ISSN 2250-3153

# Sorption Characteristics of Polished Rice in a Fluidized Bed

**Kariyawasam H.K.P.P., Amaratunga K.S.P., Bandara D.M.S.P., Dissanayake T.M.R.**

***Abstract-*** Applicability of fluidization methods in rewetting low moisture polished rice was investigated using a recirculating fluidized bed. The sphericity of polished rice was calculated using Ergun's equation to determine the effective diameter. The calculated frictional pressure drop agreed well with the observed data. The sorption characteristics were investigated under fluidizing conditions at different air temperatures and relative humidities. Sorption data were fitted to the first falling rate period drying equation with a standard error of estimate of the moisture content of polished rice ranging from 0.06 to 0.14% d.b. and the sorption coefficient followed the Arrhenius type temperature dependency. The results showed that the fluidization techniques could be effectively used for rewetting low moisture polished rice.

***Index Terms-*** Adsorption, fluidized bed, polished rice, moisture

## I. Introduction

Moisture content of paddy after harvest may vary from 18 to 30% d.b. and it is necessary to lower the moisture content down to 13 to 14% d.b. for safe storage [1]. Hulling and polishing operations reduce certain amount of moisture due to heat generation. This type of normal processing operations produce polished rice containing moisture less than 16% d.b. Moisturizing rice can have a substantial positive effect on the cooking and eating qualities of milled rice [2]. The moisture content of polished rice can be increased by rewetting. The absorption characteristics of polished rice has recently gained interest in rice processing research. The present major constraint in rewetting in commercial scale is the difficulty of achieving sorption uniformity in bulk. The other concerns are the complexity of the equipment, length of the process, and the cost. This study focuses on the fluidization technique as a possible mean of circumventing the above difficulties.

Fluidization is the operation by which solid particles are transformed into fluid like state through suspension in a gas or liquid. Fluidization can be carried out by liquids or gases and different forms of fluidization occur depending on the fluidizing medium and the properties of the particulate materials. Fluidized beds are extensively used in a wide variety of industries because of its larger capacity, low construction cost, easy operability, and high thermal efficiency [3]. There are number of food specific applications of fluidization, such as freezing, blanching and cooking [4, 5]. Shilton and Niranjan [8] have reviewed the use of fluidization in food industry. Rios et al. [7] reported the use of fluidized bed for roasting of coffee beans, resulting in improved quality compared to traditional drum roasting method.

The fluidizing characteristics of the bed facilitate smooth solid handling, especially in continuous operation. Kunii and Levenspiel [3] define a dense phase bed as one in which there is reasonably clearly defined bed surface whether the fluidizing medium is gas or liquid. Geldart [8] classified four clearly recognizable types of particle behavior from smallest to largest; cohesive, aeratable, sandlike, spoutable. The relationship between terminal velocity and the solid hold up has discussed by Joshi [9] and Lali et al. [10]. At velocities above bubbling fluidization occur, the nature of contact between gas and solids changes significantly [11]. Although, bubbling may cause passing of gas, it also causes intensive solid mixing with nearly homogenous bed temperature and relative humidity. This helps to control the temperature and relative humidity of the bed.

Compared with other sorption techniques fluidized bed sorption of granular solids offer many advantages. High heat and mass transfer rates are possible because of very good contact between particle and gas [12]. In gas fluidized beds rapid and vigorous mixing takes place in the area just above the distributor facilitating easy exchange of heat and mass between the fluid and the solid [13]. In case the sorption rate is limited by diffusion inside the particles, long residence time of solids are required, which can be achieved easily in a fluidized bed; the apparatus still remains relatively small, because of its large hold-up of solids. The apparatus is rather simple as there are no moving parts. Due to abrasion and friction between rice grains the surface of grain becomes smooth improving the appearance. In this study, fluidizing and sorption characteristics of polished rice under fluidized conditions were studied.

