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Modeling Moisture Movement in Rice

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1. Introduction

Rice is one of the leading food crops in the world with total annual production being about 448 million metric tons on milled rice basis in 2008/09 year (USDA, 2010). Rice is found in marketplace in different forms depending on level of its subsequent processing. Rough rice (or paddy rice) is the rice that is obtained just after harvest. After removal of its outer husk (or hull), it becomes brown rice. Brown rice after milling, where the bran layer and embryo is removed become whiter in color and is called white rice (or milled rice) that is favored form of human consumption in most countries.

Rough rice is generally harvested at 18-24% moisture contents on wet basis and requires drying down to 12-14% for safe storage. At commercial scale, drying is carried out by blowing heated air over grains causing them to lose moisture rapidly. In addition to drying, moisture movement inside rice kernels occurs when rice is exposed to dry or humid environments causing desorption or adsorption of moisture, respectively, during any of pre-harvest or post-harvest stages.

During any of moisture adsorption or desorption processes, the surface of kernel reaches the equilibrium moisture content in surrounding environmental conditions very rapidly, however, at center of kernel moisture changes slowly, developing moisture gradients within the kernel. Higher magnitudes of such moisture gradients are believed to be one of the major reasons causing fissures or cracks in rice, which result in broken rice on milling. Milled rice kernels that are three-fourths or more of the unbroken kernel length are called head rice while the rest are called broken rice (USDA, 1994). Since the full-length grain is preferred form of rice, broken rice has typically half market value than that of head rice (Mossman, 1986; Thompson & Mutters, 2006). Therefore, reducing rice fissuring has been an important goal in rice drying research.

In last five decades, many researchers have pursued mathematical modeling of rice drying process. Key objective of such model development was to determine the moisture of the drying rice sample after certain drying period. Development of models also assisted in understanding the impact of factors affecting drying process such that drying air temperature and speed of drying air and optimizes them for reducing drying time, without performing a large number of experiments. Mathematical models were also used to determine the moisture gradients within the rice kernels that might affect rice fissuring. In addition to improve drying process, mathematical models can also help in making decisions on whether rice at particular moisture can be exposed to certain environmental conditions for certain period of time without significant fissuring.

Among different moisture adsorption and desorption processes, drying has attracted most attention of researchers. From modeling perspective, there is very little difference between these processes except the magnitude of moisture movement is very rapid in case of drying. Drying process would be the main focus in this chapter, however, important information on other sorption processes will also be described when necessary. Modeling of two types of drying: convective air drying by heated air and radiative drying by infrared drying will be mainly covered in this chapter.

The purpose of this chapter is to illustrate different approaches pursued in modeling of drying processes in rice. Development of both empirical and theoretical models based upon principles of mass and heat transfer is described in this chapter. Near the end of chapter, brief discussion on determination of some of the key hygroscopic and thermal properties is provided. Our goal is to expose the reader to variety of options available in rice drying modeling literature and assist them to make well-informed choices for successful development of rice drying models.

2. Mechanism of moisture movement

During most of agricultural products drying, initially moisture is quickly removed, then is followed by progressively slower drying rates (Allen, 1960). Fig. 1. shows the typical rice drying curve of rice. It clearly shows that drying rate, which is slope of the drying curve, becomes smaller with progress of drying. Such drying is referred as falling rate drying.

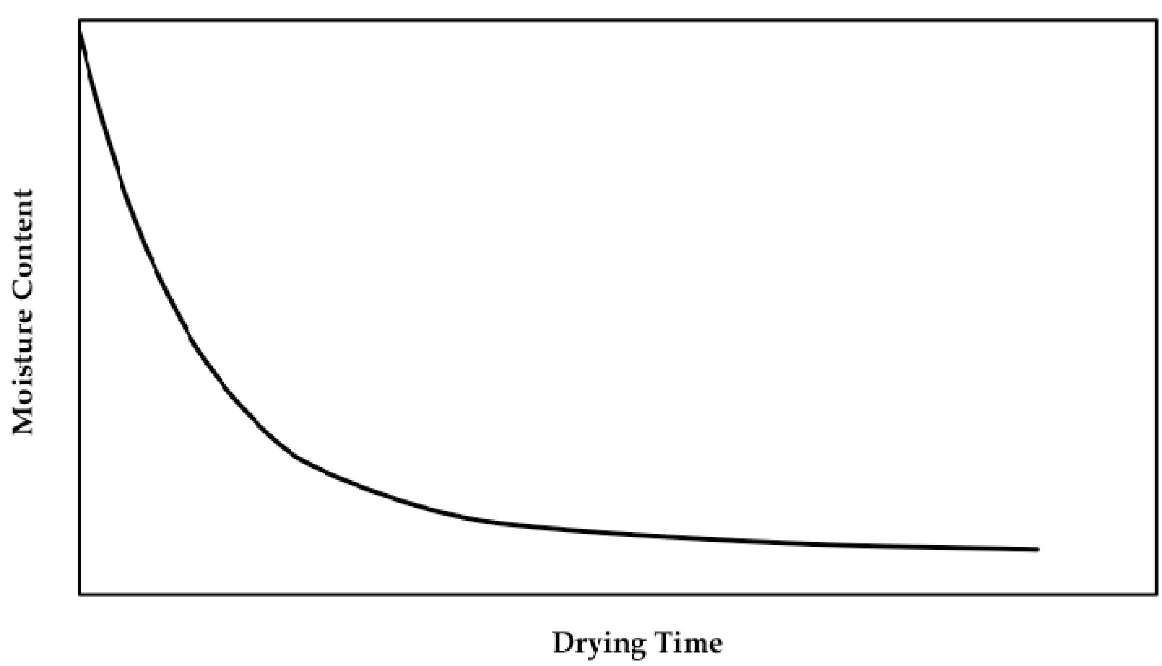

Fig. 1. Typical drying curve of rough rice

The cause of falling rate drying is inability of internal moisture movement to convey moisture to the surface at a rate comparable to that of its removal from the surface. Many theories were proposed to explain mechanism of internal moisture movement in such falling rate drying behavior. Some of them are: difference in vapor pressure, liquid diffusion, capillary flow, pore flow, unimolecular layer movement, multimolecular layer movement, concentration gradient and solubility of the absorbate. Each of these theories explains some aspects of drying in some materials but no universally applicable theory has been substantiated by experiments (Allen, 1960). Srikiateden & Roberts (2007) reviewed these mechanisms as reported in different solid foods and described the mathematical equations involved in such mechanisms.

Despite the uncertainty about the actual mechanism of moisture movement, most researchers (Mannapperuma, 1975; Steffe & Singh, 1980a; Aguerre et al., 1982; Lague, 1990; Sarker et al. 1994; Igathinathane & Chattopadhyay, 1999a; Meeso et al., 2007; Prakash & Pan, 2009) have described moisture movement in rice drying by Fick's laws of diffusion. Using such diffusion mechanism, Lu & Siebenmorgen (1992) have modeled moisture movement during adsorption and desorption processes. Their models predicted average moisture of the grain reasonably well. However, it should be noted that this alone does not establish diffusion as the mechanism of moisture movement in rice. A true criterion for the validity of the mechanism would be accurate prediction of moisture distribution within the grain (Hougen et al., 1940), which has not been fully considered in rice drying.

3. Mathematical models

Drying of any material normally involves both heat and mass transfer (or moisture transfer). Pabis & Henderson (1962) measured the center and surface temperature of yellow shelled maize kernels during heating by free convection in an oven at 71ºC (i.e. 160ºF). They observed that the surface and center temperatures differed significantly during the first 3 to 4 minutes only and therefore, grains can be considered isothermal during drying process. Citing this work as their basis, many researchers have assumed grains to be isothermal during the drying process and neglected heat transfer within the rice kernel. However, in case of infrared drying, where heating period is very short (typically less than two minutes), rice kernel cannot be considered isothermal and heat transfer within the rice kernel must be considered.

