Soybean Moisture Absorption Properties and their Related Size Changes by Imaging (Part 2) — 3D size changes —

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ABSTRACT

The study was conducted by using 2D image processing technique, actual measurements of three dimensions 'a', 'b' and 'c' mutually perpendicular axes by vernier caliper and actual volume of grain by picnometer during soaking, with an objective of estimation of volume. The study revealed that; (1) the ratio of instantaneous size to initial size \( a/a_0 \), \( b/b_0 \) and \( c/c_0 \) change with moisture content have a significant disproportion as moisture content increases. (2) The ratio \( b/a \) and \( c/a \) changes with moisture content have 3 periods: constant, falling, and equilibrium. (3) Shape factor has linear relationship with moisture content, and temperature is insignificant. (4) The product of the sizes 'a', 'b' and 'c', that is volume of the circumscribing rectangular box, closely estimates measured volume of grain based on circumscribed theoretical volume within \( r^2 = 0.90 \). (5) Specific volume (abc) and actual specific volume have linear relationship with moisture content, and temperature is insignificant. (6) Actual dry solid density of soybean can be extrapolated from specific volume-moisture content relation, and evaluated as 1.36 (g/cm³). Difference in initial moisture content is insignificant. (7) Image pixels raised to the power of 1.5 modified by shape factor can estimate measured volume within \( r^2 = 0.90 \).

Keywords: soybean, specific volume, moisture content, moisture absorption, three-dimension (3D), image pixels, shape factor.

INTRODUCTION

In small and large scale industrial processing of soybean and other legumes often requires that seeds be hydrated first to facilitate the consecutive extraction or cooking. Fast and near accurate measurements, estimations of total volume to be handled and the status of the moisture content are important parts of the process. Thus, there has been a lot of interest in the theory and mechanism of penetration of water into these materials within researchers and processing industries. Hsu (1983) employed finite difference technique to introduce a model of water movement capable of dealing with the concentration-dependent hydration of legumes. He critically examined temperature dependence of hydration, and demonstrated the dependence of diffusivity on temperature, which follows Arrhenius relation. He assumed a spherical grain and ignored the effect of volume change with moisture content in his simulations. Murata et al (1996) investigated and determined the specific volume-moisture content and temperature relationship of several grains, and derived the following empirical equation:

\[
\ln V = (\phi_1 M^2 + \phi_2 M + \phi_3)T + \phi_4 M^2 + \phi_5 M + \phi_6
\]  

In evaluating the model temperature was found to be insignificant. They applied this equation to several grains, and obtained a fairly good agreement with

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experimental data. Inoue (1998) determined the relationship between specific volume, bulk volume, and rate of volume on moisture content of five varieties of soybeans. He determined the physical properties for use in modeling drying of soybean, his method dwelt on wetting to 100% d.b. moisture content and then measure volume as drying progressed. He obtained good specific volume-moisture content relationship, and had close agreement with Murata (1996) results. However, specific volume at 0 % d.b. moisture content is a difficult and controversial measurement, and needs further research to find out whether it actually represents dry specific volume.

Gab-Soo et al (1996) applied image processing technique and developed microslicer-image data processing system to obtain the quantitative information on the morphology of agricultural products having complex forms. They proposed a prediction method to determine the surface area as well as volume of broccoli from the mass of it. They based on 2D quantitative information such as periphery and area of exposed cross sections from the sliced broccoli. They did not apply the method to cereals or legumes. Therefore, none of the reported results dwelt on determining direct measurement procedures in cereal or legumes soaking process.

In this study, which is the follow up of the previous study, three dimension measurements of soybean are related with moisture content, and finally image pixels of the longer surface of the soybean grain are related with volume and a product of (abc); circumscribing rectangular box volume. Moreover, physical dimensions are evaluated to understand more about their changes with moisture content, and provide preliminary facts on developing volume measurement method in the soaking process.

