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Khan, Md Imran Hossen, Joardder, Mohammad, Kumar, Chandan, & Karim, Azharul

(2017)

Multiphase porous media modelling: A novel approach to predicting food processing performance.

*Critical Reviews in Food Science and Nutrition*, 153(3), pp. 319-327.

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<https://doi.org/10.1080/10408398.2016.1197881>

## **Multiphase Porous Media Modelling: A novel approach to predicting food processing performance**

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### **Abstract**

The development of a physics-based model of food processing is essential to improve the quality of processed food and optimise energy consumption. Food materials, particularly plant-based food materials, are complex in nature as they are porous and have hygroscopic properties. A multiphase porous media model for simultaneous heat and mass transfer can provide a realistic understanding of transport processes and thus can help to optimise energy consumption and improve food quality. Although the development of a multiphase porous media model for food processing is a challenging task because of its complexity, many researchers have attempted it. The primary aim of this paper is to present a comprehensive review of the multiphase models available in the literature for different methods of food processing, such as drying, frying, cooking, baking, heating and roasting. A critical review of the parameters that should be considered for multiphase modelling is presented which includes input parameters, material properties, simulation techniques and the hypotheses. A discussion on the general trends in outcomes, such as moisture saturation, temperature profile, pressure variation and evaporation

patterns, is also presented. The paper concludes by considering key issues in the existing multiphase models and future directions for development of multiphase models.

## **Keywords**

Multiphase model, Food Material, Review, Drying, Frying, Cooking, Heating, Baking

## 1 Introduction

Food processing is a key concern in today's world because about one-third of the global food production is lost annually as a consequence of flawed processing methods (Karim and Hawlader, 2005a). However, appropriate food processing is a challenging task; food is complex, amorphous, hygroscopic and non-homogeneous in structure; and the physics of coupled heat and mass transfer taking place during food processing is not yet well understood. The major food processing techniques are drying, cooking, frying, baking, heating, meat roasting and rehydration. Considerable effort has been made by scientists and researchers to uncover the actual phenomena that occur during food processing.

Most researchers have considered single-phase transport for moisture migration in these processes. These types of single-phase or diffusion-based models for heat and mass transfer are oversimplified and do not consider the fundamental physics of food processing (Batista et al., 2007; Ben Mabrouk et al., 2012; Fowler and Bejan, 1991; Khan et al., 2016; Golestani et al., 2013; Kaya et al., 2008; Kumar et al., 2015). In contrast, a multiphase model considers the transport mechanisms of liquid water, water vapour and air separately. Multiphase models are more comprehensive and provide better insight into the transport mechanisms because they can account for temporal and spatial profiles of temperature, liquid water, water vapour and air inside the food material.

Therefore, a multiphase model for food processing is required for a better understanding of the processes. Development of a multiphase model for food processing, however, is a very difficult task, as fundamental physical properties and phenomena should be taken into consideration. Moreover, there is an enormous lack of appropriate material properties and

transport data for multiphase model development. Although researchers have recently started to develop a multiphase model for food processing, many simplistic assumptions have been made to overcome the complexities of the processes and lack of appropriate material properties (Dhall et al., 2012a; Dhall et al., 2012b; Halder et al., 2007; Halder et al., 2010; Ricken and de Boer, 2003). The aim of the present work is to critically review the multiphase porous media models found in the literature, identify important factors for consideration in a multiphase model, uncover the current gaps found in the literature and determine the challenges in developing a realistic multiphase model. This paper outlines an approach to multiphase model formulation and simulation, describes trends in expected results from the models and specifies the properties necessary for the models for future food processing researches.

## **2 Present status of multiphase porous media model**

Different mechanisms of heat and mass transfer during food processing have been a topic of much interest for years and have resulted in many publications. Many research works have been conducted on multiphase porous media modelling. The following sections present a discussion on multiphase porous media models available in the literature, sub-divided into specific areas of food thermal processing.

### **2.1 Drying:**

Drying is one of the food preservation methods that inhibit the growth of bacteria, yeasts, and mould by removing water from fresh materials (Karim and Hawlader, 2005b). However, the transport phenomena in the drying process are too onerous and time consuming for practical

purposes. An enormous effort has been made to determine the exact phenomena that take place during the drying process. For understanding the actual phenomena at a macroscopic level, multiphase porous media modelling is essential. Many researchers developed fundamental physics-based multiphase models for understanding the dehydration mechanism and achieved interesting results. However, most of the models were developed for the drying of materials like clay (Boukadida et al., 2000; Peishi and Pei, 1989; Saber Chemkhi, 2009), wood (Perré and Turner, 1999; Stanish et al., 1986), and ceramics (Dhall et al., 2012b). Very few multiphase models have been developed for drying food materials.

Curcio et al. (2008) formulated a multiphase model describing convective food drying. The model explained the simultaneous transfer of momentum, heat and mass inside the food; consideration, however, was focused on the analysis of those cases characterised by very weak inner evaporation, which, therefore, was neglected. They considered moisture transport inside the food only in terms of an effective diffusion coefficient that did not make any distinction between the transport of liquid water, usually expressed in terms of a capillary diffusion coefficient, and that of vapour, usually expressed by a molecular diffusion coefficient. However, Curcio (2010) overcame these problems in a subsequent paper which presented a theoretical model for potato drying based on the  $k-\omega$  approach. This model is capable of predicting the drying characteristics of foods for a wide range of processes. The effects of velocity, relative humidity, and temperature on drying rate were also addressed, and Curcio concluded that in the initial stage of drying, the moisture content increases slightly because vapour condensation occurs on the food surface. Although Curcio developed an improved model, neither the convection energy terms in the energy equation nor material shrinkage during drying were taken

into consideration. Without consideration of material shrinkage, a model cannot provide a realistic understanding of heat and mass transfer during drying.

Gulati and Datta (2015) have contributed further to describe the heat and mass transfer during drying by developing a more realistic multiphase model which shows the effect of porosity as well as material volume changes during food drying. The main drawback of their model is that they use an empirical equation for determining the Young's modulus that is formulated at room temperature. However, to predict accurate material deformation, Young's modulus used in the model must be determined at actual drying conditions. Gulati and Datta considered Young's modulus as a function of moisture content only, but in practice Young's modulus depends on moisture content, temperature, porosity and other mechanical properties of the material. Furthermore, they proposed their model for drying a hygroscopic material (food), although their model was based on a non-hygroscopic material.

Mercier et al. (2014) developed a mechanistic multiphase model for pasta drying and validated the model with the available experimental data from the literature. However, they ignored the convection energy in the energy equation. They argued that due to the hygroscopic nature of food material, the convective flux of both liquid and water vapour is almost insignificant as compared to capillary flux, because convective flux comes from negligible gas pressure gradient. Very recently, Kumar et al. (2016) developed a multiphase model for intermittent microwave convective (IMCD) drying. The model was developed based on the combined effect of microwave and convective drying that is very significant in terms of energy improvement and better quality of dried food. However, their assumptions for modelling were not very practical. They considered three phases: water, vapour and solid matrix in their model but ignored the

water present in the solid matrix. The assumption that the water in the solid matrix can be ignored that render the problem easier to formulate. However, this assumption is only valid for drying non-hygroscopic materials like brick.

It can be concluded that although some multiphase models have been developed for other (non-cellular) materials, little work has been done towards a multiphase model of food (i.e., cellular material) drying. There are many drawbacks, as reported in the previous section, in the multiphase models developed for food drying. Hence, more rigorous comprehensive work is needed to develop a multiphase food drying model that includes all significant physical phenomena.

## 2.2 Frying:

Frying is an important food processing operation that offers a unique texture and flavour to the product and is commonly used by the multi-billion dollar snack food industry. Design and optimisation of large-scale industrial frying processes require a comprehensive understanding of the process. To achieve energy efficiency in the process as well as better quality of fried food, actual physics-based modelling is necessary. Most of the models that have been developed for food frying are single-phase models (Ateba and Mittal, 1994; Dincer and Yildiz, 1996; Ikediala et al., 1996; Williams and Mittal, 1999), which do not include significant physical phenomena involved in the process. A purely diffusion-based, single-phase model does not adequately describe the moisture transport phenomenon during food frying because lumping all modes of water transport together as diffusion cannot be justified in all situations, especially when other



phenomena, such as pressure driven flow or transport due to physicochemical changes inside the food, become important.

To overcome the problem of the single-phase model, some researchers have tried to develop a multiphase model during food frying. Halder et al. (2010) developed a physics-based model for potato frying considering the non-equilibrium condition, and simulated the model by using CFD-based commercial software. The model was validated with published experimental data. They presented simulated results of pressure, temperature and moisture content profile with deep fat frying time and the effect of distance of the sample from the heating surface. They also discussed the rate of evaporation distribution within the sample, observing that the higher evaporation rate occurs at the surface of the potato sample and that it decreases with time and distance. However, although their simulated results showed a reasonably good agreement with the experimental data, their model did not consider the material shrinkage which is an obvious phenomenon in frying.

Halder et al. (2007) developed a multiphase model of deep fat frying and post-fry cooling that took into account significant physical phenomena. The novelty of their work was claimed to be the consideration of the non-equilibrium evaporation model as compared to equilibrium evaporation models available in published literature. During their study, potato was used for deep fat frying. However, the material shrinkage was ignored during their model development. The effect of capillary diffusivity, permeability and thermal conductivity on frying time was presented and results were compared with the published literature data.

Farkas et al. (1996a) considered two regions for heat and mass transfer during immersion frying of potato chips, separated by an interface. The two regions were the crust region and the core region. Their simulated results showed a significantly higher temperature distribution within the

crust region as compared to the core region, due to the formation of a crust, resulting in a lower heat transfer coefficient. Though their model can be considered comprehensive, the computational time required was enormous, suggesting the necessity of carrying some simplifications to the model in the future. It is also believed that the extension of the model to multi-dimensional geometry is difficult, especially with regards to the required computation time.

Ni and Datta (1999), and Yamsaengsung and Moreira (2002a) developed a frying model, considering distributed evaporation within the sample domain. The main weaknesses of their models were that they did not consider frying as a combination of different stages (i.e. boiling and non-boiling stages) and therefore used a constant convective heat and mass transfer coefficient through the process. However, in practice, boiling and non-boiling stages during frying should be considered separately.

With the intention of investigating the moisture and acrylamide content, Warning et al. (2012) developed a physics-based model for deep fat vacuum frying of potato chips. They studied the temperature, moisture, pressure, acrylamide content and oil content inside a potato chip and validated their results with experimental data. Although their model can be considered a significant advancement in modelling frying, as it was the first multiphase porous media transport model for vacuum deep fat frying, they failed to consider changing porosity during frying.

### 2.3 Cooking:

Cooking is a method of food processing that improves digestibility, appearance and taste. Many food products are now precooked for consumer convenience and the food industry uses various food cooking techniques for improving the quality of food to increase consumer demand. To manufacture a product of high quality at minimum cost, it is important to optimise the cooking process. For optimising the product cost and quality, it is important to know the fundamentals of heat and mass transfer during food cooking. Apart from temperature, water and fat content are other important parameters that determine food quality. For example, moisture content and distribution inside the meat protein fibres and extracellular spaces determine its juiciness and flavour (Dhall et al., 2012a).