## MATERIALS AND METHOD

Sri Lankan rice variety BG 1111 was used for the study. Paddy was hulled and polished to a polishing degree of 90%. In order to widen the range of moisture adsorption characteristic curve, the initial moisture content was selected as 14% d.b. The moisture content of the bulk of 25 kg polished rice was reduced to the desired moisture content of 14% d.b. by slow drying (temperature of the polished rice surface was not more than 30 °C). After drying, polished rice was placed in an air sealed container and stored at 5 °C until time for the tests. Figure 1 shows the experimental apparatus. The exhaust air was recirculated to keep the desired relative humidity (70% and 80%) at high air flow rate. The exhaust air from the bed was sucked by a turbo blower and the temperature and relative humidity of air was controlled at desired values. Relative humidity was achieved by adding water vapor to the inlet air by using an ultrasonic humidifier (Mammy, MUH 4400, Japan). The method was capable of maintaining relative humidity to an accuracy of ±2% at the bottom of the sample. Temperature was controlled to an accuracy of ±0.5 °C. Temperature and relative humidity of air just below the sample and just above the sample were measured by T-type thermo-couples and relative humidity sensors (VAISALA HMP115Y, USA) respectively. The flow rate of air was measured by an orifice meter (FLC-OP, WIKA, Germany). The height of the fluidizing chamber was 0.3 m and was made of transparent plastic. The diameter of the vessel was 0.19 m and it was large enough to avoid flat slugging.

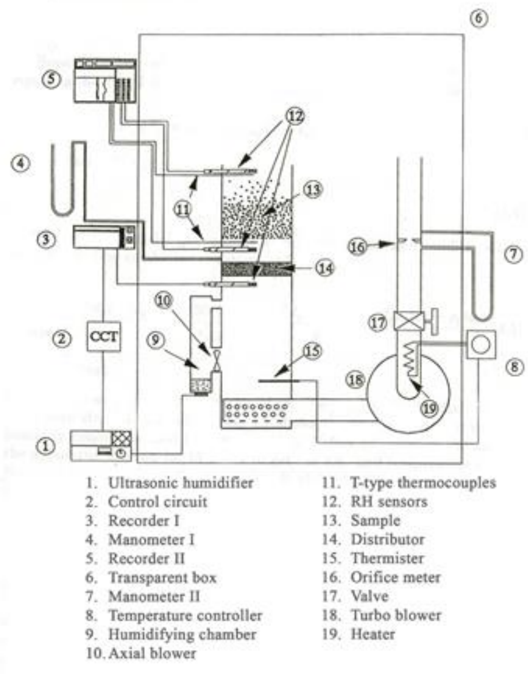


Figure 1: The experimental apparatus

*Fluidizing characteristics*

Prior to the sorption test, fluidizing characteristics of polished rice was investigated. In this test 2 kg of polished rice was placed in the fluidizing chamber and pressure drop and the flow rate data were collected. The tests were conducted separately for increasing and decreasing flow rates. Though polished rice is non-spherical in shape, it is possible to represent a bed of rice by a bed of spheres of diameter $d_{eff}$, then the two beds (rice and the spheres of diameter $d_{eff}$) have the same total surface area and same void fraction. The resistance to flow in the two beds are same. The following equation was used to estimate the effective particle diameter ($d_{eff}$) [3].

$$d_{eff} = \O_{s,eff}.d_p \tag{1}$$

Where $d_p$, the intermediate particle is size by screen analysis and $\O_{s,eff}$ is the effective sphericity of a particle. Many food substances are non-spherical, for such cases an equation based on the force balance at incipient fluidization can be used. For calculating the pressure drop at incipient fluidization, McKay and McLain [14] recommend the use of Ergun's [15] equation which has modified to account for the shape of the particles. Also an extension of the Ergun's equation for fluidized beds has discussed by Akgiray and Saatci [16] to calculate the pressure drop in a given reactor. Therefore the effective sphericity of the particle, $\O_{s,eff}$ was calculated using Ergun's equation as follows.

$$\frac{\Delta p_{fr}}{L_m g_c} = 150\frac{(1-\varepsilon_m)^2}{\varepsilon_m^3}\frac{\mu u_0}{(\O_{s,eff}d_p)^2} + 1.75\frac{1-\varepsilon_m}{\varepsilon_m^3}\frac{\rho_g u_0^2}{\O_{s,eff}d_p} \tag{2}$$

For gases operating under low pressure, frictional pressure drop ($\Delta p_{fr}$) can be taken as $\Delta p_{measured}$. The density ($\rho_g$) and viscosity ($\mu$) of air used in the equation 2 were calculated using the procedures given in Chronological Scientific Tables [17]. The superficial gas velocity at minimum fluidizing condition was calculated equating the drag force by upward moving gas to the weight of the particles.