MATERIALS AND METHODS

1. Materials

Local soybean variety (Fukuyutaka) harvested from Kawanabe Division, Kagoshima Prefecture in 1997 season was used for this experiment. Because the variety and grade of soybean is the same with previous experiment, pixel and moisture content measurement was not repeated in this experiment. Grains sample with 23% d.b. moisture content stored at 2°C cold store was packed in double sheet polyethylene bags and sealed, the sample was slowly conditioned to the test temperature for 24h before experiment. A part of the sample was carefully dried at 30°C to about 11% (d.b.) moisture content. From 23% d.b. moisture content soybean a five grains sample was selected for volume and sizes 'a' (longest), 'b' (intermediate) and 'c' (shortest) mutually perpendicular axes measurements, and twenty grains sample for size 'a', 'b' and 'c' mutually perpendicular axes measurements only. Another five grains sample from 11% d.b. moisture content soybean was selected for volume measurement to compare the effect of initial moisture content on volume-moisture content relationship.

2. Experimental set-up

Fig.1a shows a schematic diagram of the experimental apparatus. Thermal-bath (Eyela NCB, Tokyo Rikakikai Co., Ltd.) with temperature setting accuracy of ±0.1°C was used for soaking experiment. A tray with perforations for holding grains was just immersed in the thermal-bath, and then samples were immersed at intervals determined after rehearsing total time taken for one measurement. Ambient temperature was maintained at 25°C. At a predetermined time interval, volume was measured by five sets of picnometer filled with toluene (density = 0.86305g/ml at 25°C). Dimensions 'a', 'b' and 'c' were measured by digital vernier caliper (Mitutoyo Corp. Absolute Digimatic, CD-15C) with 0.01mm accuracy, and weight by electronic balance (A & D Co. ER-180A) with 0.01g accuracy (Figs.1a & b). Similarly for 5

Fig. 1a Schematic experimental apparatus for measuring volume, mass and 'a', 'b', 'c'.
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An initial grains sample at initial moisture content of 11% d.b. was treated in the same way for volume measurement. Initial conditions for all tests were measured and recorded accordingly.

When sample weight change between measurements became sufficiently small, the experiment was terminated and samples were oven dried for 24h at 105°C to determine dry matter weight. Although shape factor could be determined from above experiments, a separate shape factor experiment by using a mixed soybean sample was carried out to enable determination of practical mean shape factor for 23% d.b. initial moisture content sample.

Three temperatures 10, 20 and 30°C were used for all samples with 23% d.b. initial moisture content, and 20°C was used for the sample with 11% d.b. initial moisture content. In this case, from previous experience we assumed that temperature might be insignificant.

Data was recorded and then processed by StatMost (DataMost Corp., Salt Lake City US) data processing software.

RESULTS AND DISCUSSION

1. Size changes.

The average measurements of 'a', 'b', 'c', and shape factor are summarized in Table 1. The analysis revealed several interesting properties; when the instantaneous three dimension sizes are normalized with their initial size, a/a_o, b/b_o, and c/c_o and related to moisture content, a very significant disproportion is observed between a/a_o with the rest b/b_o and c/c_o. The value a/a_o varies sharply and longer after moisture content reaches about 1.7 times the initial moisture content, while the rest remained almost constant (Fig. 2). This is to say that, soybean size changes are predominantly in 'a' direction, and disproportion of 'a' is more than 50% of the rest. Soybean seedcoat is a viscoelastic and anisotropic material, it is stronger in 'a' than in 'b' direction (Mensah et al, 1984). Cotyledons lattice arrangement and seedcoat elongates more in 'a' direction than the rest when moisture content increases.

The expansion vary to the initial size by about 70%, 25% and 10%, for 'a', 'b' and 'c', respectively. When 'b' and 'c' expansions are related to 'a', that is ratio b/a and c/a during moisture absorption, three periods are observed.

