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A study on transverse flow pattern of soybean splits in a closed type horizontal rotating drum

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ABSTRACT

Roasting drums have generally been used in soybean roasters. The different flow patterns of transverse motions *viz.*, slipping, slumping, rolling, cascading, cataracting and centrifuging formation inside the rotating drum influenced the roasting material's bed behaviour through selection of its operating variables such as rotational speed and filling degree, thus important in the design of a roaster drum. Best performance was observed in transversal mixing (cascading and cataracting type of modes) of soaked soybeansplits, with recommended filling degree as 30% and having Froude number as 0.330 (**Keywords:** Soybean splits, rotating drum, transverse flow pattern, Froude number).

INTRODUCTION

Rotating drums have extensively been used in agricultural and food industries as mixers, dryers and reactors. Conventional grain roasters comprised of horizontal rotating drum, with or without bars installed in the internal wall mixing of nuts and beans. The use of horizontal drum reactors in industries for the processing of granular materials has been reported by Sherritt *et al.* (2003). A gas burner provided the heat required for the moving bed of beans. Heating of beans helped in drying and also raised the bean temperature up to its onset exothermic pyrolysis reactions that characterized roasting. The design features of roasting equipment does not vary much among several manufacturers and operational variables *viz.*, rotational speed and filling degree of cylinder have been fixed and pre-specified by manufacturers. During roasting, the volume of beans decreased which was dependent on the set values for operational conditions such as roasting temperature and time. Also, flow regime of beans within the horizontal cylindrical roaster and intensity of grain bed was dictated by rotational speed, filling degree of cylinder and bed material properties, with the cylinder diameter as constant. The attainment of homogeneous roasting was thus related to the effectiveness of mixing process, since the heating source has been usually located throughout the length of the cylinder and the heat transfer to the grain bed occurred primarily at the contact surface of bed. Mellmann (2001) observed that, generally, the flow regimes that occurred included slipping, surging and slumping (slower rotations), and cataracting and centrifuging (faster rotations), on consideration of the same filling degree, were not quite as effective for particle mixing in a rotating drum. On consideration of the initial stage, (filling degree < 50%) a major portion of grain bed was in effective contact with the surface of the cylinder wall. Therefore, flow regime of the bed was expected to at least be in the range of rolling to cascading motion in order to guarantee uniformity of heat transfer throughout bed. The transverse motion of solids particles in rotary drum has been extensively studied (Boateng and Barr, 1996; Henein *et al.,* 1983; Khakhar *et al.,* 1997; Perron and Bui, 1992) and a detailed description of the transverse flow regimes has been presented by Mellmann (2001). Helder *et al.* (2006) studied the processing of particles in rotating cylinders heavily influenced by the type of flow regime within the drum and longitudinal flights (Sunkara *et al.,* 2013) and number of flights (Lisboa *et al.,* 2007). Hence, in the present study, an experimental prototype rotating drum was partially filled with soaked soybean splits (10 - 50%, based on volume basis) along its axis and subjected to different rotational speed and their flow regimes of grain bed motion were investigated.

MATERIAL AND METHODS

A mild steel cylindrical drum (16 cm diameter and 17 cm length) was used in the experiment. The front side of the cylinder was fitted with a transparent acrylic sheet to allow the complete visualization of flow regimes in transversal section of drum. The back end of drum was attached to a shaft with a handle to facilitate its rotation. A digital camera (Kodak easy share CD 44, 12 Megapixel, made in China) was employed to record grain bed motion in transversal section of drum. The camera was positioned in such a way, that the camera lens' focus centre point was exactly to the centre of the rotating drum. The captured films were converted to images with 0.03s interval by using Video to Jpg Converter. A non-contact digital tachometer was used for the measurement of the speed of the rotating drum.

