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Numerical Simulation of the Shaking Separation of Paddy and Brown Rice using the Discrete Element Method

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Shaking separation of paddy and brown rice is investigated using a numerical model and by experiment at the same scale. The numerical model employs the discrete element method with two-dimensional circular particles representing rice grains. The indents on the experimental separation plate were modelled using a method of 'virtual' walls whereby only particles in contact with the base of the separation plate were affected by the walls which were positioned at regular intervals along the base. Exit of a particle from an indent was modelled as removal of a virtual wall once the particle-wall contact exceeded a threshold value. The model was validated against experimental results at the macroscopic scale in terms of mean particle distance from the sides and base of the separation plate, and the free surface profile. Particle movement in the experiments was tracked using a high speed video camera. There was good agreement between the results of the simulation and the experiment. The time required to achieve maximum separation of brown and paddy rice was the same in both experiment and simulation. The simulation also showed the same wave-like behaviour of the grain assembly as in the experiment.

1. Introduction

The discrete element (DE) method is an explicit numerical method of modelling the dynamic behaviour of granular material assemblies and has been used in a number of studies of agricultural particulate handling processes including grain flow (Sakaguchi *et al.*, 1994; Rong *et al.*, 1995a, b), soil–tool interactions (Tanaka *et al.*, 1996; Momozu *et al.*, 1997), soil–vehicle interactions (Oida *et al.*; 1997) and comminution of sugar cane stalks (Schembri & Harris, 1996). In all of these studies, particles were represented by two-dimensional (2-D) shapes such as circles, ellipses and hexagons. A common feature of most studies is the small number of particles used in the simulation relative to the numbers contained in real bulk particulate assemblies. Particle numbers in DE models are limited by the available computing power. This restriction as well as the fact that actual particles are three dimensional and often non-spherical means that direct simulation of the mechanical behaviour of typical real particulate assemblies is not possible unless the particle size scale is large relative to the bulk scale. It is necessary to consider how a DE simulation under these constraints can be effectively used as a tool to predict the dynamic behaviour of a grain assembly. Useful simulation results can be obtained if the model considers only a small part of the bulk, or if the simulated and physical systems are of equal scale. The simulation results can usually only be validated at the macroscopic behaviour of particulate media by comparison with experimental data. After qualitative or quantitative validation, analysis of the results of DE simulation can extract microscopic characteristics of the behaviour of a grain assembly. The characteristics can be used to inform the design process and to determine the optimum operation of grain processing machinery.

In Japan, shaking separation is widely used for removing paddy (unhusked) rice grains remaining in the brown (dehusked) rice bulk after dehusking. Better understanding of the separation mechanism is required for improvement of separators, and to enable modification and extension of their use to separation of other grains. Das (1986) investigated the effect of inclination of the separation plate and friction angle of rice grains on the effectiveness of an oscillating separator from analysis of the motion of a single grain of brown rice on a serrated separation plate. Separation behaviour in an assembly of paddy and brown rice was not considered. Balascio *et al.* (1987a, b) predicted the movement of plastic balls and split soybeans in an assembly of whole soybeans on the deck of a gravity separator using a Markov probability model. Such a stochastic model does not give information on the separation mechanism. Kojima *et al.* (1993) evaluated separation performance from the movement and the distribution of paddy and brown rice on the tray of a shaking separator for various mixing ratios.

These studies showed that there are two forms of grain behaviour in a vibrating bed of grain. The first is vertical segregation whereby paddy rice, which has a lower specific density and is larger in size than brown rice, moves towards the free surface. The second phenomenon is movement of the paddy rice towards the lower end of the separation plate and of brown rice to the higher end. Previous macroscopic scale models were essentially empirical in nature and were unable to predict the macroscopic mechanism of the separation because of difficulty in description of interaction between grains. Discrete element simulation has the potential to describe the macroscopic behaviour of grains during the complex separation phenomenon by modelling grain interactions at the microscopic scale. In this paper, a two-dimensional DE model of shaking separation of rice on an oscillating separation plate is developed and the macroscopic grain behaviour in the simulation is compared with the experiment at the same scale.