Different approaches were taken to mathematically model the moisture changes during the drying period. Based on the size of sample, these models can be broadly categorized into three: thin layer (or single layer) drying models, deep bed drying models and single kernel drying models. Thin layer drying models were mostly empirical or semi-empirical in nature while most single kernel drying models were based on mechanism of Fickian diffusion. Deep bed drying models are generally based on thin layer drying models. It is important to discuss the concept of equilibrium moisture content before we describe development of different models in detail.

At any fixed environmental conditions, a wet rice sample continues to lose moisture until an equilibrium state is reached. This moisture content is called equilibrium moisture content (EMC). In addition to rice variety, this EMC of a rice sample also depends on the temperature and humidity of ambient air. When a dry rice sample is exposed to humid environments, it gains moisture content and equilibrates to a value of EMC, which may be different than the EMC obtained during the moisture desorption. The difference in EMCs obtained during adsorption and desorption experiments are due to the different condition of the grains in their approach to equilibrium conditions (Allen, 1960). They cited Simmonds et al. (1953), who described the discrepancy between the EMC values obtained during adsorption and desorption to be due to the living nature of grain, which changes its chemical and physical nature according to environment.

Allen (1960) described another concept of EMC called dynamic EMC that is different than from the EMC value discussed previously, which they referred as static EMC. They considered that use of static EMC is inappropriate for drying process, because physical and chemical changes in the kernel during such process are very fast compared to the conditions used to determine static EMC. During drying, kernel surface becomes very dry while inner kernel has higher moisture content creating high moisture gradients. In such conditions, kernel surface that is exposed to drying air is not representative of the whole grain. This causes grain moisture to approach a value that is higher than its static EMC during drying. This moisture content value is called its dynamic EMC. If drying is conducted through a large range of moisture contents, this approach may reveal existence of more than one value of dynamic EMCs. They considered dynamic EMCs to be the logical choice to describe moisture loss during drying process while for gentle moisture movement processes such as exposure to humid or dry conditions, use of static EMC was more appropriate.

Bakker-Arkema & Hall (1965) dried alfalfa wafers and found that use of static EMC as boundary equations in second order differential equation of moisture transfer predicted drying behavior successfully. When static EMC was used, they found the moisture diffusivity to be almost constant during all but initial stages of drying. On the other hand, using dynamic EMC resulted in diffusivity value that changed rapidly with moisture content. Based on this work, they concluded that use of static EMC is more suitable for some biological products. In rice drying, most of recent works have used static EMCs in their models. Unless specified, EMC in this chapter refers to static equilibrium moisture content.

3.1 Thin layer drying model

Utilizing the analogy between heat transfer and drying process (Allen, 1960), drying rate of grains can be expressed as:

$$\frac{\partial M}{\partial t} = -k(M - M_e) \tag{1}$$

where, M (kg water/ kg dry solids) is moisture content of grain, t (s) is the period of drying, M_e (kg water/ kg dry solids) is the equilibrium moisture content (EMC) of the drying grain and k (s^{-1}) is the drying constant. This equation was found to be convenient, if dynamic EMC was used for M_e (Allen, 1960). Integrated form and solution of this equation is given by:

$$\log(M - M_e) = -\frac{k}{2.303}t + C \tag{2}$$

$$MR = \frac{M - M_e}{M_o - M_e} = e^{-kt} \tag{3}$$

where, C is the integration coefficient, MR is dimensionless moisture ratio, and M_0 (kg water/kg dry solids) is the initial moisture content of grains. The value of dynamic EMC used in such equations are determined using trial and error method by plotting, log(M-M_e) versus time for different assumed values of M_e. For the correct value of M_e, such plot would be a straight line. The slope of such straight line is used to determine the drying constant k.

Allen (1960) applied this drying equation to thin layer rice drying experimental data and found that the M_e and drying constant k, depended upon initial moisture content, temperature, humidity and quantity of drying air. The rice drying experimental data also revealed that initial drying period i.e. up to 30 minutes needs different treatment, since it is dependent upon M_e and k values, which is different from those used in later drying periods. However this transition was smooth and knowledge of precise discontinuity was not required.

In last fifty years, there has been considerable interest among researchers to use empirical or semi-empirical models, to describe the drying curves during thin-layer grain drying. Some of these models are described in Table 1.

Reference	Model Equation
Allen (1960)	$MR = e^{-kt}$
Henderson (1974)	$MR = Ae^{-k_1 t} + Be^{-k_2 t}$
Agrawal & Singh (1977)	$MR = Ae^{-kt^n}$
Wang (1978)	$MR = 1 + At + Bt^2$
Midilli et al. (2002)	$MR = Ae^{-kt^n} + Bt$

Table 1. Thin layer drying model equations

In these models, k, A, B, k_1, k_2, n are constants dependent upon drying conditions such as ambient humidity, temperature of drying air and air flow rate through drying column.

Hacihafizoglu et al. (2008) reviewed twelve such models to describe thin layer drying of rice. The number of parameters in these models varies from one to four. They conducted drying experiments on long grain rough rice to determine the parameters of these models and determined the statistical fit of these models to the drying experimental data. In all but one model, the correlation coefficient was found to be higher than 0.98, which means that all of these can describe the thin layer drying of rough rice satisfactorily. As expected, model developed by Midilli et al. (2002) that has four parameters gave the best fit with the experimental results.

Advantages of such thin layer drying models are in their simplicity and ease of development. However, parameters in these models depend on specific drying conditions and therefore must be experimentally determined for each drying condition.

3.2 Deep bed drying models

In deep bed drying, conditions of drying air and grain vary at different depths making it difficult to use single value of drying constant and equilibrium moisture content, required in thin-layer drying equations. Two approaches were taken to model such deep bed drying systems. First approach required determination of mean bed temperature and then, use the thin layer drying equation with drying constants at that mean temperature. In second approach, deep drying bed was considered as series of thin layer drying beds, each having different temperature and therefore, different drying constants.

Allen (1960) conducted experiments to study deep bed drying of maize and rice and used principle of dimensional analysis, to determine mean bed temperature. Their predicted drying times in case of rice and maize drying were close to the actual values, the difference being less than 10% of total drying periods. Nelson (1960) applied similar dimensional analysis and theory of similitude to study drying in deep bed grain dryers.

Boyce (1965) conducted enthalpy balances to thin layers of barley during drying, accounting both sensible heat and latent heat of vaporization and conducted layer by layer calculations to determine temperature of grains at different depths in the deep bed. Despite involving extensive computation in this approach, it has considerable merit as it uses the fundamentals principles of heat transfer, compared to empirical approach of Allen (1960).

Detailed description of deep bed drying models was considered beyond the scope of this chapter. For detailed information on these models and their implementation on computer reader can refer to works by Bakker-Arkema et al. (1967), Spencer (1969), Henderson & Henderson (1968) and Parry (1985).

3.3 Single kernel models

In last three decades, Fick's laws of diffusion have been extensively used to model moisture movement within the rice kernel in different forms namely white rice, brown rice and rough rice. In addition to average kernel moisture, such models also describe moisture distribution within the rice kernels that can be used to estimate moisture gradients and fissuring in rice. Some studies (Lague, 1990; Yang et al., 2002; Meeso et al., 2007; Prakash & Pan, 2009) have also considered heat transport within the kernel in their models.

