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Research Paper

Separation characteristics of white rice in an indented cylinder separator with a baffle

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Broken rice can gather in the core of a cylinder during rice grain separation because it is wrapped by whole rice and cannot contact the indents causing low separation efficiency. To improve contact with the indented cylinder by broken rice the actions of a baffle were simulated using the discrete element method. By analysing rice movement in the mixing area under the action of baffle, the mechanism of reducing the segregation of grains, and therefore lack of contact with the indents, was clarified. The simulations showed that effects of blade length on separation characteristics were more obvious, compared with that of the rotational speed of the baffle. Shorter blade lengths and lower rotational speeds were more favourable for separation. Optimal parameters of the baffle were obtained after a comprehensive evaluation of the separation efficiency and loss rate was determined by the intercriteria correlation (CRITIC) method. This study provides a foundation for the design of the baffle and improving separation efficiency of the indented cylinder rice separators.

1. Introduction

The efficient separation of whole rice and broken rice following milling is beneficial to improve the quality of rice products and improve economic benefits. Indented cylinder separators can precisely separate whole and broken rice based on the size difference between grains of whole and broken rice mainly in their length (Meng et al., 2019). However, broken rice can be wrapped by whole rice in the mixing area preventing the broken rice from contacting the indents, resulting in low separation efficiency (Meng, 2019). Therefore, in order to improve separation adding a baffle to the bottom of the indented cylinder has been proposed (Tawfik, El-Shal, & El-Fawal, 2011). However, the mechanisms involved by adding baffle to improve the separation efficiency and how to determine the structure and operating parameters of the baffle remain unclear.

The separation of the indented cylinder separator includes two processes, one is the mixing process where the whole rice and broken rice are mixed at the bottom of the cylinder and the other is the separation process. Only broken rice can remain in the indents to be carried up to a certain position, then ejected and dropped into the collection trough. A number

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Nomenclature

CA	Comprehensive evaluation index
C_j	Conflict coefficient
DEM	Discrete element method
F_n	Normal contact force (N)
F_n^d	Normal damping force (N)
F_t	Tangential contact force (N)
F_t^d	Tangential damping force (N)
h	Mixing area thickness (m)
H_j	Blade length of baffle (m)
H_{jD}	Dimensionless blade length of baffle
I_i	Moment of inertia of particle i (kg m^2)
J_0	Axis position of the baffle
$m_i g$	Gravitational force of particle i (N)
n_{br}	Number of broken rice entering the indents
ns'	Number of separated broken rice in trough
n_z'	Number of whole rice in trough
N_s	Total number of broken rice in the system
N_s'	Number of broken rice in the grid at a certain time
N_z	Total number of whole rice in the system
N_z'	Number of whole rice in the grid at a certain time
P	Radial broken rice ratio (%)
r_{mj}	Correlation coefficient
R_{br}	Entering indents ratio of broken rice (%)
T_t	Tangential force torque (N m)
T_r	Rolling friction torque (N m)
v	Rotational speed of cylinder (m s^{-1})
v_i	Translational velocity of particle i (m s^{-1})
v_j	Rotational speed of baffle (m s^{-1})
v_{jD}	Dimensionless rotational speed of baffle
W_1	Weight coefficients of separation efficiency
W_2	Weight coefficients of loss rate
ω_i	Angular velocity of particle i (rad s^{-1})
η_{lr}	Loss rate of the indented cylinder separator (%)
η_{se}	Separation efficiency of the indented cylinder separator (%)
σ_j	Standard deviation

of studies have focused on the separation process to improve the separation efficiency, including studying of the parameters of the cylinder, indents and collecting trough as well as the movement of rice. Fouad (1980) studied the effects of different sizes and shapes of indents on separation. The effects of relevant parameters such as the size, rotational speed and inclination angle of the indented cylinder and the inclination angle and the length of the collecting trough on the separation characteristics have been investigated (Churchill, Berlage, Bilsland, & Cooper, 1989; Lee et al., 2009; Meng et al., 2019). Through the analysis of particle dynamics in the indented cylinder separator, the theoretical separation efficiency and the escape angle of rice have been deduced, and mathematical models for separating particles from indents have been established (Buus, Jørgensen, & Carstensen, 2011; Sorica, Pirna, Bracacescu, Marin, & Postelnicu, 2012; Wang, Wu, Tang, Liu, & Deng, 2011; Yamashita, Yoshitomi, Goto, & Nguyen, 1979; Yoshitomi, Yamashita, Goto, & Nguyen, 1979). Whilst most of the rice in the indented cylinder separator is in the mixing area at the bottom of the cylinder during the separation. If the broken rice in the mixing area can be fully contacted with the indents, then separation efficiency will be increased greatly. However, the movement and mixing characteristics of rice in the mixing area of the indented cylinder separator have rarely been studied.

An in-depth study of the mixing process could improve the separation efficiency of the indented cylinder separator. In mixing equipment, which is similar to the indented cylinder rice separator, research has been carried out into the motion and mixing characteristics of particles. Particles segregate during mixing due to their different physical properties, such as size, density and shape. In terms of size or density, whether in binary mixing or ternary mixing, small particles or particles with high density tend to congregate in the radial core wrapped by the large particles or particles with low density, and medium particles are sandwiched in between (Hayter et al., 2008; He, Chen, Ding, & Lickiss, 2007; Yamamoto, Ishihara, & Kano, 2016; Yang, Zhang, Luo, & Chew, 2017). Different shapes of particles have been shown to influence flow behaviour in rotating drums including the static and dynamic angles of repose, velocity profile and the active and passive layer residence times, etc (Dubé, Alizadeh, Chaouki, & Bertrand, 2013; Norouzi, Zarghami, & Mostoufi, 2015). It is well-known that the size and shape of the broken rice and whole rice in the indented cylinder are different and this inevitably leads to segregation. Moreover, in rice separators there are indents in the inner wall of the indented cylinder separator, which is different from the structure of the common mixing equipment. This must lead to different movements and segregation phenomena in the mixing area of rice separators. Therefore, the motion characteristics of rice in the mixing area of the indented cylinder separator needs to be further clarified to provide guidance for improving the separation efficiency.

Segregation has both advantages and disadvantages, it should be avoided in mixing, whilst it is beneficial in some purification operations. From examining the working principle of the indented cylinder separator, it can be seen that increasing the contact between the broken rice and the indents can improve the probability of the separating broken rice being improved (Su, Wang, & Li, 1998). In order to increase mixing, and inhibit segregation, a number of studies focus on the influence of adding baffles in the cylinder on particle movement and mixing. The different placements of the baffles can have different effects on particle mixing. The uniform distribution of baffles on the inner wall of a drum can effectively improve the segregation phenomenon (Maione, Kiesgen De Richter, Mauviel, & Wild, 2015; Schutyser et al., 2001; Zhou, Li, Zhou, Li, & Feng, 2016). Shi, Abatan, Vargas, and McCarthy (2007) it was more advantageous to install baffles in the central position than on the inner wall of drum since better disturbed the active layer and enhanced mixing. Based on the area occupied by particles in the mixing area of the drum, Zhang, Wei, and Wang (2018) added fixed baffles to the core of the mixing area in the rotary dry distillation furnace, which showed that there was no vortex central area with concentrated distribution of small particles. In addition, the structural parameters of the baffle such as the number, length and shape also have important effects on the mixing characteristics of the particles in the drum (Bhattacharya, Hajra, & McCarthy, 2014; Jiang, Zhao, Liu, & Zheng, 2011; Scherer, Mönnigmann, Berner, & Sudbrock, 2016). Whether or not the baffle is fixed or not has different effects on the mixing behaviour of the particles in the drum. Zhang et al. (2020) compared and analysed the effects of a fixed or moving baffle on the mixing of binary particles in the drum. The results show that the moving baffle mainly depended on irregular spin to disturb the particles and had stronger randomness to the particle movement, which was more

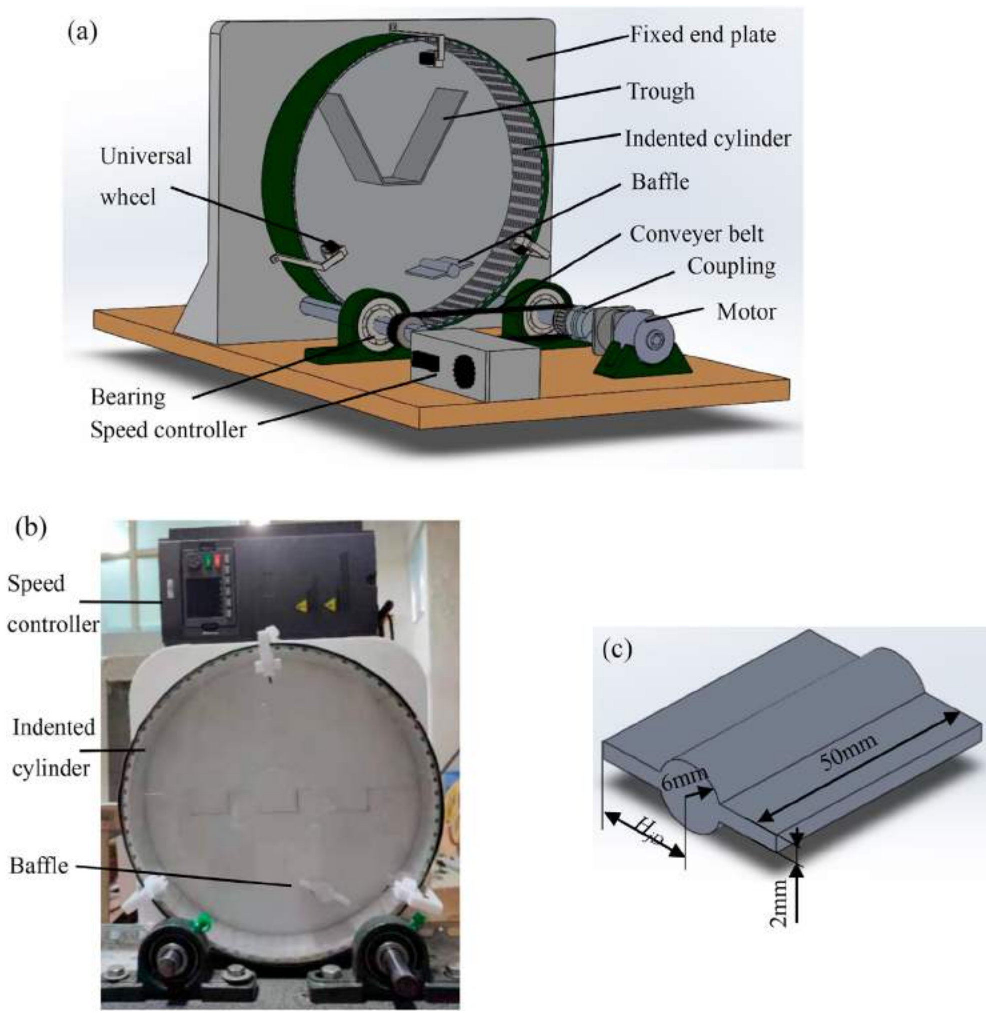

Fig. 1 – Schematic of the indented cylinder separator with a baffle: (a) geometry model, (b) experimental device, (c) baffle model.

