Water uptake in brown rice during soaking for production of no-cooking rice

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Abstract: Water uptake behavior of brown rice during soaking as a part of the process of producing '*komal chawal*', a kind of traditional no cooking rice to the population in the State of Assam, India, is modelled to Fick's diffusion equation. Grain swelling resulting from water uptake was accounted by the moving boundary formulation. The model was applied to the hydration data of brown rice at soaking temperatures of 40^{o}C-65^{o}C, with saturation moisture content estimated from experimental hydration data. Dependence of effective diffusivity on the temperature and moisture content was expressed as a factor estimated from enthalpy-entropy compensation of moisture sorption behavior. Model fitting yielded values of effective diffusivity in a range of 2.13×10^{-11} - 1.52×10^{-10} m^2 s^{-1}. Calibrated model could predict the evolution of moisture with soaking time, as validated by comparing with experimental data, enabling the prediction of end of soaking period to reach the desired moisture level for steaming.

Keywords: no-cooking rice, water uptake, effective diffusivity, moving boundary, enthalpy-entropy compensation

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1 Introduction

Rice is the staple food and one of the best crops for over half of the world's population (Ali and Pandya, 1974). For about 150 million rural households in India, the rice crop forms the basic economic activity directly or indirectly (Krishnaiah and Janaiah, 2000). After harvesting, paddy is handled almost in a globally uniform manner i.e., by subjecting either to the process of drying for safe storage or to hydrothermal treatment for further processing to produce value added forms such as parboiled rice, puffed rice, flaked rice etc.

Rice obtained from the milling of hydrothermally treated paddy is considered as one form of value added product (Thakur and Gupta, 2006). One kind of value added product of rice, called *komal chawal,* is produced traditionally in the state of Assam, India, by parboiling a low amylose paddy variety named '*chokuwa*'. This product is produced by parboiling (soaking, steaming and drying) of '*chokuwa*' paddy and subsequent milling, and has the quality of attaining a soft texture on soaking in cold to lukewarm water for about 15-20 minutes which is soft enough for consumption. Since the product does not require cooking in the process of preparation for consumption, it is regarded as one kind of no-cooking rice and is termed as *komal chawal* in the native language, meaning soft rice (Dutta and Mahanta 2014). This parboiled rice product is used by the natives in the preparation of a variety of traditional dishes and is quite popular among low-income group of the population including the farmers.

In a deviation from the traditional method of *komal chawal* production by paddy parboiling, one study is undertaken by the authors to produce *komal chawal* by the application of brown rice parboiling method, considering the possibility of saving of energy and time. Finding out the optimized process conditions at various steps of parboiling is one of the objectives of the study. In this work, the hydration behavior of the brown rice, at the soaking step of the parboiling, is being modelled to established theories with appropriate calibration of model parameters.

Researchers have mentioned the advantages and

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disadvantages of brown rice parboiling method. This method leads to faster hydration, lower bulk handling, faster and cheaper processing, and reduced operation cost (Kar et al., 1999; Parnsakhorn and Noomhorm, 2008). Some associated difficulties are the deformation of the grain that loses the exuded part of the endosperm, reduces milled yield (Parnsakhorn and Noomhorm, 2008). Also, there are possibilities of caking and cracking resulting from longer durations of soaking and steaming which subsequently causes difficulties in handling (Oli et al., 2014).

In a generic sense, any kind of severity during the steps may cause significant changes in the properties of parboiled rice (Bhattacharya, 2004). Hence, process conditions may be chosen as per the criteria of being just adequate to fulfill the requirement. In the case of soaking as the first step of parboiling, the criterion is the availability of sufficient moisture within the endosperm for gelatinization in the next step of parboiling i.e., steaming. However, the gelatinization as a reaction is a site-specific phenomenon which is affected by the temperature and moisture at the reaction site. Thus, for the desired average moisture content of 30% at the end of soaking, a flatter moisture profile at the beginning of steaming would be considered preferably than a steeper profile for adequate gelatinization during steaming. Accordingly, instead of quantifying the endosperm moisture based on an average value, a distribution profile is proposed to be obtained. Present work is undertaken to study the hydration behavior of brown rice obtained from '*chokuwa*' variety, to observe the distribution of moisture inside the brown rice to ensure the optimized soaking condition for parboiling before the steaming step.

Cereal grains absorb moisture at different rates. The water absorption characteristics during hydration of paddy, brown rice or milled rice are mathematically modelled with a solution of the diffusion equation in the works of Bello et al. (2010), Bello et al. (2004), Cheevitsopon and Noomhorm (2010), Bakalis et al. (2009), and Ahromrit et al. (2006).

An understanding of the mechanism of moisture movement in food materials during hydration is not yet conclusive. However, the application of Fick's second law of diffusion with an effective diffusion coefficient is justified based on the hypothesis, that, the resistance to water diffusion is distributed throughout the material. . This needs to be supplemented by appropriate consideration of dependence of diffusion coefficient and volume change resulting from moisture gain. Reported works are available for grains with solutions of the diffusion equation with the assumption of a constant diffusion coefficient and no change in volume (Engels et al., 1986; Thakur and Gupta, 2006). Similarly, solutions of Fick's second for drying application in some other works involve the consideration of moisture dependent diffusion coefficient, but ignoring of the volume change (Aguerre et al., 1985; Dutta et al., 1988; Tolaba et al., 1997).

However, the occurrence of swelling of biological products, which take place simultaneously with water diffusion and affect the water absorption rate, may not be ignored. It is important to study the swelling phenomena for a better understanding of the hydration process of brown rice. Perhaps the lack of adequate information on the magnitude of swelling velocity and its relationship with water diffusivity has made it difficult to consider swelling during the soaking processes. Researchers such as Viollaz and Suarez (1984), Gekas and Lamberg (1991), Hawlader et al. (1999), had applied the kinetics of volume change with the kinetics of moisture transport in solving drying problems. In an application of a similar approach for the process of water absorption during hydration, Bello et al. (2010) had included the considerations of the change in volume along with an expression for variable diffusivity for solving the Fick's law based diffusion equation. The magnitude of change in volume was linearly related to the amount of water uptake (Bello et al., 2010; Muthukumarappan et al., 1992; Bhattacharya, 1995).