Different rice varieties have their different physical, thermal and hygroscopic properties. Depending upon the variety of interest, researchers have determined these properties and developed appropriate models to describe drying. Detailed description of these modeling efforts is described in the next section.

4. Single kernel models

4.1 Kernel geometry

Rice kernel has an irregular shape. In addition to its shape, structure and thickness of husk also varies in the kernel (Fig. 2). Developing mathematical model for irregular shapes is computer power intensive and hence, most of the times rice kernel is approximated to simpler shapes such as sphere, cylinder, prolate spheroid and ellipsoid. Depending upon length-width ratio of milled rice, rice varieties are classified into three grain types: long, medium and short. Length to width ratio for long grain rice is larger than 3.0, medium grain rice is 2.0 to 2.9 and short grain rice is lower than 2.0 (USDA, 1994). Selecting the shape of model depends upon geometry of rice variety under study and computational tools available to solve the model.

Steffe & Singh (1980a) assumed spherical shape to model short grain rice forms. In rough rice model, they considered endosperm layer to have spherical shape that is surrounded by spherical shells of bran and husk. Their brown rice model consisted of endosperm and bran layers while white rice model consisted endosperm only. Assuming spherical shape made drying a one-dimensional transport process and easy to solve mathematically.

Prediction of moisture gradients accurately demanded more resemblance to the true shape of kernel. Lu & Siebenmorgen (1992), Sarkar et al. (1994), Igathinathane & Chattopadhyay (1999a) and Yang et al. (2002) assumed prolate spheroid shape to model medium and long grain rices while, Ece and Cihan (1993) considered short cylinder shape to model the short grain rice kernel. Due to their choice of model geometry, these studies have considered transport processes in two directions.

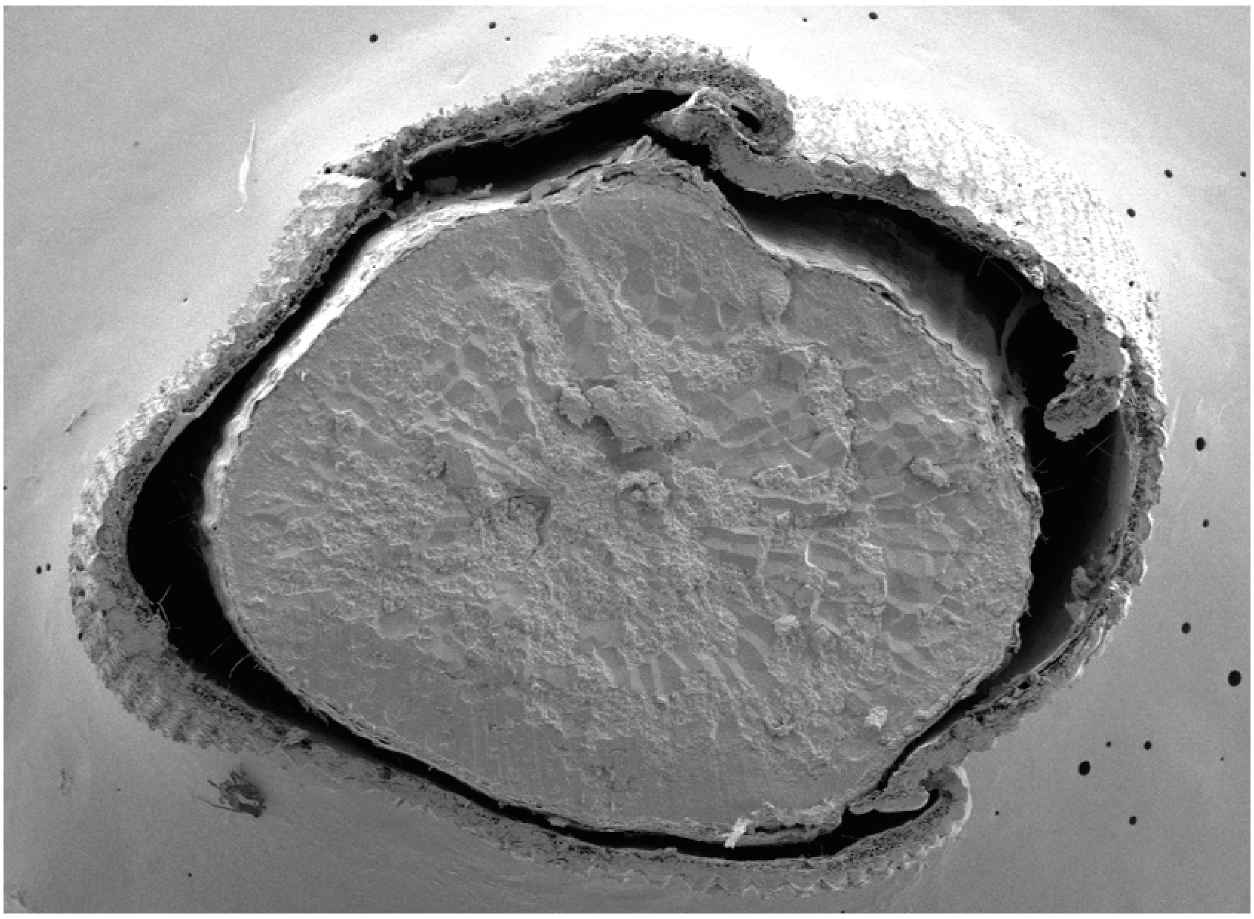

Fig. 2. Scanning electron micrograph of transverse section of rough rice (Lemont variety)

Use of prolate spheroid shape is suitable when rice kernel cross-section is circular. In case of medium grain rice variety Californian M206, kernel cross-section is not circular with one axis about 40% longer than the other. Table 2 shows the three dimensions of this rice variety. In this case, we have considered an ellipsoid shape with three unequal axes to represent the kernel. Here, moisture transport within the kernel is three-dimensional phenomenon.

		Dimensions (mm)			Weight (mg)
		Length	Width	Thickness	
White Rice	Mean	5.78	2.66	1.85	22.3
	(Std. Dev.)	(0.23)	(0.11)	(0.08)	(0.6)
Brown Rice	Mean	5.82	2.78	1.97	25.0
	(Std. Dev.)	(0.33)	(0.09)	(0.08)	(0.7)
Rough Rice	Mean	6.97	3.16	2.19	31.1
	(Std. Dev.)	(0.32)	(0.19)	(0.08)	(0.5)

Table 2. Kernel dimensions and weights of medium grain rice variety Californian M206 at 18% moisture on wet basis

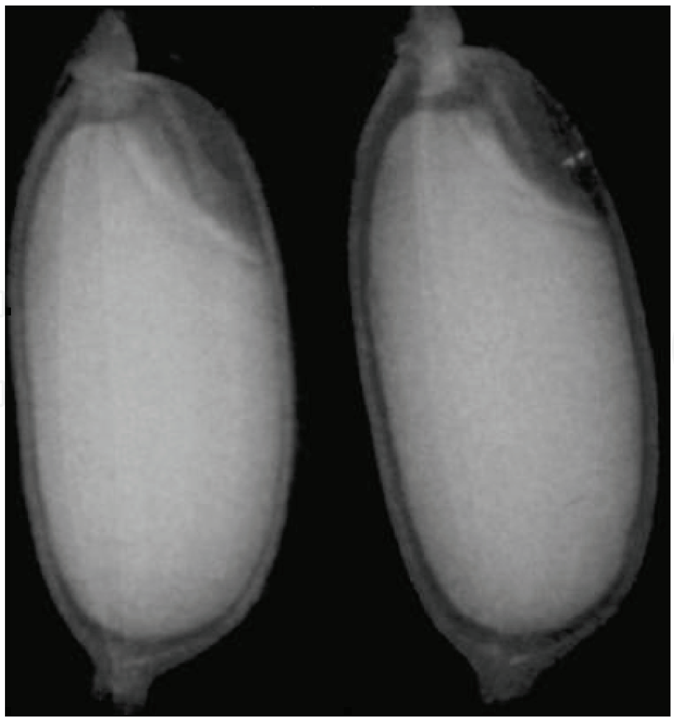

Fig. 3. X-ray images of two rough rice kernels before and after drying

In rough rice model, the kernel consists of three isotropic regions namely endosperm (or white rice), bran and husk. In addition to these regions, small air gap is also present between bran and husk regions in actual rough rice (Fig. 3). Using X-ray imaging, we observed size of this air gap to increase with progress of drying. In most models, existence of this air layer is not considered and moisture transfer resistance due to husk represents the equivalent resistances of this air gap and the husk region. Moisture transfer resistances present in the rough rice model are shown in Fig. 4.

