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The Drying Constant and its Effect on the Shrinkage Constant of Different-Shaped Food Particulates

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Abstract

Experiments were undertaken to study the relationship between the drying constant and the shrinkage constant of food products during drying. Three particular geometrical shapes of parallelepiped, cylindrical and spheres were selected from potatoes (aspect ratio = 1:1, 2:1, 3:1), cut beans (length: diameter = 1:1, 2:1, 3:1) and peas, respectively. The volumetric shrinkage behaviour and drying behaviour of food particulates were studied in a batch fluidised bed dryer connected to a heat pump dehumidifier system at three different drying temperatures of 30, 40 and 50 °C. Shrinkage constant was evaluated with non-dimensional moisture and compared with the drying constant for all materials at these three temperatures to understand the effects of the drying constant on the shrinkage constant for each material under investigated drying conditions. Simple mathematical models were obtained for the relationship between the volumetric shrinkage constant and the drying constant.

KEYWORDS: shrinkage constant, drying constant, food particulates, modelling

1. INTRODUCTION

Drying of foods is a major operation in the food industry, consuming large quantities of energy. Dried foods are stable under ambient conditions, easy to handle, possess extended storage life and can be easily incorporated during food formulation and preparation. The drying operation is used either as a primary process for preservation, or a secondary process in certain product manufacturing operations. Drying is a complex process and involves simultaneous mass and heat transfer accompanied by physical and structural changes (Fusco et al., 1991). These changes will influence drying characteristics of the materials. Also the quality of food material undergoing drying depends on their initial quality, and changes occurring during drying. Shape and size of the products change appreciably, influencing their physical properties, which in turn modify final texture and transport properties of the dry foods (Karel, 1991).

Shrinkage is one major physical property change taking place during the drying process. This change in volume of the food particulate is mainly as a result of removal of moisture in the viscoelastic matrix contracts into space previously occupied by water. Shrinkage is important to consider as it influences several other physical properties, such as bulk density and particle shape and density, and can also cause internal stresses. Shrinkage also influences moisture removal rate and estimating diffusion coefficients during drying process (Balaban, 1989; Khraisheh et al., 1997; Suarez and Viollaz, 1991).

There is experimental evidence shrinkage extent has a relation to drying conditions (Mayer and Sereno, 2004). There are two theories associated with shrinkage, glass transition temperature theory (Rahman, 2001) and, case-hardening theory (Ratti, 1994). Former suggested effect of temperature of material during drying, and plasticizing effect of water on amorphous materials. Latter explained formation of crusty layer due to formation of higher moisture gradients within the dried material, which prevent volume reduction and moisture removal.

Main parameters of drying such as temperature, relative humidity and drying air velocity are not enough to predict the behaviour when considered individually (Katekawa and Silva, 2007). The consideration of temperature, relative humidity and air velocity into the values of drying rate and moisture gradient is adequate for the description of shrinkage phenomena during drying.

In this study an attempt has been made to understand the relation between shrinkage coefficient and drying constant of different shaped food particles at three drying temperatures, keeping relative humidity and air velocity constant.

2. MATERIAL AND METHODS

2.1. Material preparation

2.1.1. Green beans

Fresh green beans *Phaseolus vulgaris* of the variety 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 10±1 mm. Size was measured using vernier caliper with an accuracy of 0.05 mm. Both ends of the beans were removed 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. After cutting, beans were kept in a plastic container in a cold room at 4^0 C for more than 24 hours before experimentation to equilibriate the moisture content. Twenty five kg of beans were needed for each experiment.

2.1.2. Potato

Potato *Solanum tuberosum* of the variety Sebago was purchased from the same supplier in 50 kg bags. Before sample preparation, potatoes were washed and brushed to remove skin and mud. First large cubicle shapes were cut from the whole potatoes removing the outer portions near the skin. Subsequently those cubes were cut carefully using a sharp knife to produce parallelepipeds with a square cross-section, the length of the sides being 6.5 mm. Then those slices were pushed through a stainless steel square cutter to make parallelepipeds in a dicing machine (Hobart, Australia), by incorporating a cutter which makes 6.5mm x 6.5mm square cross-section. In the case of aspect ratio of 1:1, the potato cubes were pushed through the same cutter and axial length was controlled to a length of 6.5 mm by a cutting blade. The required aspect ratios 3:1, 2:1 and 1:1 were obtained by cutting carefully to the lengths of 19.5, 13 and 6.5 mm respectively. Immediately after cutting all the samples were immersed in a sodium metabisulphite solution (0.1 % w/w) for 15 minutes to prevent browning during drying. The samples were drained on a mesh tray. Then samples were kept in a cold room for 24 hours at 4^o C before experimentation to equilibrate moisture content. Thirty kilograms of sample were prepared at once and used for one experiment.