2. Experimental method

Experiments were designed to closely match operating conditions within an actual shaking separation system. In an actual system, the oscillating frequency and amplitude are fixed. Separation takes place on a shaking tray set at a cross slope angle α and a longitudinal slope angle β as shown in *Fig. 1*. The surface of the tray is covered in indents whose size, shape and arrangement are typically as shown in *Fig. 2*. The angle α is usually fixed at 8°, causing grain to transfer to one side of the tray. The longitudinal distribution of grains is controlled by varying the angle β and the feed rate of the mixture. Optimal grain distribution would be complete separation of brown and paddy rice along the discharge side of the tray but in practice there will always be a region of unseparated grains as shown in *Fig. 1*. When operating correctly, a pure fraction of brown rice is discharged from the end closest to the feed inlet. The pure fraction of paddy rice is discharged from the end farthest from the

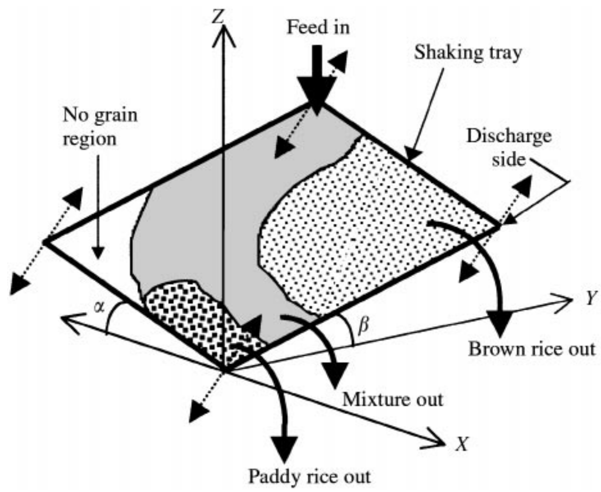

Fig. 1. Separation condition of grains on shaking tray in an actual system; ◀┈▶, the direction of the tray's oscillation in Y–Z plane; the cross slope angle α is fixed at 8°; longitudinal distribution of grains can be controlled by varying the longitudinal slope angle β and the feed rate of the mixture

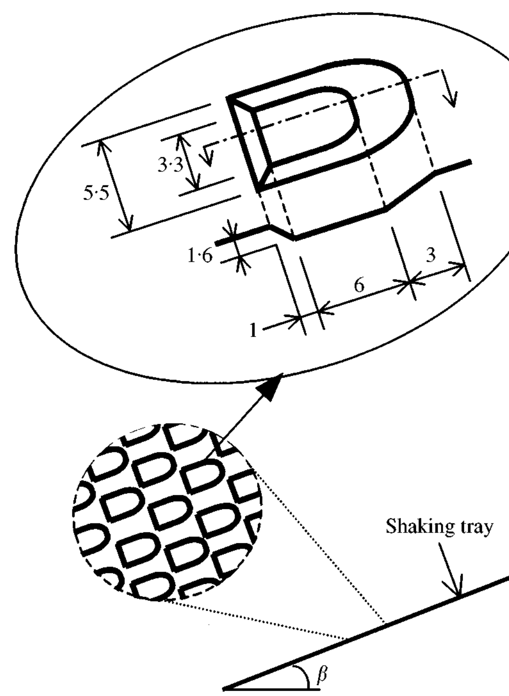

Fig. 2. Size, shape and arrangement of indents on the surface of shaking tray; β, longitudinal slope angle; all dimensions in mm

Table 1
Physical properties of paddy and brown rice; D_1, D_2 and D_3 indicate major, intermediate and minor diameters of rice, respectively

Rice	*Moisture content % w.b.*	*Diameter, mm*			*Particle density, g cm^{-3}*	*Particle mass, mg*	*Friction coefficient*	
		D_1	*D_2*	*D_3*			*Grains*	*Grain and wall*
Paddy	13·2	7·27	3·34	2·16	1·40	24·1	0·699	0·183
Brown	12·8	4·94	2·94	1·97	1·47	21·4	0·583	0·200

inlet and is sent for reprocessing in the dehusker. The unseparated grains are recovered and recycled through the separator and represent a loss in separation efficiency. The design and control objective is to maximize the size of the regions of pure fraction and the feed rate.

