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Fluidization Behaviour of Cylindrical Green Bean Particulates During Drying

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ABSTRACT. *Changes in fluidization behaviour of green bean particulates 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 (L:D), i.e. 1:1, 2:1 and 3:1.*

All drying experiments were conducted at 50±2°C and 13±2% 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. Data were analysed using SAS, and an empirical relationship of the form $U_{mf} = A + B\,e^{-Cm}$ *was developed for change of minimum fluidization velocity with moisture content during drying. A generalized equation was used to calculate minimum fluidization velocity.*

INTRODUCTION

The use of fluidization is one of the main applications in drying of agro–food materials. When an air stream is passed through a free flowing material resting on a permeable support, the bed starts to expand when a certain air velocity is reached. The superficial velocity of the air at this stage is the minimum fluidization velocity. With continual increase in air velocity, a stage is reached where the pressure across the fluidized bed drops rapidly, and the product is carried along the air stream. The velocity of air at this stage is called terminal velocity. During fluidizing operations the superficial velocity of the air should remain between minimum fluidization velocity and terminal velocity.

Fluidized bed drying has been recognized as a gentle, uniform drying, down to a very low residual moisture content, with a high degree of

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efficiency (Borgolte and Simon, 1981). This is a very convenient method for heat sensitive food materials as it prevents them from overheating (Gibert *et al.*, 1980; Giner and Calvelo, 1987). The fluidized bed drying for granular materials is now established (Masters, 1992) and many driers are operating throughout the world in the chemical and food industries. The properties of particulate materials relate to the type of fluidization technique (Shilton and Niranjan, 1993). 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 are common in drying operations. These changes affect the physical properties of the agro-food materials and hence influence fluidization behaviour (Senadeera *et al.*, 1998).

The Ergun equation (Ergun, 1952; Equation 1) is the widely accepted model (nomenclature of the model is given in Appendix 1) to determine minimum fluidization velocity of a fluid to fluidize the particle (Kunii and Levenspiel, 1969; Zenz and Harbor, 1971; Michelis and Calvelo, 1994).

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

The Ergun equation was used to calculate minimum fluidization velocity of baker's yeast (Egerer *et al.*, 1985), peas (Rios *et al.*, 1984) and diced potato and potato strips (Vazquez and Calvelo, 1980; Vazquez and Calvelo, 1983). An equation similar to Ergun was valid for peas (Michelis and Calvelo, 1994).

The values for velocity 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 does not conform to the experimental values (Mclain and McKay, 1980, 1981; McKay *et al.*, 1987). The Ergun equation consists of viscous and kinetic energy terms (1st and 2nd LHS part of the Equation 1). In the case of larger particles at higher Reynolds numbers (Re>1000) the fluidization behaviour was mainly governed by the kinetic energy term in the Ergun equation. Hence, the Ergun equation can be simplified to (Kunii and Levenspiel, 1969);

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

For wide variety of systems it was found that the value $1/\phi\ \epsilon_{mf}^{\ 3} \approx 14$ (Wen and Hyu, 1966) and a generalized equation can be applied to predict U_{mf} for larger particles when Re>1000.

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

There is a continuous change in physical properties of the particulates during drying, which also changes the fluidization behaviour of the particles. It is important to understand these changes, so that the air–flow during drying can be controlled to achieve an optimum fluidization.

The objective of this experiment was to study the continuous change in minimum fluidization velocity for a given shape of food material (green bean in this case) during drying and relate this to moisture content by a suitable model, and compare the minimum fluidization velocity with the generalized model.

MATERIALS AND METHODS

Fresh green beans [*Phaseolus vulgaris* (L.) *var.* Labrador] was used for producing cylindrical particles. Beans were purchased from the same supplier to maximize reproducibility of results. Care was taken when selecting the size of beans to obtain a consistent diameter of approximately 10 mm. Size was measured using a vernier caliper with an accuracy of 0.05 mm. Initially both ends of the beans were cut and only the middle portions, which resemble a cylindrical shape, were used to produce the required samples. Samples were prepared at three length to diameter ratios of 1:1, 2:1 and 3:1, and each experiment was repeated three times. After cutting, beans were kept in a plastic container in a cold room at 40°C for more than 12 h before experimentation to stabilize the moisture content.

Drying experimentation was carried out using a heat pump dehumidifier system at a temperature of 50±2°C and relative humidity of 13%. Materials were placed inside the drying system on mesh trays and stacked vertically to achieve maximum exposure to the air–flow. During drying, samples were taken from the dryer at ten arbitrary moisture levels. These samples were collected into a sealed container and used for fluidizing experiments and physical measurements.

