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Fluidization Behaviour of Food Materials: Effect of Moisture and Shape

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Abstract

Changes in fluidization behaviour of three geometrical shaped food particulates, cylindrical (beans), parallelepiped (potato) and spherical (green peas) with change in moisture content during drying were investigated using a fluidized bed dryer. Fluidization behaviour was characterised for cylindrical shape particles with three length diameter-ratios; 1:1, 2:1 and 3:1, parallelepiped particles with three aspect ratios, 1:1, 2:1 and 3:1 and spherical particles. All drying experiments were conducted at 50^0C and 15 % RH using a heat pump dehumidifier system. Fluidization experiments were undertaken for the bed heights of 100, 80, 60 and 40 mm and at 10 moisture content levels.

An empirical relationship of the form $\mathbf{U_{mf} = A + B\,e^{-Cm}}$ was developed for change of minimum fluidization velocity with moisture content for cylindrical shapes and for spherical shapes a linear model of $\mathbf{U_{mf} = A + B\,m}$. Due to irregularities in shape minimum fluidisation velocity of parallelepiped particulates (potato) could not fitted to any empirical model. Also a generalized equation was used to predict minimum fluidization velocity.

Introduction

Fluidized bed drying is recognized as a gentle, uniform drying, down to very low *residual moisture* content, with a high degree of efficiency (Borgotte et al., 1981). The application of this technique is best suited to smaller and spherical particles. The disadvantages of this method include entrainment of friable solids by the gas and limited application to larger and poorly fluidized materials. Simultaneous moisture removal, shrinkage and structural changes during drying operations, affect physical properties of the agro-food materials and hence influence fluidization behaviour (Senadeera et al., 1998)

The Ergun equation (Ergun, 1952) is the widely accepted model to determine *minimum fluidization velocity* of a fluid to fluidize the particle (Kunii and Levenspiel, 1977).The Ergun equation (Equation 1) is used to calculate minimum fluidization velocity of peas (Rios et al., 1984) and diced potato and potato strips (Vazquez and Calvelo, 1980; 1982). The values obtained by the Ergun equation are mostly reliable for spherical and relatively small particles. Most agro-food particulates however comprise of various shapes and sizes, and consist of larger particles. Therefore, the minimum fluidization values obtained from Ergun equation do not conform to the experimental values (Mclain and McKay, 1980, 1981; McKay et al., 1987)

$$(1-\varepsilon_{mf})(\rho_s-\rho_f)\,g = 150\frac{(1-\varepsilon_{mf})^2}{\varepsilon_{mf}^{\;3}}\frac{\mu u_{mf}}{(\phi d_p)^2} + 1.75\frac{(1-\varepsilon_{mf})}{\varepsilon_{mf}^{\;3}}\frac{\rho_f u_{mf}^{\;2}}{\phi d_p} \qquad (1)$$

where ε_{mf} – bed porosity at minimum fluidization velocity, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), μ - viscosity (N s/m^2), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), ϕ - sphericity

The Ergun equation consists of *viscous* and *kinetic energy* terms. In the case of larger particles at higher Reynolds numbers (Re > 1000) the fluidization behaviour is mainly governed by the kinetic energy term in the Ergun equation. Hence the Ergun equation can be simplified for (Kunii and Levenspiel, 1977) a wide variety of systems and a generalized equation can be applied to predict minimum fludisation velocity for larger particles when Reynolds number > 1000 using some modification.

$$u^2_{mf} = \frac{\phi\, d_p^{\,2}}{1.75} \frac{(\rho_s - \rho_f)}{\rho_f}\, g\, \varepsilon^3_{mf} \qquad (2)$$

where, ε_{mf} – bed porosity at minimum fluidization velocity, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), ϕ - sphericity, g - acceleration due to gravity (m/s^2)

For wide variety of systems it was found that value $\frac{1}{\phi\, \varepsilon_{mf}^{\,3}} \cong 14$ (Wen and Yu, 1966) and a generalized equation can be applied to predict u_{mf} for larger particles when Re > 1000.

$$u^2_{mf} = \frac{d_p(\rho_s - \rho_f)}{24.5\, \rho_f}\, g \qquad (3)$$

where, ρ_s – particle density (kg/m^3), ρ_f – fluid density (kg/m^3), u_{mf} – minimum fluidization velocity (m/s), d_p – particle equivalent diameter (m), Re – Reynolds number

It is important to understand changes in fluidisation behaviour, so that the air-flow during drying can be controlled to achieve an optimum fluidization. The objective of this study is to study the continuous change in minimum fluidization velocity for a given shape of food material during drying and relate this to moisture content by a suitable model, and compare with the generalized model.