Fig. 2 show the periods, the periods are synonymous to the periods observed in drying of wet agricultural material. The first period is characterized by constant change of b/a and c/a with moisture content up to about 50% d.b. moisture content, then followed by a
falling period up to about 100% d.b., and from this point stable and equilibrium period takes over.

This phenomenon is still under investigation, but a difference in moisture absorption between endosperm and cotyledon and removal of air in the pores under endosperm is thought to be the cause of the first period. The second period follows by continuous and free moisture absorption, and as mentioned earlier elongates structures of cells and seedcoat relatively longer and faster in ‘a’ direction. The last period is equilibrium, that is moisture saturation in both cotyledon and seedcoat, at this point seedcoat is prone to rapture because of cotyledon pressure and the fact that seedcoat strength is inversely proportional to moisture content (Mensah et al, 1984).

2. Shape factor

Shape factor is determined from a, b and c as shown in Fig. 1b and also explained in detail in part I of this paper. Shape factor of a perfect sphere is 1.0 and will increase, as the object becomes irregular. Experimental data from soybean sample was fitted by regression with moisture content, a linear relationship was obtained. Temperature change although widely varied from 10°C to 30°C is insignificant. The linear relation is of the form:

$$\eta = \beta_0 + \beta_1 M$$

(2)

Fig. 4 shows the linear relationship for 10, 20 and 30°C experiments, and Table 2 shows statistical results of the regression and values of the parameters. Combined soybean shape factor was evaluated as 1.45 at $R^2=0.7$ and SD=0.17, and no significant deviation from standardized sample shape factor ($\gamma=1.42$). Low regression coefficient and high SD might be due to mixed sample and the measurement method used. This factor is at least for now recommended for this variety of soybean when 2D measurements are converted to 3D. Shape factor provided a means for estimating the volume of soybean based on theoretical volume equation in part I of this paper.

3. Actual specific volume and specific volume calculated by a, b and c.

3.1 Actual specific volume change with moisture content

The volume and weight of the soybean grains are measured as explained earlier and converted to specific

![Fig. 4 Shape factor change with moisture content.](image)

<table>
<thead>
<tr>
<th>Temperature</th>
<th>$\beta_0$</th>
<th>$\beta_1$</th>
<th>SD</th>
<th>$r^2$</th>
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<tr>
<td>20°C</td>
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<td>0.003</td>
<td>0.012</td>
<td>0.70</td>
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<tr>
<td>30°C</td>
<td>1.18</td>
<td>0.003</td>
<td>0.011</td>
<td>0.70</td>
</tr>
<tr>
<td>Combined</td>
<td>1.18</td>
<td>0.003</td>
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</table>

Combined soybean shape factor

Table 2 Shape factor parameters for combined sample, Mo = 23% d.b.

<table>
<thead>
<tr>
<th>Temperature</th>
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<th>$\eta$</th>
<th>SD</th>
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<td>Mean</td>
<td>1.24</td>
<td>0.18</td>
<td>Mean</td>
<td>1.45</td>
</tr>
</tbody>
</table>
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Volume, and specific volume \((abc)\) after determining dry matter mass experimentally. When specific volume is correlated with moisture content at 10, 20, and 30°C, the result as expected is linear (Fig. 5). Least square minimization was applied to the data to evaluate actual dry specific volume by using equation (3).

\[
V = \left( \frac{1}{\rho_s} + \frac{M}{\rho_w} \right)
\]

According to our results dry specific volume of this variety of soybean was 0.735 (cm\(^3\)/g), this is the actual dry specific volume. Inoue (1998) obtained 0.771 (cm\(^3\)/g) for this variety. And both results evaluate to dry solid density of 1.36 and 1.30 (g/cm\(^3\)), respectively. In both cases temperature is insignificant.