A small scale experimental model was used to represent the actual separation system. A separation box (width, 20 cm; height, 10 cm; depth, 2 cm) was fixed on the separation tray of a full scale rice husking machine with a cross slope angle of 0° and parallel to the longitudinal slope angle. The bottom of the box was the same indented separation plate as the surface of the shaking tray. The side walls of the box were made of acrylic resin. In each experiment 4 g paddy and 16 g brown rice (dehusking ratio 0·8) was thoroughly mixed and loaded into the box. The box oscillated with the shaking tray at a frequency of 3·5 Hz with a horizontal and vertical amplitude of 4·0 and 4·5 cm, respectively. All experiments were carried out with the separation tray set at a longitudinal slope angle of 20°.

Paddy rice (var. Yukinosei) was harvested and dried using a heated-air dryer at Atsugi farm of Tokyo University of Agriculture. It was transported to the laboratory and dehusked with the rice husking machine and the resulting paddy and brown rice grains were used for this experiment. The physical properties of the rice are shown in Table 1.

The movement of grains was observed through the front face of the box using a high speed colour video camera at a shutter speed of 1/4000 and a rate of 60 frames per second. Separation time was recorded on each frame using a video timer. Each observation was repeated four times. Image data processed using standard image analysis techniques to extract average particle behaviour. Brown rice was stained blue using methylene blue for discriminating between brown and paddy rice during image processing.

3. Simulation method

3.1. *Simulation conditions*

Grains were modelled as circular elements using the DE method as described previously (Sakaguchi *et al.*, 1994). Two-dimensional simulation was considered adequate as a first approximation because of the constraint imposed by the small depth (20 mm) of the experimental separation box on particle motion normal to the face of the box. It was observed that in the experiment most grains were oriented with each major diameter D_1 in mm parallel to the plane of the front face (longitudinal axis of the box). The particles were therefore modelled as circular, with a diameter based on the arithmetic mean of the measured grain diameters. The ratios for paddy to brown rice of the means of the major and intermediate diameters (D_1 and D_2 in mm) and the major and minor diameters (D_1 and D_3 in mm) were 1·35 and 1·36, respectively. The model particle diameter ratio was therefore chosen as 1·4 giving particle diameters of 5 and 7 mm for brown and paddy rice, respectively.

The mass of particles representing paddy and brown rice in the simulation was determined using the depth of particles (equal to the depth of the box), particle diameter and density, and the particle mass ratio between paddy and brown rice. The number of paddy and brown rice particles was 23 and 102, respectively, which equalled the numbers observed in the experiment. Friction coefficients shown in Table 1, and the same oscillating conditions and longitudinal slope angle β as those in the experiment were used in the simulation.

Although friction with the front or back walls of the box influences grain movement in the experiment, the friction is not usually considered in two-dimensional DE simulation because the dimension of depth direction of the box is not modelled. This means that the box does not have these walls and particles do not move in the depth direction in two-dimensional DE simulation. Corresponding to this motionlessness of particles in the simulation, limited movement of grains in the depth direction in the experiment could be attained by selection of small depth of 20 mm in the box. Some friction with front and back walls resulted in the limited motion of grains in the experiment with small depth of the box. It is considered that the effect of the friction on grain movement in this experiment is reflected in this simulation through motionlessness of particles in the depth direction. This allows neglect of friction between a particle and front or back walls in the simulation, while friction between a particle and left or right walls was represented.

