CHAPTER 4 PERFORMANCE EVALUATION OF TOP-SPRAY FLUIDIZED BED COATING FOR PRODUCING TURMERIC EXTRACT COATED RICE

4.1 Introduction

Coating is an important process in industries such as pharmaceutical, chemical and food industries. For food industry, coating is applied for various reasons, for example, appearance modification, nutrition addition, functionality improvement and shelf life extension (Jone, 1985; Dziezak, 1988, Dewettinck and Huyghebaert, 1999; Werner et al., 2007). Coating of foods can be performed by various methods such as dipping, painting, pouring and spraying. The selection of coating method depends on many factors such as desired final product quality, coating volume, property of coating solution and property of core particle. Normally, spray coating of foods is relatively popular since it provides many advantages such as uniform coating, coating layer thickness control and multilayer coating (Werner et al., 2007). Spray coating can be performed by many types of equipment such as rotating drum, rotating pan, spouted bed and fluidized bed. Fluidized bed coating is one of the air suspension particle coating processes. This coating technique combines the steps of coating and drying in one unit operation. There are three different configurations of fluidized bed coating including top-spray, bottom-spray and tangential spray. The top-spray fluidized bed coating (TSFBC) is frequently applied in food industries because it has high batch size, relative simplicity and low capital cost (Dewettinck et al., 1999; Srivastava and Mishra, 2010). Although TSFBC has long been used and developed but in practice this coating technique is rather a complicated process since the coating quality by this technique depends on many factors such as operating parameters, coating solution property and core particle property (Jones, 1985; Dewettinck and Huyghebaert, 1999; Werner et al., 2007). The aforementioned coating quality is related to product quality, coating efficiency and energy efficiency (Maa et al., 1996; Teunou and Poncelet, 2002).

For TSFBC, the superficial air velocity is an important operating parameter that affects both product quality and coating efficiency. In practice, TSFBC is usually operated at high superficial velocity in order to obtain high heat and mass transfer rate, high particle circulation rate, high bed expansion and more uniformity of coating. However, operation of TSFBC at high superficial air velocity may be risk to lose of droplets due to the premature droplet evaporation and the carry-over from the coating chamber by the fluidizing air. This is because the coating solution is sprayed in counter direction with fluidizing air.

In addition to the superficial air velocity, atomization air pressure is also important operating parameter that affects the coating uniformity and coating efficiency. This is because variation in atomization air pressure of two-fluid nozzle strongly affects the droplet size, droplet distribution and droplet travelling distance. Spraying the coating solution at higher atomization air pressure creates the smaller droplet size, provides higher initial droplet speed and also leads to longer droplet travelling distance (Lefebvre, 1988; Juslin et al., 1995; Dewettinck and Huyghebaert, 1999; Ronsse, 2006), resulting in high uniformity of coating. However, the smaller droplet size may easily evaporate before contacting with fluidized particles, resulting in the low coating efficiency (Dewettinck and Huyghebaert, 1999; Ronnse, 2006; Ronsse et al., 2008).

Therefore, the droplet size of coating solution should be appropriate to the size of core particle to be coated.

After the droplets of coating solution collide with fluidized particles, the solvent on the surface of coated particles will be evaporated. The evaporation rate of the solvent depends on the type of the solvent and the evaporation capacity within the coating chamber. The temperature, velocity and humidity of fluidizing air strongly influence the evaporation capacity. Although coating at high evaporation capacity condition could avoid the agglomeration of coated particles, but it may cause poor product quality such as the crack of coating layer (Link and Schlunder, 1997; Dewettinck et al., 1999) and the fissure of core particles (Palamanit et al., 2013). In addition, the coating efficiency may be low since the droplets are completely evaporated before contacting with fluidized particles (Kage et al., 1996; Dewettinck and Huyghebaert, 1998; Ronsse et al., 2008). On the other hand, if the evaporation capacity of fluidizing air is not high enough to evaporate the solvent on the surface of coated particles, the adhesion of coated particles due to liquid bridge will occur and the bed of fluidized particles is collapsed, resulting in poor product quality and the coating efficiency of TSFBC (Dewettinck and Huyghebaert, 1998).

As mentioned above, the objective of this work was therefore to evaluate the performance of TSFBC for producing healthy coated rice, namely turmeric extract coated rice (TECR). The experiments were performed by coating of turmeric extract solution onto the Jasmine white rice kernels under different fluidizing air velocities, atomization air pressures and percentages of recycled air. The performance of TSFBC was evaluated by TECR quality, coating efficiency and energy consumption. The quality of TECR was considered in terms of final moisture content, percentage of fissured kernels, color, head coated rice yield and percentage of uncoated white rice kernels.

4.2 Materials and Methods

4.2.1 Raw Materials

The Jasmine white rice kernels (Khao Dawk Mali-105) was purchased from Chia Meng Company, Bangkok, Thailand. The mean equivalent spherical diameter and true density of white rice kernel was 3.43 mm and 1419 kg/m^3, respectively. The turmeric extract powder was purchased from Specialty Natural Products Company, Chonburi province, Thailand. Both white rice kernels and turmeric extract powder were kept in sealed plastic bag and stored in the refrigerator at 5 °C until the time of experiment.

4.2.2 Experimental set-up

Figure 4.1 shows a schematic diagram of a small scale batch top-spray fluidized bed coating apparatus. It consists of a stainless steel cylindrical coating chamber with an inner diameter of 0.27 m and a height of one metre. A high-pressure centrifugal blower with a power of 2.2 kW (Venz, model HB 2.2, Thailand) was used to supply the fluidizing air. The velocity of fluidizing air was controlled by adjusting the butterfly valve (V1). The fluidizing air before flowing through the coating chamber was heated by four electrical heaters, each rated at 1.5 kW, and the temperature of fluidizing air was controlled by proportional-integral-differential (PID) controller with an accuracy of ±1 °C (Linking, model LT400, Taiwan). The heated air entered the bed through the air distributor plate, which had a diameter of the hole of 1.5 mm. The fluidizing air leaving from the coating chamber flowed through the cyclone separator in order to remove the dust and particle. The quantity of air that exits from the cyclone was reused by adjusting the two control valves (V3 and V4). For the spraying unit, the diaphragm dosing pump (Grundfos, model Alldos DMS 12-3, France) was used to supply the coating solution through the internal mixing of two-fluid nozzle (Fluid Cap No. 40100DF, Air Cap No. 140-6-37-70°; Spraying System Co., USA). The nozzle was placed at the centre of coating chamber and it was above the distributor plate of 0.21 m. The atomization air was supplied by the air compressor and its pressure was controlled by an air pressure regulator. The air pressure regulator was equipped with a gauge pressure and an air filter.