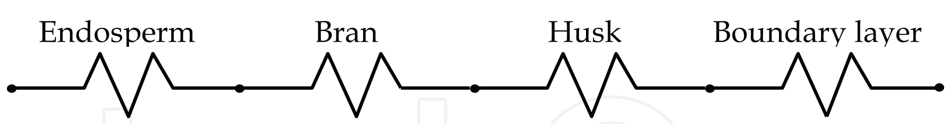

Fig. 4. Moisture transport resistances in rough rice drying model

It should be noted that size of rice kernel depends on its moisture content. During the drying process, rice kernels shrink in size. But, for the sake of simplicity, most researchers have neglected this shrinkage and assumed rice kernel to have same dimensions during the drying process.

4.2 Transport equations

Single-phase moisture diffusion and heat conduction is commonly used as the mechanism of moisture transfer and heat transfer, respectively, within the rice kernel. Fick's law of diffusion and Fourier's law of conduction are commonly used to describe these transport processes during rice drying, respectively. General equations corresponding to these laws are given by:

$$\frac{\partial M}{\partial t} = \nabla \bullet (D \nabla M) \quad (4)$$

$$\rho c_p \frac{\partial T}{\partial t} = \nabla \bullet (k \nabla T) + Q \tag{5}$$

where, M is the moisture content on dry basis (kg water/kg dry matter), t is time (s), ∇ is divergence operator, D is moisture diffusivity (m^2/s), ρ is density of rice components (kg/m^3), c_p is specific heat ($J.kg^{-1}.^oC^{-1}$), T is temperature (^oC), k is thermal conductivity ($W.m^{-1}.^oC^{-1}$) and Q is volumetric heat generation (W/m^3).

Depending upon the assumed kernel shape, these transport equations can be applied in spherical, cylindrical or cartesian co-ordinates. Igathinathane & Chattopadhyay (1999a) have used prolate spheroid co-ordinates.

4.3 Boundary and initial conditions

Two kind of boundary conditions are commonly found in the moisture transport modeling in the rice drying literature: Dirichlet boundary condition (i.e. instant moisture equilibration of kernel surface to the ambient environment) and Newmann boundary condition. Mannappeeruma (1975), Steffe & Singh (1980a), Lu & Siebenmorgen (1992) and Meeso et al. (2007) considered Dirichlet boundary condition and assumed kernel surface moisture M_s (kg water/kg dry matter) to have the same moisture as the equilibrium moisture content M_e (kg water/kg dry matter) of rice in the ambient environmental conditions. This can be written as:

$$M_s = M_e \tag{6}$$

Sarker et al. (1994) and Yang et al. (2002) equated the outward moving moisture flux to moisture taken away by convective air and obtained the following Newmann boundary condition:

$$-D \frac{\partial M}{\partial n} = h_m (M_s - M_e) \tag{7}$$

where, h_m (m/s) is the surface moisture transfer coefficient and n is the outward normal at the kernel surface. It should be noted that Eqn. 6 and Eqn. 7 become identical for larger values of h_m.

Due to existing uncertainty on mechanism of moisture movement in the rice kernel, some researchers have assumed evaporation of liquid moisture to occur both at surface and inside the kernel (Yang et al., 2002) while others have assumed evaporation to occur only at surface of kernels (Meeso et al., 2007; Prakash & Pan, 2009).

Assuming evaporation to occur only at kernel surface during drying, heat transfer by convective air to the rice surface can be equated to the conductive heat entering the surface and change in enthalpy of evaporating moisture. This enthalpy balance represents the heat transfer boundary condition and can be described by:

$$-k \frac{\partial T}{\partial n} = h(T_s - T_a) - \frac{\rho \lambda V}{A} \bullet \frac{\partial M_{av}}{\partial t} \tag{8}$$

where, h ($W.m^{-2}.^oC^{-1}$) is the convective heat transfer coefficient, T_s (^oC) is the temperature of rice kernel surface, T_a (^oC) is the temperature of drying air, λ (J/kg) is latent heat of vaporization, V (m^3) is the volume of the kernel, A (m^2) is the total surface area of the kernel and M_{av} (kg water/kg dry solids) is average moisture content of kernel at any given time on dry basis.

At internal boundaries i.e. bran-husk interface and endosperm-bran interface, moisture and heat fluxes leaving one region is equated to the respective fluxes entering other region. Rice is considered to have uniform moisture and temperature throughout the kernel before drying. This is set as the initial conditions in the models.

4.4 Volumetric heat generation

Assuming moisture evaporation to take place both at surface and inside the kernel, the heat generation due to such evaporating liquid moisture can be expressed as:

$$Q = \frac{\rho\lambda}{1+M} \bullet \frac{\partial M}{\partial t} \tag{9}$$

where, λ (J/kg) is latent heat of vaporization. Here $\partial M/\partial t$ must represent the rate of change of moisture content in liquid form. Determining this rate would require multiphase modeling that describes moisture in liquid and vapor phases separately. Such multiphase approach is not pursued in rice modeling yet. When moisture evaporation is assumed to occur only at kernel surface then there is no such volumetric generation.

Like other radiations, infrared radiation has power to penetrate the surfaces and generate heat. Heat transfer from infrared radiations to rice kernels can be modeled in two ways: assuming penetration of heat inside the kernel surface or assuming no heat penetration i.e. all of radiation heating the surface only.

Heat generated at certain depth below the kernel surface can be modeled as an exponential decay (Ginzburg, 1969). Datta & Ni (2002) described the heat generation due to infrared radiations as following:

$$Q = \frac{P_s}{d_p} e^{-\frac{d}{d_p}} \tag{10}$$

where, P_s is the infrared radiation power at the surface (W/m^2), d is the depth from the surface (m), and d_p is the penetration depth of infrared radiation (m).

Though assuming heat penetration is more fundamental approach, it requires knowledge of penetration depth that is still to be determined accurately. Some studies (Meeso, 2007; Prakash & Pan, 2009) have considered penetration depth of of 1-2 mm that was reported for grains by Ginzberg (1969) and Nindo et al. (1995). If penetration of heat is not assumed, then there is no heat generation due to infrared radiation. In such case, all radiation heat falling over the rice surface should be considered in the heat transfer boundary condition, which can then be rewritten as:

$$-k\frac{\partial T}{\partial n} = h(T_s - T_a) - \frac{\rho\lambda V}{A} \bullet \frac{\partial M_{av}}{\partial t} - P_s \tag{11}$$

4.5 Solution of models

Analytical and numerical solutions have been used to solve the transport equations in rice drying. Crank (1979) described analytical solution to Fick's law of diffusion for regular shapes such as sphere, cylinder and slab for different boundary conditions.