The effect of initial moisture content on specific volume was evaluated by comparing specific volume data for samples at 11% and 23% d.b. initial moisture content. Fig. 6 shows the combined plot of both 11% and 23% d.b. at 20°C. Regression result reveals that, there is 3.4% deviation in the dry solid density parameter between 11% d.b. and 23% d.b. sample at 20°C when fitted separately. When combined and fitted as shown in Fig. 6, the deviation is 0.7% from 23% d.b. sample when fitted separately. Hysteresis is the cause of this deviation, ideally the 11% d.b. line should pass through the 23% d.b. point when moisture content is increasing, but this is not the case because of hysteresis phenomenon. However, deviation caused by this phenomenon is small (max. 3.4%) and practically results in Fig. 6 can be used without significant error in volume determination.

3.2 (abc) specific volume relation with actual specific volume

The (abc) specific volume was related with actual specific volume by using moisture content data and earlier evaluated dry solid density, and then related by actual measured specific volume for comparison. Let \(V_0=(abc)\), theoretically the specific volume of a round object circumscribed by the rectangular box of dimension ‘\(a\)', '\(b\)', and '\(c\)' is given by:

\[
V = \frac{\pi (a \times b \times c)}{6} \frac{W_{DM}}{W_{DM}} = 0.52 (a \times b \times c) \frac{W_{DM}}{W_{DM}} = 0.52V_0
\]

The specific volume equation (4) was then used to relate \(V_0\) with specific volume by using experimentally measured specific volume as follows:

\[
V = \phi V_0
\]

Actual and (abc) specific volume data was then fitted by least square minimization method to equation (5). Fig. 7 shows the fitting results, the result was for combined three temperatures and the parameter value was evaluated as \(\phi = 0.50\) which is very close to the theoretical value \(\pi/6 = 0.52\) in equation (4), within 3.8%.
In the previous paper we referred the soybean grain specific volume as defined in equation (3). It was then rearranged to relate specific volume \( V_{abc} \) and actual specific volume as follows:

\[
V_{o} = \frac{1}{\varphi} V = \left( \frac{1}{\rho_{s}} + \frac{M}{\rho_{w}} \right)
\]

(6)

Measured moisture content data was then fitted at each temperature in equation (6), while dry solid density \( (\rho_{s}) \) and density of water \( (\rho_{w}) \) were fixed at 1.36 (g/cm\(^3\)) as evaluated earlier and 1 (g/cm\(^3\)), respectively. From fitting results the parameter \( \varphi \) was evaluated as 2.1, 2.0, and 2.0 for 10, 20 and 30°C, respectively. Inversely, the value of \( \varphi = 0.48, 0.50 \) and 0.50 for 10, 20 and 30°C, respectively. The combined temperature fit evaluated to the value \( \varphi = 0.48 \) and inversely \( \varphi \approx 0.5 \), this value deviates from theoretical value by 3.8%. There is no difference in using moisture content or actual volume data in relating both specific volumes. Fig. 8 shows three temperatures plot and fit of the relationship without fixing the dry solid density of the material, and evaluated to \( \varphi \approx 0.48 \) and \( \rho_{s} = 1.38 \) (g/cm\(^3\)), there is no significant deviation from the earlier results.

From these findings both specific volumes can be used to estimate each other within that range of accuracy. It is therefore a matter of decision as to what volume is needed by the user depending on the data available.

4. Image pixels (P), specific volume (V) and \((abc)\) relationship.

The following was to justify our main argument of using image pixel data for nearly accurate determination of volume of soybean grain during moisture absorption. Because of difficulties in calculating accurate magnification, we have used ratios or normalized volume and pixel. From the above results and previous report, it is now clear that the following relationship theoretically must hold true if soybean expansion is even:

\[
\frac{S}{S_0} = \left( \frac{V}{V_0} \right)^{\frac{3}{2}} \quad \text{therefore} \quad \left( \frac{P}{P_0} \right)^{1.5} = \frac{V}{V_0} = \frac{abc}{a_{s}b_{s}c_{s}}
\]

(7)

By using shape factor data we converted pixel to the following form:

\[
\eta \left( \frac{P}{P_0} \right)^{1.5} = \frac{V}{V_0} = \frac{abc}{a_{s}b_{s}c_{s}}
\]

(8)

The ratios were then plotted against moisture content (Fig. 9). Pixel data was from two initial moisture contents (11% and 25% d.b.), and volume data was from 11% and 23% d.b. The maximum difference within their means is 0.14 and the minimum is 0.03. Their maximum slope difference when plotted separately is about 0.27. Since experimental data is so diverse and fitting results agreed well, we can therefore use pixel data to estimate volume of the grain within this accuracy.