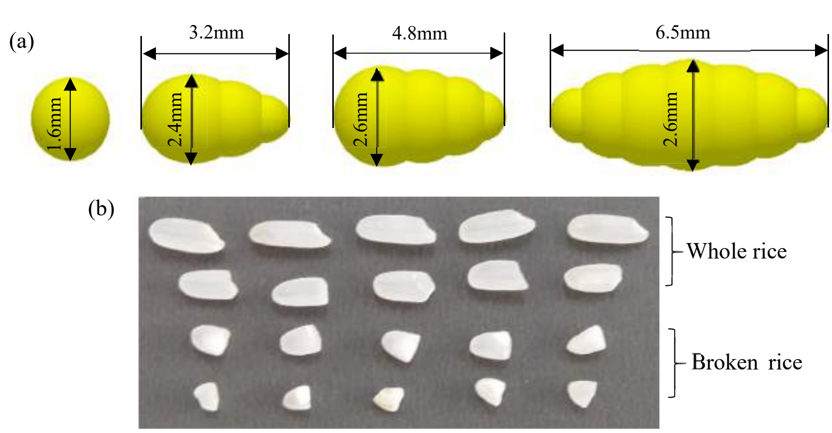

Fig. 2 – Rice Model: (a) multi-sphere model of rice, (b) experimental sample of rice.

advantageous for promoting mixing. The above studies proved that the appropriate addition of baffles can promote the mixing of particles and reduce the segregation of broken and whole grains within the cylinder. It has been proposed to add a baffle in the mixing area to improve undesirable segregation phenomenon associated with the structure of the indented cylinder separator. However, operating and structural parameters for the baffle on the distribution and movement of rice in the mixing area, and what kind of segregation form or mixing degree is beneficial to the contact between rice grain and indents remains unclear.

In this work, a baffle was added at the bottom of the indented cylinder separator to improve segregation phenomenon. The separation process of indented cylinder separator was investigated using the discrete element method based on our previous work (Meng et al., 2019). Firstly, the distribution and movement of rice in the mixing area with or without a baffle were investigated qualitatively after verifying the consistency of numerical simulation and experiment. The influence of structural and operational parameters of the baffle on separation are quantitatively explored by examining the entering indents ratio of broken rice and radial broken rice. The separation efficiency and loss rate are assessed by the intercriteria correlation (CRITIC) method, which is used to evaluate the separation comprehensively, to obtain best parameters of the blade length and rotational speed of the baffle.

2. Materials and methods

2.1. DEM model

To simulate the separation of whole and broken rice in an indented cylinder separator with a baffle, the discrete element method (DEM) has been used. Because of the low moisture content of white rice (15.1 ± 0.1% (w.b.)), the cohesive force and liquid bridge between the rice grains can be ignored (Cao et al., 2018). Every particle possesses translational and rotational motions, which can be calculated by Newton's second law of motion. The corresponding governing equations can thus be written as:

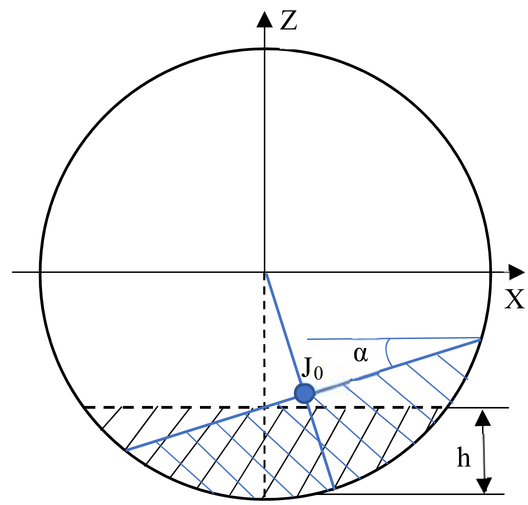

Fig. 3 – Diagram of axis position of the baffle.

$$m_i \frac{dv_i}{dt} = m_i g + \sum_{j=1}^{n_i} \left(F_n + F_n^d + F_t + F_t^d \right) \quad (1)$$

$$I_i \frac{d\omega_i}{dt} = \sum_{j=1}^{n_i} (T_t + T_r) \quad (2)$$

where m_i, v_i, ω_i and I_i are, respectively, the mass, translational velocity, angular velocity and moment of inertia of particle i; n_i is the number of particle j in contact with particle i; The normal total force is the sum of normal damping force (F_n^d) and normal contact force (F_n). Similarly, the tangential total force is the sum of tangential damping force (F_t^d) and tangential contact force (F_t). T_t is the torque caused by the tangential force. T_r is the rolling friction torque.

The popular no-slip Hertz-Mindlin contact model, which combines Hertz's theory in the normal direction and Mindlin's no-slip model in the tangential direction, was employed to

Table 1 – Geometry parameters and physical parameters used in the simulation (Meng et al., 2019).

Type	Parameters	Value
Cylinder	Radius × Length (mm)	125 × 50
Indent shape and size	Rectangle Length × Width × Height (mm)	6 × 3 × 3
Particle	Density, ρ_p (kg m^{-3})	1550
	Poisson ratio, ν_p	0.25
	Shear modulus, G_p (Pa)	1×10^6
	Number of particles	2800 × 4
Geometry	Density, ρ_g (kg m^{-3})	7800
	Poisson ratio, ν_g	0.3
	Shear modulus, G_g (Pa)	7×10^8
	Filling level (%)	10
Particle–particle	Restitution coefficient, e_{pp}	0.68
	Coefficient of static friction, μ_{spp}	0.15
	Coefficient of rolling friction, μ_{rpp}	0.01
Particle-geometry	Restitution coefficient, e_{pg}	0.68
	Coefficient of static friction, μ_{spg}	0.1
	Coefficient of rolling friction, μ_{rpg}	0.01
Simulation	Time step, Δt (s)	1.62×10^{-5}

model each contact between rice or rice and geometry. The equations used to calculate the normal total force, the tangential total force, the tangential torque and the rolling friction torque can be found in our previous study (Meng et al., 2021). The DEM simulation of rice separation progress in an indented cylinder was performed using the commercial software package EDEM (DEM Solution Ltd., Edinburgh, UK).

2.2. Simulation condition

2.2.1. Model and parameters settings

In our previous study (Meng et al., 2019), a driving method was used in which the cylinder was placed on a pair of rollers. However, in this work, due to the addition of the baffle, the indented cylinder was sleeved on the fixed end plate with a convex platform to prevent the cylinder from bouncing during rotation. Three brackets with universal wheels were used to make the cylinder adhere to the fixed end plate and prevent rice from being ejected. The shaft of the baffle passes through the fixed plate and was driven by the motor, as shown in Fig. 1. The radius of the central axis of the baffle was 6 mm, and axial length of baffle was 50 mm, which is consistent with the axial length of cylinder. The blade thickness of the baffle was 2 mm (Fig. 1c). Here, the length of the blade is defined as the distance between the axis of the baffle and the tip of the blade. In order to facilitate the observation and recording of the movement of rice in the cylinder, a transparent acrylic plate was selected for the front cover of the cylinder. In addition, using too long an axial length of the cylinder leads to axial segregation, whilst too short a length will increases wall friction effects (Jain, Ottino, & Lueptow, 2005). Therefore, the axial length of the cylinder was set to 50 mm. In the simulation process, to simplify the modelling and increase computational efficiency, drive parts were removed. Note that the coordinate origin was placed in the centre of the front plate of the cylinder. The other parameters of the indented cylinder separator were rotational speed of cylinder (47 rpm), number indents (72) and trough angle (60°), as used in our previous study.

The multi-sphere model employed to represent rice of different lengths, is shown in Fig. 2, and is the same as in our previous work (Meng et al., 2019). The number of each type of rice was 2800. Thus the ratio of whole rice to broken rice in the simulations was 1: 1. Detailed properties of particle and geometry used in the DEM simulation are shown in Table 1.

2.2.2. Determination of shaft position of baffle

A diagram of the axis position of the baffle is shown in Fig. 3. The black shadow is the initial filling state of the rice. The blue inclined shadow is the filling state when the cylinder rotates steadily, in which the blue dot J_0 represents the axis position of the baffle. The free surface of the bed forms an angle with the horizontal line under the stable condition, which is called the dynamic angle of repose α. Using image processing technology, the dynamic angle of repose was measured as 23.8° when the rotational speed of cylinder is 47 rpm. The thickness h of the mixing area was 39 mm under the given filling level (10%) according to the volume of rice particle and cylinder (Meng et al., 2019). The coordinate of the axis J_0 was calculated as (34.7 mm, −78.7 mm).

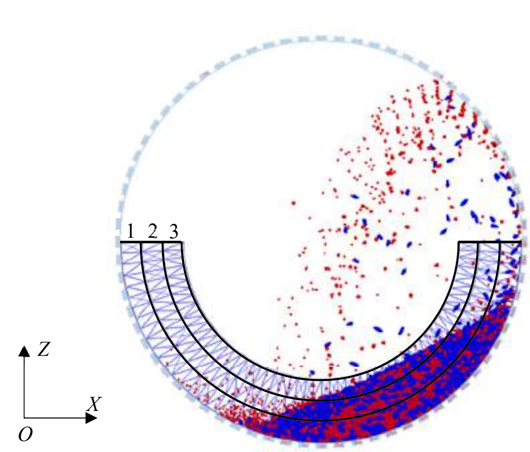

Fig. 4 – Grid for the cross-section: 1) the inner wall area, 2) the core area and 3) the free surface area of the mixing area. (thickness of each area is 13 mm).