Aguerre et al. (1982) have assumed rough rice kernel as a homogeneous sphere and considered instant moisture equilibration of kernel surface to the ambient environment.

They have used the following analytical solution to predict average moisture content (M) of the kernel at any given time:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(-\frac{n^2 \pi^2 D t}{R^2} \right) \quad (12)$$

where, M_0 is the initial moisture content, M_e is the equilibrium moisture content to rice kernel at ambient drying conditions and R (m) is the equivalent radius of the rice kernel. Equivalent radius was determined by equating the volume of rice kernel (V, m^3) to that of sphere and is given by:

$$R = \left(\frac{3}{4\pi} V \right)^{1/3} \quad (13)$$

It should be noted that neglecting third and higher terms of series in Eqn. 12 result in the thin-layer drying equation reported by Henderson (1974) in Table 1.

Ece & Cihan (1993) assumed rice as a homogeneous short cylinder with Dirichlet boundary conditions at surface and used following analytical solution to determine average moisture constant at any given time:

$$MR = \frac{M - M_e}{M_0 - M_e} = \frac{8R^2}{L^2} \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} \frac{1}{\alpha_n^2 \beta_m^2} e^{-(\alpha_n^2 + \beta_m^2)\frac{D}{R^2}} \quad (14)$$

where, R (m) is radius of cylinder, L (m) is height of cylinder. α_n (n=1,2,…) are the roots of Bessel function of zero order $J_0(x)$, and β_m (m=1,2,…) are defined as:

$$\beta_m = \frac{(2m-1)\pi R}{2L} \quad (15)$$

Aguerre et al. (1982) and Ece & Cihan (1993) did not consider presence of multiple components such as endosperm, bran and husk inside their models. If these components are considered in the model, known analytical solutions cannot be used to solve moisture transport equations. In such cases, numerical methods such as finite difference and finite element methods are used to solve heat and moisture transport equations.

Steffe & Singh (1980a) and Meeso et al. (2007) used finite difference methods in their one dimensional spherical shaped rice models. Igathinathane & Chattopadhyay (1999a) have used finite difference method in prolate spheroid co-ordinate system to model rice drying in two dimensions. Advantage of the finite difference method lies in its simplicity of implementation. However, it is not well suited to solve two or three-dimensional problems and/or problems consisting of material discontinuity. In such problems, finite element method is more suitable.

Many general-purpose finite element software packages such as Comsol Multiphysics or pdetool in MATLAB can be used to solve heat and mass transfer equations involved in the drying model. Lu & Sibenmorgen (1992), Sarker et al. (1994), Yang et al. (2002) and Prakash & Pan (2009) have used finite element method in their rice models. The representative meshed model geometry of rough rice in the three-dimensional model is shown in Fig. 5. As seen in this figure, only one-eighth of the actual rough rice volume was considered in this model. This was due to the existence of symmetry about the three axes in the rice kernel.

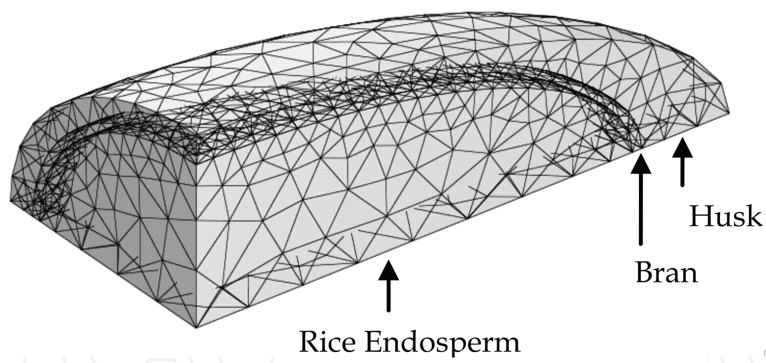

Fig. 5. Meshed rough rice model visualization in a finite element software program

4.6 Model validation

Measuring moisture distribution within the rice grain is very difficult due to its small size. Hence, most studies have measured the average kernel moisture and compared it with the model predicted average moisture to validate the model. Similarly, the center temperature of grain is measured and compared with its model predicted value to validate the heat transfer component in the models.

4.7 Moisture and temperature gradients

Single kernel models have the capability to determine moisture distribution and moisture gradients within the rice kernel. Fig. 6 shows distribution of moisture gradient produced inside the rough rice kernel after 20 minutes of drying at air temperatures of 45ºC. Highest moisture gradients are observed along the shortest axis on both sides of bran layer. Among the three rice components, bran has least moisture diffusivity, which slows the movement of moisture across it and thus, produces such high gradients on bran-endosperm and bran-husk interface. Such high moisture gradients along the shortest axis, near the center of kernel may explain the occurrence of most fissures along the axial direction of the kernel.

The maximum temperature gradient inside rice kernel appeared within 20 s of drying period and the entire temperature gradients disappeared within 2 to 3 minutes when rough rice was dried by heated air at 60ºC temperatures (Yang et al., 2002). Based on this observation, they concluded that impact of temperature gradients on fissuring is minimal. On the other hand, moisture gradients were found to increase with drying time up to about 15 to 30 minutes after which they started to decline (Sarker et al., 1996; Yang et al., 2002).

In infrared radiation drying, we determined the moisture gradients at two points located on bran-husk interface (P1) and bran-endosperm interface (P2), both along the shortest axis and close to center of kernel. These two points are expected to have highest moisture gradients. To understand the relationship between these moisture gradients and rice fissuring, drying experiments were performed for different drying periods and fissuring in rice was measured. Generally, rice fissuring is quantitatively described by head rice yield that is defined as the mass percentage of rough rice, which remains as head rice after milling. Lower values of HRY suggest more fissuring. Fig. 7 describes head rice yields obtained after infrared drying experiments conducted for different time periods and corresponding moisture gradients at points P1 and P2 obtained from the model.

Moisture gradients at bran-husk interface were higher than at the bran-endosperm interface due to rapid drying of husk. After 150 s of drying, moisture gradients at bran-husk interface remained almost constant, as husk was already very dry by this period. Significant reduction in head rice yield is observed only after 120 s of infrared heating period. While correlating fissuring and moisture gradient values, it should be noted that at higher moistures, rice kernels are more elastic and can endure higher moisture gradients while the same magnitude of moisture gradients in low moisture rice can cause it to fissure (Kunze & Calderwood, 2004).

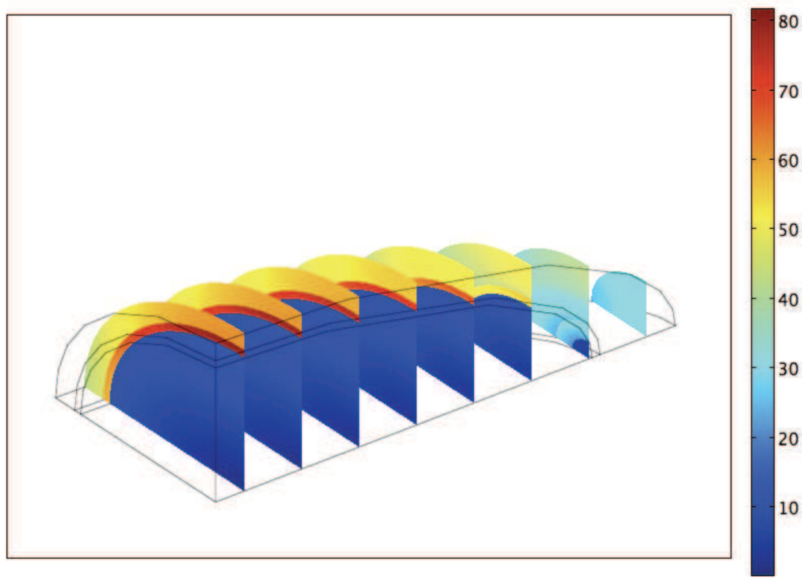

Fig. 6. Moisture gradient (% dry basis per mm) distribution in the rough rice kernel (Californian M206 variety) after 20 minutes of drying at 45ºC air temperature