2.1.3. Green peas

Fresh green peas *Pisum sativum* of the variety Bounty was purchased from the same supplier in 10 kg boxes in their pods. They were shelled by hand and graded using a wire mesh. Those with average diameter 10 $\pm$ 1 mm were selected and stored in a cold room for 24 hours at 4^{o} C before experimentation to equilibriate moisture content. Twenty five kilograms of sample was used for one experiment.

2.2. Experimental design

Three batches were prepared at once and used for three drying temperatures. Two replicate batches were prepared for cut beans (3 L:D ratios) and diced potato (3 aspect ratios). Three replicate batches were prepared for peas.

For beans and potato, a split unit design with two replications corresponding to processing time, with three sizes per block and three drying temperatures for each size was used. For peas, a randomized complete block design with three replications for each temperature was used.

2.3. Drying in a fluidised bed

One batch stored in the cold room was taken for fluidised bed drying experimentation. Fluidised bed dryer was connected to the heat pump dehumidifier system (Figure 1). A schematic diagram of the connection arrangement is shown in Figure 2. The drying conditions of 30^{0} C, 40^{0} C and 50^{0} C were set by the temperature controller in the heat pump dehumidifier system, and the drying set up was run for 2 hours to achieve steady state conditions of drying before material introduction. Initial bed height of 150 mm was used. The hot air velocity passing through the material bed was kept at a constant value of 2.2 m/s for all drying experiments. This velocity was selected, because it was within the limit of fluidisation and terminal velocity of all three materials concerned and within the capability of the fan. The air-flow entering the dryer was controlled by flow control valves. Samples were collected from the dryer at 30 minutes intervals through the sample outlet. Each time they were collected in a sealable container and immediately used for moisture determination and volume measurements.

Figure 1 Fluidised bed experimental setup

2.4. Volume measurement

The volume of the particles was measured by the liquid displacement method using liquid paraffin (SG = 0.8787 at 30^{o} C) as the medium, using a measuring cylinder of 22 mm inside diameter and 50 ml capacity (Zogzas et al., 1994). Paraffin was employed as the liquid of displacement as it does not interact with the constituents of the sample, and has a low enough density to ensure complete submergence of the samples. A known number of particles were immersed in