Many researchers have developed models for food cooking and investigated the heat and mass transfer pattern during this process (Goñi and Salvadori, 2010; Obuz et al., 2002; Pan et al., 2000; Shilton et al., 2002). However, their models consider moisture loss from the food as a lumped system without any internal resistances to transport. Their models do not include the fundamental physics of the food cooking system; therefore, the physics of moisture transport during cooking of meat are still poorly understood.

Only a limited number of studies have developed a physics-based food cooking model. Dhall et al. (2012a) formulated a multiphase model for meat cooking that accounts for the significant physical phenomena of heat, moisture and fat transfer with phase changes that take place during the cooking of meat. The model was simulated by using CFD-based commercial software, COMSOL Multiphysics. They showed that the moisture migration process is independent of the composition and has a linear relationship with temperature rise. Also, their result showed that the

migration mechanism of muscle fat is similar to the water loss. The flux due to capillary pressure is much higher than flux due to gas pressure, because the gas pressure that has been induced during cooking is not significant; this is discussed in more detail in section 8.3. Though their model showed good agreement with the experimental data, they assumed constant porosity in their model and neglected the material shrinkage during their modelling.

Van der Sman (2007a) developed a simple multiphase model based on the Flory–Rehner theory and applied it to the cooking of meat. The simulated results were validated with the experimental data and showed good agreement with the moisture distribution and temperature distribution profile with the depth of meat slab. The main limitation of their model was that they assumed that evaporation takes place only on the material surface. This assumption is reasonable when the surface still contains free water. However, once the surface moisture drops to the sorption region, internal evaporation becomes more significant and distributed evaporation can change the temperature and moisture profiles.

#### **2.4 Other food processing systems:**

Other food processing systems that are primarily used in the food industry are baking, heating, roasting and grilling: in all cases heat mass transfer plays an important role. Understanding and modelling the heat and mass transport processes in these applications help to improve the product quality and process design. There are many studies on modelling of transport processes involved in baking (Özilgen and Heil, 1994; Sablani et al., 1998; Standing, 1974; Zannoni et al., 1993), heating (Zhou et al., 1995) and roasting (Bengtsson et al., 1976; Feyissa, 2009; Singh et al., 1984). However, all of the studies mentioned have been formulated by considering a single

phase: diffusion-based transport. Using a pure diffusion-based model, it is not possible to adequately understand the heat and mass transport phenomena during the food baking, heating or roasting process, because the most important physics relating to water binding capacity, shrinkage and internal evaporation are not considered. These are, however, the main driving mechanisms for the exudation of moisture during food processing. That is why a fundamental physics-based model is necessary for better understanding of the real heat and mass transfer mechanism during food processing. Several researchers have formulated different multiphase models, based on their various hypotheses for transporting moisture during food processing such as baking (Feyissa et al., 2011; Ni and Datta, 1999a; Ousegui et al., 2010; Papasidero et al., 2015), heating (Halder and Datta, 2012; Ni et al., 1999; Zhang and Datta, 2004) and roasting (Ateba and Mittal, 1994; Feyissa et al., 2013).

To the authors' knowledge, the multiphase models discussed above are the only existing models for food processing that are based on fundamental physics; all of them are discussed are briefly summarised in Table 1.

### **3 Main driving mechanism of mass transfer in the multiphase process**

Considering food material as a porous medium, heat and mass transfer inside the material during thermal processing is described using equations for mass and energy conservation. For developing mathematical equations, it is necessary to consider different physical processes behind heat and mass transfer including diffusion, phase change, capillary and convective modes of transport. The main physical processes used for developing the multiphase porous media model for food processing are discussed below:

### 3.1 *Diffusion:*

Diffusion is the process by which molecules are transferred from one region to another on the basis of random motions, in which molecules do not have a preferred direction. Moreover, during diffusion the molecules move from the area of high concentration to that of lower concentration. During water transportation from the porous medium, two types of diffusion should be considered in the case of multiphase modelling, namely: binary diffusion and capillary diffusion.

#### 3.1.1 *Binary diffusion:*

Binary diffusion is defined as the movement of gas (vapour or air) from a region of higher concentration to a region of lower concentration. Accordingly, the binary diffusion coefficient  $D_{AB}$  is a transport property that represents the ability of species  $A$  to diffuse through a medium  $B$ . Gas can be transported in two ways: (1) binary diffusion and (2) convective diffusion, where binary diffusion is the core driver.

The binary diffusion coefficient can be calculated from the following equation:

$$D_{AW} = 2.2646 \times 10^{-5} \sqrt{T \left( \frac{1}{M_A} + \frac{1}{M_W} \right)} \frac{1}{\sigma_{AW}^2} \times \frac{1}{c \Omega_{DAW}} \quad (1)$$

where  $D_{AW}$  is the binary diffusion coefficient ( $\text{m}^2/\text{s}$ ),  $M_A$  is the molecular weight of species  $A$  (kg),  $M_W$  is the molecular weight of species  $W$  (kg),  $\sigma_{AW}$  is the binary collision diameter (m),  $c$  is the molar density of binary mixture ( $\text{mol}/\text{m}^3$ ) and  $\Omega_{DAW}$  is the collision integral for diffusion and  $T$  is the temperature (K).

A similar equation was proposed by Fuller et al. (1966) to determine the binary diffusion coefficient, as shown below:

$$D_{AW} = \frac{10^{-3} T_f^{1.75} \left( \frac{M_w + M_A}{M_w M_A} \right)^{0.5}}{P \left[ (\sum v)_v^{1/3} + (\sum v)_a^{1/3} \right]^2} \quad (2)$$

where  $T_f$  is the arithmetic average temperature between the surface temperature of the material and ambient temperature (K),  $M_A$  and  $M_w$  are the molecular weight of air and water respectively (g/mol);  $P$  is the external pressure (atm),  $(\sum v)_v$  and  $(\sum v)_a$  are the atomic diffusion volume of the vapour and air respectively.

Bolz (1976) stated that the binary diffusion coefficient is a function of temperature presented by the following equation:

$$D_{AW} = -2.775 \times 10^{-6} + 4.479 \times 10^{-8} T + 1.656 \times 10^{-6} T^2 \quad (3)$$

where  $T$  is the temperature (K).

### 3.1.2 Capillary diffusion:

Capillary diffusion is defined as the process of diffusion caused by the capillary action of liquid. Capillary action is a result of surface tension that occurs when the liquid and the other surface come into contact with each other. The capillary diffusion phenomenon is used for liquid transport in the case of multiphase transport modelling. The force responsible for the capillary action is called capillary force, which is defined by the attraction among liquid molecules and the solid matrix. Moreover, capillary rise into a pore space is a consequence of an interfacial pressure difference (Hamraoui and Nylander, 2002). These capillary forces are crucial in food

science because food materials cannot be completely drained by gravity. In addition, the water is tightly held in the regions having a solid matrix with low water content, and it is loosely held in the regions that are highly moist.

Historically, the Lucas-Washburn equation is recognised as the best equation for modelling capillary rise into small pores (Aguilera et al., 2004). The equation shows that the pressure inside a cylindrical capillary is balanced by viscous drag and gravity (Krotoev, 1999; Lucas, 1918; Washburn, 1921). From this it is possible to observe that the equilibrium height (when the hydrostatic pressure balances the interfacial pressure differences) may be expressed as:

$$h_c = \frac{2\gamma \cos(\theta)}{r\rho g} \quad (4)$$

where  $h$  is the height of capillary (m),  $\gamma$  is the surface tension (N/m),  $\theta$  is the contact angle ( $^\circ$ ),  $r$  is the radius of capillary (m),  $\rho$  is the density of water ( $\text{kg/m}^3$ ) and  $g$  is the gravitational acceleration ( $\text{m/s}^2$ ).

On the other hand, on the basis of a porous media approach, capillary flow in food may be expressed by Darcy's law (Datta, 2007a; Khaled and Vafai, 2003; Sam Saguy et al., 2005):

$$u = -\frac{k_l}{\mu} \frac{\partial P}{\partial x} \quad (5)$$

where  $u$  is the Darcy velocity (m/s),  $k_l$  is the permeability of the porous material ( $\text{m}^2$ ),  $P$  is the fluid pressure (Pa) and  $\mu$  is the dynamic viscosity (Pa. s).

Moreover, Datta (2007a) defined the capillary attraction as the result of negative pressure on the liquid and water, for instance, is held by this negative pressure. Thus, the mass flux of liquid can be written in the following form:



$$n_l^{pr.,capillary} = -\rho_l \frac{k_l}{\mu_l} \frac{\partial(P - p_c)}{\partial s} \quad (6)$$

where  $n_l^{pr.,capillary}$  is the liquid mass flux flow due to capillary effect ( $\text{kg/m}^2 \text{ s}$ ),  $\rho_l$  is the density of water ( $\text{kg/m}^3$ ),  $\mu_l$  is the dynamic viscosity of liquid ( $\text{kg/m s}$ ),  $P$  is the total pressure in the gas phase (Pa),  $p_c$  is the capillary pressure of the liquid (Pa),  $s$  is the distance (m) and  $k_l$  is the permeability in the liquid phase ( $\text{m}^2$ ),  $k_l = k k_{lr}$ , where  $k_{lr}$  is the relative permeability in the liquid phase (dimensionless). Here,  $p_c$  depends on concentration and temperature so the above equation can be written as the following form:

$$n_l^{pr.,capillary} = -\rho_l \frac{k_l}{\mu_l} \frac{\partial P}{\partial s} + \rho_l \frac{k_l}{\mu_l} \frac{\partial p_c}{\partial c_l} \frac{\partial c_l}{\partial s} + \rho_l \frac{k_l}{\mu_l} \frac{\partial p_c}{\partial T} \frac{\partial T}{\partial s} \quad (7)$$

where  $C$  is the molar concentration ( $\text{mol/m}^3$ ) and  $T$  is the temperature (K), the first term in the right-hand side of the above equation is defined as mass flux due to gas pressure, and the second and third terms are the capillary flux due to concentration gradient and temperature gradient respectively.

Chemkhi et al. (2009) defined the capillary pressure for non-saturated porous media by the following equation:

$$p_c = \sqrt{\frac{\phi}{k}} \times (0.1212 - 0.000167T) \times J(s) \quad (8)$$

$$J(s) = 0.364(1 - \exp(40s - 40)) + 0.221(1 - s) + \frac{0.005}{s} \quad (9)$$

where  $\phi$  is the porosity,  $k$  is the intrinsic permeability ( $\text{m}^2$ ),  $T$  is the temperature (K), and  $s$  is the saturation.

### 3.2 Pressure driven flow:

Moisture can migrate from the porous material when there is a pressure gradient in the food material, which is important for processes such as intensive heating, cooking and roasting. For example, the pressure driven flow was identified as the principal mechanism behind the moisture loss during frying of food materials (Kovácsné Oroszvári et al., 2006). Liquid and gas (air or vapour) can be transported by this phenomenon inside the pores; this can also be expressed by Darcy's law as discussed below:

Pressure driven flow for gas,

$$n_g^{pressure} = -\rho_g \frac{k_g}{\mu_g} \frac{\partial P}{\partial s} \quad (10)$$

Pressure driven flow for liquid,

$$n_l^{pressure} = -\rho_l \frac{k_l}{\mu_l} \frac{\partial P}{\partial s} \quad (11)$$

where  $n_g^{pressure}$  is the vapour mass flux due gas pressure effect ( $\text{kg/m}^2 \text{ s}$ ),  $\rho_g$  is the density of gas ( $\text{kg/m}^3$ ),  $\mu_g$  is the dynamic viscosity of gas ( $\text{kg/m s}$ ).