A time step Δt of 1×10^{-4} s was chosen for acceptable computational time in the simulation. This value was a factor in determination of the value of the spring constant k in N m^{-1}. Stability of solution of the difference equations for calculation of the translation and rotation of particles in the DE method depends on the relationship between the spring constant in the contact force model, particle mass m in kg, the number of particles and the time step. The spring constant was determined using the following equation based on the investigation by Ishida *et al.* (1989) in which an element contacts a wall at velocity v in m s^{-1} and rebounds from the wall at velocity v' in m s^{-1} under the condition of $|v'| < |v|$,

$$\Delta t < \frac{-\eta + \sqrt{\eta^2 + 4km}}{2k} \tag{1}$$

where η is the viscous damping constant in kg s^{-1} ($=\sqrt{2mk}$ in this simulation). Using this constraint, 2000 N m^{-1} was selected as the spring constant between two contacting particles for normal contact force. The values of k between a particle and the wall and for the tangential contact force were determined using the same method as described by Sakaguchi *et al.* (1994).

Consolidation of particles for 1 s using the same method as in our previous work resulted in an initial random arrangement of particles as shown in *Fig. 4*(*e*).

3.2. *Modelling of indents on the separation plate*

The indents on the experimental separation plate were modelled by introducing 'virtual' walls at a spacing of 1 cm. Only those particles touching the bottom of the box can make contact with the walls which are on the left of the particles. In the DE method, overlapped distance between two particles expresses deformation of the particles and causes reaction force. Above a certain overlapped distance the virtual walls have no effect on the particles. One fourteenth of the element radius was chosen as the critical overlapped distance.

4. Results and discussion

4.1. *Macroscopic behaviour of grain assembly*

Figure 3 shows snapshots of the shaking behaviour of the grain assembly in the experiment and the simulation during one oscillation of the separation plate. Each experimental snapshot has almost the same separation time and cycle number as the simulation shown on the right. Due to the ease of rotation of circular particles the particles moved closer to the lower end of the box than in the experiment [*Fig. 3*(*e*) and (*f*)]. However, the simulation showed the same wave-like behaviour as the experiment over one cycle.

4.2. *Distribution of rice during separation*

Figure 4 shows snapshots of change in the distribution of paddy and brown rice with time in the experiments and the simulation. In the experiments, paddy rice moved towards the free surface [*Fig. 4*(*b*)] and towards the lower end of the box [*Figs 4*(*c*) and 4(*d*)]. The brown rice remained in closer contact with the indented separation plate and as a result was moved towards the higher end of the box as shown in *Fig. 4*(*d*). The time taken for this configuration to stabilize was approximately 5 s. A similar phenomenon was observed in the simulation over the same time scale [*Figs 4* (*f*)–(*h*)].

Eight images during separation for 10 s were selected from the simulation at the same position in the shaking cycle as the experimental snapshots. Two mean distances, one with respect to the left side wall $\bar{d}_s$ in cm and the other with respect to the bottom of the box $\bar{d}_b$ in cm, were calculated as follows. The areas comprising only a pure fraction were calculated for each image in the experiment. These areas were then used to calculate a geometrical moment of area I_A in cm^3,

$$I_A = A_i d_i \tag{2}$$

where A_i is the area of ith region of pure fraction in cm^2, and d_i is the orthogonal distance of the centroid of the area to either the left side wall I_{As} or the bottom I_{Ab} in cm. The mean distance to the left side wall is

$$\bar{d}_s = \frac{\sum_{i=1}^{n} I_{As(i)}}{\sum_{i=1}^{n} A_i} \tag{3}$$

and the mean distance to the bottom is

$$\bar{d}_b = \frac{\sum_{i=1}^{n} I_{Ab(i)}}{\sum_{i=1}^{n} A_i} \tag{4}$$

where n is the total number of areas.