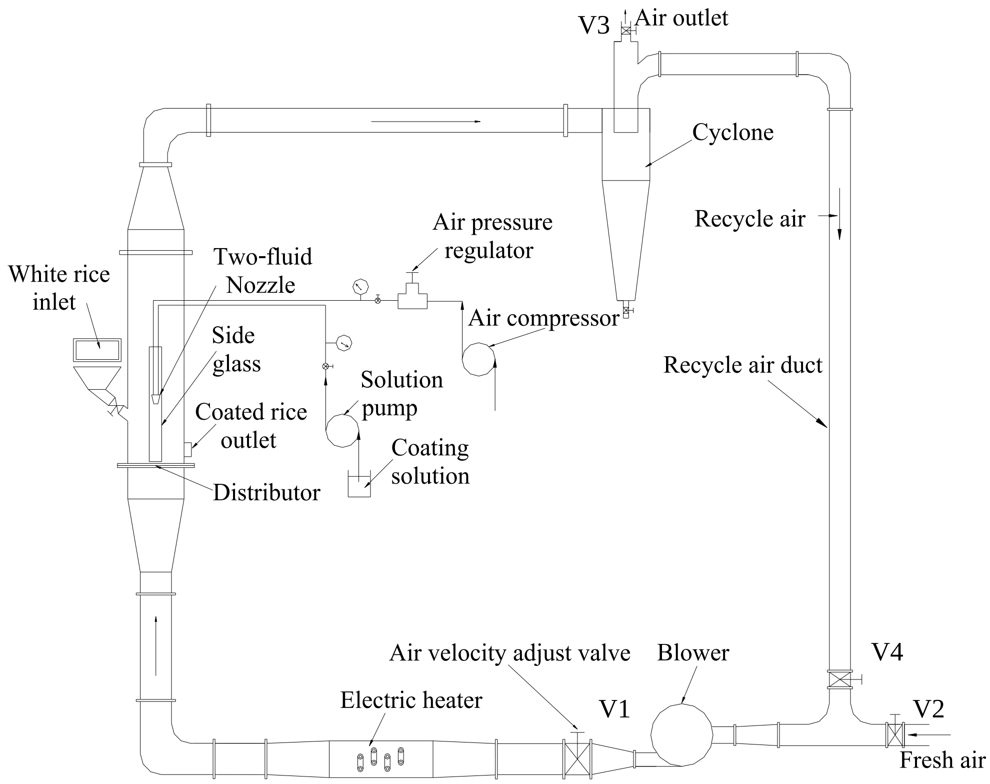


Figure 4.1 A schematic diagram of top-spray fluidized bed coating apparatus (Palamanit et al., 2013)

4.2.3 Coating Solution Preparation

The coating solution was prepared by dissolving the turmeric extract powder into the 70% (v/v) ethanol solution to obtain the turmeric extract solution at the concentration of 4% (w/v). The mixture was then filtered through white cloth of four layers. The concentration of ethanol in the filtered turmeric solution was then diluted to 40% (v/v) by adding some distilled water.

4.2.4 Coating Procedure

Five kilograms of Jasmine white rice sample was fed into the coating chamber via inlet hopper as shown in Figure 4.1. At this amount, it corresponds to the static bed height of 0.1 m. After supplying the fluidizing air through the bed and the temperature of fluidizing air reached a desired value, the coating solution was sprayed. The experiments were carried out at the superficial air velocities (V_f) of 2, 2.5 and 3 m/s which were 1.8, 2.3 and 2.7 times of minimum fluidizing air velocity, respectively and the atomization air pressures (A_p) of 1, 1.5 and 2 bar (gauge pressure). The experiment also performed at 80% recycled exhaust air (R_a) and without recycled exhaust air. The spray rate of coating solution, inlet air temperature and spraying time were fixed at 40 mL/min, 50 °C and 12 min respectively, which was referred from the previous work of Palamanit et al. (2013). After stopping the spraying of coating solution, the coated rice was dried for another 5 seconds. After that, the coated rice was taken out from the coating chamber and kept in a sealed plastic bag at a temperature of 5 °C before quality analysis.

4.2.5 Moisture Content Determination

The moisture content (MC) of raw white rice kernels and the final MC of TECR was reported on wet basis (w.b.). The moisture content was determined by drying 30 g sample in a hot air oven (Memmert, model ULE500, Schwabach, Germany) at 103 °C for 72 hours. The measurement was carried out in triplicate of each experiment and an average value together with standard deviation value was reported.

4.2.6 Fissure Determination

The fissure of TECR was determined by randomly choosing 100 TECR kernels and each kernel was inspected by a digital microscope (Dino digital microscope, model AM351, Taiwan) using the magnification power of 100-200X. The inspection was repeated five times for each experiment. The average value together with standard deviation was reported.

4.2.7 Head Coated Rice Yield Determination

The head rice yield of raw white rice and TECR was determined by an indent cylinder separator (Ngek Seng Huat, model I-1, Thailand). This separator had the size of the hole of 5 mm in diameter. The broken kernels that had the length shorter than the size of the hole of the separator was removed. The head rice yield could be determined by dividing the head rice mass by the original sample mass. The determination was performed in triplicate and the result is presented as an average value.