In this paper, the ratio H_{jD} of the blade length of baffle H_j to mixing area thickness h was treated as a dimensionless variable used to quantify the blade length. Similarly, the ratio v_{jD} of rotational speed of baffle v_j to rotational speed of the cylinder v was treated as a dimensionless variable used to quantify the rotational speed of the baffle. The value of variables used in the simulation are listed in Table 2.

2.3. Statistical method

2.3.1. Entering indents ratio of broken rice

The greater the chance of broken rice entering the indents, the greater the chance of it being lifted, which means its separation performance will be better. Therefore, the indent entry rate of broken rice was used to quantify the ability of broken rice entering the indents, which is defined as follows:

$$R_{br} = \frac{n_{br}}{N_s} \tag{3}$$

Where R_{br} is the entering indents ratio of broken rice, n_{br} and N_s are, respectively, the number of broken rice entering the indents and total broken rice in the system. It is noteworthy that when the distance between the centre of rice and the centre of the cylinder was greater than or equal to radius

Table 2 – Set-ups for blade length and rotational speed of the baffle used in simulations.

Parameters	Values					
Blade length of the baffle H_j (mm)	18	21	24	27	30	33
Dimensionless blade length H_{jD}	0.46h	0.54h	0.62h	0.69h	0.77h	0.85h
Rotational speed of the baffle v_j (rpm)	0	23.5	47	70.5	94	117.5
Dimensionless rotational speed v_{jD}	0	0.5v	v	1.5v	2v	2.5v

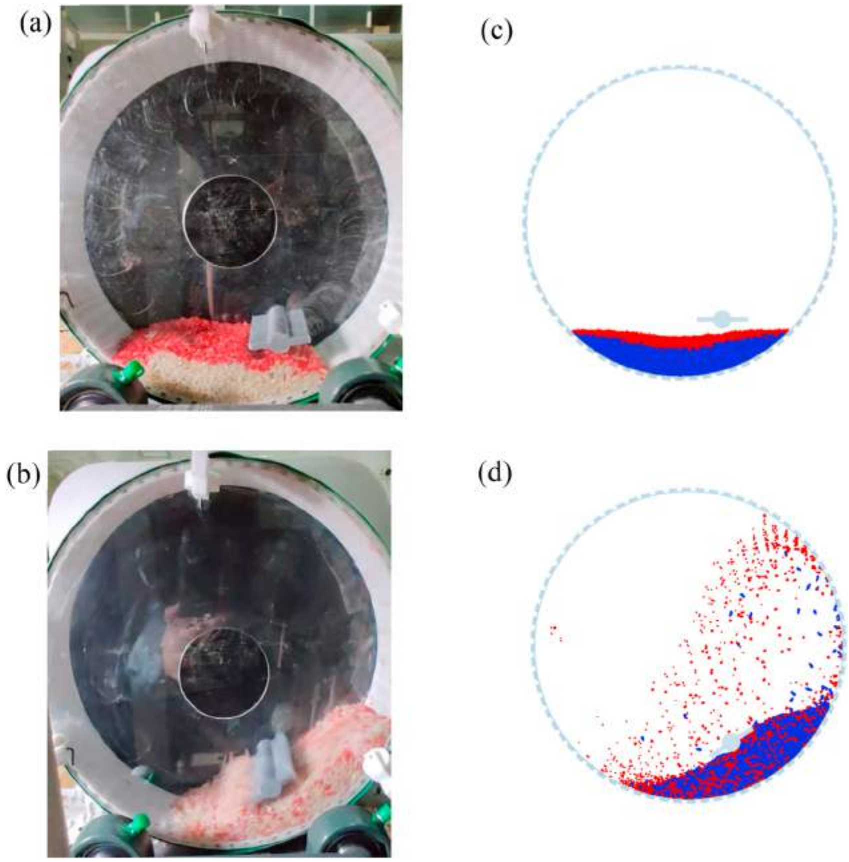

Fig. 5 – Qualitative comparison diagram: (a–b) Experiment, (c–d) Simulation.

of the cylinder, the rice can be regarded as entering the indents.

2.3.2. *Radial broken rice ratio*

In order to clarify the influence of the baffle on the entering indents ratio of broken rice and the distribution of broken rice on the inner wall, core area and free surface of the cylinder, the radial distribution of rice in the mixing area are analysed. The *xOz* plane of the cylinder was divided into three zones (Beaulieu, Vidal, Bertrand, & Chaouki, 2021), which were Zone 1 – the inner wall area, Zone 2 - the core area and Zone 3 - the free surface part of the mixing area, as shown in Fig. 4. Each zone had a sample with the radial thickness of 13 mm and the axial thickness of 50 mm. The number of each kind of rice in each zone was extracted.

The radial broken rice ratio was used to characterise the radial distribution of rice quantitatively (Zhang, Wei, & Qin, 2016), using the following:

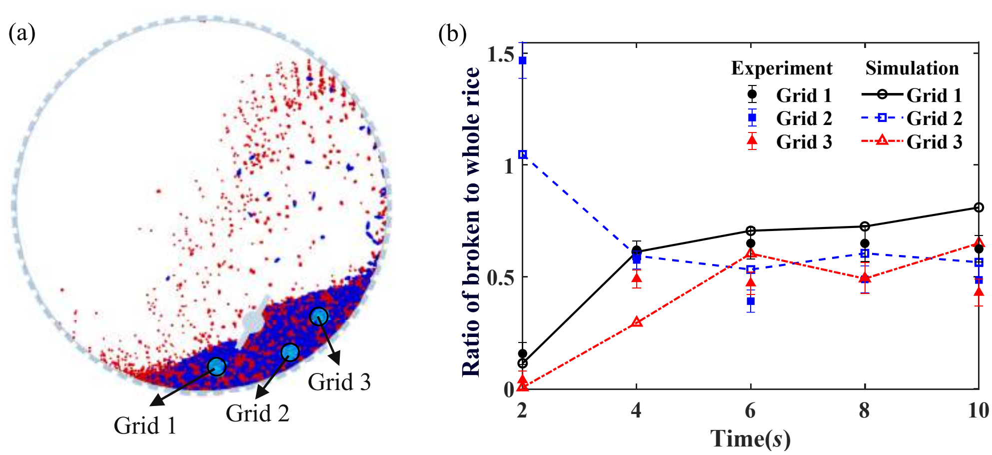

Fig. 6 – Quantitative comparison between simulation and experiment: (a) Sampling point (Grid 1, 2, 3) in the mixing area, (b) Ratio of broken to whole rice in sampling point.

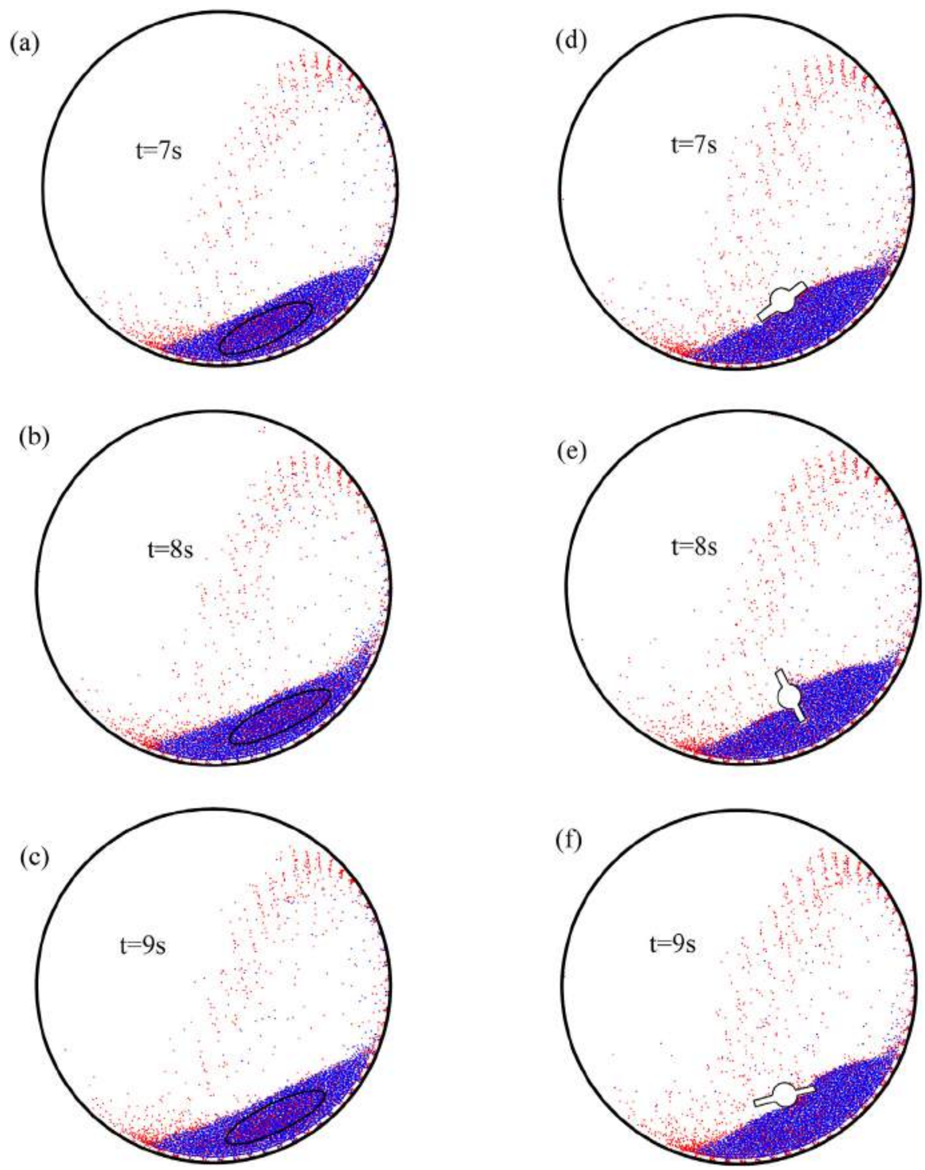

Fig. 7 – Location distribution of whole rice (Blue) and broken rice (Red) when blade length $H_{jD} = 0.54h$ and rotational speed $v_{jD} = v$: (a–c) without a baffle, (d–f) with a baffle. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

$$P = \frac{N_s' \times \frac{N_z}{N_s + N_z}}{N_s' \times \frac{N_z}{N_s + N_z} + N_z' \times \frac{N_s}{N_s + N_z}} \quad (4)$$

where P is the radial broken rice ratio, N_s' and N_z' are the number of broken rice and whole rice in the grid at a certain time; N_s and N_z are the total number of broken rice and the total number of whole rice in the system.