Experimental procedure

Soybean seed (JS-335) samples harvested from ICAR-Central Institute of Agriculture Engineering, Bhopal (India) were obtained. The soybeans were dehulled (CIAE Soybean dehuller) and its splits were made. The samples were cleaned manually to remove foreign materials, broken, cracked and damaged grains. The samples were sealed in polyethylene bags, and stored at room temperature (30 ± 2 °C). Soybean split samples (20 mg) were subjected to soaking for 4 h in tap water and the soaked splits (3.5 - 6.3 mm) were used for the experiment. The filling degree in the cylindrical drum was kept in the range of 10 - 50% by filling with soaked soybean splits (Rodrigues *et al.,* 2003). The flow regimes were studied for each batch of soaked soybean splits with respect to the filling degree and rotational speed. The samples were placed in a mild steel cylinder connected to a handle. The rotation of drum was at a low speed initially (about 5 ± 2 rpm) and was gradually increased (150 ± 5 rpm) and the transitions of one regime to another were recorded as a function of rotational speed. The transitions from one regime to another were determined solely by visual inspection and recorded by digital camera. Each test was performed thrice randomly to avoid the influence of preceding test. The rotational speed was increased until the bed achieved a centrifuging motion within the drum. This procedure was repeated for all filling degree. The recorded transitional rotational speeds were used in the calculation of peripheral Froude number using the following equation:

$$Fr = \frac{\omega^2 R}{g}$$

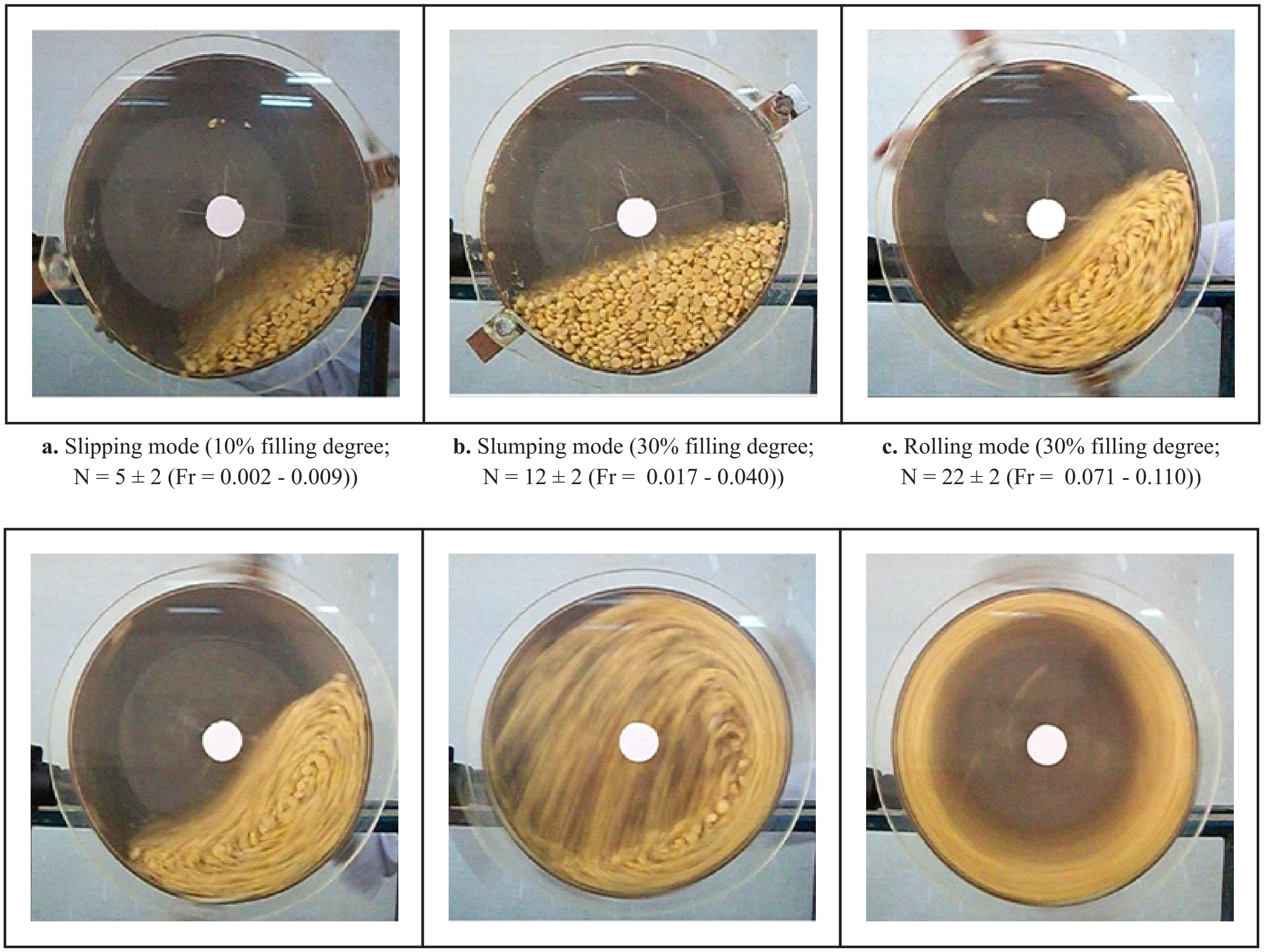
where, ω - angular rotational speed (s^{-1}), R - radius of the drum (m) and g - acceleration due to gravity ($m\ s^{-2}$). Froude number represented a balance between centrifugal and gravitational forces and it provided a good understanding of different flow regimes and their respective transitions, when plotted against parameters such as filling degree of drum.