4.2.8 Color Measurement

The color of TECR was measured by spectrophotometer (model ColorFlex, HunterLab Reston, VA, USA) with a D65 illuminant and observer angle of 10°. The CIE 1976 (L^*,

a^*, b^*) color scale was used as the color descriptor. The L^* is the degree of lightness which cover a range from white (100) to black (0), a^* is the degree of redness and greenness and b^* is the degree of yellowness and blueness. Before measuring color of the samples, the spectrophotometer was calibrated with a standard white plate (L^* = 93.19, a^* = -1.12, b^* = 1.33). The TECR kernels were randomly selected and filled into a glass sample cup and their color was measured. The measurement was carried out in ten individual replicates of each experiment and the average value together with standard deviation value is presented.

4.2.9 Uncoated White Rice Kernels Determination

The determination of uncoated white rice kernels was performed by randomly choosing 500 g TECR. The sample was inspected visually by naked eye. The kernel that was not coated by turmeric extract solution at any part of the surface was considered as uncoated kernel. The percentage of uncoated white rice kernels of TECR was calculated by dividing the mass of uncoated white rice by the total sample mass. The experiment was performed in triplicate and the result is presented as an average value.

4.2.10 Total Phenolics Content Determination for Coating Efficiency Evaluation

Curcuminoids in turmeric extract are the phenolic compounds that are stable to heat at temperatures below 70°C (Wang et al., 2009; Paramera et al., 2011). Thus, the curcuminoids were not degraded during coating and drying processes. They could be used as indicator of coating efficiency. Five grams of finely ground TECR or white rice was extracted with 100 mL of methanol. The sample was mixed in a flask and the mixture was shaken by a shaker at 175 rpm for 24 hours at the room temperature. The mixture was then filtered through the Whatman filter paper No.4. The clear solution was evaporated by a vacuum rotary evaporator at 40 °C (Buchii, Switzerland). After evaporation, the dried sample is mixed with 3 mL of methanol and it was stored at a temperature of -20 °C until further analysis. The extraction was carried out in three replicates of each experiment.

Total phenolics content (TPC) was determined using Folin-Ciocalteu reagent with modified method of Singleton and Rossi (1965). An amount of 100 µL of extract solution was diluted to 1000 µL with methanol. An amount of 320 µL of the diluted solution was mixed with 1600 µL of Folin-Ciocalteu reagent, which was previously diluted ten-fold with the deionized water. After that, 800 µL of 7.5% (w/v) of sodium carbonate (Na_2CO_3) solution was added into the mixture. In addition, 1600 µL of deionized water was added into the mixture and then the mixture was shaken. The mixture was heated in a water bath at 40 °C for 30 min. The absorbance of mixture was measured using a UV-VIS scanning spectrophotometer (Shimadzu, model UV 2101 PC, Japan) at the wavelength of 765 nm. The TPC of sample was determined against the standard curve of gallic acid. The result was expressed as milligram gallic acid equivalent per gram dry mass of the sample (mg GAE/g of dry mass sample). For the TPC of prepared turmeric extract solution (TES), it was expressed as mg GAE/mL of TES). From the above-mentioned method, the coating efficiency of the top-spray fluidized bed can be determined by the following equation.

$$CE = \left(\frac{(TDM_{\mathrm{TECR}} \times TPC_{TECR})\text{-}(TDM_{\mathrm{WR}} \times TPC_{\mathrm{WR}})}{(TES \times TPC_{\mathrm{SOL}})} \right) \times 100 \qquad (4.1)$$

where CE is the coating efficiency (%), TDM_{TECR} is total dry mass of TECR (g), TPC_{TECR} is the total phenolics content of TECR (mg GAE/g dry mass sample), TDM_{WR} is total dry mass of white rice before coating (g), TPC_{WR} is the total phenolics content of white rice before coating (mg GAE/g dry mass sample), TPC_{SOL} is the total phenolics content of prepared turmeric extract solution (mg GAE/mL) and TES is total turmeric extract solution sprayed into fluidized bed (mL).

4.2.11 Specific Energy Consumption Determination

The energy consumption of TSFBC is defined as amount of energy required to produce one kilogram of TECR, namely specific energy consumption (*SEC*). The *SEC* was calculated by Eq. (4.2).

$$SEC = \frac{E}{M_{\text{TECR}}} \tag{4.2}$$

where SEC is the specific energy consumption (MJ/kg of TECR) of TSFBC, E is the energy consumption (MJ), M_{TECR} is the mass of overall TECR (kg). In this work a kilowatt-hour meter with accuracy of 0.1 ±kWh was used to measure the electrical energy consumption of each equipment and it was converted into the energy by a multiplying factor of 3.6 (1 kWh = 3.6 MJ).

4.2.12 Statistical Analysis

All the data were analysed to indicate the significance difference of quality among treatments by the analysis of variance (One-way ANOVA) using SPSS software. Differences between mean values were established using Tukey’s HSD tests at a confidence level of 95% ($p<0.05$). The results are presented as mean values ± standard deviations (SD).

4.3 Results and Discussion

4.3.1 Moisture Content

Figure 4.2 shows the effects of superficial air velocity, atomization air pressure and percentage of recycled exhaust air on the final moisture contents of TECR. In this work, the moisture content of white rice kernels before coating was 12.50% wet basis (w.b.). After coating under the studied conditions, the final moisture contents of TECR were in the range of 11.45-12.74% (w.b.). The operation of TSFBC without recycled exhaust air for all superficial air velocities and atomization air pressures led to the lower final moisture content of TECR than 11.85% (w.b.) whereas operation at the 80% recycled exhaust air for all superficial air velocities and atomization air pressures resulted in the higher final moisture content of TECR than 12.40% (w.b.) and in some cases the final moisture content of TECR was higher than the moisture content of white rice kernels before coating. This is due to the fact that the relative humidity of inlet fluidizing air in the case of no recycled exhaust air was lower than the case of coating at the 80% recycled exhaust air. As can be seen in Figure 4.3(a) and Figure 4.3(b), the relative humidity of inlet fluidizing air was in a range of 30-35% for the case of no recycled exhaust air and it ranged between 45-50% for the case of 80% recycled exhaust air. The higher relative humidity of inlet fluidizing air causes the smaller concentration difference of water vapour between the coated rice surface and bulk air stream, hence reducing the evaporation capacity of fluidizing air.