$$\Delta p_b A_t = W = A_t L_{mf}(1-\varepsilon_{mf})\left[(\rho_s-\rho_g)\frac{g}{g_c}\right] \tag{3}$$

By rearranging the equation 3, the following expression was obtained.

$$\frac{\Delta p_b}{L_{mf}} = (1-\varepsilon_{mf})(\rho_s-\rho_g)\frac{g}{g_c} \tag{4}$$

Then the superficial gas velocity at minimum fluidizing conditions $u_{mf}$ was obtained by combining equations 4 and 2 as given below.

$$\frac{1.75}{\varepsilon_{mf}^3 \emptyset_{s,eff}}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right)^2 + \frac{150(1-\varepsilon_{mf}}{\varepsilon_{mf}^3 \emptyset_{s,eff}^2}\left(\frac{d_p u_{mf}\rho_g}{\mu}\right) = \frac{d_p^3\rho_g(\rho_s-\rho_g)g}{\mu^2} \tag{5}$$

*Sorption test*

In this trial, sorption characteristics of polished rice under fluidized conditions were studied in detail. Table 1 shows the temperature and relative humidity conditions used for sorption test. Before introducing the sample, the apparatus was run for 15 hours to get the stable relative humidity and temperature. For each test 2 kg sample was used making 0.08 m thick layer in the fluidizing chamber. Moisture content measurements were carried out using 10g samples drawn at 0, 1, 2, 3, 5, 7, 9, 12, 15, 19 and 24$^{th}$ hour for the first 24 hours and thereafter at 12 hour intervals till 72 hours. Weight of the samples were measured using an electronic balance (METLER PC2000). All reported moisture contents were calculated using 10 g samples by air-oven method (135 °C for 24 hours) [18]. Simmonds et al. [19] found that thin layer drying curves of wheat were well represented by an exponential equation, which assumed that all the resistance to moisture transfer was at the outer surface of the kernel. This equation is analogous to Newton's law of cooling and widely used in the first falling rate period of drying, given by the following expression.

$$M = (M_0 - M_e)e^{-kt} + M_e \tag{6}$$

The observed moisture content data were fitted to this equation using a method of least squares. The accuracy of the equation was expressed by the standard error of the estimate. The Arrhenius equation (equation 7) was used to express the temperature dependency of sorption coefficient ($k$).

$$k = de^{-f/T} \tag{7}$$

Table 1: The air conditions used to collect the sorption data

| Relative Humidity (%) | Temperature (°C) | | |
|---|---|---|---|
| | 20 | 25 | 30 |
| 70 | ● | ● | ● |
| 80 | ● | – | – |

RESULTS AND DISCUSSION

*Fluidizing Characteristics*

The frictional pressure drop ($\Delta p_{fr}$) versus superficial gas velocity ($u_0$) diagram is particularly useful as a rough indication of the quality of fluidization. Fluidization mainly depends on the liquid and solid properties used in the system. Figure 2 shows the pressure drop versus flow rate characteristic for polished rice. The solid line represents the calculated values by Ergun's equation and the standard error of the estimate was 16.3 Pa. For relatively low flow rates in a fixed bed, the pressure drop was approximately proportional to the gas velocity and reached a maximum and that was slightly higher than the static pressure of the bed. With further increase in gas velocity, the fixed bed 'unlocked' in other words axial slugging started resulting in non-homogeneity. In the case of fine solid powders increasing the gas velocity beyond the maximum pressure point results in increasing bed height and bed voidage. Then the pressure drop decreases to static pressure of the bed. But for polished rice, slugging starts just after minimum fluidization. So there is no smooth fluidization phase in polished rice when fluidized by air. The diameter of the bed was selected to avoid flat slugs, therefore only axial slugging was observed.