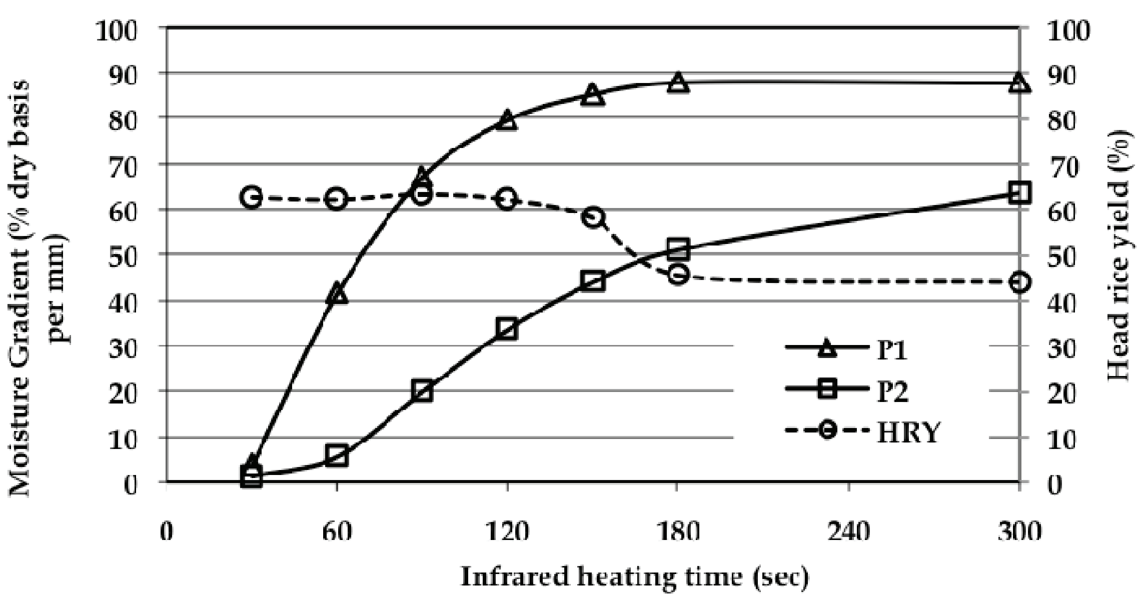

Fig. 7. Head rice yield (HRY) and moisture gradients at bran-husk interface (P1) and bran-endosperm interface (P2) during infrared drying for different time periods

5. Thermal and hygroscopic properties

Drying modeling demands knowledge of moisture diffusivity, thermal conductivity, specific heat, density, equilibrium moisture content and convective heat and mass transfer coefficients. Lague (1990) and Kunze et al. (2004) have described studies on physical, thermal, mechanical and hygroscopic properties of rice. These properties depend upon the rice variety, moisture content and sometimes temperature. Some of these properties such as equilibrium moisture content, moisture diffusivity, convective mass transfer coefficients and convective heat transfer coefficient, are described in detail in this section.

5.1 Equilibrium moisture content

At equilibrium, different components of rough rice have different moisture contents (Table 3). In addition to the rice form, variety and temperature, equilibrium moisture content (EMC) also depends upon whether rice is adsorbing or desorbing. Even among the equilibrated rice samples, the individual rice kernels were observed to have a standard deviation of 0.5% in 10% average MC rice to 4.5% in 26% average moisture rice (Siebenmorgen et al., 1990). The causes of such non-uniformity among equilibrated samples are not well understood.

R.H.	White rice		Brown rice		Rough rice		Husk	
%	ads.	des.	ads.	des.	ads.	des.	ads.	des.
20	7.5	10.2	9.5	9.8	9.9	11.1	10.5	11.3
40	10.2	13.6	9.8	11.7	10.6	13.3	13.0	14.3
60	15.2	17.4	12.7	15.0	12.7	16.5	15.8	17.6
80	19.4	21.0	16.8	18.7	17.3	20.0	18.6	21.0
98	30.9		27.2		26.7		26.3	

Table 3. Equilibrium moisture content (EMC, % dry basis) of different forms of Californian variety M206 rice and its husk during adsorption (ads.) and desorption (des.) at different relative humidities (RH, %)

At any given temperature, EMC of rice samples can be plotted versus the corresponding equilibrium relative humidity (ERH) to obtain the moisture isotherm. This ERH is also equal to the water activity (a_w) of the rice sample. There were many theoretical and empirical mathematical equations developed to describe the relationship between ERH or water activity and EMC and each equation had success in predicting the equilibrium moisture content data for a particular foodstuff at a given range of equilibrium relative humidities and temperatures. Among these numerous equations, the Guggenheim-Anderson-de Boer (GAB) equation, showed good fit to the isotherms in a broad range of a_w and was used by by several researchers to model sorption isotherms of rice (Gencturk et al., 1986; Reddy & Chakraverty, 2004; Iguaz & Virseda, 2007). It is given by:

$$M = \frac{M_0 C K a_w}{(1 - K a_w)(1 - K a_w + C K a_w)} \tag{16}$$

where, M_0, C and K are constants. A literature survey carried out by Sun (1999) for the selection of suitable isotherm model from 18 different authors' 763 data points indicated that when the sorption experiments were conducted at different temperatures then the Strohman-Yoerger equation is most appropriate to describe sorption isotherms of rice. It is expressed by:

$$a_w = \exp\left[C_1 e^{-C_2 M} \ln(P_s) - C_3 e^{-C_4 M}\right] \tag{17}$$

where, P_s is saturated pressure over liquid water and C_i (i =1 to 4) are different constants.

5.2 Moisture diffusivity

Moisture transfer within the kernel could occur in both liquid and vapor phase. Differentiating these two would require a multiphase modeling of heat and mass transfer. Such studies have not been pursued so far in rice drying. To account for both liquid and vapor phase diffusivity, usually an effective diffusivity, D_{eff} (m^2/s) is used. Effective diffusivity of different rice components namely endosperm, bran and husk are determined by minimizing the sum of squared differences between actual and predicted drying curves of white rice, brown rice and rough rice, respectively.

First, rice endosperm diffusivity is assumed. Then the white rice model is run to predict the moisture contents at different times. Error is determined by comparing the average values of model predicted moisture and experimentally measured white rice moisture. Then, the sum of squared errors (*SSE*) is computed as follows:

$$SSE = \sum_{i=1}^{n} \left(M_{ei} - M_{pi} \right)^2 \tag{18}$$

where, M_{ei} and M_{pi} are experimentally measured and model predicted moisture (%, dry basis) at a given time period, respectively, and n is the number of data points used to calculate *SSE*. Different diffusivity values are assumed in the white rice model and for each of them the corresponding *SSE* is computed. Diffusivity value that gives the lowest *SSE* is considered as the white rice diffusivity. Once rice endosperm diffusivity is known, brown rice model is run assuming different values of bran diffusivity. By comparing the *SSE* between the brown rice model predictions and the brown rice experimental data, diffusivity value of bran is determined. Similarly, diffusivity value of husk is determined.

In addition to diffusivity determinations of individual rice components, brown rice and rough rice models may be run assuming that they are composed of single homogeneous material and then these model predictions can be compared with the experimental drying data to determine the diffusivities of brown rice and rough rice as a whole.