The two mean distances of the pure fractions in the simulation were calculated as

$$\bar{d}_s = \frac{\sum_{i=1}^{l} L_{s(i)}}{l} \tag{5}$$

and

$$\bar{d}_b = \frac{\sum_{i=1}^{l} L_{b(i)}}{l} \tag{6}$$

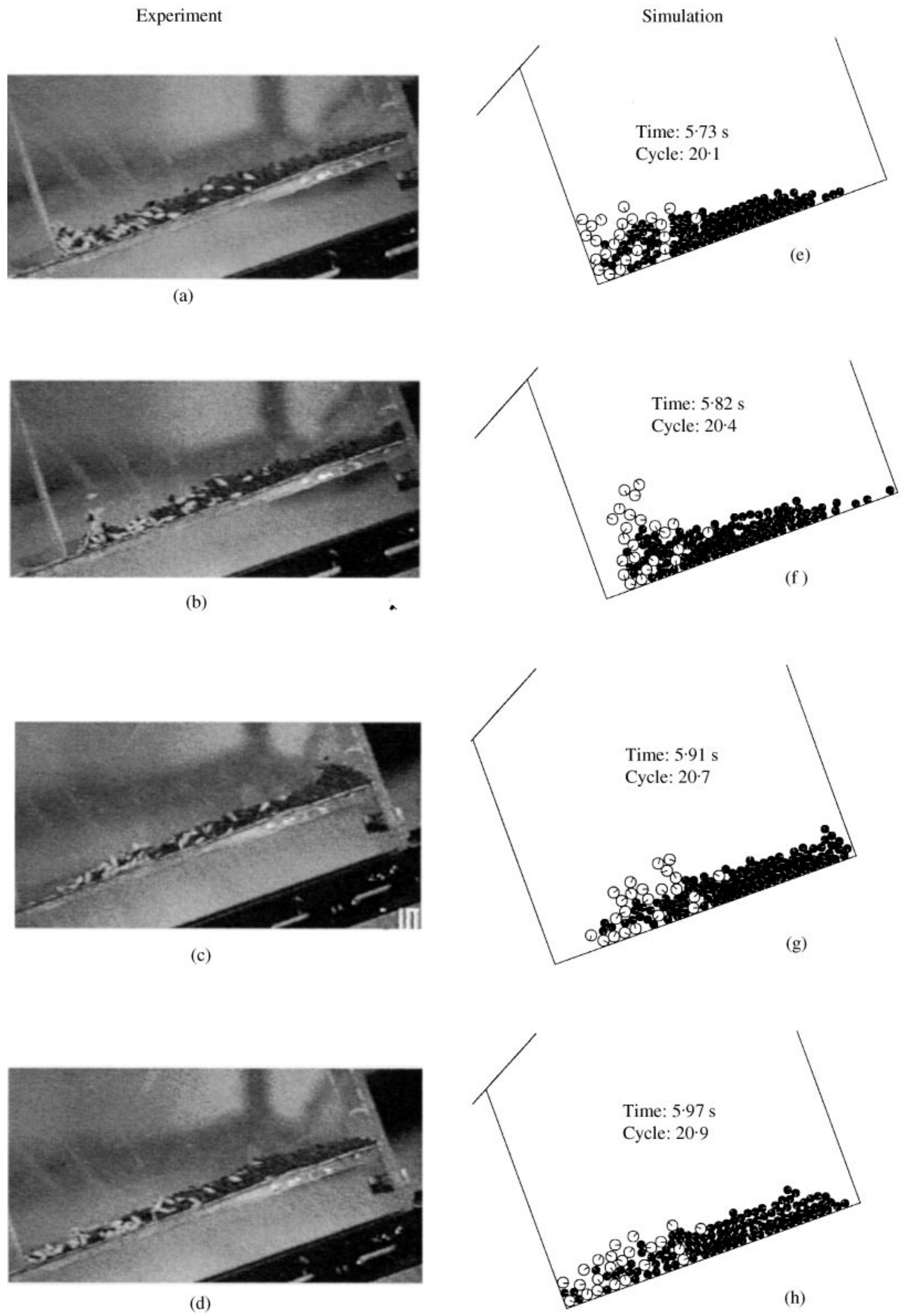

Fig. 3. Snapshots of shaking behaviour of the grain assembly, where each experimental snapshot (a)–(d) on the left has almost the same separation time as the simulations (e)–(h) shown on the right; white particles indicate paddy rice; black particles indicate brown rice