### 3.3 Evaporation:

Evaporation is the phase change process whereby atoms or molecules in a liquid phase gain sufficient energy to enter the gaseous phase. In the case of food processing, evaporation plays a significant role because water molecules can migrate only in the form of vapour and vapour is the result of the evaporation process. Accurate determination of evaporation rate inside a porous medium is a challenging task (Halder et al., 2010). In a porous medium, evaporation can be

explained in various ways, including distribution evaporation due to the domain-based local vapour pressure, non-equilibrium evaporation and, the moving interface at the boundary where phase change occurs.

Zhang and Datta (2004) expressed \_ENREF\_23evaporation rate for moisture transport as:

$$\dot{I} = \frac{h_m A (p_{v,surface} - p_{v,\infty})}{V} \quad (12)$$

where  $V$  is the volume of the sample ( $m^3$ ),  $h_m$  is the mass transfer coefficient ( $m/s$ ),  $p_v$  is the vapour pressure (Pa), and  $\dot{I}$  is the rate of evaporation ( $kg/m^3 s$ ).

For a non-equilibrium process, water evaporation is considered directly proportional to the difference between the actual vapour density and the equilibrium vapour density (Mercier et al., 2014):

$$\dot{I} = K (\rho_v - \rho_{v,E}) \quad (13)$$

where  $K$  is the proportionality constant that can be determined empirically and  $\rho_v$  is the actual vapour density ( $kg/m^3$ ).  $\rho_{v,E}$  is the equilibrium vapour density ( $kg/m^3$ ), which can be expressed as:

$$\rho_{v,E} = \frac{a_w p_{v,s} M_w}{R_g T} \quad (14)$$

where  $a_w$  is the water activity that is specific for each material,  $p_{v,s}$  is the saturation vapour pressure (Pa) which can be calculated by the Clausius Clapeyron equation,  $M_w$  is the molecular weight of water ( $kg/kmol$ ),  $R_g$  is the ideal gas constant ( $kJ/kmol K$ ) and  $T$  is the temperature (K).

A similar equation was proposed in other studies, which examined food baking (Ousegui et al., 2010) and microwave puffing (Rakesh and Datta, 2011).

#### 4 Assumptions that used in existing multiphase models

Multiphase mathematical models for food drying are very useful for understanding the simultaneous heat and moisture transfer during drying. However, food process modelling is very complicated when considering variable material properties and material deformation. Many researchers in developing their models have attempted to overcome the problem by reducing these complexities and using simplifying assumptions, such as neglecting shrinkage. The assumptions that are found in the literature are listed below.

- (i) The phases are considered in thermal equilibrium. In this hypothesis, it is assumed that the solid bulk temperature does not differ much from the average value of the fluid temperature. This assumption makes the model simpler to formulate. However, this assumption is inadequate for modelling hygroscopic material like plant-based food material (Belova and Murch, 2008).
- (ii) The material is in non-equilibrium between water in solids and water vapour in the gas phase, i.e., their concentrations are not given by the moisture isotherms (Halder et al., 2010).
- (iii) Deformation of food material (shrinkage) during modelling is neglected in most of the studies. Shrinkage should be coupled with the heat and mass transfer during modelling but to avoid the computational complexities of a coupled model, shrinkage is generally ignored except in studies aiming to determine stress and crack development (Itaya et al., 1995).
- (iv) The gas phase of the material consists of water vapour and air, and behaves as a perfect gas.

- (v) The temperature and relative humidity of the air in the interface were assumed to be in a steady state.
- (vi) The medium is taken as non-saturated (solid, liquid and gas phases) because the food matrix is usually assumed to be partially filled with water and the rest of the matrix is assumed to be occupied by air.
- (vii) The bound water was neglected in all the models reported in the literature. It is very hard to remove bound water from material because when the unbound water (i.e., free water) is removed, a considerable amount of bound water is still left in the material. Therefore, bound water transport should be considered during modelling. Bound water is discussed in detail in section 9.1.
- (viii) Energy transport and mass transport were treated as bidirectional. In the bidirectional problem, the energy is supplied equally from both sides of the sample and mass is migrated in opposite directions to the energy transfer on both sides. On the other hand, in the unidirectional problem, the heat and mass are exchanged through the top and bottom of the sample and only heat is exchanged through the lateral sides of the sample.
- (ix) In most cases, the gravity effect was neglected because the gravity effect on a food sample is very weak as compared to the capillary effect.
- (x) The convective energy term in the energy equation was sometimes neglected (Curcio, 2010; Mercier et al., 2014; Ni and Datta, 1999a) because in the food sample, the contribution of convection to total heat transfer is almost negligible as compared to conduction. Hence, the convective energy term has been neglected in the energy

equation. However, many studies consider this convective heat transfer to be significant (Datta, 2007a; Halder and Datta, 2012; Halder et al, 2007; Kumar, 2016).

- (xi) Material properties were commonly considered as isotropic due to the lack of detailed information.
- (xii) Sometimes porous materials were treated as rigid and no chemical reactions were considered in the sample.
- (xiii) In the case of liquid and gas phases, sometimes thermal conductivity was treated as constant.

## 5 Material properties

Different stages in food processing involve simultaneous heat and mass transfer and therefore appropriate thermophysical properties are essential to model the processes. Capillary pressure, intrinsic permeability, relative permeability, effective moisture diffusivity and thermal conductivity are among the key thermal and transport properties required for a comprehensive simulation of a drying model. Unfortunately, for hygroscopic porous materials, these properties are often not known. In particular, properties relevant to cellular level water transport such as bound water permeability and diffusivity for most hygroscopic materials are not known. The major properties likely to be necessary for developing multiphase food processing models at the macroscopic level are discussed below.

### 5.1 Permeability

The permeability of porous materials defines the resistance to the flow of fluid through the material under the influence of a pressure gradient. According to Darcy's law for laminar flow, pressure drop and flow rate show a linear relationship through a porous material (Scheidegger, 1974). The slope of this line is related to permeability as shown below.

$$k = \frac{Q\mu L}{A\Delta P} \quad (15)$$

where  $k$  is the permeability ( $\text{m}^2$ ),  $Q$  is the volumetric flow rate ( $\text{m}^3/\text{s}$ ),  $\mu$  is the fluid viscosity ( $\text{kg/m s}$ ),  $A$  is the sample cross sectional area ( $\text{m}^2$ ),  $L$  is the length ( $\text{m}$ ), and  $\Delta P$  is the pressure gradient.

Permeability,  $k$ , is further divided into two groups namely, intrinsic permeability,  $k_i$  ( $\text{m}^2$ ), and relative permeability,  $k_r$ , given by the following expression:

$$k = k_i \times k_r \quad (16)$$

The intrinsic permeability,  $k_i$ , represents the permeability of a liquid or gas in the fully saturated state. The relative permeability of a phase is a dimensionless measure of the effective permeability of that phase; it is the ratio of the effective permeability of that phase to the absolute permeability. The relative permeability of gases is a function of saturation. The values of intrinsic and relative permeability that are typically used for developing the multiphase model are given in the following table (Table 2), where,  $S_w$  and  $S_f$  are the saturation of water and fat respectively.

## 5.2 Capillary diffusivity

The liquid inside the food materials can flow from materials of higher concentration to the lower concentration, due to the difference in capillary action. This is referred to as unsaturated flow and is crucial in food processing. During the modelling of a multiphase flow for various food processing systems, the property of capillary diffusivity plays a vital role. The capillary diffusivity for different food processing systems used in the literature is given in the following table (Table 3), where  $M$  is the moisture content dry basis and  $M_o$  is the oil content dry basis.

## 5.3 Viscosity

In a hygroscopic material, viscosity is an important physical property that describes a fluid's internal resistance to flow and may be thought of as a measure of fluid friction. The viscosity of fluids changes significantly with temperature and pressure, therefore good control of those two parameters is required for a precise viscosity measurement.

Viscosities of water (Truscott, 2004) and gas (Gulati and Datta, 2013) as a function of temperature are given by

$$\mu_w = \rho_w e^{\left(-19.143 + \frac{1540}{T}\right)} \quad (17)$$

$$\mu_g = 0.017 \times 10^{-3} \left(\frac{T}{273}\right)^{0.65} \quad (18)$$

where  $\mu_w$  and  $\mu_g$  are the viscosity of water and gas respectively (kg/m s) and  $\rho_w$  is the density of water (kg/m<sup>3</sup>).



Viscosity is an important property for modelling multiphase porous media for different food processing methods. Viscosity values for different materials in different food processing systems, as found in the literature, are listed in Table 4.

#### 5.4 Density:

Density is an important structural property for food processing, especially in food drying, frying and heating. In the case of multiphase food process modelling, density plays an important role in studying transport phenomena during the drying or processing of foodstuffs involving changes to solid-phase volume and the concentration of movable phases. For a solid food, material density is defined as a relationship between the solid mass and its volume. Depending on the method used to measure volume, it can be classified into different categories that are discussed below:

**Apparent density or bulk density** is defined by the relationship between mass and volume of the material, including pores and water (apparent volume) as shown:

$$\rho_{app} = \frac{m_s + m_w}{V_s + V_w + V_a} \quad (19)$$

where  $\rho_{app}$  is the apparent density ( $\text{kg/m}^3$ ),  $m_s$  and,  $m_w$  are defined as mass of solid and mass of water inside the food material respectively (kg).  $V_s$ ,  $V_w$ , and  $V_a$  are the volume of solid, water and air respectively ( $\text{m}^3$ ).

**True density or particle density** is defined as the quotient of mass over the volume of a sample, without considering pores in the material, as shown:

$$\rho_p = \frac{m_s + m_w}{V_s + V_w} \quad (20)$$

where  $\rho_p$  is the particle density ( $\text{kg/m}^3$ ).

On the other hand, Ni (1997) proposed a correlation between the apparent density and true density and he stated that the apparent density is a function of the porosity of material that is defined by the following equation:

$$\rho_{app} = \rho_p (1 - \phi) + \phi S_w \rho_w \quad (21)$$

where  $\rho_{app}$  and  $\rho_p$  are the apparent and the true density, respectively,  $\phi$  is the porosity,  $S_w$  is the water saturation and  $\rho_w$  is the water density.

A series of correlations of apparent density in terms of moisture content are given by Rahman (1995a) and the values of apparent density and true density for different food materials can be found in different literature (Choi, 1985; Rodríguez-Ramírez et al., 2012; Zogzas et al., 1994).