In this work, it is proposed to apply and calibrate the mathematical model of Bello et al. (2010) to describe the water uptake in '*chokuwa*' brown rice (dehulled) with the consideration of swelling, and dependence of diffusion coefficient on moisture concentration and temperature. A finite difference method based solution of the governing equation and corresponding boundary conditions is used to simulate the water absorption process in '*chokuwa*' brown rice and to determine the liquid diffusion coefficient and its dependence on water concentration.

2 Hydration model

2.1 Diffusion equation for hydration of swelling particles

The water absorption during soaking of brown rice is considered as a diffusion process occuring in a binary system. The system consists of a solid (B), whose mass remains constant, and a diffusant (A), which is water in this case, and is diffusing in a liquid phase. For applying the Fick's law of diffusion to describe the moisture movement in the brown rice, following assumptions are made.

1. Water migration is occurring under isothermal conditions at the temperature of soaking water;

2. Dimensional change in the brown rice is occurring due to absorption of moisture only, no solid loss in the soaking water;

3. Change in brown rice volume is equal to the volume of water absorbed.

Similar assumptions are used in earlier works (Bello et al., 2010; Aguerre et al., 2008). Validity of assumption 1 is ensured with the use of temperature controlled experimental set up. Assumption 3 is justified from the linear plot of incremental brown rice volume against amount of absorbed water, which has a slope of around 1.0. Based on these assumptions, the expression for diffusion equation obtained is as below:

For a spherical particle, the one-dimensional equation (Equation (1)) for diffusion is,

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

where, ρ_A is the volumetric concentration of diffusant (A) i.e. water, in kg m^{-3}; $D_{(\rho_A)}$ represents the effective diffusivity or diffusion coefficient (function of diffusant concentration) m^2 s^{-1}; r is the radial coordinate (m) and t is the time (s).

For solving Equation (1) initial and boundary conditions considered are

$$\rho_A = \rho_{A_o} \quad \text{For } t=0 \text{ and } 0 \le r \le R \tag{2}$$

$$\rho_A = \rho_{A_i} \quad \text{For } t>0 \text{ and } r = R \tag{3}$$

$$\frac{\partial \rho_A}{\partial r} = 0 \quad \text{For } t>0 \text{ and } r = 0 \tag{4}$$

where, ρ_{A_o} is the initial moisture concentration (kg m^{-3}) and ρ_{A_i} is the saturation moisture concentration (kg m^{-3}), assuming that the surface of the solid reaches instantaneously the moisture concentration corresponding to saturation, while R represents the radius of the solid (m).

However, as the solid is undergoing a volume change, radial coordinate may be represented by $r_{(t)}$, and the instantaneous value is a function of time owing to the volume change of the solid. As a result, the Equation (1) modifies as,

$$\frac{d\rho_A}{dt} = \frac{1}{r^2}\frac{\partial}{\partial r}\left(r^2 D_{(\rho_A)}\frac{\partial \rho_A}{\partial r}\right) + \frac{\partial \rho_A}{\partial r}\cdot\frac{dr}{dt} \tag{5}$$

To overcome the difficulty of solving Equation (5) with the conditions described by Equations (2)-(4), arising from the movement of a solid boundary with respect to the coordinates, following transformation is applied, which varies between zero (at center, r = 0) and unity (at the surface, $r_{(t)} = R_{(t)}$).

$$z_{(t)} = \frac{r_{(t)}}{R_{(t)}} \tag{6}$$

Equation (5) is expressed in terms of the variable z (dimensionless, shortened from $z_{(t)}$) as,

$$\frac{d\rho_A}{dt} = \frac{1}{(z\cdot R)^2}\frac{\partial}{\partial z}\left(z^2 D_{(\rho_A)}\frac{\partial \rho_A}{\partial z}\right) + \frac{1}{R}\frac{\partial \rho_A}{\partial z}\cdot z\cdot\frac{dR}{dt} \tag{7}$$

At the center of the sphere (z = 0) application of L' Hospital rule leads to Equation (8) (in place of Equation (4)),

$$\frac{\partial \rho_A}{\partial t} = 3\frac{D_{(\rho_A)}}{R^2}\frac{\partial^2 \rho_A}{\partial z^2} \tag{8}$$

Based on material balance equation at the surface, following expression is obtained for surface movement:

$$\frac{dR_{(t)}}{dt} = -\frac{D_{(\rho_A)}}{\rho_w R}\cdot\frac{\partial \rho_A}{\partial z}\Big|_{z=1} \tag{9}$$

$$R_{(t)} = R_o \;\; at \;\; t = 0 \tag{10}$$

For estimation of the instantaneous value of average solid concentration, $\overline{\rho_B}$, (in kg m^{-3}), based on mass balance for the solid, by integration across z, Equation (11) was applied. Equations (12) and (13) were used to estimate values of solid concentration ($\overline{\rho_B}$) and moisture content (u, kg kg^{-1}).

$$\overline{\rho_B} = 3\cdot\int_0^1 \rho_B z^2 dz \tag{11}$$

$$\frac{\overline{\rho}_A}{\rho_w} = \left(1 - \frac{\overline{\rho}_B}{\rho_s}\right) \quad (12)$$

$$u = \frac{\overline{\rho}_A}{\overline{\rho}_B} \quad (13)$$

where, ρ_w (kg m^{-3}) and ρ_s (kg m^{-3}) are the density of pure water and true density of dry solid, respectively.

2.2 Equivalent dimension of irregular shaped particles

Initial condition (Equation (10)), which is required for obtaining a solution to Equation (9), needs initial radius of the hydrating grain. Brown rice under consideration is not perfectly spherical in shape. Hence R_o is estimated from equivalent diameter (d_p in m), which was calculated using Equation (14), by following Mohsenin (1986):

$$d_p = (l\frac{(w+t)^2}{4})^{1/3} \quad (14)$$

where, l is length (m); w is width (m), and t is thickness (m).