According to the screen analysis rice used for the test was -6+8 mesh size particles. The intermediate particle size ($d_p$) was 0.00285 m. The effective sphericity of polished rice ($\varnothing_{s,eff}$) calculated using equation 1 was 0.39. For this calculation the measured pressure drop ($\Delta p_{measured}$) was used as frictional pressure drop ($\Delta p_{fr}$). The bed height ($L_m$) was constant at 0.08 m. The particle density measured by pycnometer using toluene was 1418 kg·m$^{-3}$. Bulk density was 872.2 kg·m$^{-3}$. The void fraction ($\varepsilon$) of the fixed bed was 0.385. The

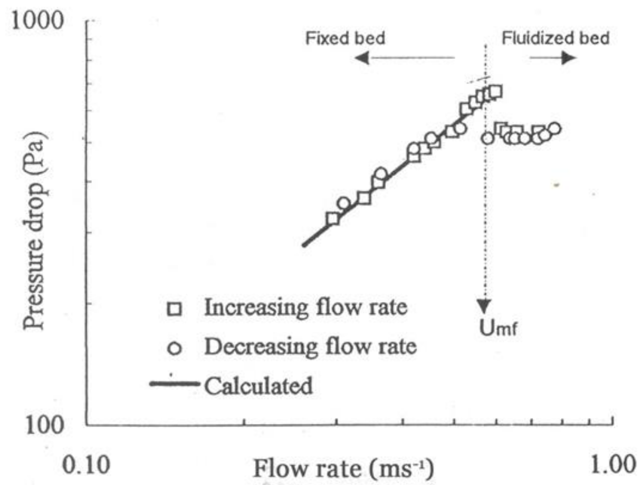


Figure 2: Pressure drop versus flow rate of polished rice fluidized in air

calculated density and viscosity of air were 0.012 kg·m$^{-3}$ and 1.8×10$^{-5}$kg·ms$^{-1}$ respectively. The calculated effective particle diameter $(d_{eff})$ for the particle size 0.00285 m was 0.0012 m. The value of effective sphericity of polished rice ($\varnothing_{s,eff}$) can be used with the measured screen size ($d_p$) to predict frictional losses in beds of any size and for wide size distribution. This method is the most reliable measure of particle size for pressure drop purposes. The calculated minimum fluidizing gas velocity was 0.59 ms$^{-1}$. The value is only 0.03 ms$^{-1}$ above the experimentally reported value. Thus the calculated effective sphericity is applicable for pressure drop calculations.

*Adsorption characteristics*

The Figure 3 shows the sorption curves of polished rice. The used moisture transfer equation well represented the sorption characteristics. The sorption coefficient and the standard error at each air condition are listed in Table 2. The Figure 4 shows the Arrhenius plot of sorption coefficient ($k$). The Arrhenius parameters for 70% relative humidity were $f = 0.5976 \times 10^4\ K$, $d = 0.1585 \times 10^9\ h^{-1}$ and the standard error of estimate was 0.06187 h$^{-1}$.

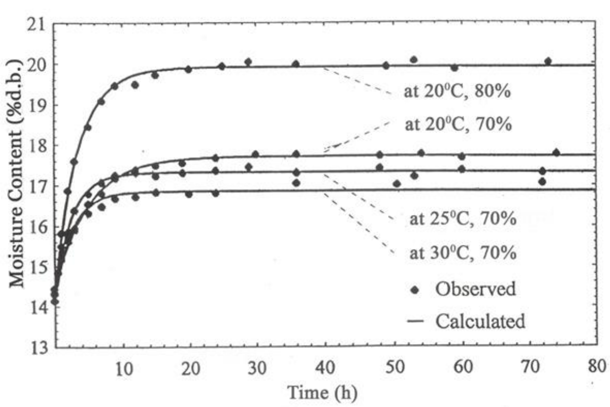


Figure 3: Water adsorption characteristics of polished rice under fluidizing conditions

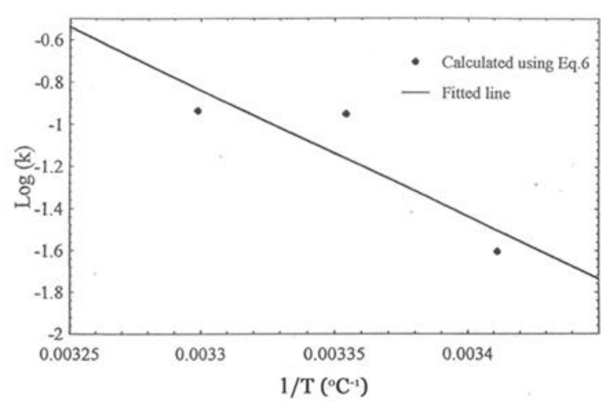


Figure 4: Arrhenius plot of sorption coefficient ($k$) at 70% relative humidity

Table 2: Initial moisture ($M_0$), sorption coefficient ($k$), calculated equilibrium moisture ($M_e$) and the standard error of estimate at each temperature and relative humidity condition