## 5.5 Porosity

Porosity of a material indicates the volume of the air space present in the food product. All hygroscopic food materials have some porosity (air space) in them. These internal pores are of three types: closed pores, where the pore space is enclosed from all sides; blind pores, where one end is closed; and through or open pores, where flow can take place. Any hygroscopic material shows an inverse relationship between the porosity and the moisture content, i.e., if the porosity increases the moisture content decreases (Marousis and Saravacos, 1990). Porosity determination requires knowledge of the total or apparent volume and the void volume included in the material matrix; their difference is also known as the particle volume. Some authors have proposed empirical and semi-empirical equations for prediction of porosity (Lozano et al., 1980; Moreira

et al., 2000; Rahman, 2003; Zogzas et al., 1994). According to Lozano et al. (1980) open pore porosity is defined by the following empirical correlation for fruit drying:

$$\varphi = 1 - \frac{0.852 - 0.462 \exp(-0.66M_d)}{1.54 \exp(-0.051M_d) - 1.15 \exp(-2.4M_d)} \quad (22)$$

where  $\varphi$  is the porosity,  $M_d$  is the moisture content (dry basis).

In the case of non-hygroscopic material, the following correlation has been proposed by Ni (1997) for calculating the apparent porosity.

$$\varphi = 1 - \frac{\rho_{app}(1 - M_w)}{\rho_p} \quad (23)$$

where  $M_w$  is the moisture content on a wet basis.

The empirical correlations discussed above only show porosity as a function of moisture content. However, Rahman (2003) demonstrated that porosity is a function of the shrinkage coefficient as he developed a physics-based model for porosity measurement, which is shown in the equation below:

$$\phi = \frac{\rho_p(\varphi_i - \varphi)}{\rho_w(\varphi - 1)} \quad (24)$$

where  $\phi$  is the shrinkage coefficient,  $\rho_w$  is the water density and  $\varphi_i$  is the initial porosity.

Very recently, Joardder et al. (2015a) developed a model for porosity prediction considering both material properties and process parameters. The model is as follows:

$$\varphi = \frac{\varphi_0 \left( \frac{T - T_g}{T_i - T_{gi}} \right) + \frac{m_i}{X_i} \left( \frac{X_{fi} - X_f}{\rho_w} + \left( 1 - \frac{\rho_w}{\rho_s} \right) \frac{X_{bi} - X_b}{\rho_w} \right)}{V_i \left( 1 - \left( \varphi_i \left( \frac{T - T_g}{T_i - T_{gi}} \right) \right) \right) - \frac{\rho_w}{\rho_s} \left( \frac{X_{bi} - X_b}{\rho_w} \right) \frac{m_i}{X_i}} \quad (25)$$

where  $\phi$  is the porosity,  $X$  is the moisture content dry basis,  $T$  is the temperature (K),  $m$  is the mass (kg),  $V$  is the volume ( $\text{m}^3$ ) and  $i$  is initial,  $f$  is final,  $b$  is bound,  $w$  is water and  $g$  is the glass transition.

## 5.6 Thermal conductivity

Thermal conductivity is one of the most important physical properties of foods used for analysing food processing where heat and mass transfer occur simultaneously. It is a function of food composition and temperature (Rahman, 1995a). Thermal conductivity for anisotropic food materials, particularly for fibrous foods such as meat, carrot and okra, varies with the direction of heat flow in relation to the orientation of the fibres. Moisture content was found to be the most important factor in determining thermal conductivity. This may be due to the relative magnitude of the conductivities of water and other food constituents (Cuevas and Cheryan, 1978). The thermal conductivity of foods decreases with a decrease in moisture content. It is common to find a linear relation between thermal conductivity and moisture content. This type of correlation has been reviewed by others (Mohsenin, 1980(a); Sweat, 1986). However, the linear correlation of thermal conductivity with moisture content is limited to small changes in moisture and the constants of the correlation vary, not only with types of food materials, but also with variety and growing or harvesting location and time. When such properties of food materials are needed for analysing food processes, the most practical way is to use predicted values from either theoretical or empirical models.

Sweat (1974) developed a linear empirical model for predicting the thermal conductivity of fruit and vegetables, giving predictions within 15% of most experimental values:

$$K=0.148+0.493M_w \quad (26)$$

where  $M_w$  is the moisture content (wet basis), and  $K$  is the thermal conductivity (W/m K).

A similar type of correlation has been proposed in different work focussing on different food materials (Lozano et al., 1979; Mattea et al., 1986; Souraki et al., 2009), which are frequently used for determining the thermal conductivity of the materials.

Rahman et al., (1995b; 1997) developed the following equation for effective thermal conductivity considering multiple phases in the sample:

$$\frac{k_{th,eff} - \phi k_{th,air}}{(1-\phi-X)k_{th,s} + Xk_{th,w}} = 0.996 \left( \frac{T}{T_{ref}} \right)^{0.713} X^{0.285} \quad (27)$$

$$1-\phi + \left[ \frac{k_{th,air}}{(k_{th,w})_{ref}} \right]$$

where  $k_{th,eff}$ ,  $k_{th,s}$ ,  $k_{th,air}$  and  $k_{th,w}$  are the effective thermal conductivities (W/m K) for solid, air and water respectively;  $X$  is the mass fraction of the instantaneous water of the food materials; and  $T_{ref}$  and  $(k_{th,w})_{ref}$  are the reference temperature and conductivity at 0°C respectively.

## 6 General multiphase model formulation:

### 6.1 Governing equations

The mathematical model consisted of conservation equations for all the transportable phases and transport mechanisms discussed above.

### 6.1.1 Mass balance equations

The representative elementary volume  $\Delta V$  (m<sup>3</sup>) is the sum of the volume of three phases (gas, water, and solid):

$$\Delta V = \Delta V_g + \Delta V_w + \Delta V_s \quad (28)$$

where  $\Delta V_g$  the volume of gas (m<sup>3</sup>) is,  $\Delta V_w$  is the volume of water (m<sup>3</sup>), and  $\Delta V_s$  is the volume of solid (m<sup>3</sup>).

The apparent porosity,  $\phi$  is defined as the volume fraction occupied by gas and water. Thus,

$$\phi = \frac{\Delta V_g + \Delta V_w}{\Delta V} \quad (29)$$

The water,  $S_w$  and gas,  $S_g$  saturation are defined as the fraction of pore volume occupied by that particular phase:

$$S_w = \frac{\Delta V_w}{\Delta V_w + \Delta V_g} = \frac{\Delta V_w}{\phi \Delta V} \quad (30)$$

$$S_g = 1 - S_w \quad (31)$$

The mass conservation equation for the liquid water is expressed by

$$\frac{\partial}{\partial t} (\phi S_w \rho_w) + \nabla \cdot (\vec{n}_w) = -R_{evap} \quad (32)$$

where  $\bar{n}_w$  is the water flux (kg/m<sup>2</sup>s), and  $R_{evap}$  is the evaporation rate of liquid water to water vapour (kg/m<sup>3</sup>s).

The total flux of the liquid water is due to the gradient of liquid pressure,  $p_w = P - p_c$  as given by Darcy's Law

$$\bar{n}_w = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla p_w = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla p_c \quad (33)$$

where  $P$  is the total gas pressure (Pa),  $p_c$  is the capillary pressure (Pa),  $k_w$  is the intrinsic permeability of water (m<sup>2</sup>),  $k_{r,w}$  is the relative permeability of water, and  $\mu_w$  is the viscosity of water (Pa.s). More details on these parameters are given in sections 5.

We note that the first term of equation (33) represents the flow due to gradients in gas pressure, which is significant only in the case of intensive heating such as microwave heating, deep fat frying and contact heating at high temperature. The second term represents the flow due to capillary pressure.

The capillary pressure depends upon concentration ( $c_w$ ) and temperature ( $T$ ) for a particular material (Datta 2007a). Therefore, equation 9 can be rewritten as

$$\bar{n}_w = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \nabla P + \rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial p_c}{\partial c_w} \nabla c_w + \rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial p_c}{\partial T} \nabla T \quad (34)$$

In turn, the second and third terms of equation (34) can be rewritten in terms of capillary diffusivity,  $D_c$  (m<sup>2</sup>/s), and thermal diffusivity,  $D_T$  (m<sup>2</sup>/s), respectively given by,

$$D_c = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial p_c}{\partial c_w} \quad (35)$$

$$D_T = -\rho_w \frac{k_w k_{r,w}}{\mu_w} \frac{\partial p_c}{\partial T} \quad (36)$$

The capillary diffusivity due to the temperature gradient,  $\nabla T$  (K), is known as the Soret effect and is often less significant than the diffusivity due to concentration gradients (Datta, 2007a); for simplification of the modelling, the capillary diffusivity due to the temperature gradient can be neglected.

The conservation of water vapour can be written in terms of the mass fraction,  $\omega_v$ , as

$$\frac{\partial}{\partial t} (\phi S_g \rho_g \omega_v) + \nabla \cdot (\bar{n}_v) = R_{evap} \quad (37)$$

where  $\rho_g$  is the density of the gas ( $\text{kg/m}^3$ ),  $\omega_v$  is the mass fraction of vapour and  $\bar{n}_v$  is the vapour mass flux ( $\text{kg/m}^2\text{s}$ ).

For a binary mixture,  $\bar{n}_v$  can be written as (Bird et al. 2007):

$$\bar{n}_v = -\rho_g \omega_v \frac{k_g k_{r,g}}{\mu_v} \nabla P - \phi S_g \rho_g D_{eff,g} \nabla \omega_v \quad (38)$$

where  $k_g$  is the intrinsic permeability of gas ( $\text{m}^2$ ),  $k_{r,g}$  is the relative permeability of gas ( $\text{m}^2$ ),  $\mu_g$  is the viscosity of gas (Pa.s) and  $D_{eff,g}$  is the binary diffusivity of vapour and air ( $\text{m}^2/\text{s}$ ).

The gas phase is a mixture of vapour and air. After calculating the mass fraction of vapour,  $\omega_v$ , from the above equations, the mass fraction of air,  $\omega_a$ , can be calculated from

$$\omega_a = 1 - \omega_v \quad (39)$$



### 6.1.2 Continuity equation to solve for pressure

The gas phase is assumed to consist of an ideal mixture of water vapour and air. The gas pressure,  $P$ , may be determined via a total mass balance for the gas phase, namely,

$$\frac{\partial}{\partial t}(\rho_g \phi S_g) + \nabla \cdot (\vec{n}_g) = R_{evap} \quad (40)$$

where the gas flux,  $\vec{n}_g$ , is given by,

$$\vec{n}_g = -\rho_g \frac{k_g k_{r,g}}{\mu_i} \nabla P \quad (41)$$

where  $\rho_g$  is the density of gas phase, given by:

$$\rho_g = \frac{PM_g}{RT} \quad (42)$$

where  $M_g$  is the molecular weight of gas (kg/mol).

### 6.1.3 Energy equation

It can be assumed that the each of the phases are in thermal equilibrium with each other and thus the energy balance equation can be written as

$$\rho_{eff} c_{peff} \frac{\partial T}{\partial t} + \nabla \cdot (\vec{n}_g h_g + \vec{n}_w h_w) = \nabla \cdot (k_{eff} \nabla T) - h_{fg} R_{evap} \quad (43)$$

where  $T$  is the temperature (K) of each phases,  $h_g$  is the enthalpy of gas (J),  $h_w$  is the enthalpy of water (J),  $h_{fg}$  is the latent heat of evaporation (J/kg),  $\rho_{eff}$  is the effective density (kg/m<sup>3</sup>),  $c_{peff}$  is the effective specific heat (J/kg/K), and  $k_{eff}$  is the effective thermal conductivity (W/m/K).