2.3 Temperature and moisture dependence of liquid diffusivity

Following the works of Bello et al. (2010), and Aguerre et al. (2008), the liquid diffusivity is expressed as a function of moisture content and temperature as the following equation:

$$D(\rho_A) = D_o \exp\left[-\frac{\left(R_g K_1 K_2^{\frac{u}{u_i}} + \lambda(T)\right)}{2R_g T}\right] \quad (15)$$

where, D_o is the diffusivity of a pure substance in m^2 s^{-1}. It isthe pre-exponential factor of the expression for effective diffusivity, $D(\rho_A)$ in m^2 s^{-1}, and is equivalent to the diffusion coefficient at infinitely high temperature. The two variables k_1 (in K) and k_2 (dimensionless)are related to sorption isotherm model derived from enthalpy entropy compensation relationship given in Equation (16). On site moisture concentration is expressed as moisture content u by the application of Equation (13), based on the local solute concentration. Mono layer moisture content is estimated by sorption isotherm modelling.

$$\psi(T)\cdot\ln(a_w) = k_1 k_2^{\frac{u}{u_i}} \quad (16)$$

where, $\psi(T) = \left(\frac{1}{T_\beta} - \frac{1}{T}\right)^{-1}$. In this expression T_β is iso-kinetic temperature (K), which is estimated by curve fitting of isotherm data, which is the slope of the plot of iso-steric heat or enthalpy (ΔH) against differential entropy (ΔS) of sorption.

2.4 Activation energy of moisture diffusion process

Equation (9) has been obtained from adopting an Arrhenius-type relation between $D(\rho_A)$ and the activation energy for diffusion (E_D).

$$D(\rho_A) = D_o \exp\left(-\frac{E_D}{R_g T}\right) \quad (17)$$

where, T is the absolute temperature (K) and R_g is the gas constant in kJ kg^{-1} K^{-1}. The activation energy for the diffusive process E_D (kJ kg^{-1}) and the heat of sorption, E_s, in kJ kg^{-1}, are related by Equation (18)

$$E_D = aE_s \quad (18)$$

Aguerre et al. (1989) suggests that the value of the parameter 'a' may be 0.5 for a various food products which is considered in this formulation. Heat of sorption E_s is expressed in terms of the isosteric heat of sorption as given in Equation (19),

$$E_s = Q_s(u) + \lambda(T) \quad (19)$$

where, $\lambda(T)$ is the heat of water vaporization at the temperature of the process (kJ kg^{-1}) and $Q_s(u)$ is the isosteric heat of sorption (kJ kg^{-1}), generally is expressed in terms of the local moisture content in dry basis, by means of the Equation (20).

$$Q_s(u) = R_g k_1 k_2^{\frac{u}{u_i}} \quad (20)$$

Use of Equation (18) along with Equation (19) and (20) leads to expression of activation energy of diffusion process as give in Equation (21).

$$E_D = 0.5\{R_g k_1 k_2^{\frac{M}{M_0}} + (2495.5 - 4.180\times(T-273) + 1.881\times(T-273))\} \quad (21)$$

3 Materials and experimental methods

3.1 Materials and physical properties

3.1.1 Paddy sample

'*Chokuwa*' variety of paddy from Assam was collected from a nearby local farmer in a single lot for analysis and was stored in a plastic tub with a cover in a place away from heat and moisture for the period of study. The initial moisture content of grains, determined by AOAC method (AOAC, 1984) was 0.132 kg water/kg dry solid. Grains were manually cleaned to remove foreign materials and damaged grains prior to conducting experiments.

3.1.2 Dehusking of paddy

The dehusking of '*chokuwa*' paddy was performed in a laboratory mill, Kett rice husker (TR 230, Japan). The dehulled brown rice was graded and broken grains were separated manually.

3.1.3 Size characterization and physical properties

As brown rice grain is irregularly shaped, the equivalent spherical radius was employed to represent brown rice grain for mathematical modeling. Linear dimensions were measured with digital Vernier calipers having a resolution of 0.01 mm (Mitutoyo Corporation, Japan) and equivalent mean radius of brown '*chokuwa*' rice was calculated by following Equation (14) (Mohsenin, 1986).

3.1.4 Dry solid density

Dry solid density of brown kernels,ρ_s, was determined after drying the grains by removing bound water and cooled in a desiccator and measured by gas pycnometer (PYC-100A).

3.2 Experimental methodology

3.2.1 Soaking conditions

Soaking experiments were carried out by immersing the brown rice in distilled water in a beaker maintained at a set temperatures maintained with the help of a temperature controlled hot water bath. Six different soaking temperatures viz., 40°C, 45°C, 50°C, 55°C, 60°C and 65°C were used in different instances. Before pouring grains, water temperature inside the beaker was checked for reaching the desired temperature. Set temperature is maintained throughout the duration of the experiments.

3.2.2 Moisture measurement of soaked grains

Moisture content of soaked grains is measured on the basis of increase in weight during soaking. For this, before conducting the soaking experiment, average value of weight of 1000 grains is determined first from three mass measurements, and is used to estimate the average initial weight of 15 grains ($w_{i,15}$). Further, initial moisture content is determined as average of three measurements by gravimetric method.

With the introduction of grains to the beaker with water maintained at desired temperature, the timing of experiment is set as zero. During the course of soaking, few grains (approx. 45-50) were removed at every 10 minutes of interval with the help of a spatula and were blotted for three to four times to remove the superficial water. One such collected lot is divided into three sub-lots, each of 15 grains. The weight of 15 grains (w_{15}) is determined from average of the weights of the three sub-lots. The gain in water is estimated as the difference between w_{15} and $w_{i,15}$ which is converted to moisture content, based on the known initial moisture content. All mass measurements are carried out using an electronic balance (ME204 from Metler Toledo with least count 0.1 mg). These measurements are continued at 10 minutes interval for three hours of soaking. Hydration data for three hours of soaking are measured at all six temperatures.

3.3 Estimation of saturation moisture content

The possibility of estimation of saturation moisture content (u_s) by prolonged soaking at desired temperatures was attempted. However, there were issues of degeneration of the grain surface, and dislodging of small fragments, particularly at temperatures closer to gelatinization, and subsequent difficulty in ensuring uniform removal of surface water.

Therefore, saturation moisture content was determined by extrapolation method as suggested by Bello et al. (2004). As per this method, for any set of three moisture contents taken at equally spaced time intervals of duration j, it can be obtained from Equation (22).

$$u_s = \frac{u_i u_{i+2j} - u_{i+j}^2}{u_i + u_{i+2j} - 2u_{i+j}} \tag{22}$$

where, u_i and u_j are the moisture contents at time i and j. This finding was applied for each hydration ranges and taken the average for each hydration temperature. The saturation moisture content resulting from Equation (22) for brown rice is given in Table 2. These were used to calculate the diffusion coefficients of water in brown rice during simulation.