CONCLUSION

1. The study has revealed that, the ratio of instantaneous to initial size \( a/a_{s} \), \( b/b_{s} \) and \( c/c_{s} \) have significant unproportional change with moisture content. And therefore in spite of raising 2D image pixels to the power of 1.5 for volume estimation, shape factor should be included in the equation to account for unproportional change in shape.

2. The ratios of intermediate and shortest size to longest size \( b/a' \) and \( c/a' \), respectively, have three periods change with moisture content. The first constant

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![Fig. 8 Specific volume (abc) change with moisture content for 10, 20, 30°C.](image)

![Fig. 9 Pixel, specific (abc) and volume with moisture content.](image)
period might be caused by difference in moisture absorption between endosperm and cotyledons and removal of air in the air pores under endosperm. The second period is continuous and free moisture absorption, and enlarges structures of cells and seedcoat relatively longer and faster in 'a' direction. The last period is equilibrium, that is moisture saturation in the cotyledon and seedcoat.

3. Shape factor has linear relationship with moisture content, and temperature change is insignificant.

4. Specific volume calculated by the product of 'a', 'b' and 'c' (abc), that is volume of circumscribing rectangular box can closely estimate volume of circumscribed soybean grain based on theoretical volume of circumscribed round object equation, within $r^2 = 0.90$.

5. Specific volume based on (abc) and actual specific volume has linear relationship with moisture content. Actual dry solid density can be extrapolated from the relationship, and was evaluated as 1.36 (g/cm³).

6. The study has developed a method for calculating volume of the seeds during moisture absorption by the direct relationship using 2D image pixel data, moisture content and shape factor. The method can at least for now be used to calculate volume of single grains. This is due to the fact that 2D image pixel data was used from experiment conducted in part I by two different initial moisture contents.

ACKNOWLEDGEMENT

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NOMENCLATURE

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<tr>
<td>s</td>
<td>solid</td>
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<tr>
<td>w</td>
<td>water</td>
</tr>
<tr>
<td>DM</td>
<td>dry matter</td>
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REFERENCES

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大豆の吸水特性と膨張度合の画像解析（第2報）
—3次元形状変化—

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要 旨

本研究では、吸水過程における大豆粒の3次元形状・比容積および2次元形状を測定し、それぞれの特性について考察するとともに、3者の関係を求めめた。その結果、以下のようなことが明らかとなった。

1) 大豆粒の3次元形状は吸水初期において急激に膨張し、その後、平衡値に至る。
2) 幅(b)および厚さ(c)の長さ(a)に対する比(b/a)、(c/a)は含水率に依存して変化する。すなわち、50%d.b.以下では一定値を示し、50〜100%d.b.では直線的に減少、100%d.b.以上で一定値を示す。
3) 形状係数は含水率に関して一次の関係を持つが、温度には依存しない。
4) 3次元形状を元に計算した扁平円球の体積は、ピクノメーターを用いて測定した比容積と相関係数0.90で良く一致した。
5) 3次元形状から求めた大豆粒比容積と実比容積は含水率に対して線形の相関を持つ。しかし、温度依存性は見られなかった。
6) 統計から求めた大豆乾物の真密度は1.36g/mlであった。
7) 大豆粒の2次元画像と形状係数をもとに比容積を推算した結果、実比容積と相関係数0.90で良く一致することが分かった。

キーワード：大豆、比容積、含水率、吸水、3次元、画素、形状係数