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A Linear Driving Force (LDF) approximation of moisture uptake kinetics in soybean

Abhishek Dutta[1,2], Runni Mukherjee[3], Tanmay Sarkar[3], Zehra Pınar[4], Runu Chakraborty[3]

[1]Faculteit Industriële Ingenieurswetenschappen, KU Leuven, Campus Leuven (@Groep T), Andreas Vesaliusstraat 13, B-3000 Leuven, Belgium
[2]Departement Metaalkunde en Toegepaste Materiaalkunde (MTM), KU Leuven, Kasteelpark Arenberg 44, B-3001 Heverlee-Leuven, Belgium
[3]Department of Food Technology and Biochemical Engineering, Jadavpur University, Kolkata 700 032, India
[4]Department of Mathematics, Faculty of Arts and Science, Namık Kemal University, 59030 Merkez-Tekirdağ, Turkey

Abstract

A comparative analysis of the theoretical-experimental study on the hydration characteristics of soybean was performed through several soaking experiments at temperatures 20, 30, 40, 50 and 60°C by measuring moisture content over 8 hour time span. The mass transfer kinetics is modeled using a Linear Driving Force (LDF) approximation with effective diffusivity, which is capable of predicting the moisture uptake profile with time. The absorption curves of soaked soybean at different time and temperatures were calculated with this approach in spherical coordinates. The objective of this present work is to develop a simplified moisture uptake model, based on LDF approximation, for this variety of soybean cultivar. The effect of time and temperature on the hydration characteristics of soybean was studied and effective diffusion coefficients at this temperature range were calculated. The method gives a reasonably good agreement with the experimental data. It is observed that the temperature has a significant importance in the soaking process.

Keywords- moisture content; linear driving force; mass transfer; soybean

1. Introduction

Soybean (*Glycine max* L. Merr.) is a major member of the legume family. Soybean seeds are largely utilized for extraction of oil and the production of various soybean products such as tofu, tempe, soymilk, soybean meal, etc. The amount of protein in soybeans (38–44%) is higher than the protein content of other legumes (20-30%) and much higher than that of the cereals (8–15%) (Synder and Kwon, 1987). Soybeans and the foods made from them are known to have good nutritional and functional qualities, not only for their high protein and oil content, but because of the phytochemicals like isoflavones (Wardhani et al, 2008).

The step of water hydration is very important during the production of traditional soybean-derived foods such as soymilk (Nelson et al, 1976) and tempe (Mulyowidarso et al, 1989). Water absorption by soybean seeds affects the grain texture which is helpful in subsequent grinding, soymilk production or protein extraction steps (Lo et al, 1968; Pan and Tangratanavalee, 2003). Grain hydration also aides in reducing cooking time as well as in minimizing losses, thereby improving the quality of the final products (Wang et al, 1979). To improve protein digestibility and reduce the processing time, soaking above ambient temperature is generally recommended (Bayram et al, 2004). The physico-chemical structure of the seeds has an important effect on the absorption of water as smaller and drier ones grain moisture very rapidly and in turn increase in volume (Saravacos, 1969). Apart from soybeans, soaking is also regularly used during the processing of other foods, such as during rice parboiling (Engels et al, 1986) and in sorghum flour preparation (Adeyemi, 1983).