3.4 Sorption model based on enthalpy-entropy compensation

Equilibrium moisture content data of brown rice was used from the work of Reddy and Chakraborty (2004) which were available at temperatures of 13°C, 30°C and 40°C. Based on the plot of iso-steric heat or enthalpy (ΔH) against differential entropy (ΔS), the isokinetic temperature was estimated and from the plots between equilibrium moisture content (EMC) and ln(ln (a_w) * $\psi(T)$) the values of k_1 and k_2 were obtained. The isotherm equation is expressed by Equation (16).

3.5 Model calibration

The kinetic model for hydration has been described in section 2.1, which needs to be solved using constitutive equations stated in subsequent sections 2.2-2.4. In the model, D_o is the material specific parameter, which needs to be obtained from this work. Thus, to fit the experimental data with the present model and with D_o as the fitting parameter, a non-linear regression was employed.

For the measurement of model adequacy, three parameters are used: correlation coefficient (CORREL) as given in Equation (23); mean relative deviation modulus (P, %) as given in Equation (24); and root mean squared error (RMSE) (Equation (25)).

$$\text{CORREL} = \frac{n\sum u_{meas}\cdot u_{pred} - \sum u_{meas}\cdot \sum u_{pred}}{\sqrt{[n\sum u_{meas}{}^2 - \sum u_{meas}{}^2][n\sum u_{pred}{}^2 - \sum u_{pred}{}^2]}} \tag{23}$$

$$P(\%) = \frac{100}{n}\sum_1^n |(u_{meas} - u_{pred})|/u_{meas} \tag{24}$$

$$\text{RMSE} = \sqrt{\frac{\sum_1^n (u_{meas} - u_{pred})^2}{n}} \tag{25}$$

The methodology followed is to estimate a value for D_o based on experimental data at three temperatures viz., 40°C, 50°C and 60°C to obtain the calibrated model equation of hydration. The calibrated model is applied to new experimental conditions e.g., 45°C and 55°C to predict the kinetics of water absorption and predictability is quantified based on values of CORREL, P(%) and RMSE. For this, values of these parameters are determined to fitted data at temperatures of 40°C, 50°C and 60°C and predicted data of 45°C and 55°C, and are compared.

The procedure is repeated with another combination of data sets for model calibration (45°C, 55°C and 65°C) and testing for validation (50°C and 60°C).

3.6 Activation energy

Equation (21) is used with values of k_1 and k_2 from of Equation (16) for estimation of activation energy of diffusion process.

4 Results and discussions

4.1 Physical properties

The physical properties of brown rice are given below in Table 1. The size and shape of brown rice are under medium category, as length and width are in the range of 5.4 to 6.13 mm and 2.1 to 3 mm respectively. The mean true density, bulk density and sphericity values of brown rice are more than paddy.

Table 1 Physical properties of '*chokuwa*' brown rice and '*chokuwa*' paddy

Physical properties	Brown rice Mean±std	Paddy Mean±std
Weight per thousand grains (g)	18.515±0.04	23.90±0.13
Length (mm)	5.650±0.14	7.93±0.43
Width/breadth (mm)	2.435±0.17	2.74±0.19
Height/thickness (mm)	1.660±0.10	1.90±0.13
Bulk density (kg m^{-3})	755.03±0.01	536.54±0.02
True density (kg m^{-3})	1509.0±0.005	1360.0±0.05
Equivalent diameter (mm)	2.87±0.13	3.37±0.07
Sphericity (%)	50.27±0.02	43.29±0.01

4.2 Moisture absorption by grain

During hydration, the plots between moisture gain by brown rice and time of soaking for different temperatures are shown in Figure 1.

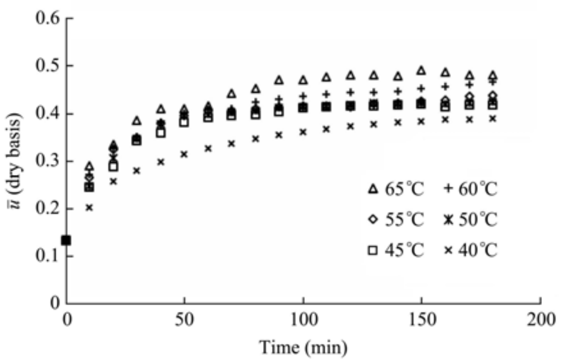


Figure 1 Effect of temperature and soaking time on mean moisture content ($\bar{u}$) of soaked brown rice

The plots demonstrate that the brown rice absorbed moisture rapidly during the initial stages of hydration until absorption ceases when they attained the saturation value. The rate of water uptake increased with the increasing temperature as suggested by the slopes of the absorption curves, getting steeper with increasing temperature, indicating a higher rate of moisture diffusion. The increased diffusion may be due to a higher value of saturation moisture indicating a steeper gradient of moisture migration to the grain from the surface along with a rise in the diffusivity value caused by raised temperature. The effects of temperature are quantified in later sections.

4.3 Saturation moisture of brown rice

Time for attainment of saturation point depends on temperature, at a lower temperature of hydration, saturation moisture content was found to be lower, but the time required to achieve the saturation point is longer. However, by increasing the temperature, the saturation moisture content increases and time required to achieve this point has decreased. The issue of degeneration of the grain surface, particularly at temperature closer to gelatinization, and subsequent difficulty in ensuring uniform removal of surface water, prompted to employ the method of extrapolation for obtaining a representative value of saturation moisture content of brown rice. Hence, the saturation moisture content was determined as mentioned in section 3.3. Tabulated values in Table 2 indicate closeness of estimated values with reported data viz., Bello et al., (2004).

Table 2 Saturation moisture content (u_s) for hydration temperature

Soaking Temperature (°C)	Estimated u_s (dry basis) kg/kg	Literature value of u_s (dry basis) kg/kg (Bello et al., 2004)
40	0.390±0.015	
45	0.412±0.099	0.420±0.013
50	0.420±0.010	
55	0.430±0.014	0.445±0.013
60	0.451±0.033	
65	0.471±0.051	0.450±0.013

4.4 Model for water absorption of brown rice

The kinetic model for hydration has been described in section 2.1 which was solved using constitutive equations stated in subsequent sections and parameters listed in Table 3. Temperature specific values of u_s used are given in Table 2.

Model fitting carried out at temperatures of 40°C, 50°C and 60°C yielded a value of D_o of 2.99×10^{-7} m^2 s^{-1}. Corresponding fitted plots are shown in Figure 2.