When the evaporation capacity of fluidizing air was not high enough to remove the solution at the surface of coated rice kernels during coating, the moisture content of coated rice kernels tended to increase and relatively higher than that of white rice before coating; the final moisture content of TECR varied in a range of 12.55-12.74% (w.b.). Such effect can be seen in the cases of 80% recycled exhaust air, superficial air velocities of 2 and 2.5 m/s and atomization air pressures of 1 and 2 bar. On the other hand, if the evaporation capacity of fluidizing air was higher than the amount of solution that adhered on coated rice kernels during coating, the final moisture content of TECR was lower than that before coating. In this case, it implied that the moisture existing in the sample before coating was removed in order to compensate the required amount of evaporation capacity of fluidizing air. From this study, it was found with the case of coating without recycled exhaust air.

Considering the effect of atomization air pressure on the final moisture content of TECR, it was found that an increase in atomization air pressure resulted in decrease or increase in the final moisture content of TECR, depending on the percentage of recycled exhaust air. In the case of coating without recycled exhaust air, the final moisture content of TECR was lower at higher atomization air pressure. This is due to the fact that the coating solution sprayed at higher atomization air pressure provides the smaller droplets size which would be partially or completely vaporized before reaching the surface of rice kernels. In addition to the droplet size, the water vapour concentration difference is high in the case of coating without recycled exhaust air as previously mentioned. The similar results were still observed with the case of 80% recycled exhaust air and atomization air pressures of 1 and 1.5 bar for all superficial air velocities. But, the final moisture content of TECR obtained at the 80% recycled exhaust air and 2 bar atomization air pressure, in turn, significantly higher than that at 1.5 bar. From this result, it indicated that operation at this condition resulted in the lower evaporation capacity than at 1.5 bar. This can be explained by the combined effects of small concentration difference of water vapour between TECR surface and bulk air stream and the cooling effect. This is because an increase in atomization air pressure from 1.5 bar to 2 bar resulted in higher mass flow rate of atomization air and this effect resulted in the lower temperature in the coating zone of fluidized particles. Such phenomenon is called cooling effect (Dewettinck and Huyghebaert, 1998; Ronsse et al., 2008). However, the cooling effect did not cause drop of the final moisture content of TECR in the case of coating without recycled exhaust air when the atomization air pressure was increased from 1.5 bar to 2 bar since the concentration difference between bulk air stream and TECR surface is high and more dominant than the cooling effect.

For the effect of superficial air velocity on the final moisture content of TECR, it was found that the final moisture content of TECR at the 80% recycled exhaust air for all atomization air pressures tended to decrease with increase in superficial air velocity. This is because operation at these conditions provided the low evaporation capacity of fluidizing air. Thus, the moisture that was evaporated during coating was the moisture at the surface of coated rice kernels which was obtained from the coating solution. Consequently, an increase superficial air velocity resulted in higher evaporation capacity. However, in the case of coating without recycled exhaust air, an increase in superficial air velocity did not affect the final moisture content of TECR. This might be because the operation with no recycled exhaust air provides high evaporation capacity of fluidizing air and it was higher than the spray rate of coating solution. Hence, the moisture that present in white rice kernels was evaporated as previously mentioned. The removal of moisture in this part is occurred by the moisture diffusion. Thus, an increase in superficial air velocity did not affect the final moisture content of TECR.

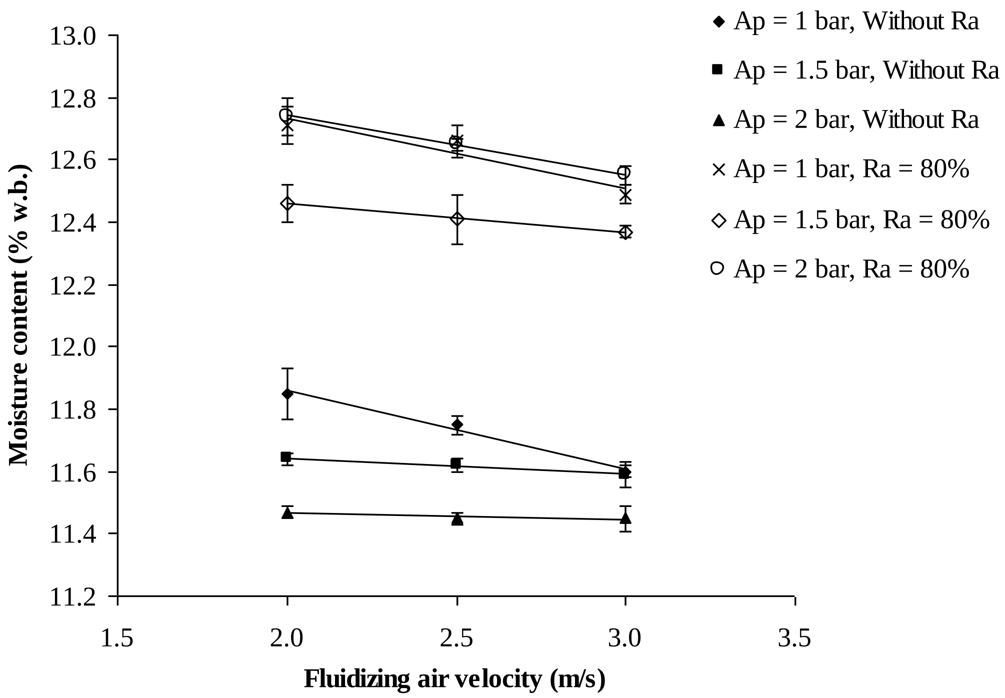
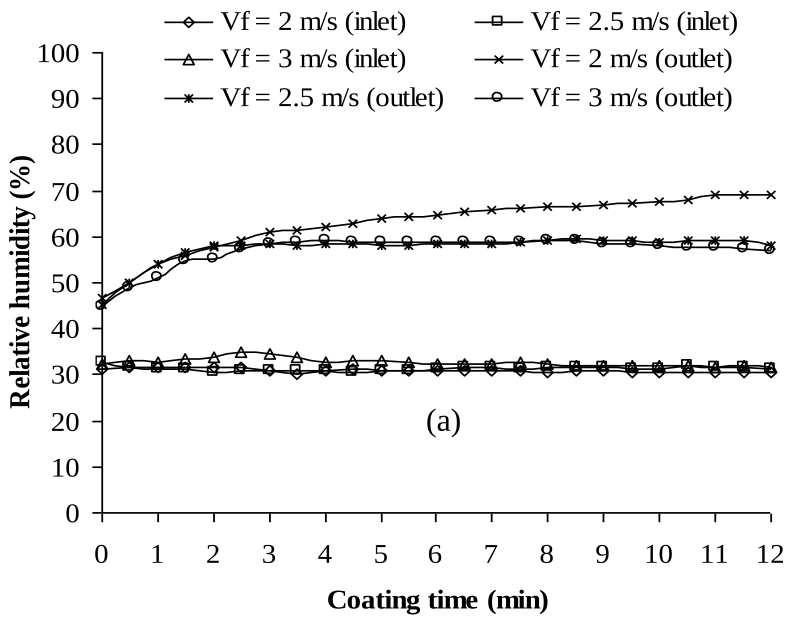