Equation (43) considers energy transport due to conduction and convection and energy sources/sinks due to evaporation/condensation.

The thermos-physical properties of the mixture can be obtained by the volume-weighted average of the different phases by the following equations,

$$\rho_{eff} = \phi(S_g \rho_g + S_w \rho_w) + (1 - \phi) \rho_s \quad (44)$$

$$c_{peff} = \phi(S_g c_{pg} + S_w c_{pw}) + (1 - \phi) c_{ps} \quad (45)$$

$$k_{eff} = \phi(S_g k_{th,g} + S_w k_{th,w}) + (1 - \phi) k_{th,s} \quad (46)$$

where  $\rho_s$  is the solid density ( $\text{kg/m}^3$ );  $c_{pg}$ ,  $c_{pw}$ , and  $c_{ps}$  are the specific heat capacity of gas, water, and solid ( $\text{J/kg/K}$ ), respectively;  $k_{th,g}$ ,  $k_{th,w}$ , and  $k_{th,s}$  are the thermal conductivity of gas, water, and solid, ( $\text{W/m/K}$ ) respectively.

## 7 Multiphase porous media model simulation technique

For numerical solutions of heat and mass transfer equations during food processing, common discretisation methods such as the finite element method (Irudayaraj and Wu, 1994; Lamberg, 1986; Peishi and Pei, 1989; Zhang et al., 2000), finite difference method (Kuang et al., 1994; Plumb et al., 1985), and finite volume method (Boukadida and Ben Nasrallah, 1995) are used. Different researchers have adopted different simulation solution techniques for their models, which are discussed below:

## 7.1 Coding:

The coding system is a way of solving any numerical problem where the user can define each of the terms and conditions. For research purposes, code development from scratch is the preferred route, but it is typically a enormously time-consuming project. In the case of food processing models, various researchers used the coding system for solving nonlinear ordinary partial differential equations (Boukadida et al., 2000; Farkas et al., 1996a; Mercier et al., 2014; Nasrallah and Perre, 1988; Ni et al., 1999; Yamsaengsung and Moreira, 2002; Zhang et al., 2005). For the user's own coding, programming languages such as FORTRAN, C<sup>++</sup>, VISUAL BASIC, MATLAB and JABA can be used. Though coding is efficient, researchers usually face many difficulties in developing their own code. As each user's coding is different, it is difficult to get support for a particular problem. Rectifying these problems is very time consuming. Moreover, it is difficult for a researcher to understand and use a code that has been developed by another researcher. That is why a general framework applicable to the majority of food processes, and which is implementable in commercial software and the public domain can potentially reduce or eliminate the code development time (Datta, 2007b).

## 7.2 Special coding software

There are numerous types of coding based special software for heat and mass transfer available. Three, PORFLOW, TOUGH2 and LSODES, are briefly reviewed here. PORFLOW (<http://www.acricfd.com/software/porflow/>) is a comprehensive CFD tool developed by Analytic & Computational Research, Inc., ACRI, to accurately solve problems involving transient or steady-state fluid flow, heat, salinity and mass transport in multiphase, variably saturated, porous

or fractured media with dynamic phase change. This software has been used for solving modelling of the capillary suction-driven liquid flow in swelling porous media behind a clear liquid-front (Masoodi, 2011). In most cases, multiphase modelling considers the isothermal process. However, if the model considers the process is non-isothermal, then the system would be more complex. For solving these types of non-isothermal multiphase flow models, a public domain code TOUGH2, (<http://esd.lbl.gov/research/projects/tough/software/>) software can be used.

The TOUGH2 simulator was developed for problems involving actively heat-driven flow that occur during the drying of the porous material. Solving the pressure gradient term using the conservation equation, is very difficult to solve by developing one's own coding (Halder et al., 2010). However, it can be easily solved by using TOUGH2 coding software (Pruess, 2004).

Finally, LSODES is excellent coding software that is based on FORTRAN. It is easily implementable and less time consuming and can be successfully used (Stanish et al., 1986) for drying. However, the limitation of this software is that it is inefficient or unstable in solving any intermittent high-speed transient problems.

### 7.3 Commercial CFD-based software:

Many CFD-based commercial software has been developed for solving the multiphase porous media mathematical model, including COMSOL Multiphysics (Comsol Inc, [www.Comsol.com](http://www.Comsol.com)), FLUENT (Fluent Inc, [www.ansys.com](http://www.ansys.com)), ANSYS (Ansys Inc, [www.ansys.com](http://www.ansys.com)), CFX (Ansys Inc, [www.ansys.com](http://www.ansys.com)), STAR-CD (CD Adapco Group, [www.cd-adapco.com](http://www.cd-adapco.com)), PHOENICS

(CHAM Ltd, [www.cham.co.uk](http://www.cham.co.uk)), and ADINA (ADINA Inc, [www.adina.com](http://www.adina.com)). Of these, three software platforms are the most popular.

Firstly, COMSOL Multiphysics is a general-purpose software platform, based on advanced numerical methods, for modelling and simulating physics-based problems. COMSOL has a built-in transient convection-diffusion equation with non-zero source terms. Specifically, the conduction-convection equation, convection-diffusion equation, Stefan-Maxwell diffusion equation and Darcy's law are used to solve for temperature, liquid water concentration, and vapour mass fraction and pressure fields respectively. COMSOL is full package software, where all steps in the modelling process are facilitated, including defining the geometry, meshing, specifying physics, solving and then visualising the results. It can handle the variable properties that are a function of the independent variables. Therefore, this software is very useful in drying simulations where material properties change with temperature and moisture content (Khan et al., 2016). Recently, most researchers have used this software to efficiently implement their model in different food processing systems like drying (Curcio, 2010; Dhall et al., 2012b; Kumar, 2015; Kumar 2016; Zhang, 2012, Khan et al. 2016), frying (Halder, 2007; Warning et al., 2012), baking (Feyissa et al., 2011; Ousegui et al., 2010), cooking (Dhall et al., 2012a) and roasting (Feyissa et al., 2013).

Secondly, FLUENT is multi-purpose finite volume-based menu-structured CFD software and allows either body-fitted structured meshes (FLUENT 4.5) or solution-adaptive unstructured meshes (FLUENT 5). FLUENT contains physical models for a wide range of applications including turbulent flows, heat transfer, reacting flows, chemical mixing and multiphase flows.

The fluent software also has been used for designing and predicting heat and moisture transfer during food drying (Darabi et al., 2015; Erriguible et al., 2007; Wang et al., 2008).

Thirdly, ANSYS includes CFD features but these are mainly intended for structural and conduction heat transfer analysis. This software is a finite element analysis tool used for multiphysics heat transfer problems coupled with structural analysis. This software can be used for solving multiphase porous media models.

## **8 General trends in output parameters**

A wide variety of results have been reported regarding output parameters from multiphase models. This is mainly due to the diverse material properties and process conditions the various researchers have considered in their studies. Therefore, it is difficult to get a general idea of output from the models. Based on an extensive review of the existing multiphase modelling literature and the authors' current research, the general trends of the different output parameters are identified and presented in the following sections.

### **8.1 Moisture spatial distribution**

Throughout the processing time, water exists in the form of liquid and vapour at different proportions within the food sample. At the initial stage of processing, liquid water migrates from the core to the surface. Then, the water transforms to vapour and finally water vapour migrates from the surface to the surroundings. Fig. 1 shows the spatial distribution of moisture in a sample during food processing. It can be seen that the moisture curves can be divided into three regions, namely, a solid region, a crust-core transition region and a high moisture saturation region. The

solid region is defined as the region where moisture becomes almost zero; whereas the zone with a high moisture gradient is termed as the crust-core transition region. The high moisture saturation region is defined as the region with high moisture content, having a lower moisture gradient.

It is found that the vapour migration from core to surface is significantly greater than the amount of vapour removed from the surface (Oroszvari et al., 2006). Consequently, excess vapour migrates back towards the centre instead of evaporating from the surface. This excess vapour condenses to liquid water due to a lower temperature at the core region. It causes an increase in liquid saturation until the first falling rate of processing is induced, as shown in Fig. 1. However, in the crust-core transition region, a sharp gradient of moisture and temperature is observed (Kumar et al., 2016). Consequently, the moisture saturation falls very sharply from core to crust in the transition zone. Within a very short time, the liquid water saturation on or near the surface becomes negligible due to rapid evaporation (Halder et al., 2007).

It can be seen in Fig. 1 that as processing progresses, the evaporation on the surface becomes insignificant and the evaporation front moves towards the core, as shown in Fig. 4. Overall, significantly higher moisture content exists in the core than on the surface (Mercier et al., 2015).

## 8.2 Temperature profile:

The multiphase nature of food material greatly affects the temperature profile of the food sample. The effective heat capacity ( $\rho c_{p,eff}$ ) plays a significant role in raising the temperature of the food sample. During the time of food processing, heat capacity varies from point to point within a material, due to uneven moisture distribution of the sample. In other words, the effective heat

capacity of the solid saturated portion is much lower than the high water saturated portion. On the basis of this concept, Fig. 2 was developed to show the temperature profile of a food sample during food processing.

In Fig. 2, it is clearly depicted that temperature increases sharply at the surface and reaches a substantially higher temperature within a very short processing time. For instance, Farkas et al. (1996b) found 120 °C temperature at the surface of potato sample within 2 minutes of frying at 150 °C. This faster temperature enhancement is due to the crust formation of the surface (Halder et al., 2007, Kumar et al., 2016). Moving further from the surface to the core, heat starts increasing after some time, because of the initial energy that is being taken by the evaporation at the surface. Due to the higher heat capacity of the core region, the increment of temperature is much slower than the surface. An interesting phenomenon occurs in the transition area of crust and core, where a sharp bend in temperature distribution is observed. One of the possible reasons for this phenomenon is the occurrence of rapid evaporation in this transition region.

### 8.3 Pressure distribution

Similar to moisture and temperature distribution, gauge pressure is not spatially constant at any processing time. Due to a higher evaporation rate on or near the surface, the gauge pressure peaks at those points. The value of gauge pressure in the crust region is always positive in cases of frying, drying, heating and baking of low moisture content material, as quick evaporation takes place in this region. The peak pressure of the crust-core interface increases with time and shifts towards the core because of both the receding zone of higher evaporation and the



temperature increase (Datta, 2007b) (Figs. 3a and 3b). After the pressure reaches its peak, it starts to decrease, as less vapour saturation exists towards the core region.

At the initial stage of processing, gauge pressure in the core region shows a negative value, caused by condensation of migrated water and vapour from the surface to core region (Halder et al., 2007). When the core temperature starts increasing, vapour saturation in the region rises, leading to an increase in the gauge pressure. The maximum gauge pressure was estimated at around 1.0 kPa in the case of potato frying (Halder et al., 2007, Kumar et al., 2016), and 0.4 kPa for convective drying (Datta, 2007b). In spite of this small positive value of gauge pressure, it still influences the moisture migration significantly. Due to difficulties of gauge pressure measurement inside the food sample during the processing, there are no experimental results of gauge pressure available in the literature.