Most researchers have described the temperature dependence of effective diffusivity by Arrhenius type exponential relationships. Table 4 shows some of such relationships. To compare predictions of moisture diffusivity from these relationships, moisture diffusivity (D, m^2/s) was calculated for one certain drying conditions i.e. drying air temperature of 43ºC and drying air velocity (V) of 3 m/s. This diffusivity value is described in the last column of the Table 3.

Diffusivity predictions from these relationships vary significantly; for example endosperm diffusivity varied from 2.3E-11 to 1.7E-10 m^2/s. These differences can be explained on the basis of biological variations in rice kernels of different varieties, the specific assumptions such as kernel shape used in rice modeling and the drying conditions such as drying bed thickness, drying air velocity used in different studies. For a given volume, sphere has minimum surface area and therefore, models assuming spherical shape of rice grain would predict highest diffusivity values for same set of experimental data.

Rice endosperm has highest diffusivity among the three rice components. Between husk and bran, some researchers (Steffe & Singh, 1980a; Lu & Siebenmorgen, 1992) determined that husk had lower diffusivity but others (Sarker et al., 1994; Igathinathane & Chattopadhyay, 1999b) found that bran had lower diffusivity. For medium grain rice variety Californian M206, we have found diffusivity of bran to be smallest among rice components. Cause of such differences is not well understood.

Process, Rice type and Reference	Rice Component	Model	D (m^2/s)[#]
Drying Short grain (S6) Steffe & Singh (1980a, 1982)	 Endosperm Bran Hull Brown Rice Rough Rice	$D = \frac{Ae^{-(B/T)}}{3600}$ A = 2.57E-3 B = 2880 A = 0.797 B = 5110 A = 484 B = 7380 A = 0.141 B = 4350 A = 33.6 B = 6420	 7.9E-11 2.1E-11 9.7E-12 4.1E-11 1.4E-11
Drying Rewetted Short grain (S6) Steffe & Singh (1980b)	 Endosperm Bran	$D = \frac{Ae^{-(B/T)}}{3600}$ A = 1.29E-2 B = 3430 R^2 = 0.84 A = 1.82 B = 5400 R^2 = 0.99	 6.9E-11 1.9E-11
Drying Long grain (Bluebelle) Steffe & Singh (1982)	Rough Rice	$D = \frac{Ae^{BM}}{3600}$ $A = (9.8787E-3)e^{-(4295/T)}$ $B = 0.159T - 37.88$	3.2E-11
Adsorption Long grain (Lemont) Lu & Siebenmorgen (1992)	 Endosperm Bran Hull Brown Rice Rough Rice	$D = \frac{Ae^{-(B/T)}}{3600}$ A = 1.6163 B = 5289.5 R^2 = 0.91 A = 110.969 B = 7042.5 R^2 = 0.98 A = 3.0101 B = 6000.5 R^2 = 0.99 A = 79.2446 B = 6639.4 R^2 = 0.98 A = 5.9835 B = 6101.4 R^2 = 1.00	 2.4E-11 6.5E-12 4.7E-12 1.7E-11 6.8E-12
Adsorption Long grain (NewBonnet) Lu & Siebenmorgen (1992)	 Endosperm Bran Hull Brown Rice Rough Rice	$D = \frac{Ae^{-(B/T)}}{3600}$ A = 1.1855 B = 5206.1 R^2 = 0.91 A = 3.2867 B = 6013.5 R^2 = 0.99 A = 1.4641 B = 5842.8 R^2 = 0.98 A = 12.8355 B = 6080.8 R^2 = 0.97 A = 2.968 B = 5917.4 R^2 = 0.98	 2.3E-11 5.0E-12 3.8E-12 1.6E-11 6.1E-12
Drying Rocco Ece & Cihan (1993)	Rough rice	$D = \frac{0.05915V^{-0.85}e^{\left(\frac{-4706}{TV^{0.076}}\right)}}{3600}$	7.3E-12
Drying Long grain (Lemont) Sarker et al. (1994)	 Endosperm Bran Hull	$D = \frac{A \times 10^{-(B/T)}}{3600}$ A = 3.768E-3 B = 1213.3 R^2 = 0.95 A = 3.822E-2 B = 1941.1 R^2 = 0.91 A = 2.277E-1 B = 2046.6 R^2 = 0.96	 1.5E-10 7.6E-12 2.1E-11
Drying Medium grain parboiled rice (Pankaj) Igathinathane & Chattopadhyay (1999a, 1999b)	 Endosperm Bran Hull	$D = Ae^{-(B/T)}$ A = 1.08E-7 B = 2036 R2 = 0.99 A = 3.99E-6 B = 4096 R2 = 0.99 A = 1.66E-5 B = 4230 R2 = 0.99	 1.7E-10 9.4E-12 2.6E-11

[#] Diffusivity value (*D*) calculated at drying conditions: *T* = 316 K (43°C) and *V*= 3 m/s.

Table 4. List of relationships to determine diffusivity (m^2/s) of rice fractions

It is well known that diffusivity of starch varies with change in its moisture content. We determined moisture diffusivity of rice components during adsorption and desorption process in different moisture contents ranges. We found that diffusivity of rice endosperm was higher during desorption than adsorption at moisture contents higher than 8% on dry basis. Between 8% and 19% moisture, white rice diffusivity increased with increase in moisture. On the other hand, diffusivity of husk decreased with increase in moisture content at all moisture contents. Bran diffusivity remained almost constant with change in moisture.

5.3 Convective heat transfer coefficient

Convective heat transfer coefficient determines the flux of heat input from the drying air to rice grains. It depends upon properties of drying air, porosity of rice bed and the shape of rice grains. Deep bed drying can be considered as packed bed of grains, while single layer or single kernel drying can be considered as grain being immersed in fluid.

Bird et al. (1960) described convective heat transfer coefficient h ($W.m^{-2}.^{o}C^{-1}$) in packed beds by the following correlation:

$$h = \left(\frac{\rho v' c_p}{\varepsilon}\right) \times \left(A\psi \,\mathrm{Re}^{-B}\right) \times \left(\frac{\mu c_p}{k}\right)_f^{\frac{-2}{3}} \tag{19}$$

A = 0.61 and B = 0.41 for $Re > 50$

A= 0.91 and B = 0.51 for $Re < 50$

where, ρ is density (kg/m^3), v' is superficial velocity (m/s), c_p ($J.kg^{-1}.^{o}C^{-1}$) is specific heat, ε is the void fraction, Re is dimensionless Reynolds number, μ ($kg.s^{-1}.m^{-1}$) is viscosity, k ($W.m^{-1}.^{o}C^{-1}$) is the thermal conductivity of the flowing gas and ψ depends upon shape of particles in bed. Value of ψ is 1 for sphere, 0.91 for cylinder and 0.86 for flakes. The subscript f indicates properties evaluated at the film temperature with others at the bulk temperature.

Taking a theoretical approach, Geankoplis (2000) has described a packed bed column as bundle of crooked tubes of varying cross-sectional area. For heat transfer in the bed of spheres and Reynolds number (Re) range of 10-10000, convective heat transfer coefficient is expressed by:

$$h = \left(\frac{\rho v' c_p}{\varepsilon}\right) \times \left(\frac{2.876}{\mathrm{Re}} + \frac{0.3023}{\mathrm{Re}^{0.35}}\right) \times \left(\frac{\mu c_p}{k}\right)_f^{\frac{-2}{3}} \tag{20}$$

For sphere submerged in a fluid surface heat transfer coefficient can be described as (Geankoplis, 2000):

$$Nu = \frac{hd}{k} = 2 + 0.6\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3} \tag{21}$$

where, Nu is the dimensionless Nusselt number, d (m) is the characteristic dimension, and Pr is the dimensionless Prandtl number. Using this correlation, Bal (1968) found the value of surface heat transfer coefficient to vary between 57-85 $W.m^{-2}.^{o}C^{-1}$ over a wide range of temperatures.