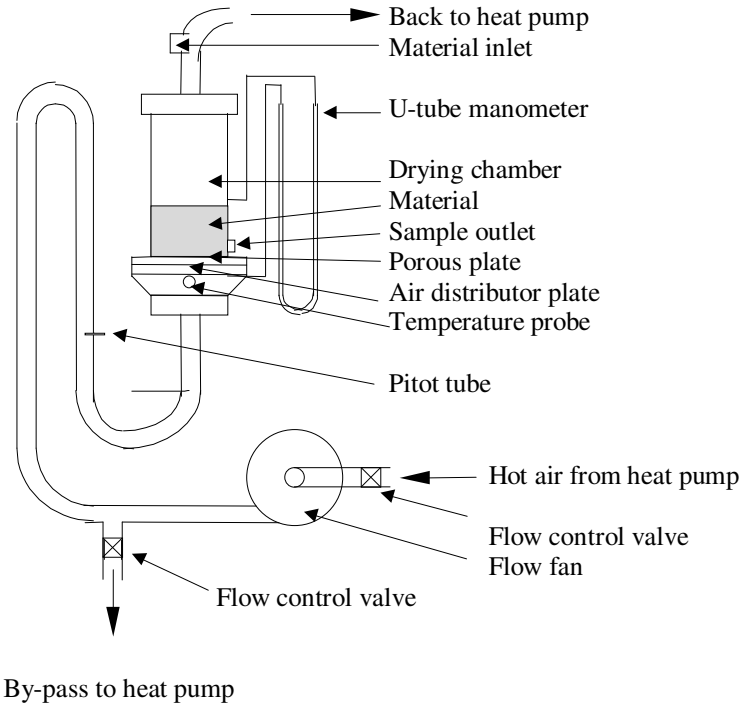

Figure 2 Schematic of the fluidised bed drying set up

paraffin. The number of samples for volume determination was increased progressively as drying progressed to maintain an approximately constant total volume measurement. Volume was measured by the difference of meniscus levels before and after immersion, using vernier calipers (accuracy 0.05 mm). Considering the high viscosity of paraffin, care was taken to avoid formation of air bubbles, and also the adherence of liquid to the glass walls of the cylinder above liquid meniscus by gently lowering the samples into the liquid. For each sample, an average of three readings, were recorded. All the measurements were taken quickly to avoid any possibility of absorption of paraffin into the product.

2.5. Moisture determination

The vacuum oven was used to measure the moisture content of the particles according to AOAC method 934.06 (1995) used by Rosello et al. (1997). Sample weighing dishes made of aluminium, 60-80 mm diameter and 25 mm deep, with well fitting but easily removable lids were pre-washed, dried and kept in a desiccator with silica gel for two days prior to experimentation. Duplicated

samples of 5-10 g in mass weighed by an electronic balance (Sartorius, $\pm$ 0.001g) were thoroughly homogenised and put into tared weighing dishes from the desiccator, and placed them inside a vacuum oven. The metal dishes, containing the samples were in direct contact with the metal shelf of the oven. Moisture content was determined by measuring the loss in weight of finely chopped samples held at 70^0 C and 13.3 kPa vacuum for more than 24 hours. Samples were transferred from the vacuum oven to the desiccator to cool. When cool, samples were weighed as quickly as possible to an accuracy of 0.1 mg.

2.6. Analysis of experimental data

The data were analysed for the analysis of variance (ANOVA) to evaluate differences, and, linear regression and non-linear regression to obtain suitable models. For all the analysis the Statistical Analysis System software (SAS, 1985) was used. The experimental data on shrinkage and drying were analysed for significance (ANOVA) using the SAS routine GLM (general linear models), and the model coefficients were estimated using SAS least squares routine, (GLM for linear models and NLIN for non-linear models) on a personal computer.

Several criteria for adequacy of the model fit such as R^2 (coefficient of correlation), MSE (error sum of squares) and mean absolute error percentage (MAE%) were used to select an appropriate mathematical model. As other researchers (Noomhorn and Verma, 1986; Palipane and Driscoll, 1994, Madamba et al., 1996) the best model describing the behaviour was selected as the one with highest coefficient of correlation and least mean absolute error percentage.

$$R^2 = 1 - \frac{\text{residual sum of squares}}{\text{corrected total sum of squares}}$$

$$\text{MAE\%} = \frac{100}{n} \sum \frac{\left|\text{predicted value - observed value}\right|}{\left|\text{observed value}\right|}$$

3. RESULTS AND DISCUSSION

3.1. Shrinkage behaviour

3.1.1. Beans

It was observed that the shrinkage was not a homogenous phenomenon. Change in volume and shape were different for different L:D ratios. During the initial stage of drying, beans retained their smooth surface and shape, though some reduction in volume was observed.

Irregular shrinkage was more evident after 75 ~ 83 % wb (313 ~ 520 % db) moisture. The two ends closed as the beans shrunk due to dehydration. This closure of ends was more evident as the L:D ratio increased. The skin surface of the beans was wrinkled showing change of external surface roughness, and that the internal tissue structure of the skin has some plasticity to resist cracking and that the skin surface remains relatively unaffected as compared to the total volume of shrinkage of the particulate.

Change in volume ratio (VR) with moisture ratio (MR) is shown in Figure 3 for L:D = 1 at 30^{o} C. Similar shrinkage behaviour was observed for all the other L:D ratios and temperatures. It was observed a sudden decrease in shrinkage between MR = 1 and MR = 0.8 for all L:D ratios. After MR = 0.8, an uneven shrinkage was more evident due to an increased cellular porosity. The shrinkage followed an exponential curve for all L:D ratios at drying temperatures of 30^{0}C, 40^{0}C and 50^{0}C. For MR > 0.8, sudden drop of shrinkage value, may be due to closing of voids already present and created by rapid moisture loss at the initial stages of drying. The initial point was not considered in the modeling and points MR < 0.8, likely to represent most of the shrinkage range. To the contrary, most of the models reported by other researchers for various other food materials where linear correlation existed with the moisture ratio.