RESULTS AND DISCUSSION

The typical recorded and transferred images of different transversal flow regimes (slipping, slumping, rolling, cascading, cataracting and centrifuging) of the soybean splits in rotating drum have been presented in Figure 1 and Table 1 for different filling degrees (10%, 20%, 30%, 40% and 50%), Froude numbers with increasing rotational speeds.

Slipping

Sherritt *et al.* (2003) observed slipping as an undesirable behaviour in which the bed of particle slips on drum wall surface and usually occurs at low volumetric fill. Slipping motion behavior (Figure 1) of 10% filling of soybean splits with rotational speed of 5 ± 2 rpm (Froude no. 0.006-5.920) revealed that the solid bed adhered on the rotating wall up to a certain angle of deflection and subsequently slid back on the wall surface. Also, soybean splits bed remained at rest and the bed slip at the drum wall and no particle mixing occurred. As this state of motion was undesired and must be prevented by using rough walls or bar/baffles attached to the wall as suggested by Mellmann (2001).



a. Slipping mode (10% filling degree; N = 5 ± 2 (Fr = 0.002 - 0.009))

b. Slumping mode (30% filling degree; N = 12 ± 2 (Fr = 0.017 - 0.040))

c. Rolling mode (30% filling degree; N = 22 ± 2 (Fr = 0.071 - 0.110))

d. Cascading mode (30% filling degree; N = 40 ± 2 (Fr = 0.071 - 078))

e. Cataracting mode (30% filling degree; N = 100 ± 5 (Fr = 0.300 - 0.700))

f. Centrifuging mode (30% filling degree; N = 150 ± 5 (Fr = 1.170 - 5.160))

Figure 1. Typical transition flow regime of soaked soybean splits at various motion modes

Table 1. Typical flow regime with respect to Froude number for varying filling degree (10 - 50%) for soaked soybean splits

Mode of motion ↓ / Moisture content (%) →	Froude Number				
	10 %	20 %	30 %	40 %	50 %
Slipping mode	0	0	0	0	0
Slumping mode	0.2	0	0	0	0
Rolling mode	0.5	0	0	0	0
Cascading mode	1.0	1.0	1.0	0.8	0.4
Cataracting mode	4.2	2.5	1.5	1.4	1.2
Centrifuging mode	5.5	3.8	2.5	2.4	2.0

Slumping

When the rotational speed was minimum (< 3% of critical speed), slipping and slumping of bed occurred in general (Sherritt *et al.*, 2003). It was observed that the rotational speed of cylinder wall, the solid bed continuously elevated, then leveled off repeatedly by successive avalanches at the surface (Figure 1b). The slumping mode of motion occurred in rotational speed range of 12 ± 2 (Fr: 0.017-0.040). The slumping frequency depended on rotational speed, particle size and cylinder diameter (Henein *et al.*, 1983). As rotational speed increased, transition of flow region was from slumping to rolling.