Figure 4.2 Moisture content of TECR at different operating conditions (Ap and Ra are atomization air pressure and percentage of recycled exhaust air respectively.



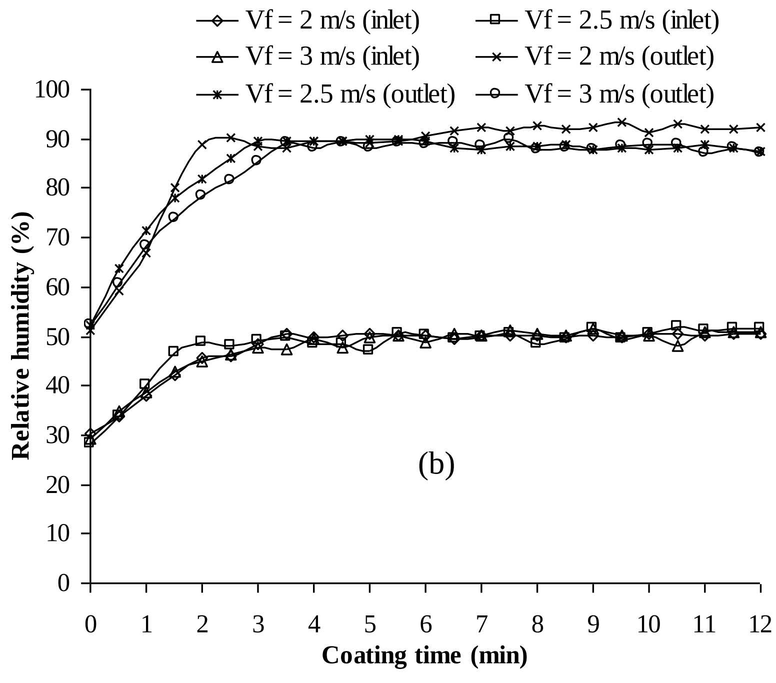


Figure 4.3 Relative humidity of inlet and outlet fluidizing air at different superficial air velocities and atomization air pressure of 2 bar: (a) without Ra (b) Ra = 80%

4.3.2 Fissure and head coated rice yield

In the present study, the number of fissured kernels and the head rice yield of white rice kernels before coating were about 4% and 95%, respectively. After coating at different superficial air velocities, atomization air pressures and percentages of recycled exhaust air, the number of fissured kernels and the head coated rice yield of TECR are shown in Table 4.1. It was found that the number of fissured kernels of TECR varied widely from 5% to 100%, depending on the operating conditions, particularly the percentage of recycled exhaust air. The number of fissured kernels of TECR was 100% for the case of coating without recycled exhaust air for all superficial air velocities and atomization air pressures, except for atomization air pressure of 1 bar and superficial air velocities of 2 and 2.5 m/s at which the number of fissured TECR kernels did not exceed 10%. All kernels of TECR were fissured in the case of coating at no recycled exhaust air because the final moisture contents of TECR obtained from such conditions were lower than 11.80% (w.b.) which was dropped below the moisture content of white rice before coating. Hence, the moisture gradient inside the TECR kernels is produced and the starch granules shrinkage is occurred. This shrinkage of starch granules leads to produce the stress. As the tensile stress is higher than the maximum allowable stress, the fissure appears on the rice kernels (Kunze and Choudhury, 1972). For this work, the fissuring feature of fissured TECR kernels was small cracks and spread over the entire surface of TECR kernel as shown in Figure 4.4. Also, the cracks appeared only at the coated rice surface whereas the internal area of TECR kernel did not found any cracks which are similar to the previous work of Palamanit et al. (2013).

Considering the head coated rice yield (HCRY) of TECR at different operating conditions, it was found that the HCRY of TECR was in the range of 94.20-94.87%, which did not differ from the head rice yield of white rice kernels before coating. Although all of TECR kernels were fissured in case of coating without recycled exhaust air, the kernels of fissured TECR did not break after coating. Palamanit et al. (2013) reported that the quality of cooked fissured TECR was poor after cooking because the fissured TECR broke as small pieces, which is not preferred by the consumers.