All fluidization trials were conducted in a batch type flexi–glass fluidizing column of 185 mm inside diameter and 1 m long (Figure 1). The hot air was taken from a heat pump dehumidifier system coupled to the dryer. Hot air entered the material bed through a perforated plate with circular holes of 1 mm diameter (18 holes cm^{-2}). An even air distribution was achieved by placing another perforated plate (with 10 mm diameter holes with a diametral pitch of 40 mm in concentrically arranged holes), 10 mm vertically below the perforated plate. Air flow entering the dryer was varied by means of varying the incoming flow to the fan and velocity of the incoming air was read from a digital manometer (EMA 84, range 0–10 kPa) connected to a pitot tube (Dwyer DS–300). Pressure drop across the bed was measured by a U–tube manometer connected to the drying chamber below the air distributor plate and above the bed of bean samples. In order to determine the optimum bed height for improved fluidization, bed heights of 100, 80, 60 and 40 mm were used. Used samples were collected in a separate container and reused for the drying experimentation.

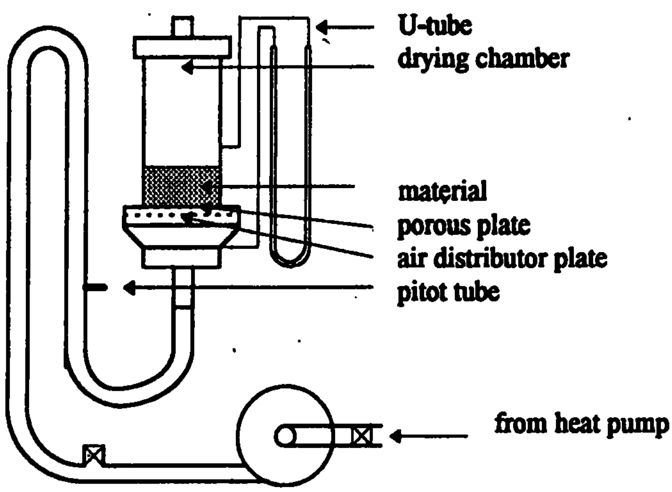


Figure 1. A fluidized bed experimental setup.

To determine the particle density, a known number of particles were weighed by a Sartorious electronic balance, and the volume was measured by the difference in meniscus levels before and after immersion of particles in liquid paraffin in a measuring cylinder. The difference in meniscus levels was measured by a vernier caliper (accuracy 0.05 mm). This value was used to calculate the equivalent diameter of the particle, which was used in the generalized equation (Equation 3). Moisture content was determined by measuring the loss in weight of finely chopped samples held at 70°C and -13.3 kPa vacuum for 24 h (AOAC, 1995).

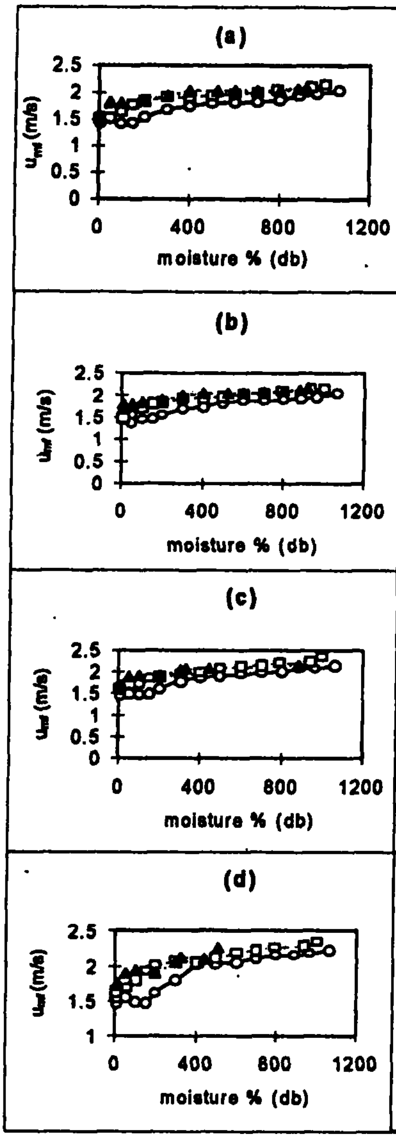
RESULTS AND DISCUSSION

Modeling of minimum fluidization velocity with change in moisture content

The behaviour of minimum fluidization velocity is given in Figure 2 for different length:diameter (L:D) ratios and different bed heights. Slugging and channelling were a common phenomena at the initial higher moisture levels for every L:D ratio. It was difficult to achieve good fluidization at initial moisture levels. This was more evident when the L:D ratio increased. Visual observation of the bed at an instance of fluidization after bed expansion was the criteria considered to categorise minimum fluidization. This value was compared with graphical variation, the pressure drop of the bed with velocity. Both observed and graphical values were identical.