The shrinkage behavior (change in volume ratio) of the beans with moisture ratio for different L:D ratios at different drying temperatures were correlated to the moisture ratio using an equation of the form:

$$VR = 1 - B\, e^{-KMR} \qquad (MR \leq 0.8) \qquad (1)$$

Where VR = volume ratio, B = constant, MR = moisture ratio (db), K = constant

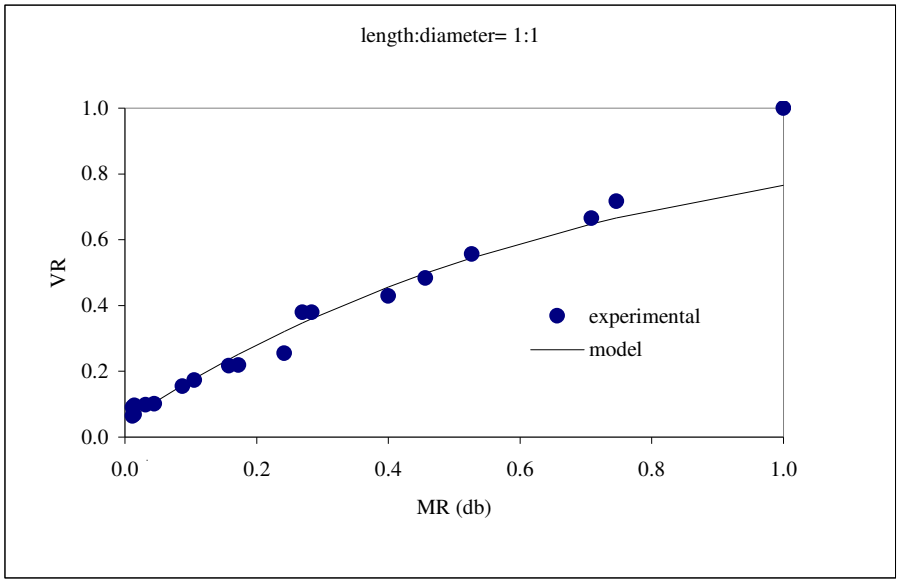

Figure 3 Shrinkage behaviour of beans (L:D = 1:1) at 30 °C

In equation 1, at zero moisture content, volume ratio (VR) would equal (1-B). An individual analysis of the data for L:D ratios showed very close B value (0.93±0.026). The constant B is therefore an indicator of measurement of maximum shrinkability of the product which is a material characteristic. It is reasonable to assume the same degree of maximum shrinkability of the product, when the moisture level of the product approaches towards zero. K is the rate of change of shrinkage with moisture ratio, which varies with the temperature for each size. Increased k value means higher rate of shrinkage.

The B (maximum shrinkability) value is lowest at higher temperature drying (50° C) and higher at lower temperature of drying (30° C). K value (rate of shrinkage) was also higher at reduced temperature. This suggests that the product shrinkage is higher at lower temperature drying conditions, may be due to higher porosity development.

3.1.2. Potato

Shrinkage was not a perfectly homogenous phenomenon same as in the case of beans. Change in volume and shape was different for different aspect ratios. The middle portion exhibited more shrinkage than the ends, probably due to supporting of the structure and shape by the edges and heat transfer controlled by the outer layer of the particle. At lower moisture values some material was lost in powder form due to attrition and abrasion of particles. Also at low moisture values volume remained constant.

Linear model is adequate to describe the shrinkage phenomena. Variation of volume ratio with moisture ratio for different aspect ratios and different drying temperatures were correlated using a linear equation:

$$VR = A + B\,MR \qquad (2)$$

Where VR = volume ratio, A = constant, B = constant, MR = moisture ratio (kg/kg db)

Either potato shows negligible porosity development or a uniform porosity development during drying. The final shrinkage of potato was fixed before moisture reached a minimum value ($m \simeq 0$) for all ratios at all temperatures. Many researchers (McMinn and Magee, 1997; Wang and Brenan, 1995) have also reported that the shrinkage is proportional to the moisture removal. This was due to the homogenous internal structure of potato.