Smith et. al. (1971) measured impact of shape, air velocity and air temperature on convective heat transfer coefficient of ellipsoid bodies. They defined geometry index, G to accommodate impact of shape as follows:

$$G = \frac{1}{4} + \frac{3c^2}{8a^2} + \frac{3c^2}{8b^2} \tag{22}$$

where, a, b, and c are the three dimensions of the ellipsoid. They allowed the test objects to cool down from a defined temperature and measured the change of temperature with time. With this temperature time data, they determined Nusselt number for different conditions and then it was fitted to a regression equation that is described below:

$$Nu = (0.32 - 0.22G)\,\mathrm{Re}^{(0.44+0.23G)} \tag{23}$$

Correlation coefficient for this model varied between 0.90 and 0.99 for values of G between 0.3 and 1.0. Mannapperuma (1975) used this equation to determine convective heat transfer coefficient for brown rice. For geometry index of 0.526, he found the coefficient to vary very small with drying temperatures. For air speed varying from 0.25 to 2.03 m/s the coefficient varied from 17-68 W.m^{-2}.^{o}C^{-1}.

Sokhansanj and Bruce (1987) used following empirical equation for use in grain drying simulation:

$$\begin{aligned} h &= 3.27cG\,\mathrm{Re}^{-0.65}\,\mathrm{Pr}^{-0.67} \\ \mathrm{Re} &= \frac{Gd}{\mu} \end{aligned} \tag{24}$$

where, G is mass velocity of air (kg.m^{-2}.^{o}s^{-1}), d (m) is the particle diameter and μ (kg.s^{-1}.m^{-1}) is the viscosity of the air.

Apart from the above described methods, the convective heat transfer coefficient for a given drying process can also be measured experimentally by enthalpy balance as follows:

$$hA_s(T_a - T)dt = mc_p dT + \lambda dm \tag{25}$$

where, A_s is kernel surface area (m^2), T_a is air temperature in drier (^{o}C), T is temperature of kernel (^{o}C) at drying time t (s), m is mass of wet kernels (kg/m^3), c_p (J.kg^{-1}.^{o}C^{-1}) is specific heat of grains and λ (J/kg) is latent heat of vaporization. Assuming, no moisture loss in the thin layer of kernel during heating i.e. period when M = M_e, Pabis & Henderson (1962) simplified this equation to determine convective heat transfer coefficient as follows:

$$h = \frac{\rho_g V c_p}{A_s t} \ln\left(\frac{T_a - T_0}{T_a - T}\right) \tag{26}$$

where, ρ_g (kg/m^3) is density of wet grain, V is the kernel volume (m^3), c_p (J.kg^{-1}.^{o}C^{-1}) is specific heat of grains, T_0 is the initial temperature of grain (^{o}C). When logarithm of temperature ratio is plotted versus time, the slope of curve can be used to evaluate the convective heat transfer coefficient.

5.4 Convective mass transfer coefficient

Surface mass transfer coefficient is dependent upon shape of kernels, air speed flowing over the kernels and properties of air in immediate environment. Patil (1988) and Sarker et al. (1994) have determined surface mass transfer coefficient, h_m (m/s) using following relationship:

$$Sh = \frac{h_m d_k}{D_{wa}} = 2 + 0.522\,\mathrm{Re}^{0.5}\,Sc^{0.33} \quad (27)$$

where, Sh is the dimensionless Sherwood number, D_{wa} is diffusivity of water in air (m^2/s), d_k is equivalent diameter of the kernel (m) and Sc is dimensionless Schmidt number.

6. Scope for future research

Describing moisture movement accurately for small and complex biological material such as rough rice is very challenging. Despite decades of modeling work, still many assumptions in these models remain untested and they provide a wide horizon for future research.

Moisture distribution within the rice kernel has rarely been validated by experimental techniques, thus the uncertainty over the actual mechanism is still unresolved. Nagato et al. (1964) investigated moisture distribution in the rice kernel by taking hardness measurements at different points in the kernel. Recently, there has been interest in using magnetic resonance imaging (MRI) technique to determine moisture distribution within the rice kernels (Frias et. al., 2002; Ishida et al., 2004; Hwang et al., 2009). However, due to small moisture present in the kernels, MRI signal is weaker in rice kernels than in other fruits and vegetables making it difficult to determine moisture distribution quantitatively. We performed MRI experiments to determine moisture distributions within the rough rice kernel and found that moisture removal within the rice kernel was not uniform during drying. Moisture removal is faster near the embryo (also called germ) region than other parts of kernel. Such moisture removal was also observed by Nagato (1964). Cause of such non-uniformity of moisture removal from the kernel is yet to be understood and implemented in the model. Similarly, impact of the changing air-layer between bran and husk is yet to be investigated.

There has been progress in determining impact of moisture gradients on rice fissuring. Still, more research is required to determine limiting values of moisture gradients that must be avoided to minimize fissuring. As discussed earlier, such gradients would depend on moisture content of rice.

7. Conclusion

In this chapter, we have discussed the important advances made in development of mathematical models to describe moisture movement in rice. With progress of computation technologies, the modelling studies have shifted from empirical or semi-empirical approach to more rigorous and mechanistic approach. In this chapter, three such approaches to model rice drying namely thin-layer models, deep-bed models and single kernel drying models are discussed. Among these, single kernel models are based upon diffusion mechanism and can determine moisture distribution within the rice kernel. Since moisture gradients within the grain were found to affect fissuring in kernels, such models have found widespread use in recent times. Using robust computational tools, recent models have used two-dimensional and three-dimensional models of prolate spheroid and ellipsoid shape, respectively, to model moisture movement in rice kernel. These shapes resemble the actual kernel geometry more closely and therefore, such models are expected to predict moisture distribution more accurately. In drying processes such as infrared drying, heating of kernels is very rapid and therefore, temperature dependent properties such as moisture diffusivity would vary within the rice kernel and vary with time. In such cases, both heat transfer and moisture transfer processes needs to be solved simultaneously in the model. Knowledge of physical, thermal and hygroscopic properties of the rice variety under study are very important for accurate model predictions.

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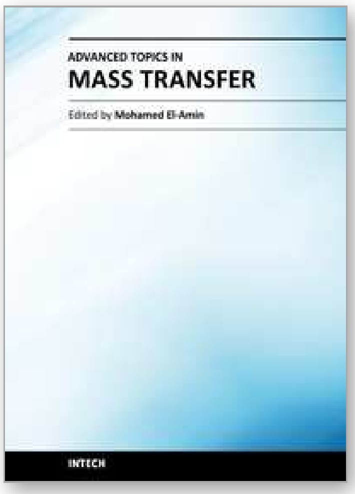

Advanced Topics in Mass Transfer

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This book introduces a number of selected advanced topics in mass transfer phenomenon and covers its theoretical, numerical, modeling and experimental aspects. The 26 chapters of this book are divided into five parts. The first is devoted to the study of some problems of mass transfer in microchannels, turbulence, waves and plasma, while chapters regarding mass transfer with hydro-, magnetohydro- and electro- dynamics are collected in the second part. The third part deals with mass transfer in food, such as rice, cheese, fruits and vegetables, and the fourth focuses on mass transfer in some large-scale applications such as geomorphologic studies. The last part introduces several issues of combined heat and mass transfer phenomena. The book can be considered as a rich reference for researchers and engineers working in the field of mass transfer and its related topics.