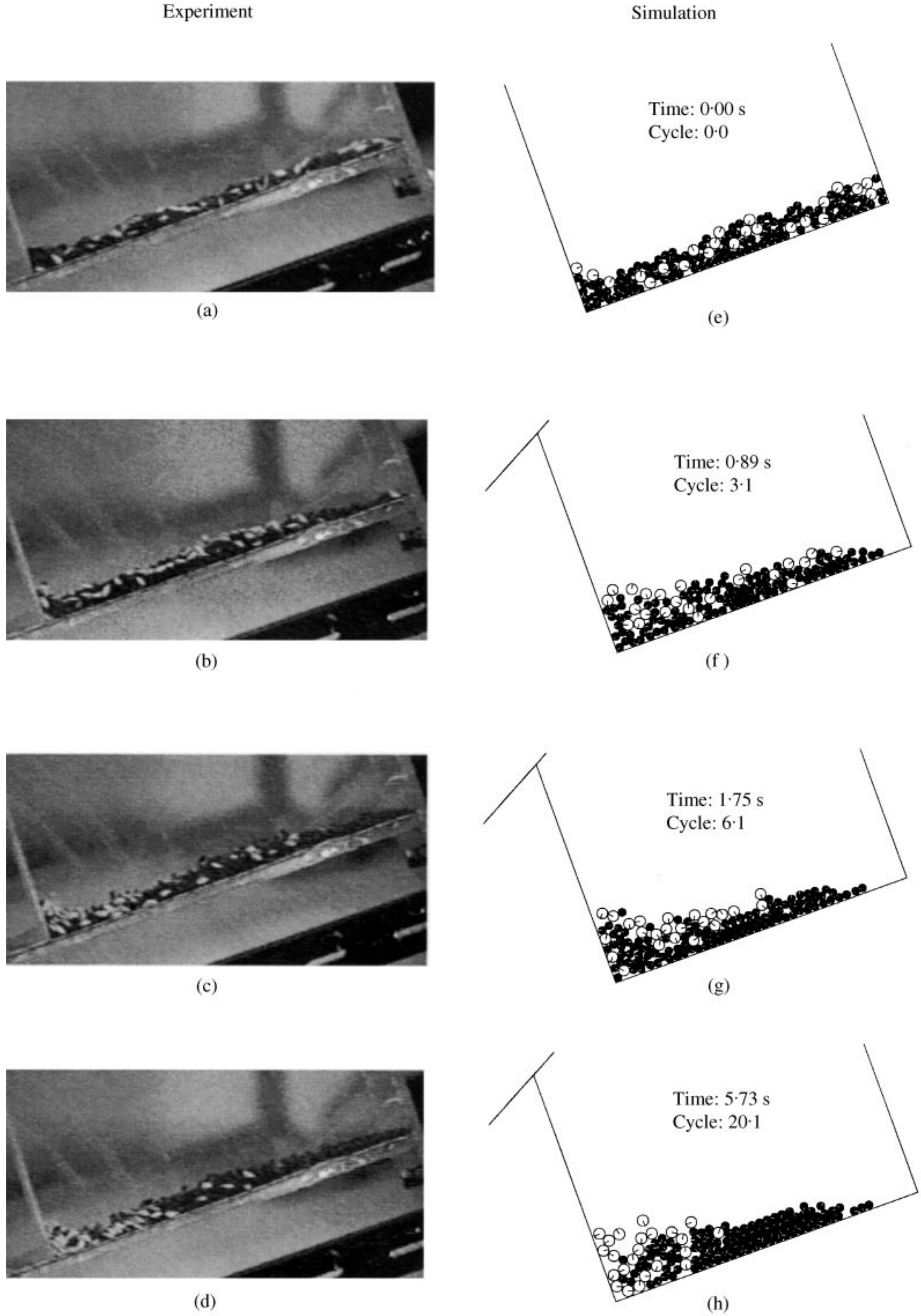

Fig. 4. Snapshots of change in separation condition during separation, where each experimental snapshot (a)–(d) on the left has almost the same separation time as the simulations (e)–(h) shown on the right; white particles indicate paddy rice; black particles indicate brown rice

where L_s and L_b are the orthogonal distances of the centre of the model particles to the left side wall and the bottom in cm, respectively, and l is the total number of particles of the pure fraction of interest. Quantitative investigation into vertical and horizontal movements of particles to the separation plate was carried out using these mean distances.