3.1.3. Peas

It was observed that the shrinkage behaviour changes linearly with moisture removal similar to Potato. The shrinkage behaviour of peas was correlated to equation 2. The shrinkage in this research followed a linear behaviour similar to models reported by other researchers for potato, apple and carrot (Karthanos et al., 1996; McMinn and Magee, 1997 and Wang and Brennan, 1995).

For peas it can be seen that maximum shrinkage occurs at 30^0C drying temperature. This was also supported by the significantly lower average diameter value of the final product dried at 30^0C. It can also be seen that the value of B of the equation 2, tends to decrease as the drying temperature is increased. This means that the rate of change of shrinkage is lower at higher temperature conditions.

The effect of temperature increase on the shrinkage was statistically significantly higher in the temperature range 40^o C to 50^o C compared to the range 30^o C to 40^o C. This may be due to case hardening at 50^o C.

Table 1 Calculated shrinkage constants (K or B)

Material	30° C	40° C	50° C
Bean L:D =1:1	1.40	1.31	1.03
Bean L:D = 2:1	1.45	1.37	1.27
Bean L:D = 3:1	1.71	1.40	1.33
Potato AR = 1:1	0.890	0.880	0.871
Potato AR = 2:1	0.887	0.874	0.907
Potato AR = 3:1	0.906	0.861	0.862
Peas	0.7961	0.7785	0.7484

Shrinkage constants given in Table 1 are significantly different ($p < 0.05$) with drying temperature

3.2. Drying kinetics

Figures 4, shows the drying kinetics of peas at three drying temperatures. Similar diagrams were constructed for potato and beans at three drying temperatures. Drying occurred only in the falling rate period for all materials during this investigation. Initial moisture content of the material had uncontrollable natural variation among the replicates. However, the initial moisture variation within the replicates was not significant ($p>0.05$).

The average moisture content was expressed as non-dimensional moisture ratio 'mr' (Equation 3) and used to model the drying curves with time (h). Initial moisture content was used as the critical moisture content due to the absence of a constant rate drying period (Page, 1949).

$$mr = (m - m_e)/(m_o - m_e) \quad (3)$$

Where, m = moisture at given time (kg/kg db), m_o = initial moisture (kg/kg db) and, m_e = equilibrium moisture content (kg/kg db)

Equilibrium moisture content, m_e for each product at different drying temperatures and each product was determined from the sorption isotherms. A separate experiment was conducted to plot sorption isotherms for all products concerned. Data were fitted to the model of the form:

$$mr = \exp(-kt) \quad (4)$$

where, $mr = m - m_e / m_o - m_e$, k= drying constant t= time (h)

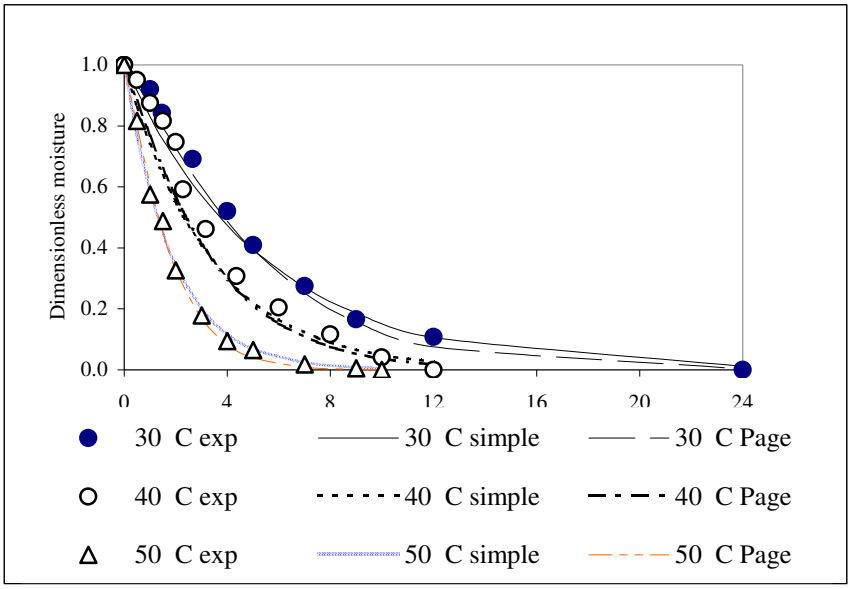

Figure 4 Drying kinetics of pea

Equation 4 is a simple model (Table 2), which showed that only surface resistance to moisture transfer is significant and internal resistance to moisture transfer and moisture gradient within the material is negligible. However, this model tended to over predict the early stages of drying and under-predict the later stages of drying (Figure 4). Also Page model (Page, 1949) was used for the same data but not included in this paper.