#### 8.4 Evaporation rate

Evaporation rate is highly dependent on temperature and pressure gradients. The high temperature gradient at the sample-processing media (air, oil and water) interface causes a high evaporation rate. Therefore, the peak of evaporation rate occurs at the core-crust interface as shown in Fig. 4. In other words, the non-equilibrium formulation of evaporation is higher when the difference between vapour pressure and equilibrium vapour pressure is higher. After reaching the peak, the evaporation rate starts to reduce sharply at both sides of the peak. With increase in the processing time, the peak of the evaporation rate drops sharply due to the lower temperature gradient and thermally insulating crust formation (Dhall et al., 2012a; Halder et al., 2007).

Furthermore, the liquid water saturation becomes lower near the surface of the sample that contributes the same value of vapour pressure and equilibrium vapour pressure. Consequently, the evaporation front moves inside the material as processing progress. Both distributed evaporation and sharp boundary formulation for evaporation are found in the literature (Kumar et al., 2016).

### 8.5 Moisture flux

Moisture flux is a rate measurement that refers to how fast the moisture migrates across a defined cross section. The total flux of moisture encompasses flux of liquid water and water vapour. Both liquid and vapour phases of water migrate due to gas pressure gradient (convective flux) and capillary pressure gradient (diffusive flux).

**Liquid water flux:** It can be seen in Fig. 5(a) that the total liquid water flux decreases over time. In addition to this, the greatest liquid flux exists near the surface and moves towards the core. The explanation for this could be that the moisture gradient is higher initially near the surface and the peak of the gradient moves towards the core with time. Moreover, from the literature it is found that almost 90% of total water is migrated as a liquid phase (Mercier et al., 2014, Kumar et al., 2016).

**Water vapour flux:** Water vapour flux is increased over the time of drying, as shown in Fig. 5(b). Similar to liquid flux, the maximum total vapour flux is located at the surface of the sample due to a significant concentration gradient between the vapour at the surface and the ambient air. Moreover, the vapour flux decreases in the direction of the core region because of the lower molecular diffusivity of vapour water (Kumar et al., 2016).

The question may arise as to which flux is dominant during food processing. Due to the hygroscopic nature of food material, the convective flux of both liquid and vapour water is almost insignificant. In other words, convective flux takes place due to a gas pressure gradient that is inadequate (as discussed in section 8.3) for the transport of moisture. For instance, it has been reported that only 1–10% moisture transport contribution is due to convective flux or gas pressure gradient (Halder and Datta, 2012; Mercier et al., 2014). Therefore, diffusive flux dominates over convective flux throughout the food processing time.

## **9 Challenges in multiphase modelling:**

Various complicated physiochemical changes such as non-uniform evaporation of water, crust formation, shrinkage and pore evolution take place during food processing because of the amorphous, anisotropic and hygroscopic nature of plant-based food materials. Modelling of food processing without considering these changes results in less accurate, unreliable outcomes. To eliminate such complexities, researchers have relied on various assumptions for developing multiphase models of coupled heat and mass transfer during food processing. In order to simplify the modelling approaches, some key physical phenomena such as shrinkage and bound water transport have been excluded. Incorporating all the necessary and fundamental physics into the models is the key challenge in developing a multiphase food processing model. This key challenge can be broken down into three aspects for multiphase porous media modelling: proper consideration of bound water, material shrinkage and the physical properties of the plant-based food materials modelled. These three aspects are discussed further below.

### 9.1 Bound water consideration

In hygroscopic material (plant-based food material), water generally exists in the following forms: free water, physically bound water and chemically bound water (Joardder et al., 2015). Free water is recognised as the water that exists in the intercellular space of the food domain (Halder et al., 2011). Physically bound water is categorised as two types namely, bound water (intracellular water) and strongly bound water (cell wall water) (Caurie, 2011). Strongly bound water (SBW) has some distinguishing characteristics; for instance, SBW is not free to act as a solvent for salts and sugars, can be frozen only at very low temperatures (below the freezing point of free water), and it exhibits negligible vapour pressure. The main difference between intracellular and intercellular water is that the former has low diffusivity when the cells remain intact. Therefore, the variation of binding energy of bound water strongly affects the drying process, since it requires more energy than free water (Shafiur, 2007). However, without removal of bound water, food cannot be defined as dried food (Troller, 1978). On the other hand, SBW migration also affects the material structure; if this bound water is removed from the material, anisotropic shrinkage and storage stability problems are likely to occur (Kuprianoff, 1958).

The existing food processing literature has not considered bound water transport in its models. Most of the existing multiphase models have considered all of the water inside the food materials to be transportable (i.e., bulk water). From Fig. 6, it can be seen that the current models consider three phases inside food structure such as water, gas (vapour and air) and solid matrix (Datta, 2007, Halder and Datta, 2012, Feyissa et al., 2013, Gulati and Datta, 2015, Kumar et al., 2015). During their modelling, these researchers considered all the water is intercellular (free water),

and therefore there is no water inside the solid matrix (as modelled). However, in practice, plant-based food materials are considered as hygroscopic materials, as shown in Fig. 7.

Though very few bound water transport models were developed for the drying of wood (Skaar and Babiak, 1982), food (Peishi and Pei, 1989, Feng et al., 2001), and sludge (Lee, 1996), the model was developed using very simplistic assumptions such as equilibrium formulation and no gas pressure effect. In their models, they used the same value of permeability for both free and bound water transport. However, in practice, the permeability of free and bound water should differ because of their different transport pathways. The major limitations of their models were that they did not consider material shrinkage in connection with the migration of bound water.

In addition, migration of bound water has a significant effect on the material structure. Migration of intracellular water causes cell shrinkage and pore shrinkage as well as the collapse of cell structure, whereas the movement of cell wall water causes overall tissue shrinkage (Prothon et al., 2003, Joardder et al., 2015c) as shown in Fig. 8. However, there is no correlation of material shrinkage with different types of water transport. Therefore, physics-based modelling that incorporates bound water transport is a significant challenge for future research.

## 9.2 Material shrinkage consideration

During food processing, microstructural stress due to the moisture gradient within the product leads to shrinkage. Material shrinkage during food processing has two main causes. Firstly, the tissue is incapable of holding its structural arrangement when the space occupied by water is constantly emptied and air-filled. Secondly, the exterior skin structure collapse leads to shrinkage (Panyawong and Devahastin, 2007). Thus, when moisture migrates from a porous material,

shrinkage must take place in that material (Joardder et al., 2015c). Nevertheless, in the multiphase food process modelling discussed above, all of the models have been developed assuming no material shrinkage (i.e., constant volume). On the other hand, pore formation works in the opposite direction to the shrinkage of food material during food drying. During the processing time, moisture migrating from the material cell leads to pore formation. Therefore, it can be said that porosity is a variable food property; yet despite this variability, most of the existing multiphase models consider porosity as a constant property. That is to say, neither material shrinkage nor variation in porosity are considered in present models. Hence, it can be concluded that consideration of shrinkage and variable porosity is crucial for improved accuracy in multiphase food process modelling.

### 9.3 Properties and parameters required

Consideration of accurate physical properties of plant-based food materials during modelling is crucial for optimising heat and mass transfer prediction and for ensuring high quality of processed food (Khan et al., 2016). The accuracy of a mechanistic model, with respect to the physical phenomena it represents, depends on the availability of appropriate transport properties. The most significant properties of plant-based food materials that need to be considered are water diffusivity, thermal conductivity, permeability, capillary pressure and mechanical properties; various parameters such as real-time heat and mass transfer coefficients are not available for most of the materials and processes. Input parameters, such as heat and mass transfer coefficients, are difficult to measure directly through experiments and require a different formulation of the simulation. Because of the lack of sufficient data on thermal properties,

researchers use their estimated values in complex models, which can lead to large errors in final solutions (Feng et al., 2001). Although there are some publications (Poling et al., 2001; Fikiin and Fikiin, 1999; Becker and Fricke, 1999) that provide generic properties of gases and liquids and provide insights into properties and their predictions, these are not directly useful for instantaneous food properties estimation.

In addition, some properties, including intrinsic permeability, diffusivity of different types of water (bound and free), are crucial in a prediction model and difficult to measure. Measurement of these properties, along with real-time heat and mass transfer, demands special attention.

In summary, accurate models of food processes, which include all the physics addressed above, still do not exist because fundamental, physics-based modelling for food processing model is still in the developing stages and this is ultimately the challenge for future researchers in the food industry.

## 10 Conclusion

In this article, multiphase porous media models for food drying, frying, cooking, heating, baking, and roasting have been critically reviewed. Input parameters for the model and the relationships for determining necessary material properties were discussed. The hypotheses used in other studies for developing the multiphase models were presented in an organised manner. The contributions and limitations of the existing multiphase models were summarised. A general multiphase model formulation technique was presented, including a mass conservation equation and an energy equation. A rigorous comparative study of various output parameters such as moisture content, temperature, and pressure distribution, water evaporation rate, diffusive flux

and convective flux was presented. This paper has also discussed challenges for the future development of a multiphase model.

### **Acknowledgement**

The authors are sincerely grateful to the Queensland University of Technology, Australia for funding a QUTPRA scholarship and HDR Tuition Fee Sponsorship, which has enabled the conduct of this research.



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Table 1: Present status of multiphase food processing models

Process	Process condition	Material	Remarks	Source
Drying	Convective drying	Wheat pasta	(1) A mechanistic model was developed where convection energy and bound water effect were ignored.	(Mercier et al. 2014)
			(2) Estimated overall moisture transport where about 88% of total water is transported in the liquid state while other is in vapours and air state.	
	Convective drying	Apple	(1) A comprehensive porous media model for drying was developed.	(Kumar 2014)
			(2) Moisture content and vapour pressure profile were presented	
	Oven drying	Potato	(1) A simple multiphase food drying model is developed where the convection energy term, material shrinkage, and the material bound water were neglected.	(Curcio 2010)



			(2) The model can be used for those situations in which semi-empirical correlation are not currently available.	
	Freeze drying	Beef	<p>(1) A 1D multiphase porous media model was developed for beef drying with a distributed, non-equilibrium sublimation front that calculates pore ice fraction, pressure, and temperature.</p> <p>(2) The simulated results were validated with the experimental data where, temperature, pressure, sublimation, water saturation and heat flux pattern were discussed.</p>	(Warning et al. 2015)
Frying	Deep fat frying	Restructured potato	(1) A fundamental physics-based non-equilibrium model was developed. Bound water and shrinkage were not taken into consideration.	(Halder et al. 2010)

			(2) Temperature, moisture content and pressure variation profile were investigated.	
	Immersion frying	Potato chips	<p>(1) A simplistic model was developed considering two individual regions for heat and mass transfer separated by and interface boundary.</p> <p>(2) The model was validated with experimental data and showed the temperature and moisture content profile as well as the vapour flux at the crust-core interface region.</p> <p>(3) However, the proposed model and its solution technique are a huge time consuming.</p>	(Farkas et al. 1996a; Farkas et al. 1996b)

	Deep fat vacuum frying	Potato chips	(1) Developed a multiphase model for vacuum frying in the first time without considering material shrinkage and bound water effect.	(Warning et al. 2012)
			(2) Validated the model with the experimental data and showed temperature, moisture, pressure, acrylamide content and oil content profile.	
	Deep fat frying and post frying cooling	Potato	(1) Physics-based 1 D model was developed for deep fat frying and post frying cooling of potato slab. In their model the bound water transport and gravity effect also the material shrinkage was ignored.	(Halder 2007) (Halder et al. 2007)

			(2) Temperature, pressure, water saturation profile with the distance from the surface of the material was investigated. They also showed the effect of capillary diffusivity, permeability and thermal conductivity on frying time.	
Cooking	Double sided contact heating	Hamburger patty	(1) A 1D mechanistic model was developed where transportable liquid phase comprised liquid water, liquid fat and gas, and solid phase comprised protein, frozen water and fat.	(Halder et al. 2010)
			(2) Pressure variation, evaporation and temperature profile were discussed in the literature.	