Rolling

The rolling behaviour of grain bed, an advanced stage of slumping mode of motion, occurred between 3% and 30% of critical speed (Sherritt *et al.*, 2003). Rolling behaviour, which occurred at lower bed depth and fraction of the critical speed than cascading behaviour, was characterized by a flat upper surface (Figure 1c). The experimental data showed that the rolling mode of motion occurred in the rotational speed range of 22 ± 2 rpm (Fr: 0.071 - 0.110) depending on the filling degree. For the lower filling degree (10 - 20%), rolling mode took place at a rotational speed of less than 20 rpm (Fr = 0.071-0.078) , whereas for the higher filling degree (40 - 50%) rolling mode took place at a rotational speed of greater than 20 rpm (Fr = 0.086-0.110).

Helder *et al*. (2006) and Liu *et al*. (2005) have also reported similar results for the effect of filling degree on transition from slumping to rolling for coffee beans, gravel, limestone and sand. Henein *et al*. (1983) observed that for a range of materials, the bed operated in rolling regime at Froude numbers above 10^{-3} even at their lowest filling degree of 40%. Mellmann (2001) also reported that rolling beds typically occured at Froude numbers between 10^{-4} and 10^{-2} with a filling degree of greater than 0.100. Dury *et al*. (1998) noticed a transition (mustard seeds) from slumping to rolling around $Fr = 1.2 \times 10^{-3}$ when the drum diameter was 69 mm with 50% filling degree.

Rogers and Gardner (1979) described the behavior for a particle in a rolling bed. On bed surface, the particle was free to roll or tumble until it re-entered the bed at a new radius. While on surface, the particle collided with other particles. Due to collisions, the angle at which the particle descended deviated from the angle of maximum descent. The radial position determined the time for the particle to complete a cycle and the distance the particle rolled on the bed surface. Thus, the angle of descent determined the axial movement of the particle. The rolling bed became a cascading bed at a higher rotational speed and fill.

Cascading

The experimental study showed that cascading mode of motion occurred in a rotational speed of 38 to 42 rpm (Fr = 0.300 to 0.700) for soaked soybean splits depending on various filling degree (10 - 50%). The bed flowed in a transitional rolling-to-cascading-type of motion, in transversal section (Figure 1d). It was clearly observed that the flow was divided in two different layers: active layer in the upper part of the flowing bed, and passive layer that moved at the same angular rotation speed as the cylindrical drum. A segregated core, located near the central axis of the drum was also observed, where the soaked soybean splits velocities were rather low compared to the rest of the bed. Thus, the mixing was good in the region. As the rotational speed increased, the flow regime changed to a full cascading-type of motion and the segregated core tend to reduce or even disappear, improved the mixing of particles in that portion of the bed (Helder *et al.,* 2006). The height of arch of kidney-shaped bed increased with increasing rotational speed. According to Sherritt *et al.* (2003), the cascading behaviour also occured between 3-30% of critical speed.

Cataracting

The transition of bed from cascading to cataracting when the rotational speed of the bed was increased (Figure 1e), thus the individual particles were detached from the bed and were thrown off in to the free space of the cylindrical drum. The cataracting mode of motion for soaked soybean splits occurred at a rotational speed that ranged from 90 to 105 rpm (Fr =1.170 to 5.160). Thus, there existed a difference in rotational speeds with different filling degree and breakage of soybean splits. The breakage of particles was minimum in the cataracting flow regime, as verified by the presence of a considerable amount of broken and smaller fractions on emptying the cylinder (Helder *et al.,* 2006). However, this type of motion was not recommended for fragile materials, but for the soaked soybean splits (as a part of the soy butter preparation process), the early stage of cataracting was adapted. As rotational speed increased, cascading motion was strongly pronounced, that the individual particles detached from the bed and were thrown off into the free space of the drum (Boateng and Bar, 1996). Sherritt *et al.* (2003) observed that the cataracting behavior occurred when the drum rotation was more than 30 % of the critical speed.