The time-temperature binomial is the main process of water absorption in soybean grain. The amount of water absorbed increases proportionately with soaking time and temperature (Wang et al., 1979; Pan and Tangratanavalee, 2003). Fundamentally, there are two models of moisture hydration of grains namely, empirical and phenomenological. Singh and Kulshrestha (1987), Peleg (1988) used empirical models that are generally obtained from simple mathematical correlation of experimental data. Phenomenological models consider the elementary steps of diffusion and/or convection mass transfer using lumped parameter or distributed parameter approach and generally present the main process tendencies through a mass balance equation. Glueckauf and Coates (1947) first derived a linear driving force (LDF) approximation in which the mass balance equation is eliminated from the Fickian diffusion model, leaving only the mass balance equation in the fluid phase (adsorbate) to be solved. The complex partial differential equation is thus replaced by a much simpler ordinary differential equation, which states that the uptakerate of a species is proportional to the difference between the surface concentration and the average concentration within the particle (Li and Yang, 1999). Liaw et al. (1979) showed that a LDF approximation can be obtained if a parabolic intraparticle concentration profile is postulated. The equivalence of LDF approximation, in solving the intraparticle diffusion equation, to a parabolic concentration profile is shown by Yao and Tien (1992) and Dutta et al (2008). In this study, the moisture hydrationkinetics of soybean grains have been solved by a LDF approximation, thereby presenting a simplified approach to a distributed parameter approach. Furthermore, the variation of grain size during the hydration process is taken into consideration in the LDF approximation.

2. Linear Driving Force (LDF) Approach

Mathematically, it is well known that Taylor series and power-series expansions havea polynomial profile. As the degree of polynomial increases, the approximation becomes closer to its exact solution. However higher degree polynomials yieldmore complex expressions, whereas the so-called Linear Driving Force (LDF) approximation is a consequence of truncating the polynomial to a parabolic profile (Glueckauf, 1955). Thus a LDF model provides substantial simplification in computation and is applied to complex processes such as intraparticle mass transfer. This approximation expresses the rate of interphase mass transfer as the product of a rate coefficient times a driving force written as a concentration difference. The LDF approximation can be considered to be equivalent to the long-time diffusion result (Jury, 1967) and the parabolic profile approximation for intraparticle diffusion (Rice et al., 1983; Liaw et al, 1979). An equivalent approach to the use of the LDF approximation is to have a generalized concentration profile within the particle. The LDF approximation provides a clue forderiving the concentration profile within the particle as the approximation to the intraparticle concentration reduces the transient radial diffusion model with complex boundary conditions to a first-order simple ordinary differential equation. The model approximation is explained as follows:

$A(t)$ and $B(t)$ are considered as time-dependent parameters with n as an order of approximation as in Li and Yang (1999); so the generalized concentration profile is given by an order of polynomial approximation:

$$X(r,t) = A(t) + B(t)r^n \tag{1}$$

A 2nd order binomial parabolic concentration profile (when n = 2) is obtained for Eq. (1) which corresponds to the LDF approximation (Dutta et al, 2008). Eq. (1) becomes a parabolic concentration known as LDF approximation. If the order of approximation is different from 2, a generalized concentration profile is obtained. $A(t)$ and $B(t)$ can be solved from two boundary conditions $dX/dr|_{r=0}$ and $X(r = R_p) = X(t, R_p)$.

On substituting $A(t)$ and $B(t)$ in Eq.(1) (see later in the text), a non-linear mass transfer model can be reduced to a numerically or analytically (wherever feasible) solvable equation.

3. Theoretical Model Development

Hsu (1983) developed a phenomenological model using distributed parameter approachfor soybean grains with the assumption that they are spherical, diffusion takes place only in the radial direction, and the diffusion coefficient is a function of volumetric moisture content. A mass balance on a differential volume element of the soybean grain, combined with Fick's first law of diffusion is given as:

$$\frac{\partial X}{\partial t} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D \frac{\partial X}{\partial r}\right) \tag{2}$$

where $D = D_0 e^{k_1 X}$ which determines the functional relationship between diffusion coefficient D and moisture content X. The initial and boundary conditions for the above equation are given as:

$$X(r,0) = X_0 \text{ for all } r \tag{3}$$

$$\partial X / \partial r = 0 \text{ for } r = 0 \tag{4}$$

$$X(R_p,t) = (1-e^{-\beta t})X_{eq} + X_0 e^{-\beta t} \text{ for all } t \tag{5}$$

Eq.(4) represents the symmetry condition. The moisture content on the surface behaves as a first order with respect to time according to Eq. (5). Furthermore, the following assumptions are necessary for the model development:

(a) Unsteady-state liquid diffusion is the mechanism of moisture movement.
(b) The components of the grain material are homogeneous and isotropic.
(c) The grain is considered to be isothermal during soaking, i.e., the heat Transfer equations may be neglected.
(d) During soaking, the mass transfer coefficient is assumed high enough such that the boundary layer instantaneously achieves the saturation moisture content.