Channelling and slugging were observed at the beginning of the drying of potato and beans. This resulted in the escape of air without contacting the whole surface area of the particles, hence, lower moisture removal was observed at the beginning of drying (lower drying rates initially). It might have effected the drying rate. After the establishment of proper fluidisation the drying rates were decreased with time. This obviously will affect the accuracy of above models.

Table 2 Estimated parameters of simple model

Material	**Temperature(^{0}C)**	**k**	**R^2**	**MSE**	**MAE%**
Bean	30	0.4005	0.99	0.0016	11.71
L:D = 1:1	40	0.5679	0.99	0.0059	13.54
	50	0.8770	0.99	0.0100	17.29
Bean	30	0.2361	0.99	0.0008	15.11
L:D = 2:1	40	0.3798	0.99	0.0012	12.98
	50	0.6016	0.97	0.0049	12.01
Bean	30	0.1170	0.97	0.0019	10.56
L:D = 3:1	40	0.2428	0.97	0.0047	17.20
	50	0.4497	0.97	0.0039	15.75
Potato	30	0.7274	0.94	0.0078	14.98
AR = 1:1	40	0.8692	0.97	0.0029	7.84
	50	1.206	0.99	0.0190	14.77
Potato	30	0.6295	0.96	0.0044	15.10
AR = 2:1	40	0.7126	0.95	0.0054	14.54
	50	0.8750	0.97	0.0030	15.28
Potato	30	0.5933	0.99	0.0014	19.08
AR = 3:1	40	0.6428	0.95	0.0067	15.22
	50	0.8518	0.98	0.0025	16.52
	30	0.1867	0.98	0.0024	12.82
Pea	40	0.3001	0.98	0.0006	11.18
	50	0.5342	0.99	0.0005	9.83