	Oven	Beef	<p>(1) A multiphase model based on Flory–Rehner theory of rubber elasticity was developed considering the permeability of the meat is anisotropic and does not vary with temperature.</p> <p>(2) Evaporation of water inside the meat and general gas pressure were ignored.</p> <p>(3) Discussed the effect of different process parameters on the permeability of the beef piece</p>	(Van der Sman 2007a)
	Contact heating	Hamburger	<p>(1) A multiphase model was developed for meat cooking and validated the model with other literature experimental results.</p> <p>(2) Identified the dominant modes of heat and mass transport in operation.</p>	(Dhall et al. 2012a)

			(3) Temperature, pressure profile, moisture content and fat content profiles were presented and discussed.	
Roasting	Convection oven	Pork meat	<p>(1) A 3D multiphase model was developed and partially validated with the experimental result.</p> <p>(2) The model is capable of incorporating the effect of permeability, water holding capacity and elastic modulus of the meat during the roasting process.</p>	(Feyissa et al. 2013)
Heating	Microwaveheating	Porousmaterial	(1) A transient one-dimensional model was developed considering two types of material such as low moisture material and high moisture	(Ni et al. 1999)

			(2) material with transport properties that can change with structure, moisture and temperature.	
			(3) Compared the temperature, pressure profile of low moisture material with high moisture material.	
	Microwave heating	Restructured potato	(1) Without considering the deformation of the material, a 2D axisymmetric conjugate model was developed where the gravitational effect was ignored.	(Halder and Datta 2012)
			(2) Heat and mass transfer coefficient, vapour flux due to convection and diffusion, and velocity effect was investigated at different heating conditions.	

Table 2: Permeability for different materials (liquid and gases)

Parameter	Relative permeability ( $k_r$ )			Intrinsic permeability ( $k_i$ ), ( $m^2$ )			Comments
	Symbol	Expression	Source	Symbol	value	source	
Water	$k_{rw}$	$\left((S_w - 0.08)/0.92\right)^3$	(Bear 1972)	$k_{iw}$	$5 \times 10^{-16}$	(Stanish et al. 1986)	Necessary for drying, frying, cooking, heating, baking, etc.
Air/vapour	$k_{rg}$	$1.01e^{-10.86S_w}$	(Feng et al. 2004)	$k_{ig}$	$1 \times 10^{-15}$	(Stanish et al. 1986)	
Oil	$k_{ro}$	$\left((S_f - 0.08)/0.92\right)^3$	(Ni and Datta 1999b)	$k_{io}$	$5 \times 10^{-14}$	(Ni and Datta 1999b)	Especially necessary for frying model
Fat	$k_{rf}$	$\left((S_f - 0.08)/0.92\right)^3$	(Dhall et al. 2012a)	$k_{if}$	$1 \times 10^{-7}$	(Dhall et al. 2012a)	Especially necessary for cooking model



Table 3: Capillary diffusivity value or expression for different food processing systems

Parameter	Symbol	Expression ( $\text{m}^2/\text{s}$ )		Value ( $\text{m}^2/\text{s}$ )	Source
Water	$D_{cap,w}$	$10^{-8} \exp(-2.8+2M)$	(Datta 2007b)	$1 \times 10^{-7}; 4 \times 10^{-10}$	(van der Sman 2007b)
Oil	$D_{cap,o}$	$10^{-8} \exp(-2.8+2M_o)$	(Ni and Datta 1999b)		
Fat	$D_{cap,f}$			$1 \times 10^{-7}$	(Dhall et al. 2012a)

Table 4: Dynamic viscosity value or expression for different food processing systems

Parameter	Symbol	Expression / value	Source
Water	$\mu_w$	$-\log \mu_w = 0.0072T + 2.8658, 0.998 \times 10^{-3}$	(Feyissa et al. 2013)
Air/vapour	$\mu_g$	$1.8 \times 10^{-5}$	
Oil	$\mu_o$	$5.05 \times 10^{-6} \exp(2725/T)$	(Tseng et al. 1996)
Fat	$\mu_f$	0.02	(Dhall et al. 2012a)

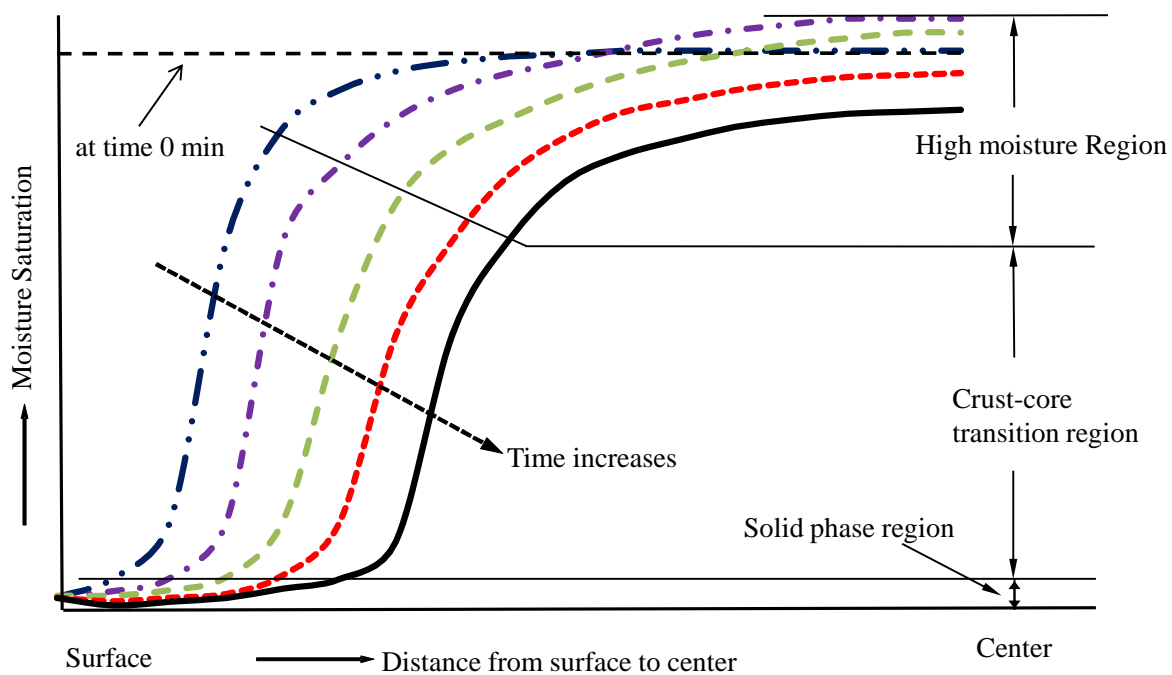


Fig. 1. Water saturation profile with distance from surface to centre

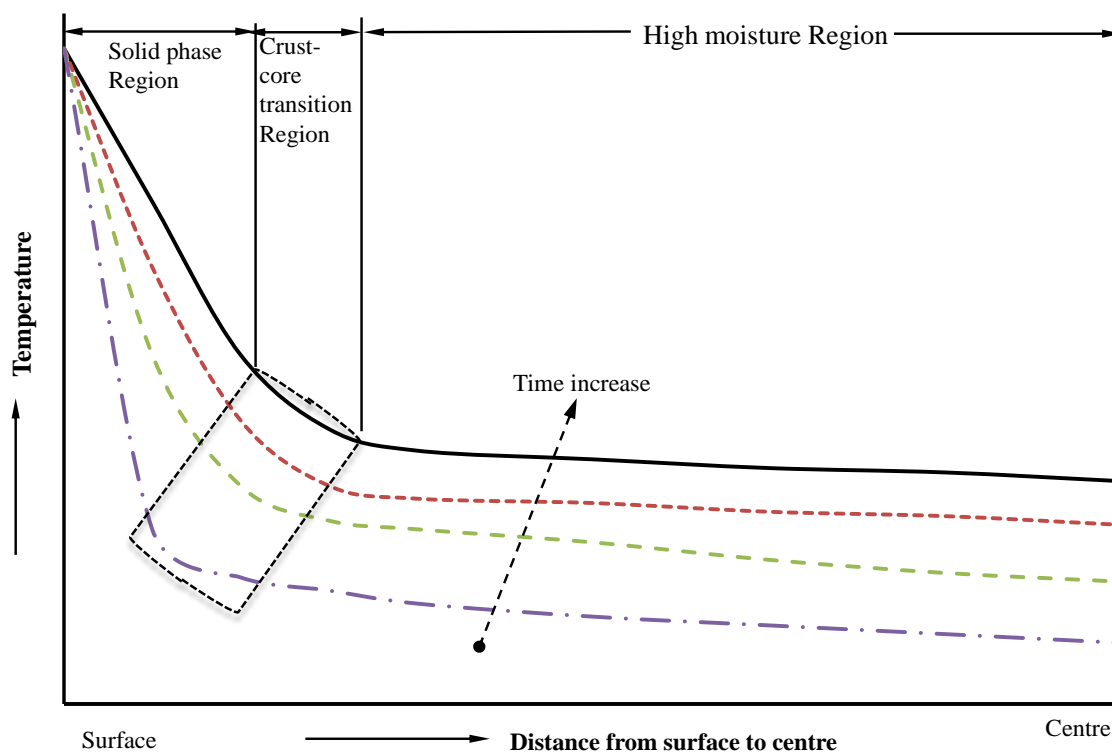


Fig. 2. Temperature profile with distance from surface to centre

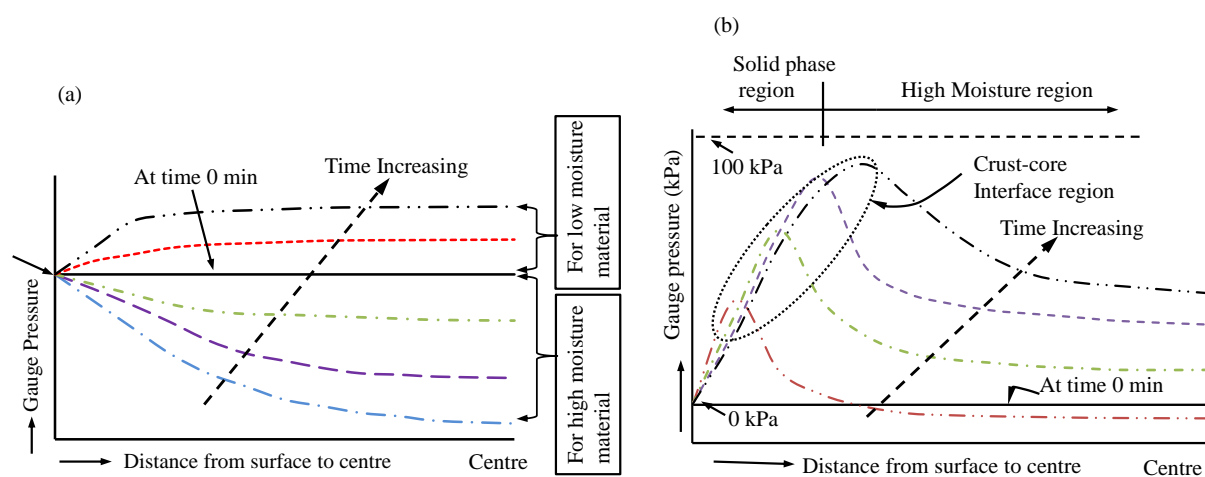


Fig. 3. Pressure profile (a) for drying, heating or baking process, (b) for frying