P has values between 0 and 1. The more broken rice is in the grid, the greater the P value is. The more whole rice, the smaller the P value is. When $P = 1$, $N_z' = 0$ (N_s is non-zero) it corresponds to a grid that is full of broken rice. When $P = 0$, $N_s' = 0$ (N_z is non-zero), it corresponds to a grid that is full of whole rice. The latter is the worst of these two limiting cases. In addition, when $P = 0.5$, the ratio of broken rice to whole rice in this zone is equal to that of the system, which means that the mixing of rice is at its best.

2.3.3. *Separation efficiency and loss rate*

Screening efficiency and loss rate are two important indices to evaluate the working performance of the indented cylinder separator, which can effectively reflect the accomplishment of separation. During the separation process, some of the broken rice will fall into the bottom of the indented cylinder separator, resulting in incomplete separation. Also, some of the whole rice will be lifted by the indents to a higher position where it will fall into the collecting trough causing losses.

To quantify the separation ability, efficiency was calculated as the percentage of separated broken rice in the trough as follows (Tawfik et al., 2011):

$$\eta_{se} = \frac{n_s'}{N_s} \quad (5)$$

Meanwhile, the separated whole rice in the trough was calculated as losses by:

$$\eta_{lr} = \frac{n_z'}{N_z} \quad (6)$$

where η_{se} and η_{lr} are, respectively, the separation efficiency and the loss rate of the indented cylinder separator; n_s' and n_z' are, respectively, the number of separated broken rice and whole rice in trough; N_s and N_z are the number of broken rice and whole rice in the system.

2.3.4. *The CRITIC method*

The evaluation indices involved in this study included separation efficiency and loss rate. It is necessary to employ a comprehensive index to evaluate the separation effect. During the separation process, there will inevitably be some losses in the indented cylinder separator, but the loss rate is expected not to be high. Overall, there is a correlation and a conflict between the separation efficiency and the loss rate. The CRITIC method, proposed by Diakoulaki, Mavrotas, and Papayannakis (1995), is a multi-criteria decision-making method that focuses on the objective weight of criteria, which is based on the information of the indices and the correlation between them. Therefore, the CRITIC weighting method was selected to establish a mathematical model for comprehensive evaluation of two indices, which provides a reference for the optimisation of blade length and rotational speed of baffle. The steps of the CRITIC method in details are:

Step 1. Non-dimensional pre-treatment of data. For the separation efficiency, the higher it is, the better, using the following equation:

$$y = \frac{x_{ij} - \min(x_{ij})}{\max(x_{ij}) - \min(x_{ij})} \quad (7)$$

Conversely, the lower the loss rate is, the better, using the following equation:

$$y = \frac{\max(x_{ij}) - x_{ij}}{\max(x_{ij}) - \min(x_{ij})} \quad (8)$$

where $\max(x_{ij})$ and $\min(x_{ij})$ are the maximum value and minimum value of the separation efficiency or loss rate, respectively. x_{ij} is the j_{th} evaluation index of the i_{th} factor level.

Step 2. Calculation of the variability of the evaluation index. The standard deviation σ_j of the evaluation index is used to characterise its variability. The equation is shown as follows:

$$\sigma_j = \sqrt{\frac{1}{n}\sum (x - \bar{x})^2} \quad (9)$$

Step 3. Calculation of the conflict coefficient of evaluation indices, which is based on the correlation coefficient between indicators. The equation is calculated as follows:

$$C_j = \sum_{m=1}^{n} (1 - r_{mj}) \quad (10)$$

where C_j is the conflict coefficient of evaluation index, $j\varepsilon[1, n]$. r_{mj} is the correlation coefficient of the evaluation index. The formula is shown as follows:

$$r_{xy} = \frac{\sum (x - \bar{x})(y - \bar{y})}{\sqrt{\sum (x - \bar{x})^2 \sum (y - \bar{y})^2}} \quad (11)$$

Step 4. Calculation of the weight coefficient according to following equation:

$$W_j = \frac{\sigma_j C_j}{\sum_{j=1}^{n} \sigma_j C_j} \quad (12)$$

A comprehensive evaluation model was established for the separation efficiency and loss rate by CRITIC method to optimize the parameters of baffle. The comprehensive evaluation model is:

$$CA = W_1 \eta_{se} + W_2 \eta_{lr} \quad (13)$$

where *CA* is the comprehensive evaluation index. W_1 and W_2 are the weight coefficients of separation efficiency and loss rate, respectively.

3. Results and discussion

3.1. *Model validation*

In order to ensure the reliability of the DEM model of the indented cylinder separator with a baffle, it was necessary to carry out experimental validation of the techniques before simulation. The rotational speed of the baffle was set to be υ, and the rotational direction is opposite to that of the cylinder. Meanwhile, the length of baffle blade selects 0.54 *h*. Experimental verification was conducted from both qualitative and quantitative perspectives. The distribution pattern of whole rice and broken rice at different moments was compared qualitatively, and the ratio of broken rice to whole rice in the sampling grid at different moments was compared quantitatively. Figure 5(a) - (b) shows the separation process of the indented cylinder separation with a baffle during the experiment, in which the broken rice was dyed red to make it easier to distinguish. Figure 5(c) - (d) is the discrete element simulation process, in which blue particles represent the whole rice. It can be seen that the distribution patterns of rice in the experiment and simulation were substantially consistent.

To give a quantitative comparison, the ratio of broken rice to whole rice in the sample was used to characterise performance. During the experiment, three holes with a diameter of 12 mm were randomly drilled into the transparent acrylic plate of the indented cylinder separator as sampling points. Similarly, three cylindrical bins with a diameter of 12 mm are established at the corresponding positions of the simulation, as shown in Fig. 6(a). The number of whole rice and broken rice grains in each sample or grid were extracted. The ratio of broken to whole rice grains in the sampling points was statistically calculated. Figure 6(b) shows a comparison of the ratio of broken rice to whole rice between the test and the simulation. It can be observed from the figure that the ratio of

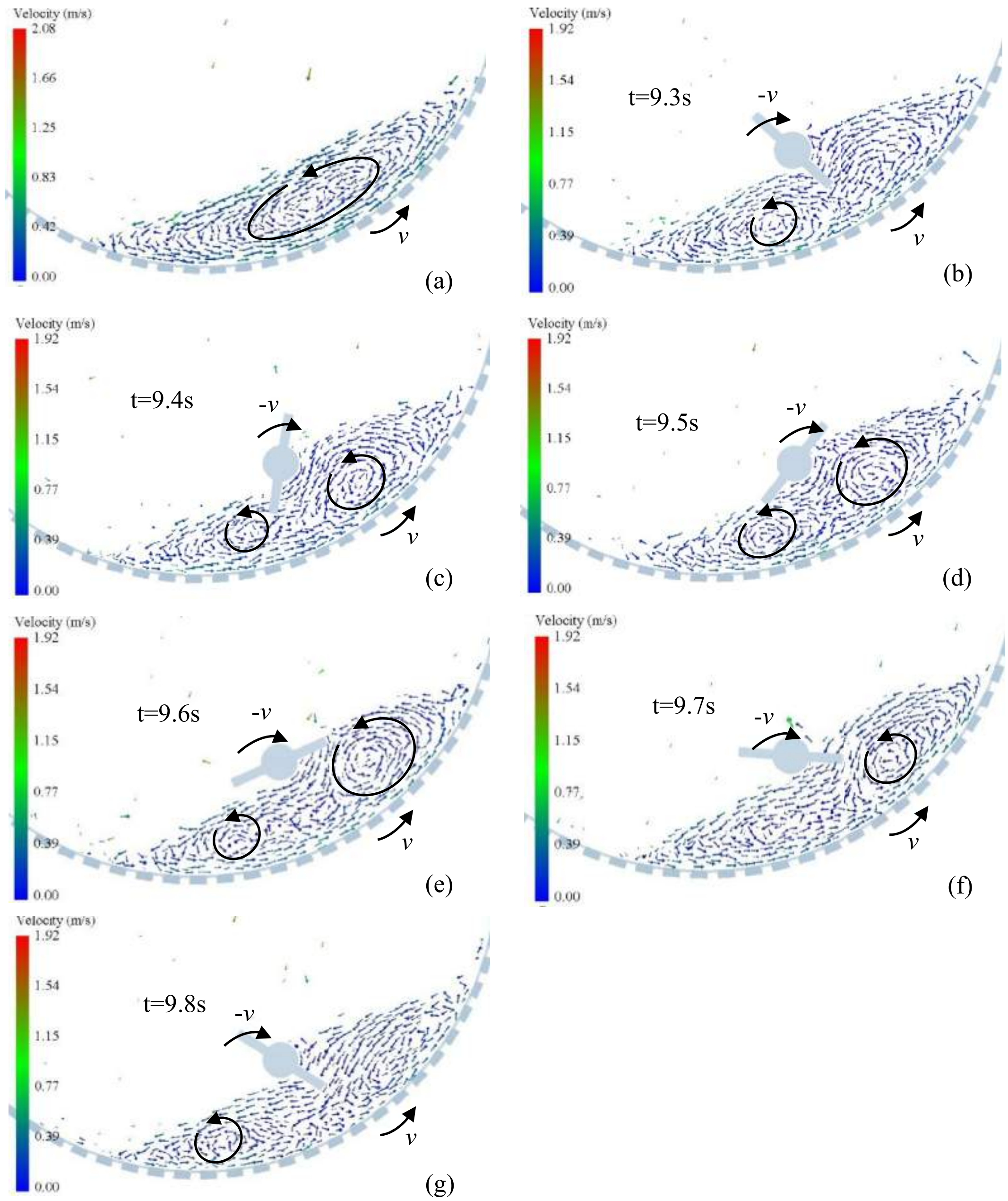

Fig. 8 – Velocity vector of rice when blade length $H_{jD} = 0.54\ h$ and rotational speed $v_{jD} = v$: (a) without a baffle, (b–g) with a baffle.

broken rice to whole rice in the three sampling points finally tends to be stable, and the simulation results were therefore consistent with the experimental results. Thus, one can conclude that there was good agreement between the numerical and physical results confirming the validity of the current DEM model.