For the validity of the estimated value of D_o, the model is applied to predict hydration behavior at two intermediate temperatures viz., 45°C and 55°C. The predicted hydration curve is compared with experimental data at these two temperatures. The modeled hydration curves followed the observed data in a close agreement. Both the predicted and observed values are plotted in Figure 3.

Table 3 Parameters used for simulation

Parameter	Reference
R_0 = 1.436 mm	This work
u_o = 0.1321 kg water/ kg dry solid	This work
ρ_s = 1540 kg m^{-3}	This work
u_i = 0.0712	Tolaba et al. (1997)
$\lambda(T)$ = 2495.46 + 1.881(T–273) – 4.180(T–273)	Treybal (1980)
R_g = 0.462 kJ kg^{-1} K^{-1}	
ρ_w = 1000 kg m^{-3}	
k_1 = 13192, k_2 = 0.227	Estimated in this work based on isotherm data of Reddy and Chakraborty (2004)

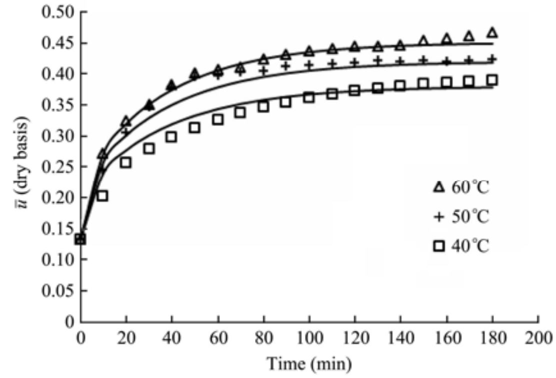
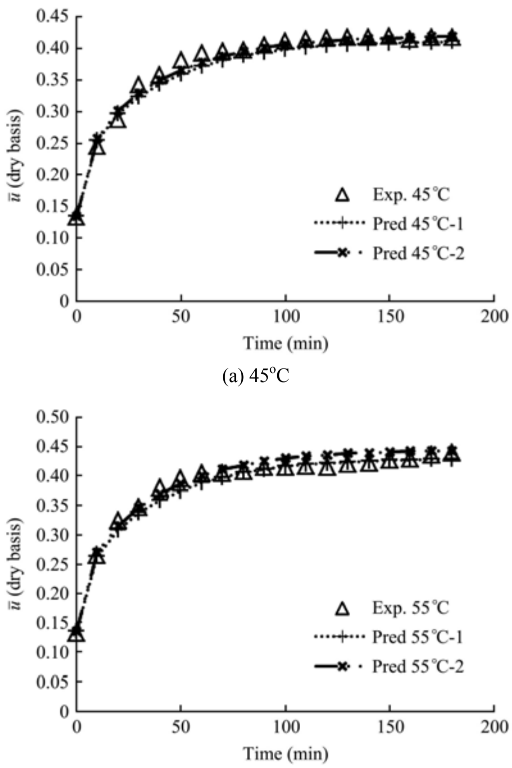


Figure 2 Fitted plot of time variation of mean moisture content ($\bar{u}$) of brown rice for estimation of D_o based on hydration data at 40°C, 50°C and 60°C



(a) 45°C

(b) 55°C

Figure 3 Comparison of predicted hydration curve at temperatures of 45°C and 55°C, based on calibrated model using experimental data at temperatures of 40°C, 50°C and 60°C.

Statistics of data fitting during model calibration using experimental data at 40°C, 50°C and 60°C and during prediction of average moisture content during soaking at 45°C and 55°C are given in Table 4. Range of CORREL for both fitting is >0.985, P<4.2 (%) and RMSE<0.015, indicating a good fit. Corresponding values during prediction are >0.993, 3% and 0.012 respectively. These values are within the range obtained for fitting, indicating the validity of calibrated model. The plots in Figure 3 show two predictions at given hydration temperatures of 45°C (Figure 3a) and 55°C (Figure 3b), obtained based on the use of two different values of saturation moisture contents i.e., Prediction (1) is based on u_s values estimated in this work and prediction (2) is based on u_s values from Bello et al (2004). The plots indicate that predicted moisture profile is sensitive to value of saturation moisture content.. Hence, precise measurement or estimation of saturation moisture is critical for improving the statistics of reproducing moisture content as evident from the tabulated values in Table 4.

Table 4 Statistics of fitting and prediction of hydration kinetics

Soaking Temperature (°C)	u_s (dry basis) kg/kg	Statistics of Fitting			Value of D_o ($m^2\ s^{-1}$)
		CORREL	P (%)	RMSE	
(a) Calibration based on experimental data at 40°C, 50°C and 60°C, prediction at 45°C and 55°C					
40	0.390	0.985	0.042	0.015	
50	0.420	0.993	0.027	0.013	2.99×10^{-7} (Estimated)
60	0.451	0.998	0.011	0.006	
45	0.412	0.995	0.030	0.012	
45	0.420	0.995	0.018	0.008	2.99×10^{-7} (for prediction)
55	0.430	0.993	0.019	0.010	
55	0.445	0.993	0.026	0.012	
(b) Calibration based on experimental data at 45°C, 55°C and 65°C, prediction at 50°C and 60°C					
40	0.390	0.985	0.042	0.015	
50	0.420	0.993	0.027	0.013	2.58275×10^{-7} (Estimated)
60	0.451	0.998	0.011	0.006	
45	0.412	0.995	0.030	0.012	2.58×10^{-7} (for prediction)
45	0.420	0.995	0.018	0.008	
(c) Calibration based on experimental data at 40°C,45°C, 50°C, 55°C, 60°C and 65°C					
40	0.390	0.979	0.050	0.018	
45	0.412	0.996	0.025	0.010	
50	0.420	0.994	0.021	0.010	2.785×10^{-7} (Estimated)
55	0.430	0.995	0.016	0.007	
60	0.451	0.996	0.014	0.007	
65	0.471	0.995	0.026	0.013	

The procedure is repeated for another combination of temperatures i.e., 45°C, 55°C and 65°C for model calibration and hydration behavior is predicted for temperatures of 50°C and 60°C. Resulting predicted plot is given in Figure 4 and statistics are given in Table 4 (part-b). Values of the statistical parameters of fitting and prediction are similar to those carried out for earlier combination, however, value of D_o varied slightly from 2.99×10^{-7} to 2.58×10^{-7} $m^2\ s^{-1}$.