Using Statistical Analysis System (SAS), a model which correlate with a L:D ratio of 1:1 was fitted to the variation of minimum fluidization velocity with moisture during drying (Figure 3). The data were best fitted to the model $U_{mf} = A + B\, e^{-Cm}$ and its parameters are shown in the Table 1 for different bed heights. The same model was used for other ratios (2:1, 3:1). They were poorly correlated for L:D = 2:1 and 3:1. It should be noted that for L:D = 2:1 and 3:1, the slugging and channelling were commonly observed phenomena (data not shown).

At initial moisture values, minimum fluidization occurs together with channelling and slugging. This were more pronounced in larger L:D ratios. As moisture was reduced, the quality of fluidization improved reducing slugging and channelling. Good fluidization was observed at 32% (wb) for L:D ratio 3:1, 52% (wb) for L:D ratio 2:1 and 60% (wb) for L:D ratio 1:1.



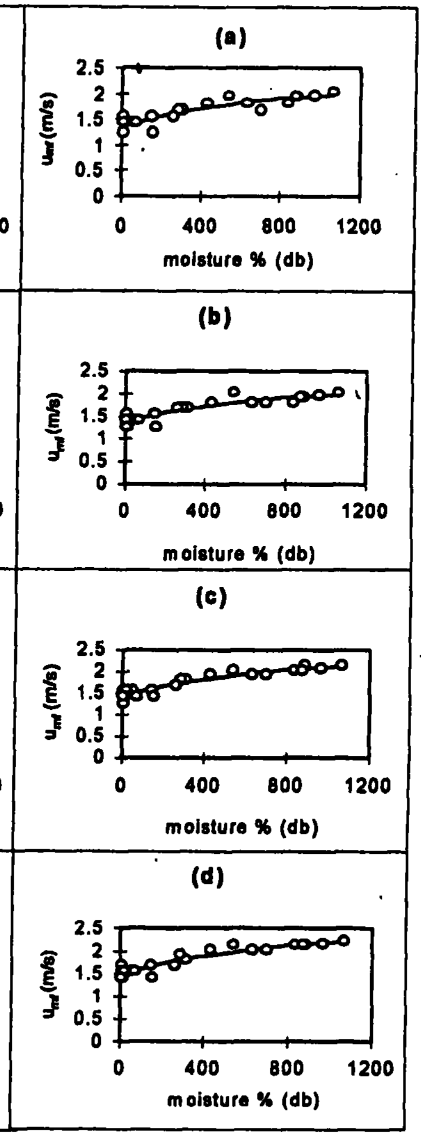


Figure 2. Fluidization behaviour of beans.

[Note: (a) 40 mm (b) 60 mm
(c) 80 mm (d) 100 mm
o L:D=1:1□ L:D=2:1Δ L:D=3:1]

Figure 3. Fluidization models length:diameter (L:D) = 1:1

[Note: (a) 40 mm (b) 60 mm
(c) 80 mm (d) 100 mm
o experimental – model]

Table 1. Parameters for Equation $U_{mf} = A + B\, e^{Cm}$ for variable bed heights.

Bed height (mm)	A	B	C	r^2	MAE %
100	2.3541	0.8825	0.0017	0.91	3.8973
80	2.2990	0.8514	0.0015	0.91	4.0703
60	2.0793	0.7097	0.0019	0.86	4.6296
40	2.1202	0.7691	0.0016	0.86	4.5223

MAE - Mean absolute error

There was an increase in minimum fluidization velocity at very low moisture levels (<4.1% db), which can probably be attributed to an increase in the particle density due to shrinkage. This is also supported by the generalized equation (Equation 3). Mean absolute error percentage (MAE%) (Equation 4) was calculated according to the methods given by Mayer and Butler (1993) for different L:D ratios and are given in Table 1.

$$MAE\% = 100 \left[\sum \left(| y_i - \hat{y}_i | \, / \, | \hat{y}_i | \right)\right] / n \qquad (4)$$

U_{mf} calculation based on dimensional changes during drying

The generalized model was used to calculate the predicted values of minimum fluidization velocity. For all three L:D ratios, this generalized model gave underestimated values except at lower moisture levels. The predicted versus observed plots of minimum fluidization velocity are presented in Figure 4. The MAE% values were less than 10% (Table 2), indicating that the use of these models can be satisfactorily applicable (Kleijnen, 1987) to predict the minimum fluidization velocity of green bean particulates, with reasonable accuracy.