4.2.1. *Movement normal to the separation plate*

The relative movement normal to the separation plate (*i.e.* the bottom of the box) of paddy and brown rice was expressed as the difference between the mean distances of each fraction from the bottom. However, as shown in *Figs 3* and *4*, the height of the grain bed in the simulation was higher than in the experiment. This was due to the difference in size and shape between the circular model particles and the rice grains. The difference in mean distance was therefore normalized by the average height of the bed $\bar{h}$ in cm and normalized distance termed the normalized average segregation (NAS) and denoted by S_n:

$$S_n = \frac{\bar{d}_{b(P)} - \bar{d}_{b(B)}}{\bar{h}} \qquad (7)$$

where the subscripts P and B denote paddy and brown rice, respectively. *Figure 5* shows the change of NAS with separation time in the experiment and the simulation. The values of NAS in the experiments indicated distinct upward movement of paddy rice for around 2 s after the start of shaking. The greater vertical movement of paddy relative to brown rice results in segregation. The onset of accumulation of paddy rice near the lower end of the box resulted in stabilization of the value of the NAS. The magnitude and trend of the NAS from the simulation were in good agreement with those of the experiments.

Vertical segregation is an important phenomenon in shaking separation contributing to overall separation along the longitudinal axis. Previous investigation of factors governing segregation between paddy and brown rice in vertically vibrated bed of grains based on experimental and DE simulation has shown the strong effect of differences in size between two types of rice (Tobita, 1995). The results shown here suggest that this factor as well as particle density may be critical to the mechanical behaviour at the particle length scale.

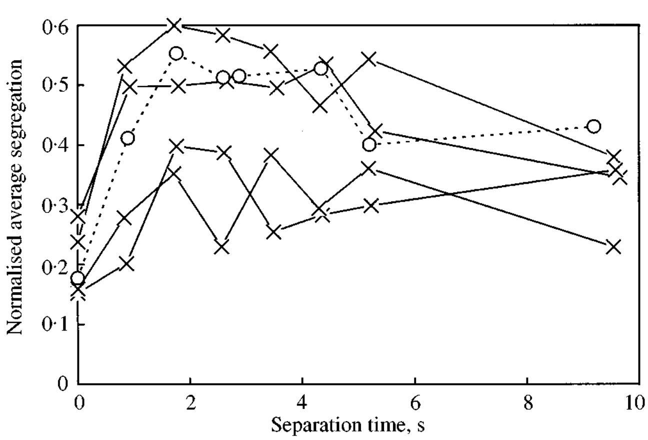

Fig. 5. Comparison of change in segregation condition with separation time between experimental and simulated results using normalized average segregation, which indicates the position normal to the separation plate for paddy relative to brown rice: ×*, experiment;* ○*, simulation*

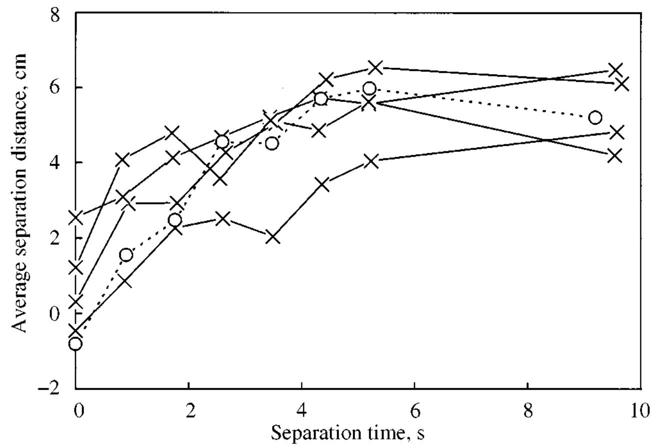

Fig. 6. Comparison of change in separation condition with separation time between experimental and simulated results using average separation distance, which indicates the distance parallel to the separation plate between paddy and brown rice: ×*, experiment;* ○*, simulation*