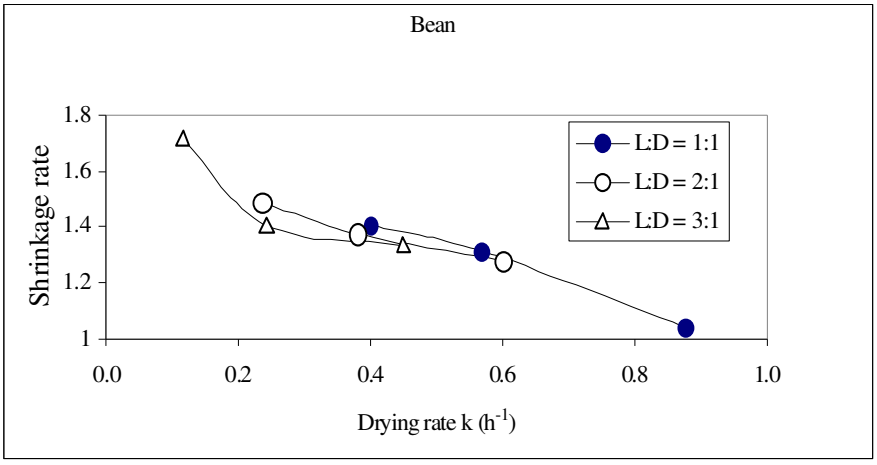

Figure 5 Change of shrinkage constant with drying constant for Beans

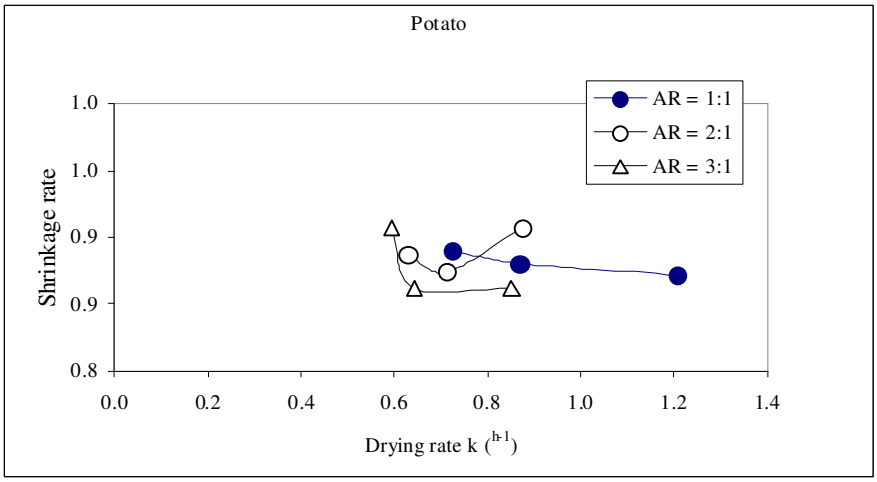

Figure 6 Change of shrinkage constant with drying constant for Potato

3.3. Effect of drying rate on shrinkage rate

Figure 5, 6 and 7 shows the variation of the shrinkage rate (K in equation 1 for beans, B in equation 2 for potato and peas) with the drying rate k (Equation 4) for all materials considered.

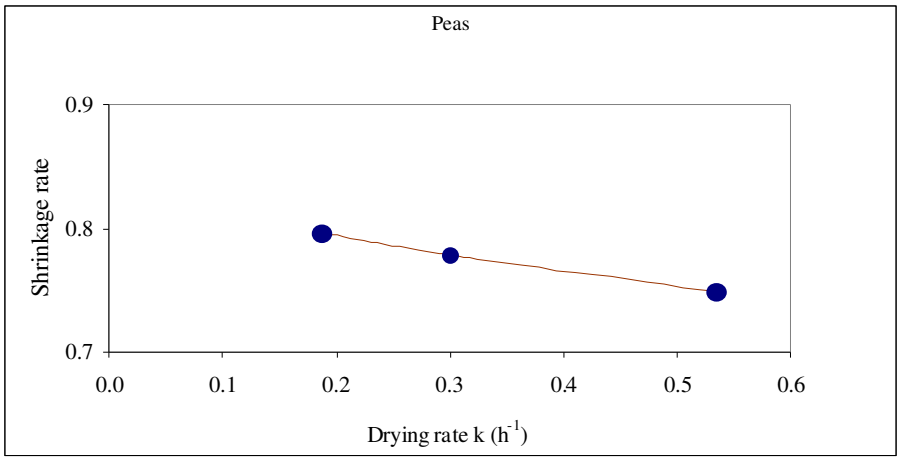

Figure 7 Change of shrinkage constant with drying constant for Potato

3.3.1. Beans and peas

Shrinkage constant for beans and peas increased with decreased drying constant (lower rate of drying results in the higher shrinkage) for all L:D ratios. Rate of shrinkage is higher at lower temperature conditions showing higher porosity development. The relation shows non-linear trend may be due to irregularities in surface roughness on the skin which prevented water transfer and sphericity changes during drying of the particles (L:D = 1 shows more close linear behaviour as during drying sphericity approaches 1). Peas showed linear behaviour due to sphericity (initial value is 1) of the particles which is more favourable in fluidization and hence water removal efficiency.

3.3.2. Potato

But, for potato shrinkage constant changed in a very narrow range compared to the drying constant in an irregular fashion. Three dimensional moisture transfer was evident due to absence of skin layer. Comparatively higher shrinkage at the middle portion of the parallelepiped particles along longer dimension with higher aspect ratios contributed to irregular changes of shrinkage. But aspect ratio 1:1 gave more linear changes as its sphericity change helped good fluidization.

4. CONCLUSIONS

It was observed that there is a relation exists between shrinkage constant and drying constant. But this relation depends on the cellular structure of the material, shape of the material and intensity of drying and how functionality of the structure behaves during moisture transfer. Further experiments are necessary to investigate effects of change of cellular structure and skin surface roughness at micro-structural level on the water removal process during drying.

NOMENCLATURE

A, B, K	constant	
k	drying constant	h^{-1}
m	moisture	kg/kg_{db}
MAE	mean absolute error	
MR	moisture ratio	
MSE	error sum of squares	
n	integer	
R^2	coefficient of determination	
VR	volume ratio	m^3/m^3

Subscripts

e	equilibrium
o	initial

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