3.2. *Comparison of separation phenomenon with or without a baffle*

3.2.1. *Position distribution of whole rice and broken rice*

In order to compare the distribution of whole rice and broken rice in mixing area with or without a baffle, the coordinates of whole rice and broken rice on *xOz* plane were extracted. Figure 7 shows the position distribution of whole rice and broken rice at different times, in which blue scattered points are whole rice, red scattered points are broken rice. Figure 7(a) - (c) show the distribution of whole rice and broken rice without a baffle at four different times. It can be clearly observed that the broken rice gathers in the mixing area, whilst the whole rice disperses around the broken rice. This segregation phenomenon hinders the contact between broken rice and the indents, so that the broken rice cannot be lifted, which is not conducive to the final separation and leads to a low separation efficiency. The reason for this phenomenon is the leakage mechanism which is due to size difference, with

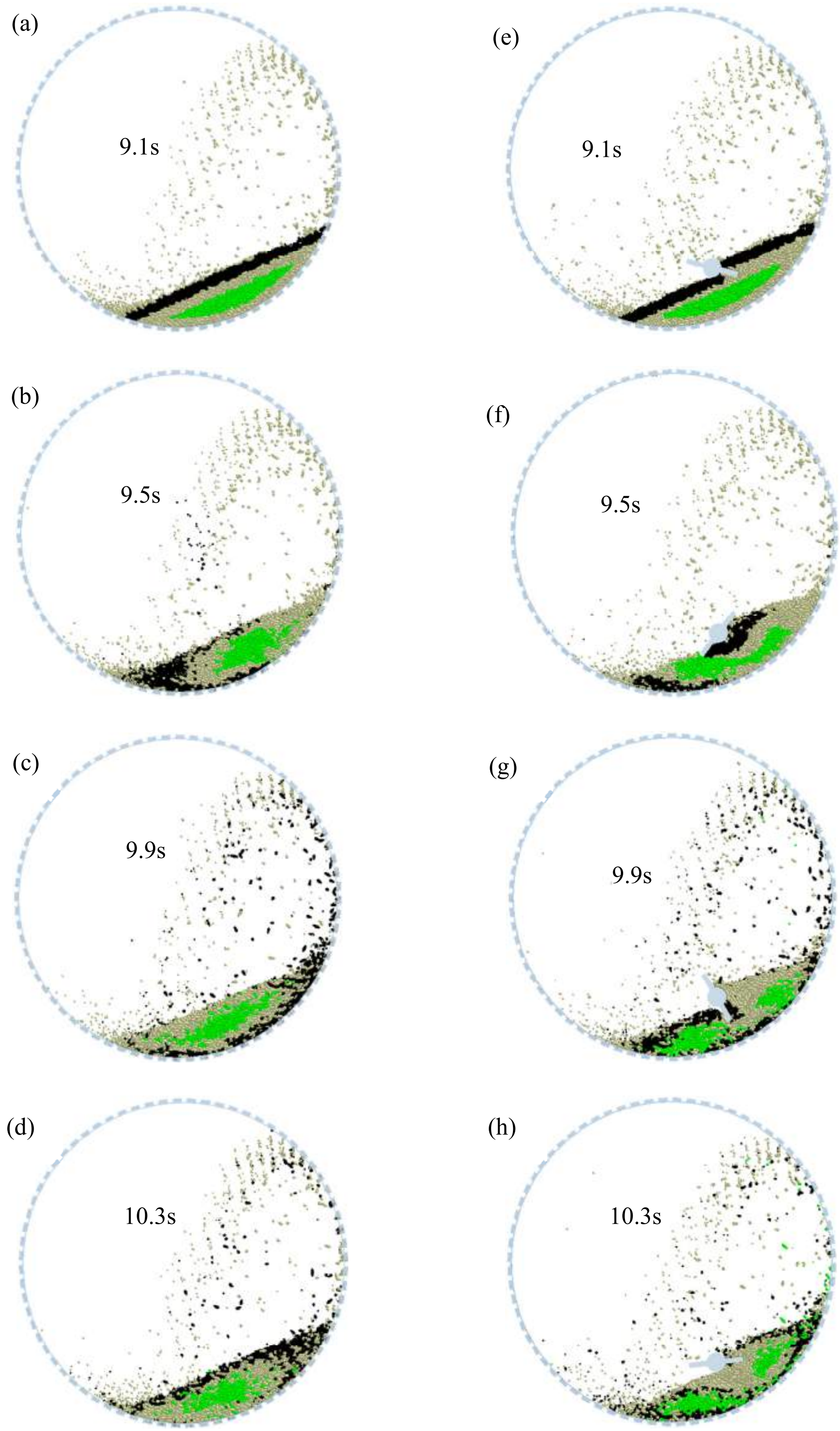

Fig. 9 – Movement of core and peripheral rice in the mixing area when blade length $H_{jD} = 0.54\,h$ and rotational speed $v_{jD} = v$: (a–d) without a baffle, (e–h) with a baffle.

small particles filling the gaps between larger particles and smaller particles tending to move toward the centre of the active area (Liu et al., 2017). Figure 7(d) - (f) show the distribution of whole rice and broken rice with a baffle. Compared with the distribution of whole rice and broken rice without a baffle, the segregation phenomenon has changed, which showing that adding a baffle in the mixing area is beneficial to white rice separation.

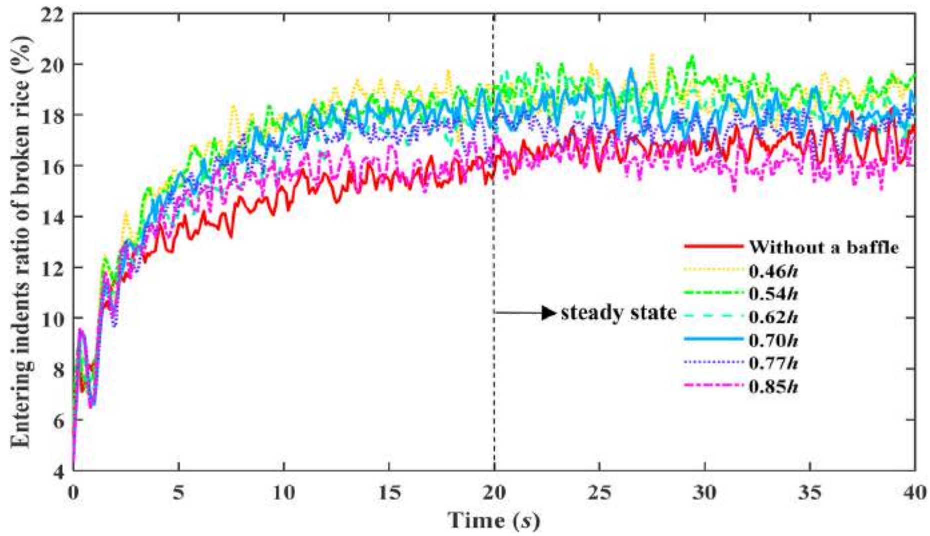

Fig. 10 – Entering indents ratio of broken rice as a function of time for different blade lengths when rotational speed $v_{jD} = v$.

3.2.2. *The velocity vector distribution of rice*

The influence of baffle on the distribution of whole rice and broken rice was further studied from the aspect of velocity vector distribution of rice. In the axial centre of the cylinder, a cylindrical bin with a diameter of 128 mm and a height of 3 mm, which is coaxial with the cylinder, was established to display the velocity vector of the rice, as shown in Fig. 8. The direction of the vector arrow of rice represents the velocity direction of rice, different colours and vector sizes represent magnitude of rice velocity. Figure 8(a) is the velocity vector distribution of rice without a baffle. It can be observed that rice grains present a large circular motion with the rotation of the indented cylinder, which forms a core in the mixing area. The moving direction of the core is the same as that of the cylinder, and the moving velocity of rice in the core area is less than that of rice in the outer ring.

Figure 8(b) - (g) are the velocity vector distribution of rice when the baffle rotates once in the indented cylinder separator with a baffle under stable condition, which is completely different from that without the baffle. At 9.3 s, a small core can be seen to form in the lower left corner of the mixing area, and its movement direction is the same as that of the cylinder, but no cores appear in the upper right corner. The core begins to appear in the upper right corner at 9.4 s. The two cores then move in the same direction, which is consistent with the movement direction of the core. From 9.5 s to 9.6 s, the core in the lower left corner gradually becomes smaller, whilst the core in the upper right corner becomes larger. Until at 9.7 s, the core in the lower left corner disappears, only one remains in the upper right corner. At 9.8 s, the baffle exactly rotates one round, and the movement state of rice grains at this moment is similar to that at 9.3 s. Overall, the velocity vector distribution of rice changes periodically with the rotation of baffle. It can be seen that the single regular movement of the rice without the baffle is destroyed after the addition of the baffle. The rice group in the mixing area changes from a large core to the movement mode of one or two small cores. This reduces the rotation time of the rice, that is, the time for the broken rice to move from the core to the outer ring is reduced. Thus, contact between the broken rice and the indent increases.