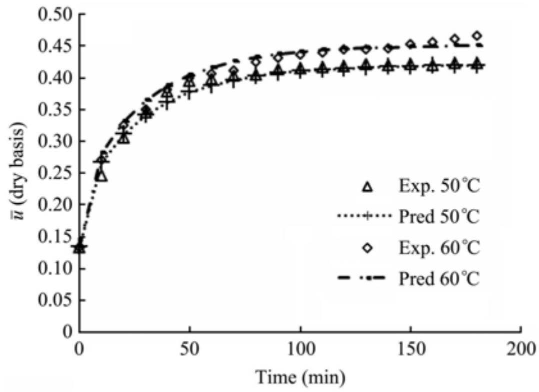


Figure 4 Comparison of predicted hydration curve at temperatures of 50°C and 60°C, based on calibrated model using experimental data at temperatures of 45°C, 55°C and 65°C, based on u_s values estimated in this work

Finally, a single value of D_o = 2.785×10^{-7} $m^2\ s^{-1}$ is obtained using experimental data of all six hydration temperatures, with values of statistics of fitting as given in part-c of Table 4. The hydration model with this calibrated D_o is used for further analysis.

4.5 Estimation of effective diffusivity

Making use of the respective moisture profiles (temporal), the moisture dependence of effective diffusivity was determined from the Equation (15). The variation of diffusion coefficient with time, based on mean moisture content, for all hydration temperatures has shown in the Figure 5.

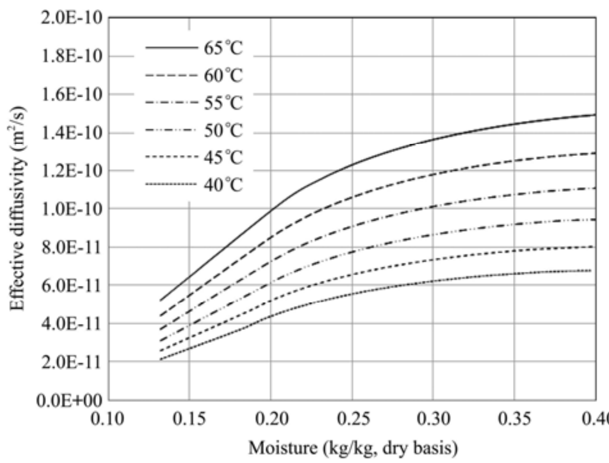


Figure 5 Variation of the diffusion coefficient $D(\rho_A)$ for different hydration temperatures with moisture

Value of effective diffusivity increases with the increasing hydration temperature for which the values are given in Table 5. During the initial period of soaking, the moisture diffusivity increased instantaneously, however, as the saturation moisture content is approached, the effective diffusivity gradually attained a constant value. The values of effective diffusivity of brown rice, estimated from hydration data at different temperatures (40°C-65°C), were in the range of 2.13×10^{-11} to 1.52×10^{-10} m^2 s^{-1}. Similar results of diffusivity were reported in earlier works: (i) for brown rice at 45°C-65°C the range of diffusivity values as 1.79-3.38×10^{-10} m^2 s^{-1} by Bello et al. (2010), and (ii) for raw paddy at a temperature range of 25°C-70°C the range of diffusivity values as 5.58×10^{-11} to 3.57×10^{-10} m^2 s^{-1} (Kashaninejad et al., 2007). The reason behind the increase in the diffusion coefficient with moisture content can be the decrease in the heat of adsorption as kernel hydration proceeds (at high moisture content molecules are less firmly bind to the sorption sites). It can also be seen that as the brown rice moisture content approaches the saturation value, the effects of moisture diminishes significantly after a moisture values of 0.3 kg kg^{-1}.

Table 5 Diffusion coefficient $D(\rho_A)$ range and average diffusion coefficient $D(\rho_A)$ for '*chokuwa*' brown rice

Hydration temperature (°C)	Range of diffusion coefficient (m^2 s^{-1})	Average $D(\rho_A)$ (m^2 s^{-1})	$D(\rho_A)$ (Bello et al., 2010)
40	$2.13\times10^{-11} – 6.78\times10^{-11}$	6.35×10^{-11}	-
45	$2.58\times10^{-11} – 8.08\times10^{-11}$	7.81×10^{-11}	1.79×10^{-10}
50	$3.10\times10^{-11} – 9.53\times10^{-11}$	9.26×10^{-11}	-
55	$3.70\times10^{-11} – 1.12\times10^{-10}$	1.09×10^{-10}	2.60×10^{-10}
60	$4.40\times10^{-11} – 1.31\times10^{-10}$	1.28×10^{-10}	-
65	$5.22\times10^{-11} – 1.52\times10^{-10}$	1.50×10^{-10}	3.38×10^{-10}

4.6 Activation energy

The activation energy was calculated from the Equation (21) and it was in the range of 22.24-22.76 kJ mol^{-1}. The values of activation energy were well within the range of those values reported in the literature. Engels et al. (1986) found values ranging from 22.5 to 64.51 kJ mol^{-1}, depending on the moisture concentration of the rice grain. Viollaz and Suarez (1984) reported an activation energy value of 39.41 kJ mol^{-1} for water absorption in corn.

4.7 Predicted moisture concentration profile

Equation (26) was used to calculate moisture concentration from moisture content values at radial positions, from spatial moisture distribution.

Table 6 Activation energy range for each hydration temperature

Temperature (°C)	Activation energy (kJ mol^{-1})
40	21.66-23.59
45	21.55-23.48
50	21.45-23.39
55	21.35-23.28
60	21.24-23.18
65	21.14-23.08

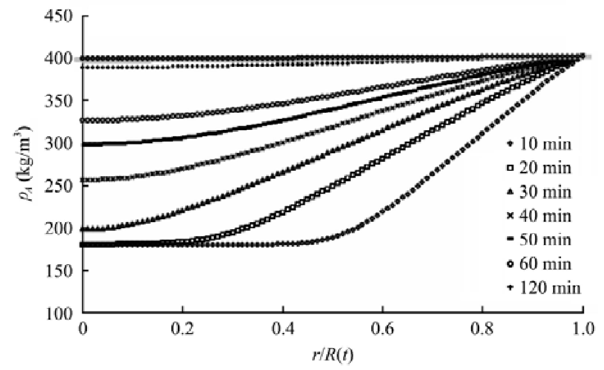
$$\rho_A = \frac{\rho_w \rho_s u}{\rho_w + \rho_s u} \tag{26}$$

Moisture concentration (ρ_A) is plotted against $r/R_{(t)}$, at two representative temperatures of 45°C and 60°C as shown in Figure 6 (a and b). The plots show that moisture and solid concentrations are not uniformly distributed within the solid, i.e., solid concentration is much higher in the center of the solid than in the surface.