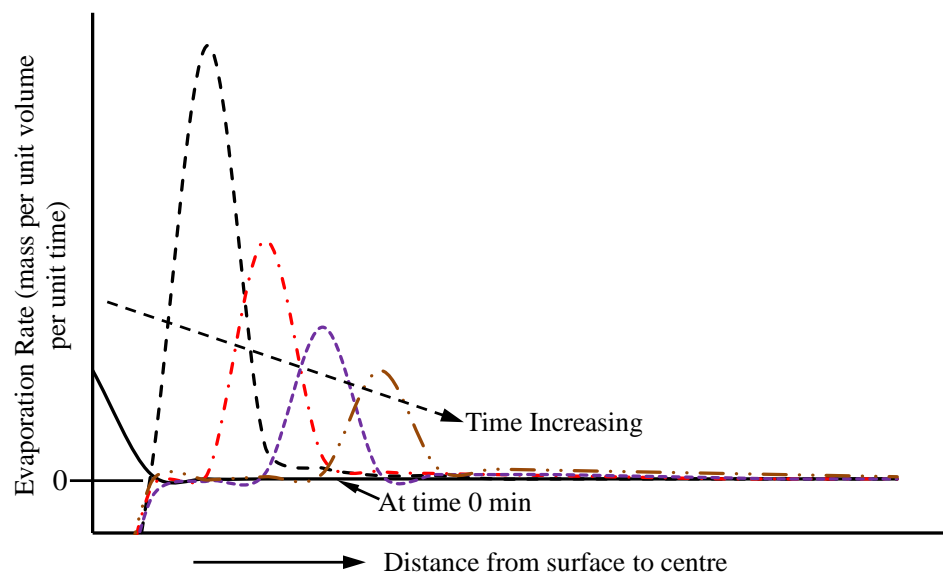


Fig. 4. Spatial distribution of evaporation rate

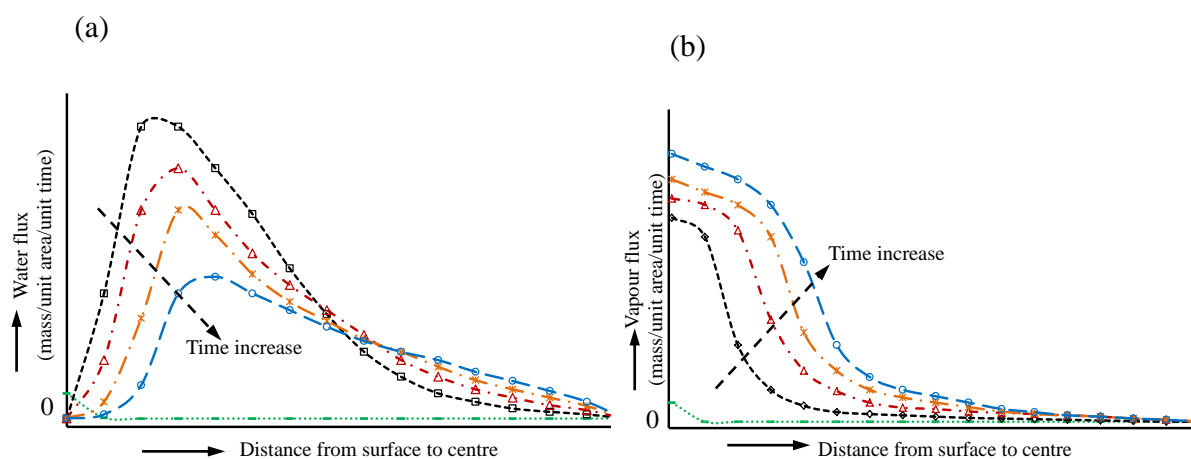


Fig. 5. Spatial distribution of fluxes (a) water flux, (b) vapour flux

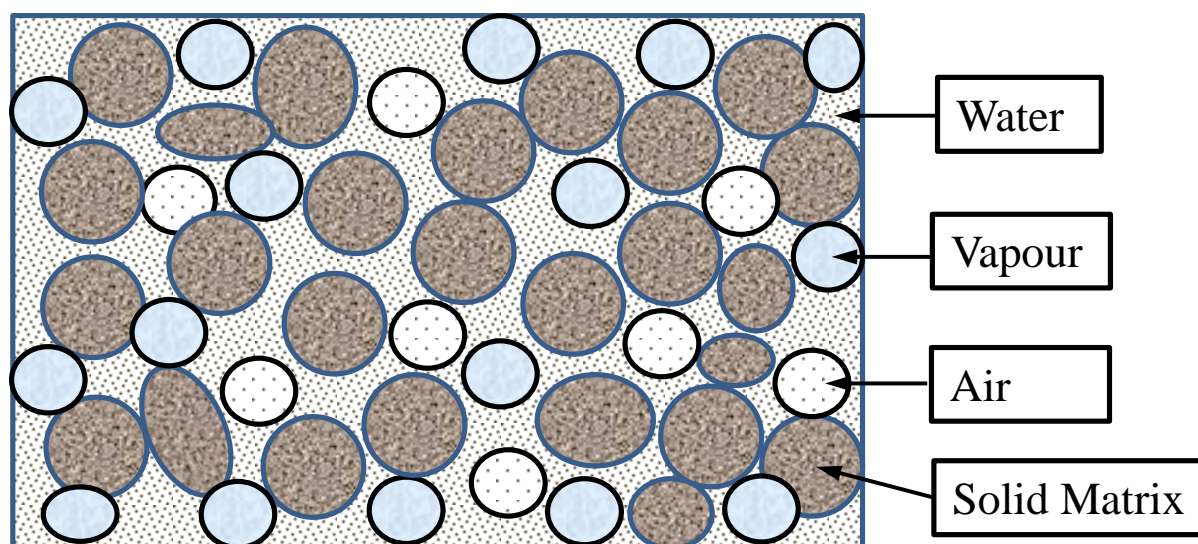


Fig. 6. Microstructure of plant-based food materials was considered for model formulation in the existing literature (Datta 2007a; Feyissa et al. 2013; Gulati and Datta 2015; Halder and Datta 2012; Kumar et al. 2016).



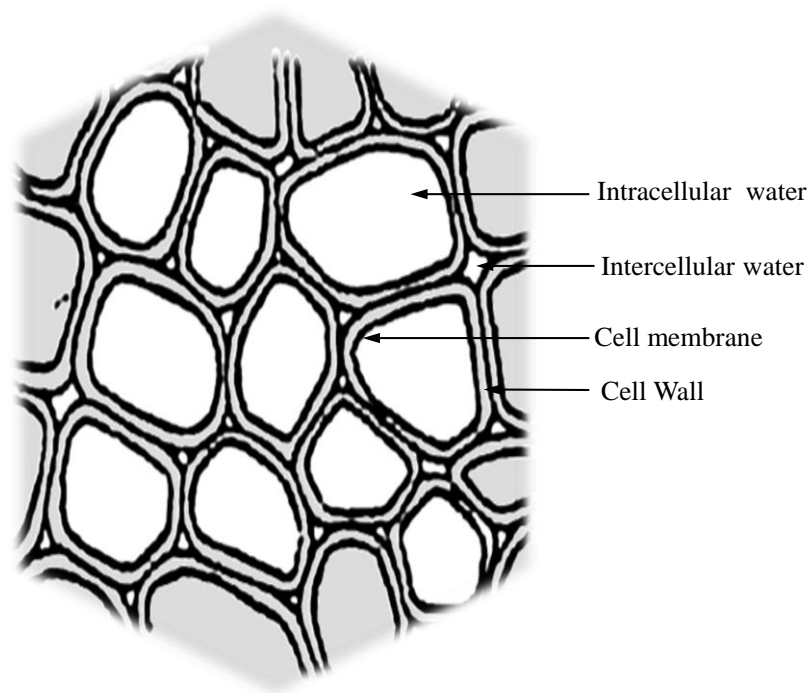


Fig. 7. General water distribution inside plant-based food materials

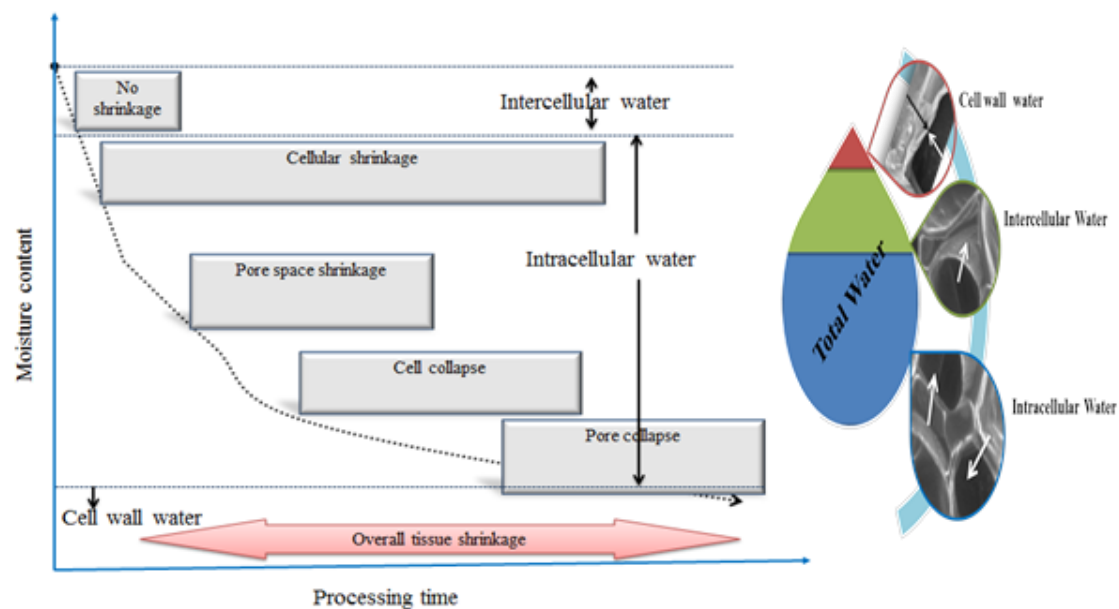


Fig 8 Water distribution with material shrinkage (Joardder et al. 2015c)