3.2.3. *Movement of core and peripheral rice in mixing area*

In order to explore the movement of the core and the peripheral rice grains, rice in the free surface and the core were tracked from 9.1 s in the simulation, as shown in Fig. 9. Particles in the free surface moved all along the periphery to the inner wall of the cylinder, which indicated that the particles on the free surface had a great chance of contacting the indents. However, the movement of rice in the core area was completely different with or without a baffle. The rice in the core always moved in the core without a baffle in Fig. 9(a)–(d), which illustrated that the rice in the core area, (whole or broken) was not likely to be in contact with the indents. It can

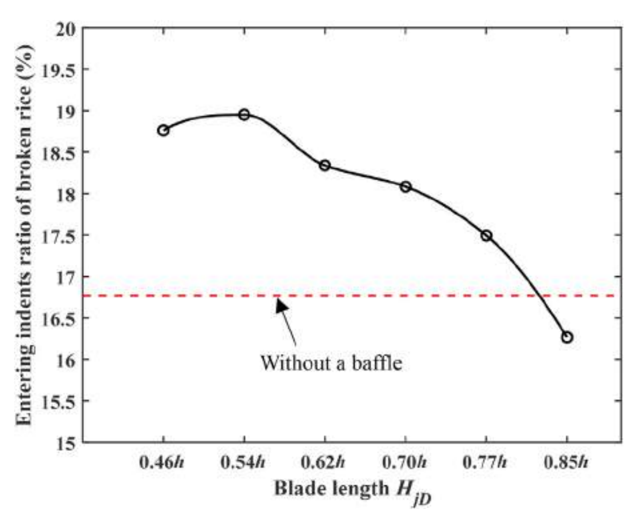

Fig. 11 – Effect of blade length on entering indents ratio of broken rice when rotational speed $v_{jD} = v$.

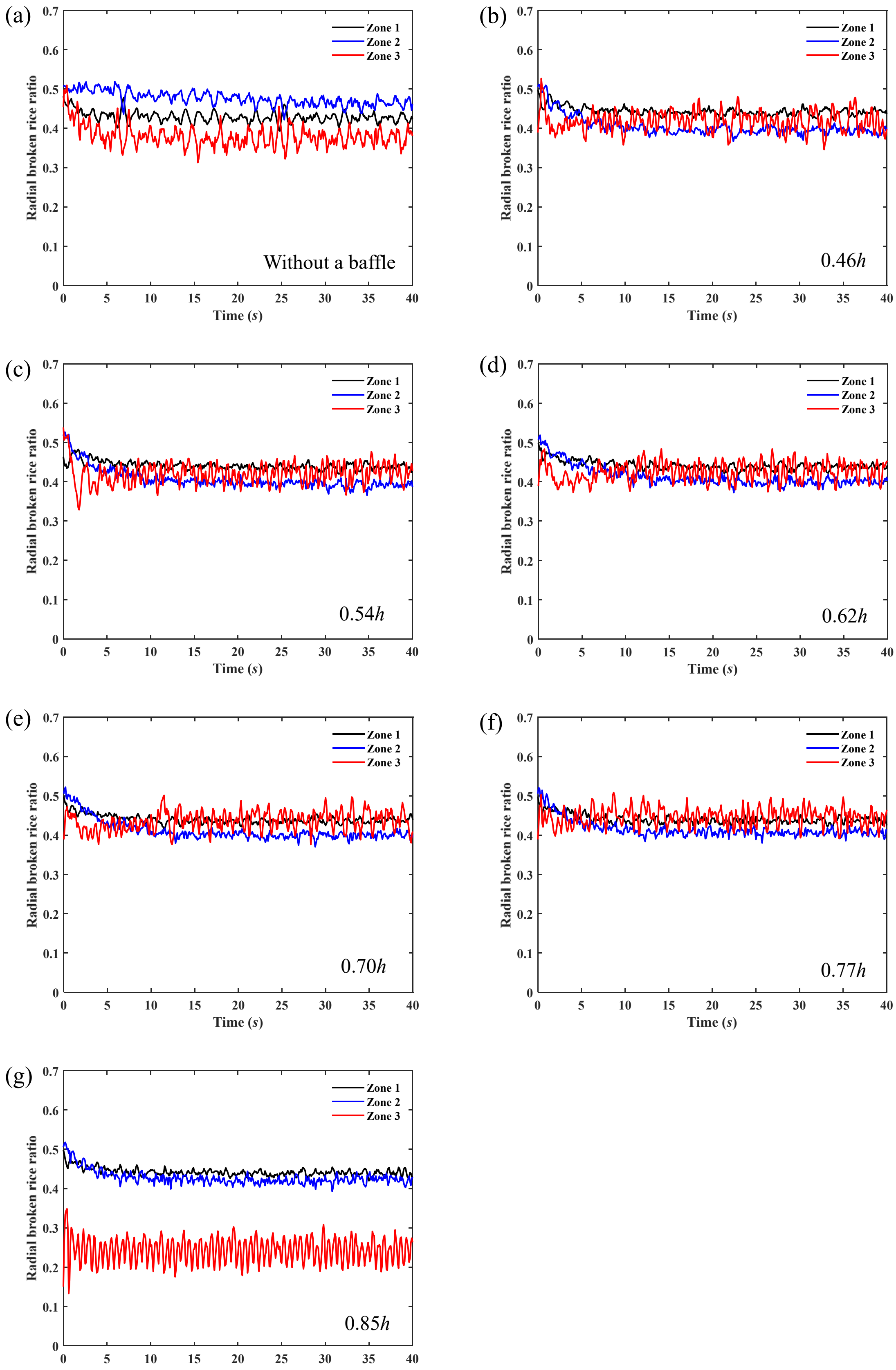

Fig. 12 – Radial broken rice ratio as a function of time for different blade lengths when rotational speed $v_{jD} = v$: (a) without a baffle, (b) 0.46*h*, (c) 0.54*h*, (d) 0.62*h*, (e) 0.70*h*, (f) 0.77*h*, (g) 0.85*h*.

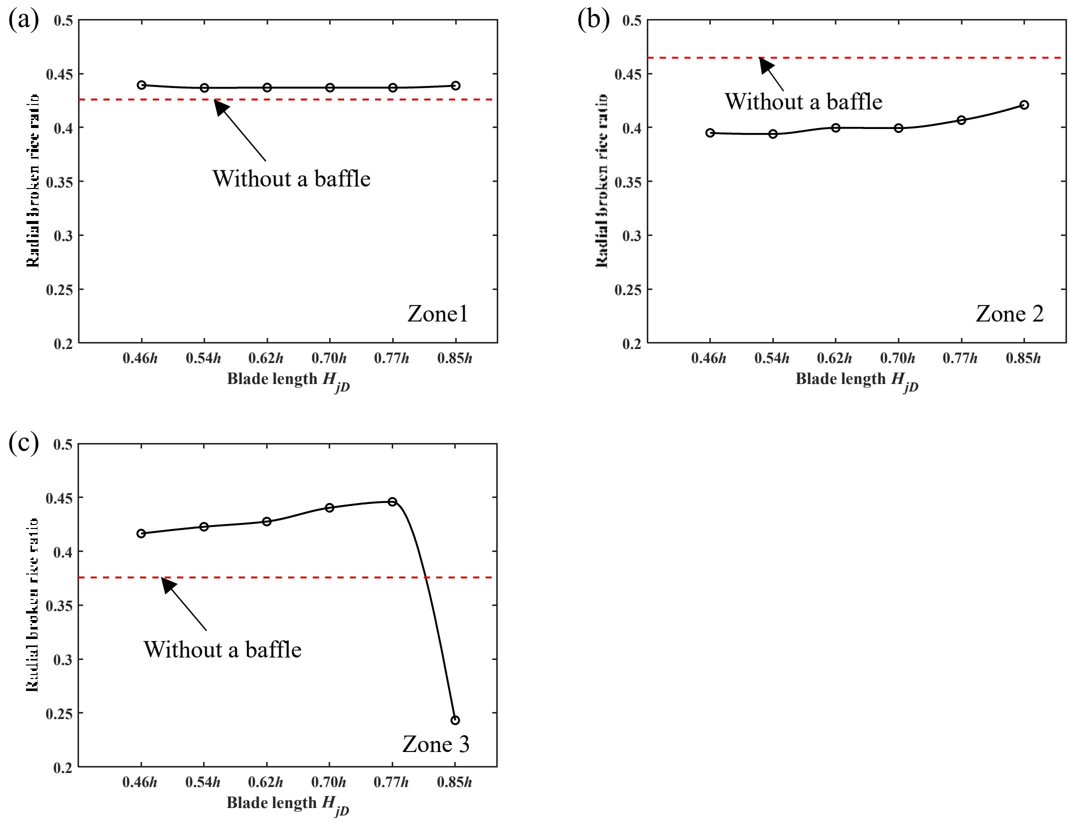

Fig. 13 – Effect of blade length on radial broken rice ratio when rotational speed $v_{jD} = v$: (a) zone 1, (b) zone 2, (c) zone 3.

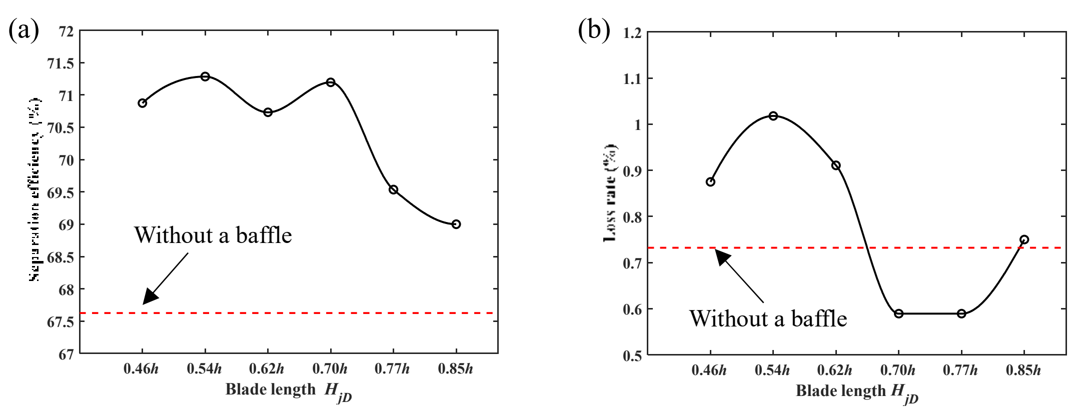

Fig. 14 – Separation ability for different blade lengths when rotational speed $v_{jD} = v$: (a) separation efficiency, (b) loss rate.

be seen from Fig. 9(e)–(h) that the baffle scraped the rice out, enabling it to reach the free surface so as to contact more easily with the indents. Moreover, one core gradually evolves into two smaller cores.

In general, a baffle can improve mixing with the main being that the blade can breaks up the original single circular motion, so that the rice in the core area reaches the free surface which is more conducive to contact with the indents, thereby improving the separation efficiency of the indented cylinder separator. However, the effects of the structure and operational parameters of the baffle on the separation performance need to be further explored.