4.2.2. *Movement parallel to the separation plate*

Average movement of grains parallel to the separation plate was expressed as an average separation distance (ASD) calculated by subtracting the mean distance from the left side wall for paddy rice from that of brown rice and denoted by S_p in cm:

$$S_p = \bar{d}_{s(B)} - \bar{d}_{s(P)} \qquad (8)$$

The change of ASD with separation time in the experiment and the simulation is shown in *Fig. 6*. These changes of the experimental ASD showed an increase in separation into pure fractions over a period of approximately 5 s from the start of shaking followed by stabilization. A good quantitative correlation was obtained between the experimental and simulation results expressed as ASD. Paddy rice moved towards the lower end of the box at the surface of the bed after the segregation, while brown rice migrated towards the higher end along the indented separation plate. This implies shear behaviour in the bed of grains. The good correlation between experiment and simulation demonstrates that the DE model provides a good basis for investigation of the effect of particle physical properties and the separator design and operating parameters on the location and thickness of shear bands within the bed of grains.

4.3. *Effectiveness of the discrete element model*

The DE model provided a good approximation of the phenomenon of shaking separation of paddy and brown rice even though the experimental system was simplified in the model which was two dimensional, and represented the rice grains as circular particles and the indents of the separation plate as virtual walls. It is likely that the reasons why a good correlation was achieved are related to particular features of the system such as the mode of separation and particle properties. The mode of separation, *i.e.* grain movement predominantly vertical and parallel to the bottom of the separation box, was the same in experiment and simulation and was thus independent of particle shape. The physics of system is thus well represented by a micro-mechanical model which generates bulk behaviour based on laws operating at the particle scale. However, the two-dimensional shape of a rice grain resembles an ellipse and simulation using elliptical particles would limit particle rotation and cause more interlocking between particles. This suggests that the method of separation could be appropriate for other seed types if the operating parameters were tuned to optimize performance. It is also possible that the particles to be separated should be similar in shape. The similarity in shape between paddy and brown rice may be another reason for the correlations between experiment with ellipsoidal particles and simulation using circular particles. There is a significant computational advantage in using circular particles due to the complexity of contact detection between elliptical particles (Sakaguchi *et al.*, 1994).

The results also showed that the effect of the indents on the behaviour of the grains was successfully modelled using them as virtual walls. In the actual separator reaction force, due to movement of a grain toward to the higher end of the box, acts on the grain entering an indent. A corresponding reaction force can act on a particle in contact with a virtual wall in the simulation. Once the force acting on a grain increases above a threshold the grain leaves an indent toward the lower end of the box. Removal of a virtual wall by the choice of an appropriate threshold value for overlapped distance between a particle and the wall makes possible the movement of the particle toward the lower end. This simplification was useful to simplify programming and reduce computation time.

5. Conclusions

A two-dimensional discrete element (DE) model was developed for numerical simulation of the shaking separation of paddy and brown rice. The model used circular particles to represent grains and virtual walls in the bottom of the separation box to represent contact between grains and the indents of the experimental separation plate. The results of simulation and experiment were in good agreement with respect to the wave-like behaviour of the grain assembly and the macroscopic separation behaviour of the rice. Segregation caused by upward movement of paddy rice relative to brown rice and shearing of the grain bed to accumulate paddy rice near the lower end of the box were observed in both experiment and simulation. The results suggest that a simple DE model using two-dimensional circular particles and virtual walls was effective. This enabled modelling at the same scale as the experiment with reasonable computation times. Experimental validation of the DE model at the macroscopic scale makes possible more detailed analysis of the microscopic mechanism of grain segregation and shear behaviour. The model will allow further investigation of the separation mechanism and exploration of the effect of different physical and process parameters on the efficiency of grain separation in shaking separators.

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