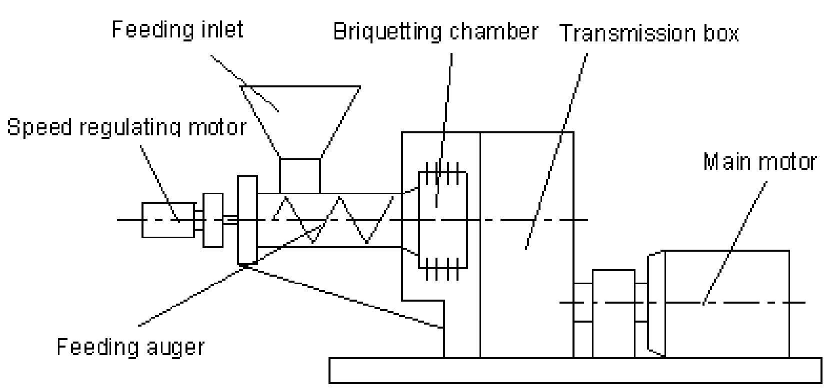

Fig. 7. Schematic of overall structure of experiment device

Experimental Device

A self-developed SKR-25 ring-die granulator for straws was adopted, which consists of feeding auger, main motor, main transmission box, briquetting chamber and so on, as shown in Fig. 7.

In Fig. 7, the rollers number Z=2; the ring-die radius R=175 mm; the roller radius r=102 mm; the swoop angle β=45^0; the ring-die opening percentage ε=14%; the ring-die speed n=5r/s; the die-hole diameter d=10 mm; the die-hole height l=42 mm to 62 mm; and the productivity Q=500 kg/h.

Experimental Materials

Typical raw materials of wheat straws, rice straws, and corn straws that are naturally dried were chosen. These materials were crushed and screened respectively by using sieves with different meshes (2 mm, 4 mm, 6 mm, 8 mm) of the combined granulator, and then dried and watered to condition to different moisture ratios (8%, 12%, 16%, 20%, 24%) set in the experimental scheme; finally they were each stored in a plastic bag and sealed for 1 day to enable the water to permeate into the raw materials fully and uniformly.

Experimental Method

In the straw briquettes pushed out, the briquettes were weighed with an electronic balance and then chosen such that their minimum dimension greater than 1.5 mm and their radial average size of two ends was greater than 2/3. The weight percentage in total weight of straw briquettes was defined as the briquetting rate, which is determined by being averaged three times, and then calculated and analyzed with Excel, which can be shown as follows:

$$L=\frac{W_L}{W_L+W_S}\times 100\% \tag{21}$$

In these equations L means the average of briquetting rate, %; W_L means the mass of straw briquettes (kg); and W_S means the mass of powder and cuttings (kg) coming out together with the briquettes.

Results and Analysis

Influence of granularity on briquetting rate

Although the raw materials of straws were crushed by the same granulator, the crushed materials had different granularities due to their different biological structures (Obernberger and Thek 2010). The granularities of crushed materials were averaged, and the result shows that the granularities were well reflected by the mesh of granulator (Hu 2008). In this work three kinds of straws were crushed respectively by the meshes of 2 mm, 4 mm, 6 mm, and 8 mm, and then cold briquetting experiments were carried out for such straws in the conditions that the moisture ratio is 16% and the length-diameter ratio is 5.2, with experimental results shown in Fig. 8.

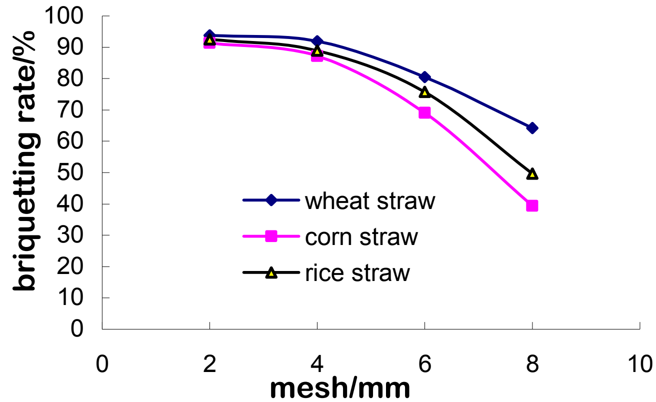

Fig. 8. Relationship between granularity and briquetting rate with three kinds of straws