Table 4.1 Percentage of fissured kernels (PFK) and head coated rice yield (HCRY) of TECR

Operating condition			PFK (%)	HCRY (%)
Vf (m/s)	Ap (bar_g)	Ra (%)		
2	1	0	$7\pm2^{a,b}$	94.29 ± 0.19^{a}
		80	$8\pm2^{a,b}$	94.36 ± 0.23^{a}
	1.5	0	100 ± 0^{c}	94.87 ± 0.10^{a}
		80	10 ± 2^{b}	94.81 ± 0.60^{a}
	2	0	100 ± 0^{c}	94.25 ± 0.19^{a}
		80	10 ± 2^{b}	94.43 ± 0.10^{a}
2.5	1	0	$7\pm2^{a,b}$	94.22 ± 0.17^{a}
		80	$6\pm3^{a,b}$	94.82 ± 0.20^{a}
	1.5	0	100 ± 0^{c}	94.68 ± 0.20^{a}
		80	5 ± 2^{a}	94.82 ± 0.21^{a}
	2	0	100 ± 0^{c}	94.20 ± 0.13^{a}
		80	$6\pm2^{a,b}$	94.44 ± 0.10^{a}
3	1	0	100 ± 2^{c}	94.21 ± 0.15^{a}
		80	5 ± 3^{a}	94.79 ± 0.17^{a}
	1.5	0	100 ± 0^{c}	94.64 ± 0.28^{a}
		80	$8\pm2^{a,b}$	94.87 ± 0.13^{a}
	2	0	100 ± 0^{c}	94.31 ± 0.21^{a}
		80	5 ± 2^{a}	94.49 ± 0.27^{a}
Initial white rice kernels			4 ± 2^{a}	95.06 ± 0.04^{a}

Different superscripts in the same column mean that the mean values are significantly different at $p<0.05$.

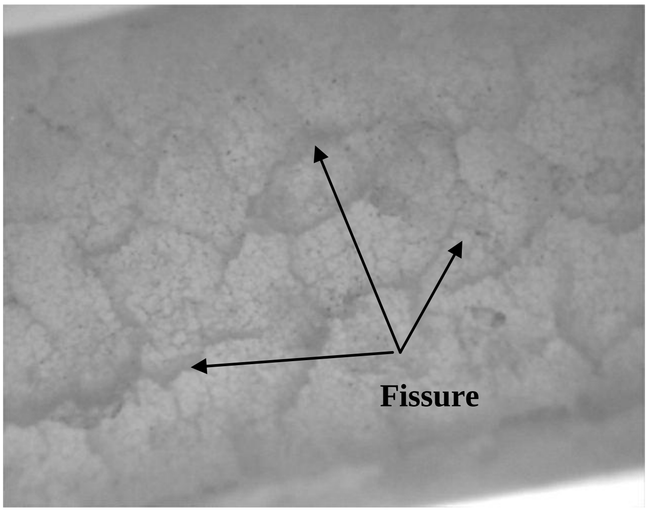


Fig. 4.4 Feature of fissured TECR kernel

4.3.3 Color of TECR

Table 4.2 shows the color of TECR at different superficial air velocities, atomization air pressures and percentages of recycled exhaust air. It was found that the color of TECR was in the reddish-yellow range which corresponded to the lightness (L^*) of 69.50-70.79, redness (a^*) of 12.69-14.68 and yellowness (b^*) of 69.55-72.35. Recently, Palamanit et al. (2013) have reported that the amount of turmeric extract adhered on white rice kernels was higher at higher redness value (a^*) of TECR. This is because turmeric extract possess curcuminoids as a major component and the color of curcuminoids is in the range of red and yellow and their color is redder at a higher concentration of curcuminoids. Thus, in this study the redness value of TECR will be mentioned. From Table 4.2, it is seen that most redness value of TECR was low at superficial air velocity of 2 m/s for all atomization air pressures and percentages of recycled exhaust air, except for the case of atomization air pressure of 1.5 bar and without the recycled exhaust air, as well as at atomization air pressure of 2 bar and 80% recycled exhaust air that the redness value of TECR was relatively high. The higher redness value of TECR at these conditions related to the coating efficiency of TSFBC as will be discussed in next section. When the superficial air velocity was increased from 2 m/s to 2.5 or 3 m/s, the redness value of TECR for all atomization air pressures and percentages of recycled exhaust air clearly increased. At superficial air velocity of 2.5 and 3 m/s and at without recycled exhaust air, the atomization air pressure did not affect the redness value of TECR. At these velocities and at the 80% recycled exhaust air the atomization air pressure had a significant effect on the redness value of TECR. The redness value of TECR at the atomization air pressure of 1.5 bar was lower than at the atomization air pressures of 1 and 2 bar. This is because an increase in atomization air pressure from 1 bar to 1.5 bar tended to have a lower coating efficiency. But, the coating efficiency tended to increase when the atomization air pressure was increased from 1.5 bar to 2 bar as will be discussed in the section of coating efficiency.

Table 4.2 Color of TECR at different coating conditions

Operating condition			L^* value	a^* value	b^* value
Vf (m/s)	Ap (bar_g)	Ra (%)			
2	1	0	70.51±0.28^{g}	13.03±0.32^{b}	69.74±0.67^{a}
		80	70.14±0.20^{c,d,e}	12.86±0.36^{a,b}	69.95±1.18^{a}
	1.5	0	69.15±0.21^{a}	14.27±0.32^{f}	71.20±0.66^{f,g,h}
		80	70.44±0.22^{f,g}	12.69±0.32^{a}	70.07±0.49^{a,b}
	2	0	70.79±0.20^{h}	13.10±0.27^{b}	70.25±0.53^{a,b,c}
		80	70.05±0.18^{b,c,d}	13.69±0.32^{c,d}	70.61±1.03^{b,c,d,e}
2.5	1	0	70.29±0.20^{e,f}	13.99±0.25^{e}	70.97±0.73^{e,f,g}
		80	69.52±0.23^{a}	14.03±0.25^{e,f}	71.59±0.77^{h,i}
	1.5	0	70.02±0.20^{b,c,d}	13.99±0.17^{e}	70.82±0.31^{d,e,f}
		80	70.13±0.20^{c,d,e}	13.53±0.20^{c}	70.90±0.32^{e,f}
	2	0	70.14±0.23^{c,d,e}	14.01±0.23^{e}	71.88±0.52^{i,j}
		80	69.65±0.19^{a}	14.62±0.19^{g}	71.52±0.41^{g,h,i}
3	1	0	70.74±0.13^{h}	13.73±0.25^{c,d}	70.29±0.32^{a,b,c,d}
		80	69.51±0.21^{a}	14.27±0.32^{f}	71.20±0.66^{f,g,h}
	1.5	0	69.96±0.23^{b,c}	13.88±0.24^{d,e}	71.08±0.37^{e,f,g,h}
		80	69.92±0.27^{b}	13.70±0.27^{c,d}	70.53±0.33^{b,c,d,e}
	2	0	70.21±0.18^{d,e}	13.88±0.17^{d,e}	72.35±0.33^{j}
		80	69.50±0.31^{a}	14.68±0.22^{g}	70.64±0.58^{c,d,e}

Different superscripts in the same column mean that the mean values are significantly different at $p<0.05$.