| Temperature (°C) | Relative Humidity (%) | $M_0$ (% d.b.) | $K$ ($h^{-1}$) | $M_e$ (% d.b.) | Standard Error of Estimate |
|---|---|---|---|---|---|
| 20 | 70 | 14.442 | 0.2009 | 17.703 | 0.0649 |
| 20 | 80 | 14.308 | 0.2849 | 19.910 | 0.1042 |
| 25 | 70 | 14.329 | 0.3858 | 17.317 | 0.1825 |
| 30 | 70 | 14.141 | 0.3921 | 16.851 | 0.3172 |

## CONCLUSION

Considerably large amount of gas was needed to fluidize polished rice. Polished rice does not have a smooth fluidizing period. Just after minimum fluidization, it starts turbulent-churning and slugging. The diameter of the vessel should be carefully selected to avoid flat slugs. According to the fluidizing characteristics, polished rice can be categorized as Geldart D particle, the particle diameter is greater than 500µm, spoutable, difficult to fluidize and behaves erratically giving large exploding bubbles. Therefore, spouted beds would be more suitable which need much less gas. Even though, the shallow bed with sufficient diameter and gas velocities not more than the minimum fluidizing velocity would produce solid mixing effectively. Slugging can be avoided using vessels having larger-diameter upper section.

Fluidized bed sorption of polished rice well followed the first falling rate period drying equation, and the sorption coefficient followed the Arrhenius type temperature dependency. The calculated sorption coefficients can be used to predict the moisture contents at respective air conditions. The effective sphericity and effective particle diameter is applicable for pressure drop calculations. It can be concluded that fluidizing polished rice with moist air can be effectively adopted for rewetting low moisture polished rice.

*Nomenclature*

| | |
|---|---|
| $A_t$ | cross-sectional area of bed, $m^2$ |
| $d$ | parameter, $h^{-1}$ |
| $d_{eff}$ | effective particle diameter, m |
| $d_p$ | intermediate particle size by screen analysis, m |
| $f$ | parameter, K. |
| $g$ | acceleration of gravity, 9.8 $ms^{-2}$ |
| $g_c$ | conversion factor, $1 kg \cdot m \cdot N^{-1} \cdot s^{-1}$ |
| $k$ | sorption coefficient, $h^{-1}$ |
| $L_m$ | height of fixed bed, m |
| $L_{mf}$ | height of bed at minimum fluidization, m |
| $M$ | moisture content at time t, % d.b. |
| $M_e$ | equilibrium moisture content, % d.b. |
| $M_o$ | initial moisture content, % d.b. |
| $T$ | absolute temperature, K |
| $t$ | time, h |
| $W$ | mass of solids, kg |
| $u_{mf}$ | superficial gas velocity at minimum fluidizing conditions, $ms^{-1}$ |
| $u_0$ | superficial gas velocity, $ms^{-1}$ |

*Greek symbols*

| | |
|---|---|
| $\mu$ | viscosity of gas, $kg \cdot m^{-1} \cdot s^{-1}$ |
| $\rho_g$ | gass density, $kg \cdot m^{-3}$ |
| $\rho_s$ | density of solids, $kg \cdot m^{-3}$ |
| $\Delta p_b$ | pressure drop across the bed, Pa |
| $\Delta p_{fr}$ | Frictional pressure drop, Pa |
| $\varepsilon_m$ | void fraction in the fixed bed |
| $\varepsilon_{mf}$ | void fraction in the bed at minimum fluidizing conditions |
| $\varphi_{s,eff}$ | effective sphericity of a particle |

## REFERENCES


[1] A.K. Shyamali, H.H.E. Jayaweera and T.B. Ariyaratne, Thin layer drying of some Sri Lankan paddy varieties under low humid conditions. Proceeding of the Technical Session, Institute of physics, Colombo, Sri Lanka, 2009, pp. 36-44.