Centrifuging

Cataracting motion, in extreme cases, further increased the rotational speed, the particles on outer paths $r \approx R$ adhered to the wall and thus centrifuging occured. Generally, critical speed was used as a reference for other types of motion behaviour (Sherritt *et al.,* 2003). The particles remained fixed to the cylindrical drum wall. The speed at which centrifuging began was referred to as the critical speed. The centrifuging mode of motion for soaked soybean splits at a rotational speed of 145 to 155 rpm (Fr: 1.820 - 7.880) (Figure 1f), demonstrated that the flowing bed was characterized as a uniform film evenly distributed along the wall of the cylinder, with a weak showering of particles in the upper right half of the transversal section of the cylinder. Also, it was visualized that there existed two concentric layers, with outer flowing layer having a higher speed than the inner core. No mixing of particles was observed, hence, this type of motion was not recommended for soaked soybean splits.

CONCLUSION

The transition of curve from one region to another region for soaked soybean splits depended on the various rotational speeds and filling degree of a cylindrical drum. The best performance in transversal mixing of soaked soybean splits was observed in the cascading type motion and just before the cataracting type motion. Since filling degree affected the flow regime, filling degree of 30% and its corresponding Froude number (0.330) was recommended.

REFERENCES

Boateng, A.A. and Barr, P.V. 1996. Modelling of particle mixing and segregation in the transverse plane of a rotary kiln. *Chem. Eng. Sci.* **51**, 4167 - 4181.

Dury, C.M., Ristow, G.H., Moss, J.L. and Nakagaw, M. 1998. Boundary effects on the angle of repose in rotating cylinders. *Phys. Rev.* **57,** 4491 - 4497.

Helder, P.C., Marcio, A.M., Leandro, S.O. and Adriana, S.F. 2006. Transverse flow of coffee beans in rotating roasters. *J. Food Eng.* **75**, 142 - 148.

Henein, H., Brimacombe, J.K. and Watkinson, A.P. 1983. Experimental study of transverse bed motion in rotary kilns. *Metall. Trans. B*, **14**, 191 - 205.

Khakhar, D.V., McCarthy, J.J., Shinbrot, T. and Ottino, J.M. 1997. Transverse flow and mixing of granular materials in a rotating cylinder. *Phys. Fluids* **9**, 31 - 43.

Lisboa, M.H., Vitorino, D.S, Delaiba, W.B., Finzer, J.R.D. and Barrozo, M.A.S. 2007. A study of particle motion in rotary dryer. *Braz. J. Chem. Eng.* **24**, 365 - 374.

Liu, X.Y., Specht, E. and Mellmann, J. 2005. Slumping - rolling transition of granular solids in rotary kilns. *Chem. Eng. Sci.* **60**, 3629 - 3636.

Mellmann, J. 2001. The transverse motion of solids in rotating cylinders-forms of motion and transition behaviour. *Powder Technol.* **118**, 251 - 270.

Perron, J. and Bui, R.T. 1992. Rotary cylinder: Transverse bed motion prediction by rheological analysis. *Can. J. Chem. Eng.* **70**, 223 - 231.

Rodrigues, M.A.A., Borges, M.L.A., Franca, A.S., Oliveira, L.S. and Correa, P.C. 2003. Evaluation of physical properties of coffee during roasting. Agricultural Engineering International: *CIGR J. Sci. Res. Dev.* **5**, 1 - 12.

Rogers, R.S.C. and Gardner, R.P. 1979. A Monte Carlo method for simulating dispersion and transport through horizontal rotating cylinders. *Powder Technol.* **23**, 159 - 167.

Sherritt, R.G., Chaouki, J., Mehrotra, A.K. and Behie, L.A. 2003. Axial dispersion in the three-dimensional mixing of particles in a rotating drum reactor. *Chem. Eng. Sci.* **58**, 401 - 415.

Sunkara, K.R., Herz, F., Specht, E. and Mellmann, J. 2013. Influence of flight design on the particle distribution of a flighted rotating drum. *Chem. Eng. Sci.* **90**, 101 - 109.

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