From the figure above, the granularities and the briquetting rates of three kinds of straws showed the same trend: when the mesh was 2 mm and 4 mm, the briquetting rate was higher and had no obvious dependency on mesh size; when the mesh was 4 mm, 6 mm, and 8 mm, the briquetting rate sharply decreases, in an essentially linear manner. This shows that the meshes of 2 mm and 4 mm ensure a higher briquetting rate even if the raw materials are different. According to Bond's assumption in crush theory, the crush energy is inversely proportional to the square root of diameter of crushed material, and if it is assumed that the materials before being crushed have the same granularity, the Bond's assumption essentially demonstrates the crush energy consumption is exponent-tially related to the diameter of crushed material (Serrano et al. 2011); this is to say, the energy consumption when the mesh is 2 mm is far greater than that when the mesh is 4 mm. Therefore, the best mesh would be 4 mm in order to ensure a higher briquetting rate and a lower power consumption per ton of material. Regarding different raw materials of straws, the granularities have different influence on the briquetting rate: the wheat straw was least influenced, the corn straw was most influenced, and the rice straw was in between, due to joint effect of biological structures and chemical ingredients of different raw materials.

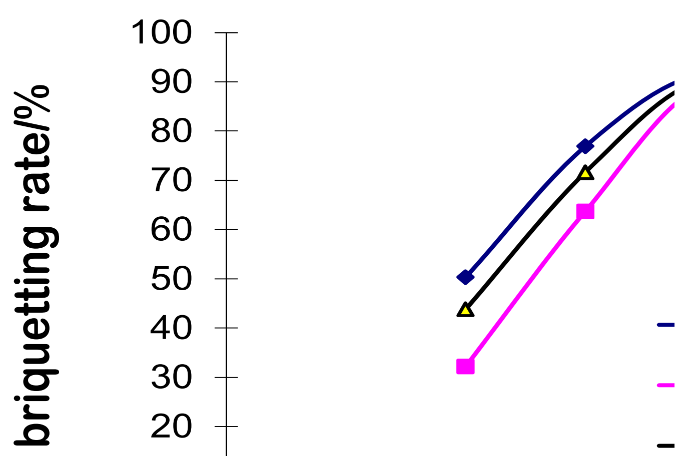

Fig. 9. Relationship between moisture ratio and briquetting rate with three kinds of straws

Influence of moisture ratio on briquetting rate

In the cases that the mesh is 4 mm and the length-diameter ratio is 5.2, raw materials with moisture ratios of 8%, 12%, 16%, 20%, and 24% were respectively investigated to demonstrate the influence on briquetting rate, with the results shown in Fig. 9. As shown although three kinds of raw materials showed different influence curves, they exhibited a common trend with a downward parabolic curve. The moisture ratio of 16% is the inflection point of these curves, and on the left of the point the moisture ratio is proportional to the briquetting rate, but on the right the moisture is inversely proportional to the briquetting rate. This indicates the point with the best moisture ratio was 16%, which is not far from 18%, the best moisture ratio of material when in hot briquetting (Lei 2005; Li and Zhang 2011). From the analysis above, the moisture ratio should not be too high or too low, because excessive moisture ratio will cause loose pellets due to excessive water between pellets, and this will yield a poor briquetting effect (Serrano et al. 2011). From the experiments, when the moisture ratio exceeds 20%, the equipment will be always blocked. When the moisture ratio is too low, the diffusion capability of water is reduced and the mobility of pellets becomes poor (Larsson et al. 2008), causing a poor briquetting effect. From the experiments, when the moisture ratio is close to 8%, the briquetting rate will be low and the equipment's power consumption per ton of material increases sharply (Hu et al. 2007). So control of moisture ratio to some extent is the key to the cold briquetting of straws.