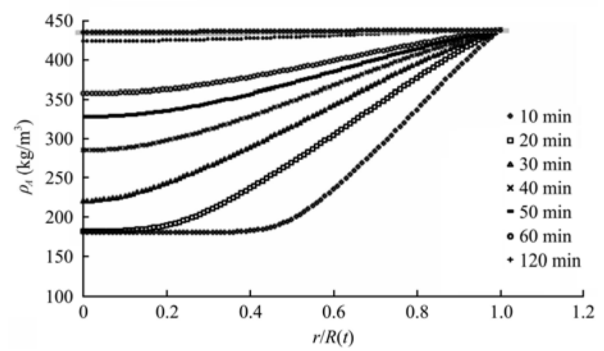
In Figure 6a, i.e at 45°C, the changes in volumetric concentration of moisture from 10 min to 180 min was in the range of 179.67 to 401.78 kg m^{-3}, and for 60°C at 180 min, the moisture concentration increases to 437.74 kg m^{-3} respectively. It is also observed that during the first time of soaking moisture migration conducts to a kind of frontier that moves within the solid at an almost constant rate, this can be seen by observing the position where moisture profiles intercept the horizontal axis. When the time of soaking increases, moisture content is almost uniform across the solid. Such rapid increase of moisture concentration near the solid surface may be due to the variation of the diffusion coefficient with moisture concentration. The increase of the diffusion coefficient in the outer zones of the solid tends to accelerate the absorption rate with the corresponding sudden increase of moisture concentration.

4.8 Swelling kinetics

Water absorption leads to the increase of volume of the mix in the grains. The increase of moisture which is expressed as swelling due to the volume addition, which leads to the changes in the radial position during soaking (Figure 7) for each of the hydration temperatures. With the increase in the temperature, the addition of moisture increases and volume in terms of swelling in the grains increases.



(a) 45°C



(b) 60°C

Figure 6 Local moisture variation with time as predicted by the model for soaking temperature of 45°C and 60°C

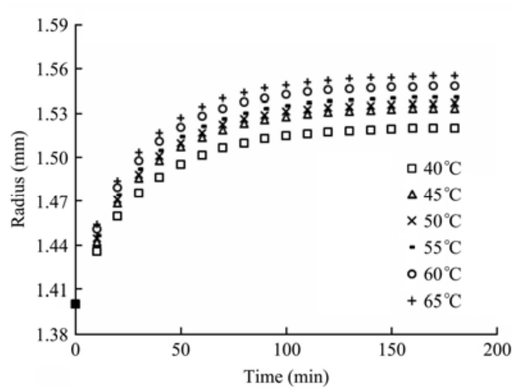


Figure 7 Variation of the 'instantaneous' radius with time of soaking at different temperatures

4.8 Soaking condition for the production of parboiled rice from *'chokuwa'* brown rice

Hydration or soaking of grain up-to 30% of moisture content is recommended for the production of parboiled rice (Bhattacharya, 2004; Pillaiyar, 1988), as this level of moisture considered as desirable for inducing starch gelatinization during steaming. In this brown rice hydration study of particular '*chokuwa*' variety, the desirable moisture range has been achieved for different temperatures, with different time requirements.

During hydration at temperatures of 55^{o}C, 60^{o}C and 65^{o}C, the required time to attain 30% moisture content (wet basis) are approximately 180 min, 90 min and nearly 60 min respectively. When soaked at 45^{o}C or 50^{o}C, it is expected to reach 30% moisture after prolonged soaking as the saturation moisture content is approximately 30% (at 50^{o}C estimated u_s is approx. 30% and at 45^{o}C, reported u_s is approx. 30%).

Below these temperatures, it may be hard to reach to 30% as the saturation moisture range was less than 30%. The traditional soaking condition for kola '*chokuwa*' paddy reported by Dutta and Mahanta (2014) justifies this interpretation. Dutta and Mahanta (2014) reported a soaking condition for the paddy which involved brief cooking in boiling water for 1-3 min, and then covering the boiling vessel with a gunny bag to retain the temperature for a longer time thereby achieving moisture level of 37%, (wet basis) after a soaking period of 18 h. Such a soaking condition used traditionally has soaking water temperature above 50^{o}C for initial period. However the reported method requires prolonged soaking.

To complete the soaking process within 2-3 hours, a soaking condition at temperature above 55^{o}C may be recommended to produce parboiled brown rice of '*chokuwa*' paddy. Since, soaking above 65^{o}C was not within the scope of the study due to the possibility of surface gelatinization and subsequent effects on moisture migration, the validity of the predicted moisture migration behavior remains restricted within the temperature of 65^{o}C.

5 Conclusion

During the process of producing *komal chawal*, a kind of no cooking rice traditional to the state of Assam India by the method of parboiling of brown rice from '*chokuwa*' variety of paddy, the rice is soaked in water at a temperature below that of gelatinization. For the quantification of the rate of water migration behavior during soaking and subsequent prediction of water absorption rate, soaking experiments were carried out at temperatures in the range of 30^{o}C-65^{o}C. The rate of water uptake increased with the increase in the temperature, indicating a higher rate of moisture diffusion. The increased diffusion is the result of higher value of saturation moisture leading to a steeper gradient of moisture migration from the surface to the core as well as due to the rise in the diffusivity value caused by raised temperature. Saturation moisture content increased from 0.39 (kg kg^{-1}) at 40°C to 0.47 (kg kg^{-1}) at 65°C.

Simulation of the kinetic of moisture gain by grain across time with the application of Fick's law yielded effective diffusivity values in the range of 2.13×10^{-11}-1.52×10^{-10} m^2 s^{-1}, the lower value corresponding to the combination of lowest of the moisture and minimum of the temperature of the experimental range. These are the diffusivity values obtained with the consideration of change in volume of grains as a result of water absorption, which is incorporated in the model with moving boundary formulation.