Material and Methods

Fresh green beans *Phaseolus vulgaris* of Labrador variety with consistence diameter 10 $\pm$ 1 mm was used for producing cylindrical particles. Samples were prepared at three length to diameter ratios of 1:1, 2:1 and 3:1, respectively. Potato *Solanum tuberosum* of the variety Sebago was used to make parallelepipeds in a Dicing Machine (Hobart, Australia), by incorporating a cutter which makes 6.5mm X 6.5mm square cross-section and lengths of 19.5, 13 and 6.5 mm to obtain aspect ratios of 3:1, 2:1 and 1:1, respectively. Fresh green peas *Pisum sativum* of the variety Bounty were shelled by hand and graded using a wire mesh. Those with average diameter 10$\pm$1 mm were selected.

Particle density was obtained measuring the volume of the weighed particles by the liquid displacement method using liquid paraffin (SG = 0.8787 at 30^o C) as the medium (Zogsas, 1994). The vacuum oven was used to measure the moisture content of the particles according to the AOAC method 934.06 (1995).

First, fluidisation characteristics of the un dried samples were measured in the fluidizing column (Figure 1) with the prepared samples. After that samples were dried on a fixed bed in a heat pump dehumidifier system (Intertherm P/L, Brisbane, Australia) and withdrawn at nine pre-determined time intervals during drying and used for measurement of minimum fluidisation velocity at four bed heights of 100, 80, 60, and 40 mm in same fluidized bed column.

Graphs of bed pressure drop versus velocity of fluidising air were constructed to determine the minimum fluidisation velocity at different moisture contents. This was also confirmed with the visual observation of the bed, such as expansion and movement.

Figure 1 Fluidisation column connected to the heat pump dryer

Analysis of experimental data and modelling procedure

The data were analysed for the analysis of variance (ANOVA) to evaluate differences, and, linear and non-linear regression to obtain suitable models. The coefficients were estimated using SAS (1985) least squares routine on a personal computer. Model validity was tested using measures of coefficient of determination (R^2) and mean absolute error percentage (MAE%).

Results and Discussion

Fluidisation behaviour of cylindrical food particulates - beans

Slugging and channelling were a common phenomena at higher moisture contents for every L:D ratio. It was difficult to achieve good fluidisation at initial moisture levels. This was more evident as the L:D ratio increased. As moisture was reduced, the quality of fluidisation improved, with reduced slugging and channelling.

Modelling the minimum fluidisation velocity with change in moisture content

The data were best fitted to the model $u_{mf} = A + B\ e^{-C\ m}$ and its parameters are shown in the Table1 for L:D = 1:1 and Table 2 for 2:1 for different bed heights.

Table 1 Parameters for Equation $u_{mf} = A + B\ e^{-Cm}$ for L:D = 1:1

Bed height (mm)	A	B	C	R^2	MAE%
100	2.3541	-0.8825	0.0017	0.91	3.89
80	2.2990	-0.8514	0.0015	0.91	4.07
60	2.0793	-0.7097	0.0019	0.86	4.62
40	2.1202	-0.7691	0.0016	0.86	4.52

Table 2 Parameters for Equation $u_{mf} = A + B\ e^{-Cm}$ for L:D = 2:1

Bed height(mm)	A	B	C	R^2	MAE%
100 mm	2.3632	-0.7446	0.0021	0.73	11.23
80 mm	2.3409	-0.7480	0.0025	0.72	11.54
60 mm	2.1965	-0.6884	0.0020	0.76	11.23
40 mm	2.1204	-0.6532	0.0032	0.79	9.58

This model adequately described the fluidisation behaviour of beans at L:D = 1:1. The model for L:D = 2:1 and 3:1 gave poor correlation coefficients and higher mean absolute error percentage values, could be due to irregular variation of the minimum fluidisation velocity.

Calculation of minimum fluidisation velocity based on dimensional changes during drying

The Generalized model (Equation 3) was used to calculate the predicted values of minimum fluidisation velocity. For all three L:D ratios (Table 3).

Table 3 Mean Absolute Error % for predicted versus observed minimum fluidisation values in the generalized model

L:D ratio/ Bed height	MAE%			
	100mm	80mm	60mm	40mm
1:1	9.54	3.81	1.61	3.18
2:1	7.66	1.83	6.13	2.74
3:1	5.32	1.62	0.36	4.03

Fluidisation behaviour of parallelepiped particles - potato

Good fluidisation was impossible at higher values of moisture at all aspect ratios. Decreasing the moisture resulted in a bed which was fluidised, but was accompanied by channelling and slugging. At lower moisture levels quality of fluidisation improved. An increase in minimum fluidisation velocity was attributed to the increase in particle density and interlocking of particles in the bed (Figure 2).