4.3.4 Uncoated White Rice Kernels

The effects of superficial air velocity, atomization air pressure and percentage of recycled exhaust air on the number of uncoated white rice kernels (UCWR) of TECR are depicted in Figure 4.5. The experimental results showed that when the superficial air velocity of 2 m/s, at which the bed expansion and the mixing between fluidizing air and rice kernels were rather poor, was used, the atomization air pressure and the percentage of recycled exhaust air were strongly influential in the number of UCWR. The number of UCWR varied in wide range of 0.10-0.41%. In the case of no recycled exhaust air, the operation at higher atomization air pressure resulted in the lower number of UCWR. This may be because the droplets of coating solution could penetrate more deeply in the bed of fluidized rice kernels. However, at the 80% recycled exhaust air, the effect of atomization air pressure on the number of UCWR was not similar to the case of no recycled exhaust air. In the case of 80% recycled exhaust air, the number of UCWR was increased with increasing atomization air pressure. This can be explained by the fact that at this condition the evaporation capacity of fluidizing air was relatively low. Thus, an increase in atomization air pressure leads to the lower evaporation capacity of fluidizing air due to the previously-mentioned cooling effect. Consequently, the moisture content at the surface of TECR was relatively high during coating and then the liquid bridge between the coated rice kernels is formed, leading to the poor both bed expansion and the mixing of fluidized rice kernels (Dewettinck and Huyghebaert, 1998) and the number of UCWR at higher atomization air pressure.

When the superficial air velocity was increased to 2.5 or 3 m/s, at the bed expansion and the mixing of fluidized rice kernels was improved, the number of UCWR was clearly decreased as compared to that at superficial air velocity of 2 m/s for all atomization air pressure and percentage of recycled exhaust air. At both superficial air velocities, the atomization air pressure did not affect the number of UCWR while the percentage of recycled exhaust air still influenced the number of UCWR. The operation of TSFBC with no recycled air exhaust air resulted in lower number of UCWR that at the 80% recycled exhaust air for all atomization air pressures. However, it is seen that the operation of TSFBC at superficial air velocity of 2.5 and 3 m/s for all atomization air pressures and percentages of recycled exhaust air provided the number of UCWR lower than 0.10% which was rather small number of UCWR.