Although most hydration studies in soybean did not consider the volume increase (Singh and Kulshrestha (1987); Deshpande et al, 1994; Coutinho et al, 2005; Gulati et al, 2010). The grain volume variation is represented by the radius r versus time t obtained from the relation given in Nicolin et al (2012). It was suggested by Coutinho (2006) that temperature had no significant influence on the relationship of moisture content with time, indicating water diffusion inside soybean grain as the mass transfer limiting step.

4. Materials and Methods

SBM was obtained from Ruchi Soya Industries Ltd. (Kolkata, India). Soaking of SBM was done at 20, 30, 40, 50 and 60°C for the time intervals 1 to 10 hours. For soaking at each time and temperature, SBM was added to water (1:10 ratio of SBM to water) kept at that temperature. For the measurement of moisture content in percentage dry basis (% db), previously weighed soaked samples were dried in an air oven at 110°C for 20 hours. The samples were covered and weighed immediately after drying.

5. Results and Discussions

To have a better understanding of the transient diffusion inside the soybean grain, it is necessary to find out a suitable concentration profile which best matches the LDF approximation. It is observed that using n = 2 and the adjusted parameter values of D_0, β and k_1, a second order binomial concentration profile can be obtained. The intraparticle concentration X(r,t)is represented by a generalized concentration profile to be a function of two time-dependent parameters $A(t)$ and $B(t)$ as follows:

$$A(t)=X_{eq}-X_{eq}e^{-\beta t}+12e^{-\beta t}-0.9025\left(\frac{400\beta e^{\left(\frac{-361\beta t+400\beta r^2 t+2400tD_0}{(20r-19)(20r+19)}\right)}(X_{eq}-12)}{-361\beta+400\beta r^2+2400D_0}+\_C1\right)e^{\left(\frac{2400tD_0}{(20r-19)(20r+19)}\right)}$$

$$B(t)=\left(\frac{400\beta e^{\left(\frac{-361\beta t+400\beta r^2 t+2400tD_0}{(20r-19)(20r+19)}\right)}(X_{eq}-12)}{-361\beta+400\beta r^2+2400D_0}+\_C1\right)e^{\left(\frac{2400tD_0}{(20r-19)(20r+19)}\right)} \tag{6}$$

Substituting $A(t)$ and $B(t)$ for n = 2 in Eq. (1)gives the expression for a generalized concentration profile:

$$X(r,t)=X_{eq}-X_{eq}e^{-\beta t}+12e^{-\beta t}-0.9025\left(\frac{400\beta e^{\left(\frac{-361\beta t+400\beta r^2 t+2400tD_0}{(20r-19)(20r+19)}\right)}(X_{eq}-12)}{-361\beta+400\beta r^2+2400D_0}+\_C1\right)e^{\left(\frac{2400tD_0}{(20r-19)(20r+19)}\right)}$$
$$+\left(\frac{400\beta e^{\left(\frac{-361\beta t+400\beta r^2 t+2400tD_0}{(20r-19)(20r+19)}\right)}(X_{eq}-12)}{-361\beta+400\beta r^2+2400D_0}+\_C1\right)e^{\left(\frac{2400tD_0}{(20r-19)(20r+19)}\right)}r^2 \tag{7}$$

Using n = 2 , the LDF approximation for moisture uptake in soybean for temperatures 20, 30, 40, 50 and 60°C is shown in Figure 1(a-e).

It is observed that the LDF approximation matches closely with the absorption curves at soaking temperatures 40 and 50 °C, while for the remaining temperatures the approximation slightly overpredicts the data. A closer look into the experimental data reveals a non-uniform increase in moisture content from 2-6 hours for the initial soaking temperatures 20 and 30 °C. This behavior is also observed for the final soaking temperature (60°C) for the soybean cultivar chosen in the study. Being inherently an approximation approach, it is a limitation of the generalized concentration profile. Although the integer n does not influence the accuracy of the LDF approximation too much (Başağaoğlu et al, 2000), it does have strong effects on the shape of the concentration profile (Li and Yang, 1999).