[2] J. Chrastil, Correlation between the physicochemical and functional properties of rice, *Journal of Agricultural and Food Chemistry*, 1992, 40(9):1683-1686.

[3] D. Kunii, and O. Levenspiel, Fluidization Engineering Butterworth- Heinemann, USA, 1991, pp. 61-92.

[4] R. Jowitt, Heat transfer in some food processing applications of fluidization. *Chemical Engineer*, 1977, 11:779-782.

[5] P.G. Smith, Application of fluidization to food processing. Blackwell Science: Oxford, 2007, pp. 1-52.

[6] N. C. Shilton and K. Niranjan, Fluidization and its applications to food processing, *Food Structure*, 1993, 12(2):199-215.

[7] G.M. Rios, M. Marin and H. Gibert, “New developments of fluidization in the IQF food area|”, In Engineering and Food Processing Applications, Vol 2, B. M. McKenna, Ed. Elsevier Applied Science Publishers: London,1984, pp. 669– 667.

[8] D. Geldart, Types of gas fluidization, *Powder Technology*, 1973, 7:285-292.

[9] J.B. Joshi, Solid liquid fluidized beds: Some design aspects. *Chemical Engineering Research and Design*, 1983, 61(3):143-161.

[10] A.M. Lali, A.S. Khare, J.B. Joshi, and K.O.P. Nigan, Behaviour of solid panicles in viscous non-newtonian solutions- settling velocity, wall effects and bed expansion in solid liquid fluidized beds. *Powder Technology*, 1989, 52(1):39-50.

[11] P.G. Smith, Application of fluidization to food processing, Blackwell Science: Oxford, 2007, pp. 1-52.

[12] J.F. Richardson, “Incipient fluidization and particulate systems”. In Fluidization, J.F. Davidson and D. Harrison, Eds. Academic Press: London, 1971, pp. 29-64.

[13] S. Hovmand, “Fluidized bed drying”, In Handbook of Industrial Drying, A.S. Mujumdar, Ed. Marcel Dekker: New York, 1987, pp 165-225.

[14] G. McKay and H. McLain, The fluidization of cuboid panicles, *Transactions of the Institute of Chemical Engineers*, 1980, 58:107-115.

[15] S. Ergun, Fluid flow through packed columns. *Chemical Engineering Progresses*, 1952, 48(2), 89-110.

[16] O. Akgiray and A.M. Saatci, A new look at filter backwash hydraulics. *Water Science and Technology: Water Supply*, 2001, 1(2):65-72.

[17] Tokyo Astronomical Observatory, Chronological Scientific Tables Maruzen Co. Ltd., Tokyo, 1986, p. 1017.

[18] T. Ban and K. Susawa, Study on grain moisture content measurements by air oven methods (II): Investigation on the methods without the apparent loss of dry matter. *Agricultural Machinery*, 1973, 35(2): 406–415.

[19] W.H.C. Simmonds, G.T.Ward and E. McEwen, The drying of wheat grain (Part I): The mechanism of drying. *Transaction of Institute of Chmical Engineering*, 1953, 31:265-278.


## AUTHORS


**First Author** – Ms. H.K.P.P. Kariyawasam, Postgraduate Institute of Agriculture, University of Peradeniya, 20400, Peradeniya, Sri Lanka. ppkariyawasam@gmail.com

**Second Author** – Dr. K.S.P. Amaratunga, Dept. of Agricultural Engineering, Faculty of Agriculture, University of Peradeniya, 20400, Peradeniya, Sri Lanka. sanath.amaratunga@gmail.com

**Third Author** – Ms. Bandara, D.M.S.P., Institute of Postharvest Technology, Jayanthi Mawatha, Anuradhapura, 50000, Sri Lanka. srimapriyangika@yahoo.com

**Fourth Author–** Mr. Dissanayake T.M.R., Institute of Postharvest Technology, Jayanthi Mawatha, Anuradhapura, 50000, Sri Lanka. mrdissanayake@yahoo.com

**Correspondence Author** – – Ms. H.K.P.P. Kariyawasam, Postgraduate Institute of Agriculture, University of Peradeniya, 20400, Peradeniya, Sri Lanka. ppkariyawasam@gmail.com.