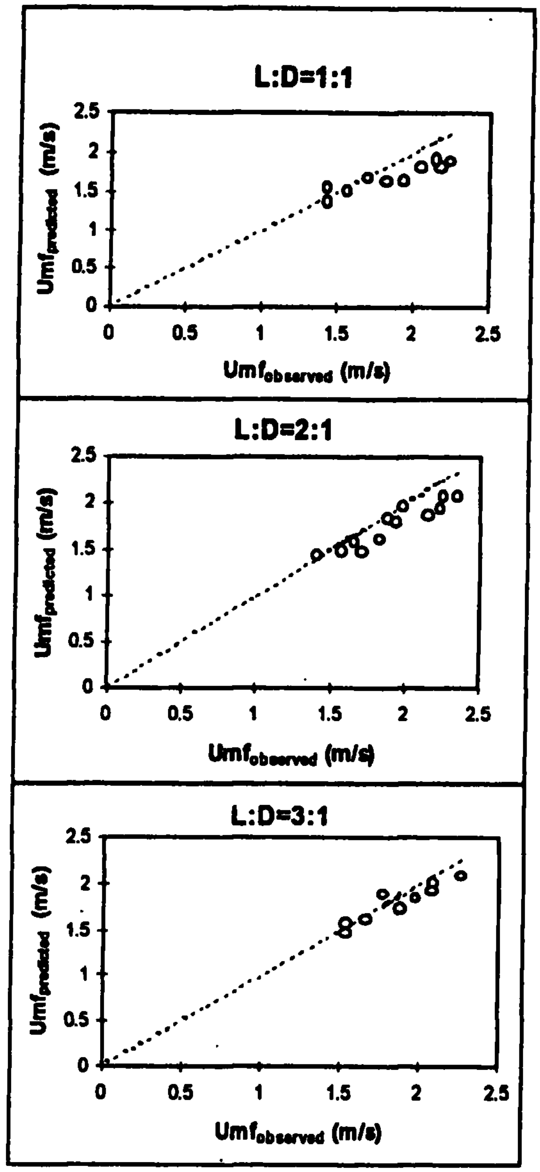


Figure 4. **Predicted versus observed plots for diffefent L:D ratios.**

[Note: Predicted values were calculated using $u^2_{mf} = [d_p (\rho_s - \rho_f)/24.5\, \rho_f]\, g$, and dotted line represents y = x, which helps to determine over or under estimation by the model]

Table 2. Mean Absolute Error (MAE) % for predicted *vs* observed minimum fluidization values.

L:D	MAE %
1:1	9.54
2:1	7.66
3:1	5.32

L : D - length : diameter ratio

CONCLUSIONS

The minimum fluidization velocity decrease as the drying proceeded. The minimum fluidization velocity of green bean with change in moisture can be predicted with an empirical model $U_{mf} = A + B\,e^{-Cm}$ with a satisfactory fit for L:D = 1:1. Further, the calculated U_{mf} using a generalized equation $u^2_{mf} = [d_p(\rho_s - \rho_f)/24.5\,\rho_f]\,g$, based on the dimensional changes of the product during drying can be applied to predict minimum fluidization velocity for all L:D ratios. Further investigation of relationship between L:D change with moisture and bed height with minimum fluidization velocity is necessary.

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APPENDICES

Appendix 1. Nomenclature for models given in the text.

A	constant	
B	constant	
C	constant	
d	equivalent diameter	(m)
D	diameter	(m)
g	acceleration due to gravity	($m\ s^{-2}$)
L	length	(m)
m	moisture content (dry basis)	($kg\ kg^{-1}$ db)
Re	Reynolds number	
u	velocity	($m\ s^{-1}$)
y	value	
ϕ	sphericity	
ϵ	porosity	
ρ	density	($kg\ m^{-3}$)
μ	viscosity	($N\ s\ m^{-2}$)

Superscripts

$\wedge$	predicted value

Subscripts

f	fluid
i	integer
mf	minimum fluidization
n	no. of observations
p	particle
s	solid