Application of the principle of enthalpy-entropy compensation of sorption behavior to explain the functional dependence of effective water diffusivity on temperature and water content has led to the estimation of D_o as m^2 s^{-1}. Value of D_o, estimated based on experimental data at select temperatures, could predict the hydration kinetics at unseen temperatures. This was demonstrated for two combinations: (i) estimation of D_o based on data at 40°C, 50°C and 60°C for prediction of hydration kinetics at 45°C and 50°C and (ii) estimation of D_o based on data at 45°C, 55°C and 65°C for prediction of hydration kinetics at 50°C and 60°C. The measures of prediction error are very similar to the statistics of fitted data at parameter estimation phase.

Validation of the ability to reproduce hydration kinetics in isothermal soaking condition should encourage the use of the model for designing soaking condition for parboiling of the brown rice.

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References

Aguerre, R. J., J. F. Gabitto, and J. Chirife. 1985. Utilization of Fick's second law for the evaluation of diffusion coefficient in food process controlled by internal diffusion. *Journal of Food Technology*, 20(5): 623–629.

Aguerre, R. J., C. Suarez, and P. E. Viollaz. 1989. Relationship between energies of water sorption and diffusion in grains. *International Journal of Food Science & Technology*, 24(3): 317–320.

Aguerre, R. J., M. Tolaba, and C. Suarez. 2008. Modeling volume changes in food drying and hydration. *Latin American applied research*, 38(4): 345–349.

Ahromrit, A., D. A. Ledward., and K. Niranjan, 2006. High pressure induced water uptake characteristics of Thai glutinous rice. *Journal of Food Engineering*, 72(3): 225–233.

Ali, N., and A. C. Pandya. 1974. Basic concept of parboiling of paddy. *Journal of Agricultural Engineering Research*, 19(2): 111–115.

AOAC (Association of Official Analytical Chemists). 1984. *Official Methods of Analysis. Association of Official Analytical Chemists*. 14th ed. Washington, DC: AOAC International.

Bakalis, S., A. KyritsI, V. T. Karathanos, and S. Yanniotis. 2009. Modeling of rice hydration using finite elements. *Journal of Food Engineering*, 94(3-4): 321–325.

Bello, M., M. P. Tolaba, R. J. Aguerre, and C. Suarez. 2010. Modeling water uptake in a cereal grain during soaking. *Journal of Food Engineering*, 97(1): 95–100.

Bello, M., M. P. Tolaba, and C. Suarez, 2004. Factors affecting water uptake of rice grain during soaking. *LWT-Food science and Technology*, 37(8): 811–816.

Bhattacharya, S. 1995. Kinetics of hydration of raw and roasted corn semolina. *Journal of Food Engineering*, 25(1): 21–30.

Bhattacharya, S. 2004. Parboiling of rice. In *Rice Chemistry and Technology*, ed. E. T. Champagne, ch. 13, 329-404. Michigan, USA: American Association of Cereal Chemists.

Cheevitsopon, E., and A. Noomhorm 2010. Kinetics of hydration and dimensional changes of brown rice. *Journal of Food Processing and Preservation*, 35(6): 840–849.

Dutta, H., and C. L. Mahanta 2014. Laboratory process development and physicochemical characterization of a low amylose and hydrothermally treated ready-to-eat rice product requiring no cooking. *Food and Bioprocess Technology*, 7(1): 212–223.

Dutta, S. K., U. K Nema, and R. K. Bhardwaj. 1988. Drying behavior of spherical grains. *International Journal of Heat and Mass Transfer*, 31(4): 855–861.

Engels, C., M. Hendrickx, S. De Semblanx, I. De Gryze, and P. Tobback. 1986. Modelling water diffusion during long-grain rice soaking. *Journal of Food Engineering*, 5(1): 55–73.

Gekas, V., and I. Lamberg. 1991. Determination of diffusion coefficients in volume-change systems—Application in the case of potato drying. *Journal of Food Engineering*, 14(4): 317–326.

Hawlader, M. N. A., J. C. Ho, and Q. Zhang, 1999. A mathematical model for drying of shrinking materials. *Drying Technology*, 17(1-2): 27–47.

Kar, N., R. K. Jain, and P. P. Srivastav. 1999. Parboiling of dehusked rice. *Journal of Food Engineering*, 39(1): 17–22.

Kashaninejad, M., Y. Maghsoudlou, S. Rafiee, and M. Khomeiri. 2007. Study of hydration kinetics and density changes of rice (*Tarom Mahali*) during hydrothermal processing. *Journal of Food engineering*, 79(4): 1383–1390.

Krishnaiah, K., and A. Janaiah. 2000. The role of rice in India's food security-projections and future directions. *India Grains*, 2(11): 27–31.

Mohsenin, N. N. 1986. *Physical Properties of Plant and Animal Materials*. 2nd ed. New York: Gordon and Breach Science Publishers.

Muthukumarappan, K., V. K. Jindal, and S. Gunasekaran. 1992. Volumetric changes in rice kernels during desorption and adsorption. *Transactions of the ASAE*, 35(1): 235–241.

Oli, P., R. Ward, B. Adhikari, and P. Torley. 2014. Parboiled rice: understanding from a materials science approach. *Journal of Food Engineering*, 124: 173–183.

Parnsakhorn, S., and A. Noomhorm, 2008. Changes in physicochemical properties of parboiled brown rice during heat treatment. *Agricultural Engineering International*: *CIGR Journal*, 10:1-20. Manuscript FP 08 009.

Pillaiyar, P. 1988. *Rice – Post Production Manual.* ed. New Delhi, India: Wiley Eastern Ltd. Publishers.

Reddy, B. S., and A. Chakraverty. 2004. Equilibrium moisture characteristics of raw and parboiled paddy, brown rice, and bran. *Drying Technology*, 22(2): 837–851.

Thakur, A. K., and A. K. Gupta. 2006. Water absorption characteristics of paddy, brown rice and husk during soaking. *Journal of Food Engineering*, 75(2): 252–257.

Tolaba, M. P., R. J. Aguerre, and C. Suárez. 1997. Modelling cereal grain drying with variable diffusivity. *Cereal Chemistry*, 74(6): 842–845.

Treybal, R. E. 1980. *Mass Transfer Operations*. 2nd ed. New York: McGraw Hill Book Co.

Viollaz, P. E., and C. Suarez. 1984. An equation for diffusion in shrinking or swelling bodies. *Journal of Polymer Science Part B: Polymer Physics*, 22(2): 875–879.