3.3. *Effects of the blade length on the separation ability*

When studying the effect of blade length on separation ability, the rotational speed of baffle was set as v. Figure 10 shows the change in the ratio of broken rice entering the indents with time for different blade lengths of baffle. The ratio at first increased but flattened off after around 20 s.

Table 3 – Final comprehensive evaluation for different blade lengths.

Blade length (mm)	0.46*h*	0.54*h*	0.62*h*	0.69*h*	0.77*h*	0.85*h*
Separation efficiency (%)	70.875	71.286	70.732	71.196	69.536	69.000
Loss rate (%)	0.875	1.018	0.911	0.589	0.589	0.750
Comprehensive evaluation	35.913	36.190	35.860	35.931	35.100	34.912

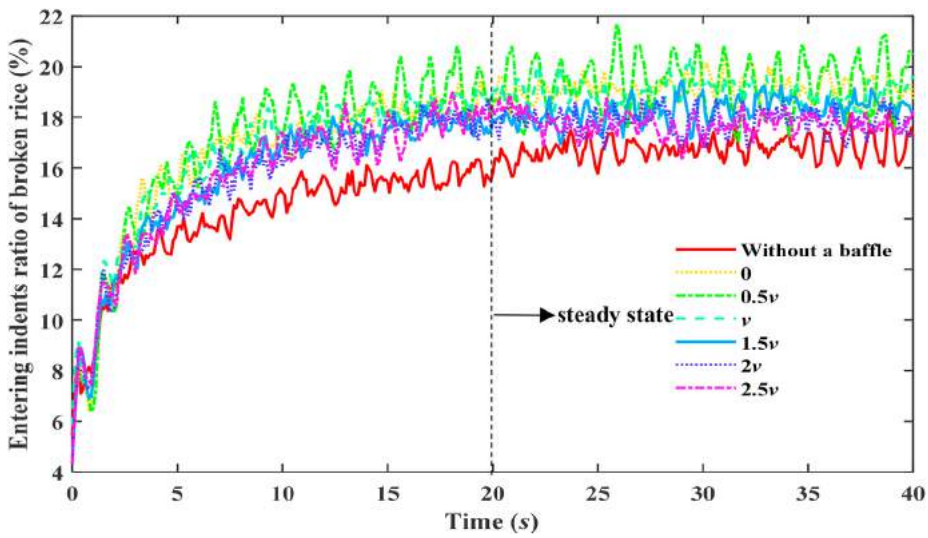

Fig. 15 – Entering indents ratio of broken rice as a function of time for different rotational speeds when blade length $H_{jD} = 0.54h$.

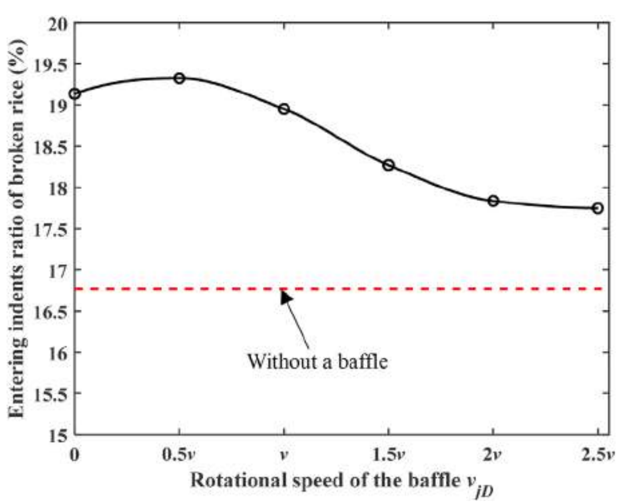

Fig. 16 – Effect of rotational speed on entering indents ratio of broken rice when blade length $H_{jD} = 0.54h$.

Therefore, the average value of the ratio was calculated over the period 20 s–40 s. The effect of blade length on the ratio of broken rice entering the indents is shown in Fig. 11. It can be seen that for increasing blade length the entering indents ratio for broken rice firstly increased and then decreased with time, and the ratio was highest at the length of 0.54 *h*. It was not conducive for the blade length to be too long or too short since that can bring undesirable disturbances and lead to low separation.

With rotation of the baffle, rice in the mixing area was mixed and segregated to varying degrees, thus affecting the entering indents ratio for broken rice. Figure 12 plots the change of radial broken rice ratio with time for different length of blades. Figure 12 (a) shows the ratio without a baffle. There was more broken rice in zone 2 and in the centre of the mixing area when there was no baffle. This distribution of rice was consistent with the analysis in Section 3.2.1, which leads to low entering indents ratio for broken rice. As can be seen from Fig. 12 (b)–(g), with a baffle present, there was relatively more broken rice in zones 1 and 3, which are the periphery of the mixing area. However, when the blade length is 0.85 *h*, the radial broken rice ratio in zone 3 decreased significantly, which explains the reason that the entering indents ratio for broken rice decreased when the blade length is too long. The average values of the radial broken rice ratio in the three zones under stable condition (20 s–40 s) were calculated. Figure 13 shows the effect of the blade length on the radial broken rice ratio. Within a reasonable blade length, the radial broken rice ratio in zones 1 and 3 was greater than that without a baffle, whilst in zone 2 that trend was reversed. This means that the contact opportunities between broken rice and indents increase, which is beneficial to the improvement of separation efficiency.

Figure 14 (a) and (b) show the separation efficiency and loss rate of the indented cylinder separator with a baffle of different blade lengths. The separation efficiency with a baffle was greater with a baffle than without. When the blade length was less than 0.70 *h*, the separation efficiency fluctuated with increasing blade length. But when the blade length was longer

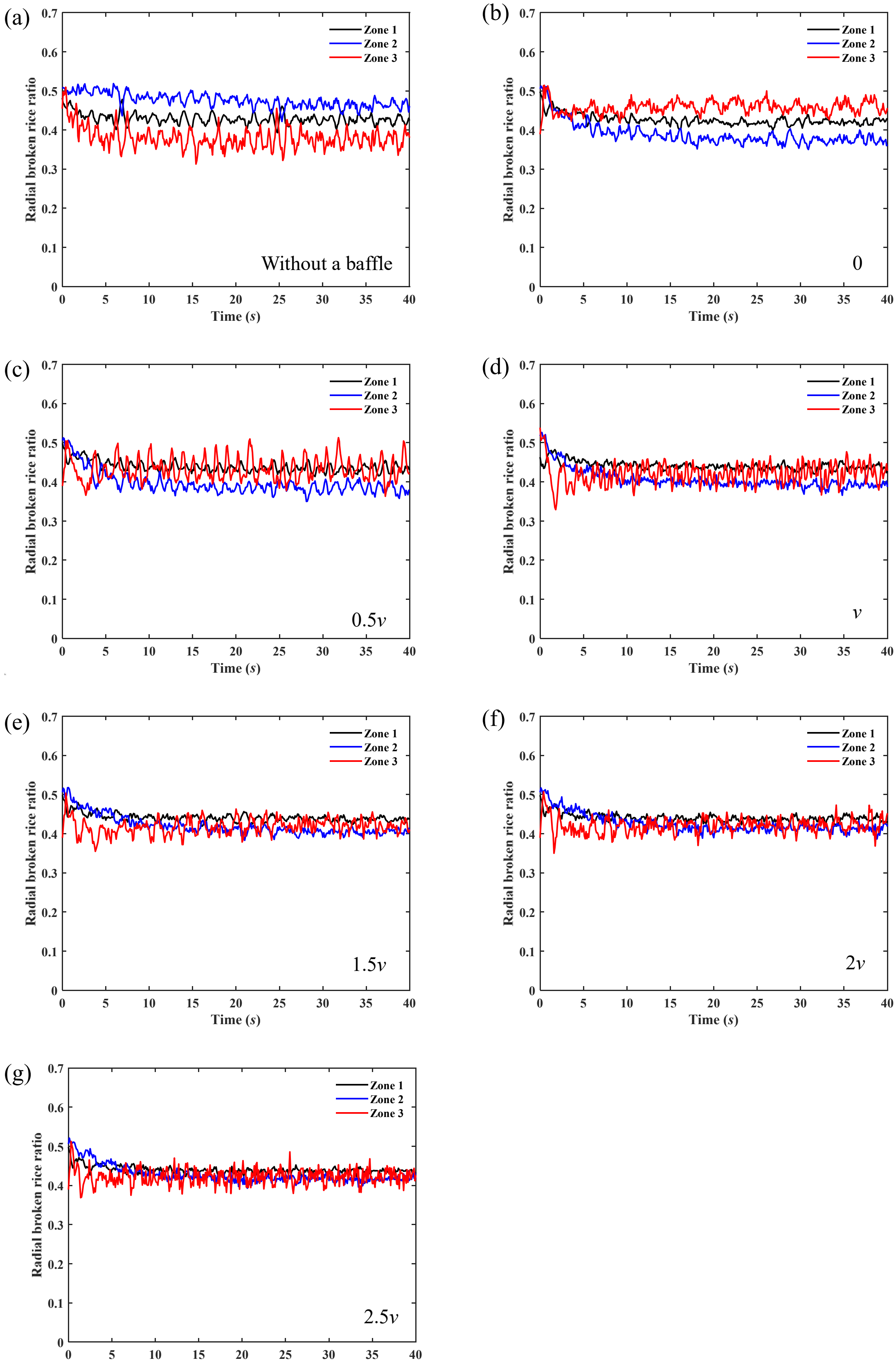

Fig. 17 – Radial broken rice ratio as a function of time for different rotational speeds when blade length $H_{jd} = 0.54h$: (a) without a baffle, (b) 0, (c) 0.5v, (d) v, (e) 1.5v, (f) 2v, (g) 2.5v.