Figure 9 also shows that, regarding different raw materials of straws, their moisture ratios have different influence degree on briquetting rate. Regarding the three kinds of straws provided in this paper, the influence degree of moisture ratios on briquetting rate is sorted in a descending order: corn straw > rice straw > wheat straw. In addition, when the moisture ratio is 8%, 12%, and 16%, the intervals between and the slopes of curves of three kinds of raw materials are greater; when the moisture ratio is 16%, 20%, and 24%, the intervals between and the slope of curves of three kinds of raw materials are smaller. This demonstrates that the influence of lower moisture ratio on briquetting rate is more than that of higher moisture ratio.

Influence of length-diameter ratio on briquetting rate

The length-diameter ratio is an important performance parameter of ring-die granulator, and proper selection of such parameter has direct influence on physical quality of briquettes. Under the conditions that the granularity is 4 mm and the moisture ratio is 16%, briquetting experiments were carried out with length-diameter ratios of 4.2, 4.7, 5.2, 5.7, and 6.2 obtained by changing effective length of die hole. Experimental results are shown in Fig. 10.

From Fig. 10, the length-diameter ratios showed obvious influence on briquetting rate of three kinds of raw materials: when increasing from 4.2 to 5.2, the length-diameter ratio basically showed a linear increment relationship with briquetting rate, and the increment was significant; when increasing from 5.2 to 6.2, the length-diameter ratio showed a small influence on briquetting rate, which is represented by an approximately horizontal line. This demonstrates the length-diameter ratio providing the best value.

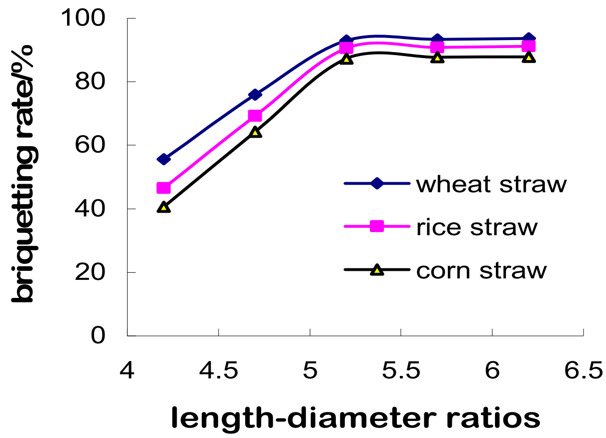

Fig. 10. Relationship between length diameter ratio and briquetting rate with three kinds of straws

From the analysis above, greater length-diameter ratio facilitates the briquetting, but it does not mean the greater, the better (Brewin et al. 2008). This is because when the length-diameter ratio is greater, the briquetting rate is higher and the density of briquettes is greater; but the required briquetting pressure increases sharply (Deng et al. 2004) and the power consumption is also greater (Serrano et al. 2011), thus increasing the production cost of briquettes. Therefore, regarding the power consumption per ton of material and the briquetting rate, the best length-diameter ratio of wheat straw, rice straw, and corn straw should be 5.2.

CONCLUSIONS

In an analysis of the cold briquetting process, this study provides an optimal design of structural parameters of a ring-die granulator. The study employed three kinds of raw materials of wheat straw, rice straw, and corn straw for experimental research on briquetting rate under the conditions of different granularities, moisture ratios, and length-diameter ratios. Conclusions of the research were as follows:

1. When the swoop angle is 45^{o} and the roller-to-die diameter ratio is 0.585, the equipment would have higher productivity and lower die-roller contact strength, yielding a good comprehensive briquetting effect.
2. When the roller radius is constant, the greater the roller-to-die diameter ratio, the greater the contact stress, and the easier the ring die is damaged and the shorter the service life of ring die.
3. When designing the ring die and roller, the same material of equipment should be avoided; otherwise the contact stress of ring die will be maximal.
4. Regarding three kinds of raw materials used in the experiments, the wheat straw showed the best briquetting effect, the rice straw was intermediate, and the corn straw was worst.
5. Granularity, moisture ratio, and length-diameter ratio showed obvious influence on the briquetting rate and power consumption per ton of material. When the granularity

was 4 mm, the moisture ratio was 16%, and the length-diameter ratio was 5.2, the equipment would have higher productivity and minimal power consumption per ton of material, yielding the best briquetting effect.

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