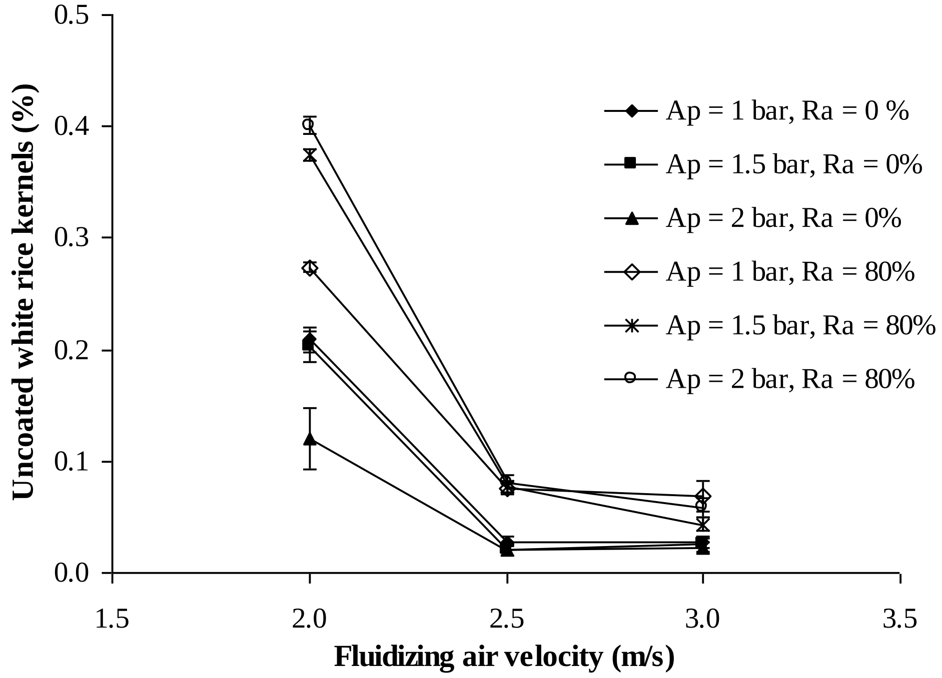


Figure 4.5 Uncoated white rice kernels of TECR at different operating conditions

4.3.5 Coating Efficiency

Table 4.3 shows the effects of superficial air velocity, atomization air pressure and recycled exhaust air on the coating efficiency of TSFBC for producing TECR. It was found that the superficial air velocity was more important to the coating efficiency than the atomization air pressure and recycled exhaust air. The operation of TSFBC at the superficial air velocity of 2 m/s and 1 bar atomization air pressure together with 80% recycled exhaust air or no recycled exhaust air provided the coating efficiency lower than 80%. The low coating efficiency at such conditions is due to possibly to the low bed expansion, in addition to the poor mixing as mentioned in previous section, which cause a longer distance for droplet travelling from nozzle to the bed of fluidized particles. As a result, some droplets of coating solution are evaporated before reaching the surface of fluidized rice kernels (Dewettinck and Huyghebaert 1998; Ronsse et al. 2008) and moreover, the loss of some droplets might be occurred by carrying over from coating chamber since the coating solution was sprayed in counter direction to the fluidizing air. However, when TSFBC was operated at higher atomization air pressure with 80% recycled exhaust air or without recycled exhaust air, the coating efficiency might be improved or the same value as that obtained from 1 bar atomization air pressure. The improvement of coating efficiency is caused by the combined effects of moisture evaporation capacity, droplet size and droplet penetration depth into the bed of fluidized rice kernels, each of which will be dominated depending on the operating condition. The coating efficiency was higher at 1.5 atomization air pressure with no recycled exhaust air than at 1 bar because an increase in atomization air pressure not only produces the smaller droplet size but also provides higher droplet speed and higher droplet penetration depth. However, at 80% recycled exhaust air, the drop of coating efficiency at atomization of 1.5 bar was found. The lower coating efficiency at such condition is due possibly to the fact that the bed of fluidized rice kernels is difficult to expand since the rice kernels were rather adhesive due to the higher surface moisture during coating. Hence, some of coating solution droplets would be vaporized before reaching the rice kernels and some droplets might be carried over from coating chamber by fluidizing air.

At the superficial air velocity of 2 m/s with no recycled exhaust air, the coating efficiency at 2 bar atomization air pressure became lower than at 1.5 bar. This is can be explained that the size of coating solution droplet produced at 2 bar is too small and the evaporation of droplet thus occurs before contacting with fluidized rice kernels although the droplet speed and droplet penetration depth are higher at higher atomization air pressure. However, when the evaporation capacity of fluidizing air was decreased by recycling the exhaust air with an extent of 80%, the coating efficiency was, in turn, significantly higher.

When the superficial air velocity was increased to 2.5 m/s or higher, the coating efficiency was in a range of 81-86% and the atomization air pressure and the recycled exhaust air did not affect the coating efficiency. The insignificant effect of atomization air pressure and the recycled exhaust air may be due to the fact that the bed of particles at these superficial air velocities is relatively expanded and result in a shorter distance for droplet travelling from the nozzle to the bed of particles. From these results, it indicated that the bed expansion is more important than the droplet size, droplet speed and droplet penetration depth. Hence, the selection of superficial air velocity is more important than the other operating parameters such as atomization air pressure and recycled exhaust air.

Table 4.3 Coating efficiency (CE) of TSFBC at different operating conditions

Operating condition			CE (%)
V_f (m/s)	A_p (bar_g)	R_a (%)	
2	1	0	74.96±1.30[a]
		80	75.54±2.35[a]
	1.5	0	83.85±1.98[b]
		80	77.32±1.86[a]
	2	0	75.36±1.31[a]
		80	82.15±1.61[b]
2.5	1	0	83.01±1.14[b]
		80	83.63±2.86[b]
	1.5	0	82.68±1.85[b]
		80	81.34±1.29[b]
	2	0	82.87±1.85[b]
		80	85.86±2.37[b]
3	1	0	81.63±1.51[b]
		80	83.67±2.06[b]
	1.5	0	82.77±1.76[b]
		80	82.37±1.96[b]
	2	0	82.98±1.58[b]
		80	86.08±1.87[b]

Different superscripts in the same column mean that the mean values are significantly different at $p<0.05$.

4.3.6 Specific Energy Consumption

Table 4.4 lists the specific energy consumptions (SEC) in each part of TSFBC including the SEC of high-pressure blower (SEC_{blower}), electric heaters (SEC_{heater}) and spraying system ($SEC_{spraying}$) at various coating conditions. It is seen that the SEC_{blower} and $SEC_{spraying}$ were about 0.14 MJ/kg TECR and 0.22 MJ/kg TECR, respectively. For the

SEC_{heater}, it was in the range of 0.21-0.23 MJ/kg TECR for coating at 80% recycled exhaust air and it was increased to 0.36-0.43 MJ/kg TECR for coating at without recycled exhaust air, which depended on the superficial air velocity. These results revealed that the energy was mainly consumed in the parts of heating and spraying system. The operation of TSFBC at 80% recycled exhaust air could save the energy in the heating part about 41.7-46.5% as compared to coating with no recycled exhaust air. As shown in Table 3, it was observed that the SEC_{blower} did not significantly change at a higher superficial air velocity. This is because the change of superficial air velocity in the designed coating system was adjusted by the butterfly valve and thus the high-pressure blower still worked at the constant revolution and subsequently it consumed constantly the electrical power. Similarly, the energy consumption of the spraying system including the solution pump and air compressor that did not change at higher atomization pressure. The solution pump consumed constant electric power since it was operated at the same spraying time for all atomization air pressures. For the air compressor, it consumed constant electric power since the air compressor was controlled by automatic air pressure switch. The air pressure in the air storage tank of air compressor was set up between 4 and 8 bar. The air compressor will be worked when the pressure dropped below 4 bar and will be stopped at 8 bar. During coating experiment, the operating time of the compressor was identical for all atomization air pressures so that the energy consumption of the spraying system was constant for all atomization air pressures.

Table 4.4 Specific energy consumption (SEC) in each part of TSFBC

Operating condition			SEC_{blower} (MJ/kg TECR)	SEC_{heater} (MJ/kg TECR)	$SEC_{spraying}$ (MJ/kg TECR)
V_f (m/s)	A_p (bar_g)	R_a (%)			
2	1	0	0.14	0.36	0.22
		80	0.14	0.21	0.22
	1.5	0	0.14	0.36	0.22
		80	0.14	0.21	0.22
	2	0	0.14	0.36	0.22
		80	0.14	0.21	0.22
2.5	1	0	0.14	0.40	0.22
		80	0.14	0.22	0.22
	1.5	0	0.14	0.40	0.22
		80	0.14	0.22	0.22
	2	0	0.14	0.40	0.22
		80	0.14	0.22	0.22
3	1	0	0.14	0.43	0.22
		80	0.14	0.23	0.22
	1.5	0	0.14	0.43	0.22
		80	0.14	0.23	0.22
	2	0	0.14	0.43	0.22
		80	0.14	0.23	0.22