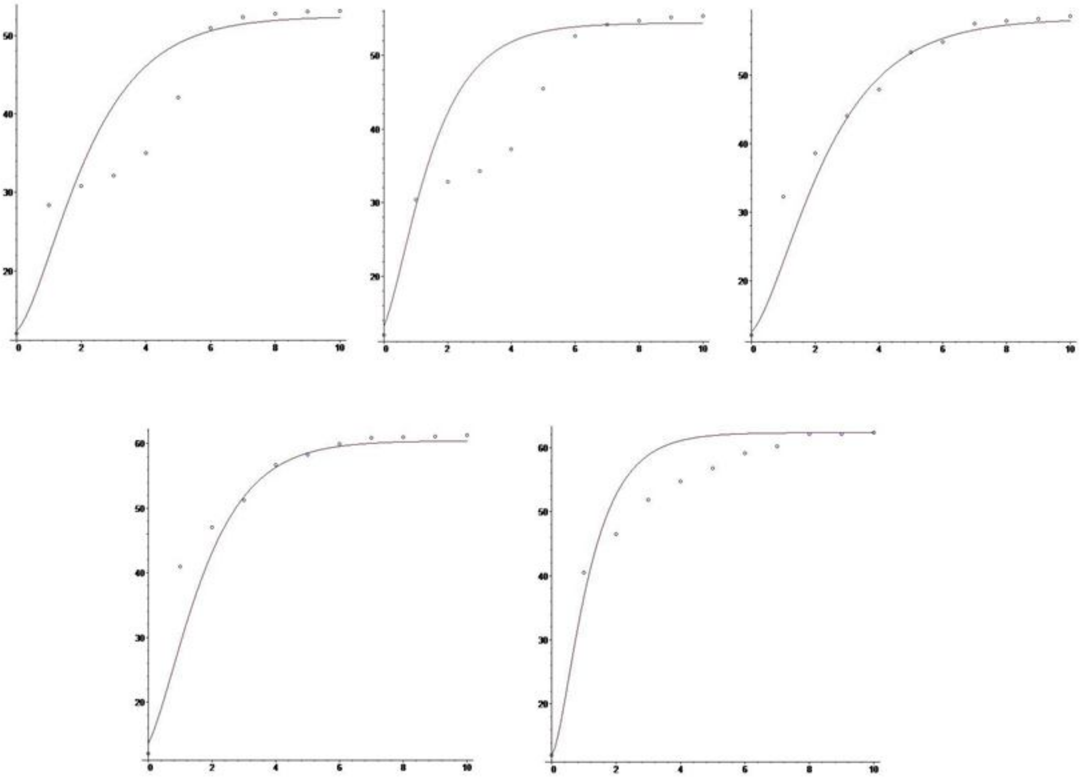

Figure 1(a-e).LDF approximation (with n = 2) of moisture uptake rate with effective diffusivity for the time-temperature binomial 20, 30, 40 °C (top three figures a-c from left to right respectively) and 50, 60 °C (bottom two figures d-e from left to right respectively). The x-axis represents the soaking time t (in hour) and y-axis represents the volumetric moisture content X (in % d.b).

Conclusions

Linear driving force approximation indicates a simplified approach to obtain analytical solutions of soaking characteristics in food grains. The absorption curves of soaked soybean grans at different time (0-8 hours) and temperatures (20, 30, 40, 50 and 60°C) closely match the second-order binomial concentration profile i.e. for n = 2. The effect of time and temperature on the hydration characteristics of soybean was studied using the generalized concentration profile. Although the method gives a reasonably good agreement with the experimental data, further improvements in the LDF approximation approach could be made in order to account for the irregularities in the soaking phenomenon.

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