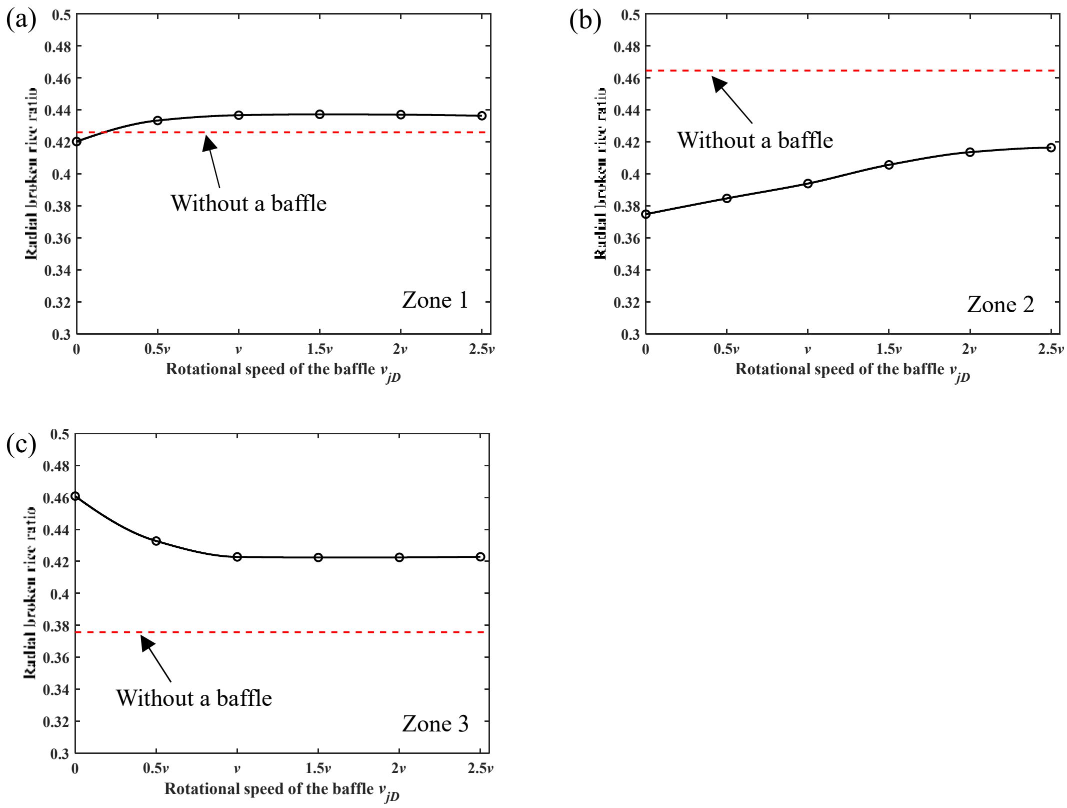

Fig. 18 – Effect of rotational speed on radial broken rice ratio when blade length $H_{jD} = 0.54h$: (a) zone 1, (b) zone 2, (c) zone 3.

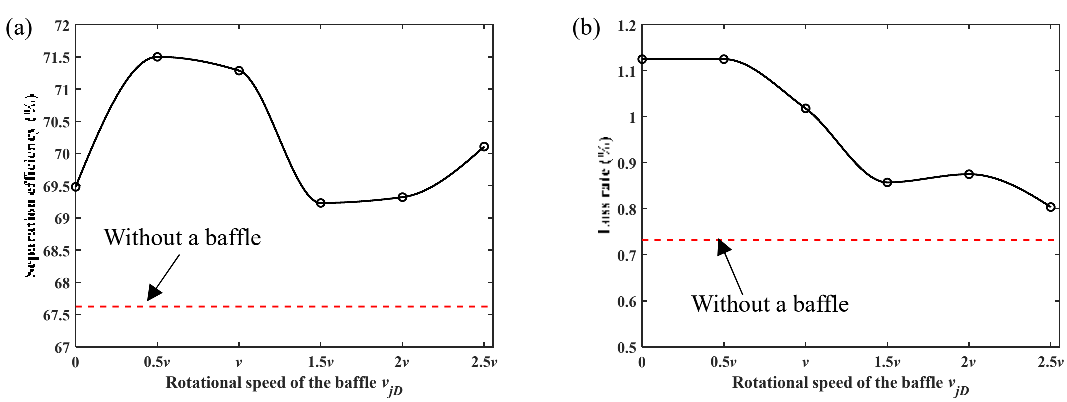

Fig. 19 – Separation ability for different rotational speeds when blade length $H_{jD} = 0.54h$: (a) separation efficiency, (b) loss rate.

than 0.70*h*, the separation efficiency declined drastically. With the increase in the blade length, the loss rate increased at first, then fell and then increased again. Under the condition of ensuring separation efficiency, the loss rate was acceptable when the blade length was in the range 0.46*h*–0.70*h*, so the separation effect in this range was better, which is consistent with the previous analysis. Based on the CRITIC method, the weight coefficients of separation efficiency and loss rate were 0.501 and 0.499, respectively. The final comprehensive evaluation scores are displayed in Table 3, in which the highest score was at 0.54*h*, that is, the separation effect was best at this length of baffle.

3.4. *Effects of the rotational speeds of baffle on the separation ability*

Based on the analysis of the previous section, the optimal blade length, 0.54*h*, was selected to analyse the effects of

Table 4 – Final comprehensive evaluation for different rotational speeds.

The rotational speed of baffle (*rpm*)	0	0.5υ	υ	1.5υ	2υ	2.5υ
Separation efficiency (%)	69.482	71.500	71.286	69.232	69.321	70.107
Loss rate (%)	1.125	1.125	1.018	0.857	0.875	0.804
Comprehensive evaluation	35.513	36.528	36.367	35.254	35.308	35.668

rotational speed of baffle on separation ability. Figure 15 shows the change of the entering indents ratio of broken rice with time under different rotational speeds of baffle. Similarly, the ratio increased at first but then flattened off at around 20s. Also, the average value of the ratio was calculated from 20s to 40s. The effect of the rotational speed of the baffle on the entering indents ratio of the broken rice is shown in Fig. 16. The entering indents ratio of broken rice increased at first and then decreased with the increasing rotational speed. If the rotational speed of the baffle is too fast, the velocity of the rice will be too high, resulting in a centrifugal movement of grain, which will causes it to distribute everywhere or even break. When the baffle is fixed, the indented entry ratio of broken rice was less than that when the rotational speed of baffle was 0.5υ. This means that the lower rotational speed of the baffle is beneficial for broken rice entering the indents.

Figure 17 shows the changing of radial broken rice ratio with time under different rotational speeds of the baffle, where (a) is the ratio without a baffle, (b) - (g) are ratios with a baffle under different rotational speeds. There is relatively more broken rice in zones 1 and 3 with the existence of baffle, which it shows that adding a baffle is beneficial to broken rice entering the indents. As the rotational speed of the baffle increased, the difference of the radial broken rice ratio in the three regions decreased, indicating better mixing in each region, thus the mixing degree of whole rice and broken rice in the system improves. The average values of the radial broken rice ratio in the three zones under stable conditions (20s–40s) were calculated. Figure 18 shows the effect of the rotational speed of baffle on radial broken rice ratio. The number of rice grains in zone 3 was lowest, whilst the number in zone 1 is the highest and played a dominant role. It can be seen that when the baffle was fixed, the radial broken rice ratio in zone 1 was lower than that without a baffle, which explains the reason for the low ratio of broken rice entering indents. With the increase in rotational speed, the radial broken rice ratio in the core of the mixing area (zone 2) increased, which is not conducive to broken rice entering the indents. This shows that the whole rice and the broken rice were evenly mixed, which may not be conducive to separation.

Figure 19 (a) and (b) show the separation efficiency and loss rate of the indented cylinder separator with a baffle under different rotational speeds of baffle. The separation efficiency with a baffle was greater than that without a baffle. With the increase of the rotational speed of baffle, the separation efficiency firstly increased then decreased and then increased slightly, whilst the loss rate showed a downward trend, which is consistent with the previous analysis. Based on the CRITIC method, the weight coefficients of separation efficiency and loss rate were 0.503 and 0.497, respectively. The final comprehensive evaluation scores are listed in Table 4, in which the highest score was at 0.5υ, thus the separation effect was the best at this rotational speed.

On the basis of the objective evaluation of the separation efficiency and loss rate of the indented cylinder separator with a baffle by the CRITIC weighting method, this work provides a reference for the determination of the structure and operation parameters of the baffle. It is worth noting that the equipment investigated in this work was at a laboratory level. Considering computational efficiency, in order to conveniently scale up the simulation to an industrial scale, the parameters for the key parts of the separator were dimensionless, e.g. dimensionless blade length and dimensionless rotational speed of the baffle. Therefore, when the device needs to be scaled up, such as when the diameter of the cylinder is increased, the blade length can be modified according to the variation of the filling level of particles which corresponds to the change of mixing area thickness. Of course, the similarity of particle flow behaviour when one goes from a small scale to a large scale process is still worthy of investigation. In addition, the distribution of the broken rice near the wall is almost the same as that at the axial centre of the device. As Huang, Miao, Ding, Sang, and Jia (2021) showed, the radial segregation phenomenon can be used to quantify the overall degree of segregation for a short drum (drum length to diameter ratio <0.25). Whilst with the increasing of length to diameter ratio, the end-cover effect is enhanced. Therefore, the effect of segregation phenomenon on separation with large length to diameter ratios remains worthy of study.

4. Conclusion

In this study, a DEM model was adopted to simulate the separation process of an indented cylinder separator with a baffle to illustrate the influence mechanism on separation characteristics. The main conclusions were as follows:

(1) By adding a baffle, the segregation phenomenon where broken rice gathers in the core wrapped by the whole rice was improved, which mainly occurred because of the motion of the rice in the core area changing from one large core into one or two smaller cores. The rice moving in the free surface was also shown to be beneficial to enable contact with the indents compared with the core area. The rice in the core could be scraped off to the free surface by the baffle, which increased the chance of broken rice contacting the indents.

(2) As the blade length increased, the indent entry ratio initially increased to a maximum and then decreased. Blade lengths has little effect on the radial broken rice ratio in zone 1, while that in zone 2

and zone 3 increased when the blade length varied from 0.46h to 0.77h. The optimal separation effect was obtained at the length of 0.54h based on the comprehensive analysis.

(3) As the rotational speed of baffle increases, the indent entry ratio firstly increased and then decreased. When the baffle was fixed or the rotational speed was too high, the entering indents ratio of broken rice was not as expected, and the radial broken rice ratio in zone 2, that is the core of mixing area, was high. The final comprehensive evaluation showed that the optimal separation effect was obtained when the rotational speed was 0.5v.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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