Modelling of minimum fluidisation velocity with change in moisture content

Fluidisation behaviour of potato particles could not be modelled due to the irregular trend of change of minimum fluidisation velocity with moisture content for all aspect ratios.

Minimum fluidisation velocity calculation based on the generalized equation

The Generalized model was used to calculate the predicted values of minimum fluidisation velocity. For all three aspect ratios, this generalized model value was compared with the experimental value. The mean absolute error percentage value is more than 10% for the aspect ratio 3:1, for the bed heights of 100, 80 and 60 mm (Table 4).

Table 4. Mean absolute error percentage (MAE%) of observed and predicted values of potato based on the generalized model

Aspect ratio	MAE%			
	100mm	80mm	60mm	40mm
1:1	8.83	4.09	2.75	2.03
2:1	7.55	6.26	1.03	1.02
3:1	13.46	12.98	10.80	3.68

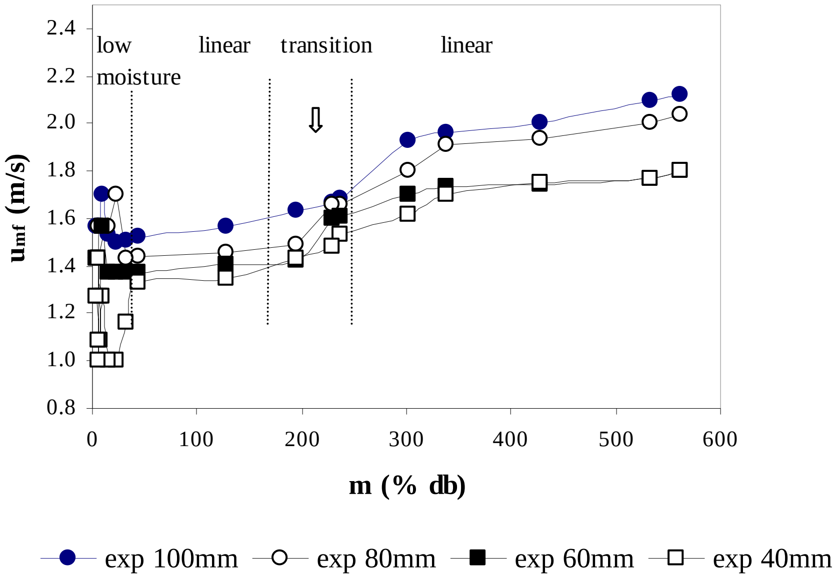

FIGURE 2 Fluidisation behaviour of potato L:D = 1:1

Fluidisation behaviour of spherical particles -green peas

In the case of peas, fluidisation was possible even at the higher moisture contents. Minimum fluidisation velocity decreased as drying proceeded. Slugging, and channeling phenomena was less than in the case of beans and potato due to good packing and spherical shape of the material in the bed.

Modelling of minimum fluidisation velocity with change in moisture content

The change in minimum fluidisation velocity was modelled linearly with the moisture content of the form u_{mf} = A + B m for all bed heights. Model parameters are given in Table 5. MAE% lower than 10% indicating that the model equations can be used to predict the fluidisation behaviour reasonably.

Table 5. Coefficients for green pea models at different bed heights

Bed height (mm)	A	B	R^2	MAE%
100	1.5589	0.025	0.88	3.93
80	1.4786	0.0023	0.88	4.20
60	1.3853	0.0022	0.87	4.69
40	1.2685	0.0023	0.81	7.07

Minimum fluidisation velocity calculation based on the Generalized equation

The Generalized model (Equation 2) was used to calculate the predicted values of minimum fluidisation velocity of peas, and found that it can be used to predict minimum fluidisation velocity accurately for all bed heights and all moistures.

Table 6. Mean absolute error percentage (MAE%) for different bed heights of

peas for Generalised model

Bed height (mm)	MAE %
100	7.24
80	1.75
60	4.76
40	9.51

Conclusion

This work showed effect of moisture and shape on fluidisation behaviour of three real food materials. Fluidisation behaviour was modelled into empirical equations for cylindrical (beans) and spherical (peas) with moisture and could not be for parallelepiped (potato) particles due to its irregular nature. Generalised equation predicts the minimum fluidisation with a reasonable accuracy for all particle shapes. If sphericity changes during drying is measured an accurate predictions of minimum fluidisation velocity could be obtained using Ergun Equation.

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