Multiphysics Modelling of convective drying of food materials

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1. Abstract

Currently, 1.3 billion tonnes of food is lost annually due to lack of proper processing and preservation method. Drying is one of the easiest and oldest methods of food processing which can contribute to reduce that huge losses, combat hunger and promote food security. Drying increase shelf life, reduce weight and volume of food thus minimize packing, storage, and transportation cost and enable storage of food under ambient environment. However, drying is a complex process which involves combination of heat and mass transfer and physical property change and shrinkage of the food material. Modelling of this process is essential to optimize the drying kinetics and improve energy efficiency of the process. Since material properties varies with moisture content, the models should not consider constant materials properties, constant diffusion .The objective of this paper is to develop a multiphysics based mathematical model to simulate coupled heat and mass transfer during convective drying of fruit considering variable material properties. This model can be used predict the temperature and moisture distribution inside the food during drying. Effect of different drying air temperature and drying air velocity on drying kinetics has been demonstrated. The governing equations of heat and mass transfer were solved with Comsol Multiphysics 4.3.

Keywords: Drying, Heat and mass transfer, Modeling, Multiphysics, Comsol-Multyphysics

2. Introduction and background

Drying is a heat and mass transfer process to remove moisture by evaporation. It is a cross and multidisciplinary area because it requires optimal combination of heat and mass transfer, and material science. The objective of drying is not only to supply heat and remove moisture, but to produce a dried product of desired quality (Mujumdar 2004). Now a days, not only food and beverage products but also industrial and municipal wastewater sludge, and other manufacturing and environmental product is being dried regularly in order to enhance the quality and life span of these product and to facilitate their storage and transportation (Jamaleddine and Ray 2010).

However, food drying is one of the oldest and most cost-effective means of preservation of grains, crops and foods of all varieties(Askari, Emam-Djomeh et al. 2006). Fruits and vegetables contain more than 80% moisture and therefore are classified as highly perishable (Orsat, Yang et al. 2007). About 1.3 billion tonnnes of food is lost annually due to lack of proper processing which is one third of global food production(Gustavsson, Cederberg et al. 2011). This loss is even more in the developing countries like Bangladesh, where 30-40% of fruit and vegetables are wasted due to lack of appropriate food processing (Karim and Hawlader 2005b). So proper food processing should be emphasized to reduce this massive loss, promote food security and combat hunger. Food drying is simplest and widely used way of food preservation and inhibiting growth and reproduction of microorganism. It increases shelf life, reduce weight and volume thus minimizing packing, storage, and transportation cost and enable storage of food under ambient environment. However, drying is an energy intensive process and maintaining food quality during drying is a major concern. Hence, approach of improving energy efficiency and quality of dried product in drying process are important concern if food drying. Mechanism of drying should be investigated properly for that purpose. Modelling is essential to understand the mechanism and optimize the drying process to improve energy efficiency of the process and product quality(Kumar, Karim et al. 2012). However, empirical model does not help towards optimization, although most of the drying models found in the literature are empirical model. Moreover there are very few models that allow visualization of temperature and moisture distribution inside the food product. The objective of this article is to develop a fundamental multiphysics based model which can capture the basic physics during convection drying process. This model was developed in engineering based simulation software COMSOL Multiphysics. The model can predict the temperature and moisture content of the food product. It also provides visualization of temperature and moisture distribution and evolution inside the food product. The developed model is very flexible which can easily adapt to any product and extra physics for example can be added without much effort.

3. Modeling of drying

Feng, Yin et al. (2012) recently presented an excellent review on modelling heat and mass transfer process in microwave drying. Generally the drying model can be categorized into two groups empirical and fundamental.

3.1. Empirical Models

Empirical models are simple to apply and often used to describe drying curve. The page equations and exponential models are most commonly used. The following Table 1 below shows the list of the empirical models used to describe drying kinetics:

Table 1: List of empirical models

Model	Name of the Model	Reference
$MR = exp(-kt)$	Newton	(Sutar and B.N.Thorat 2011) and (Baini and Langrish 2007)
$MR = exp(-kt^n)$	Page	
$MR = exp(-(kt)^n)$	Modified Page	
$MR = a\,exp(-kt)$	Henderson and Pabis	
$MR = a\,exp(-kt) + c$	Logarithmic	
$MR = a\,exp(-k_0 t) + a\,exp(-k_1 t)$	Two-term	
$MR = 1 + at + bt^2$	Wand and Singh	
$MR = a\,exp(-kt) + (1 - a)exp(-kbt)$	Approximation of diffusion	
$MR = a\,exp(-kt) + (1 - a)exp(-gt)$	Verma	
$MR = a\,exp(-kt) + b\,exp(-gt) + c\,exp(-ht)$	Modified Henderson and Pabis	
$MR = a\,exp(-kt) + (1 - a)exp(-kat)$	Two term exponential	
$MR = exp\left(-k\left(\frac{t}{L^2}\right)^n\right)$	Modified Page equation – II	

Here, M_t is moisture content at time t, M_e is equilibrium moisture content and M_0 is initial moisture content the moisture ratio, $MR = \frac{M_t - M_e}{M_0 - M_e}$, and *a,b,c* are model constants (dimensionless) and *k, g,h* are the drying constants (s^{-1}). These models are originally derived from Newton's law of cooling and Fick's law of diffusions (Erbay and Icier 2010).

Regression analysis is often used to find constant and fit the drying curve. However these empirical models are not able to capture the exact physics behind the drying. They do not help towards development and optimization of the process as they are not capable to provide engineering understanding and thereby not predictive in nature and cannot readily be applied to different conditions (Rakesh and Datta 2011). While theoretical model explain the drying behaviours of the product clearly and can be used at all processing condition, empirical models are only valid for within the specific process condition applied (Erbay and Icier 2010).

3.2. Fundamental models

Fundamental model can be divided into two groups as diffusion based model and heat and mass transfer model. In this paper a diffusion based model is developed and heat and mass transfer model are not discussed. Interested reader are referred to the article of Feng, Yin et al. (2012) for more information.

Diffusion model: Transport in porous medium can be driven by concentration gradient for liquid and by a partial vapour pressure gradient for vapour. The governing equations for moisture transport can be described by Fick's second law

$$\frac{\partial c}{\partial t} = \nabla.(D_{eff}\nabla c) \qquad (1)$$

Determination of diffusion coefficient is important for the accuracy of model prediction. The diffusion coefficient can be regressed as a function of temperature and concentration by using the experimental data (Wang and Sun 2003). Alternatively the diffusion coefficient can be determined by Arrhenius law as shown below (Wang and Brennan 1995).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{2}$$

4. Model Development

The model was developed in this research considered cylindrical geometry of the food product as shown in figure 1. In developing the model the following assumption were made:

(1) No chemical reaction takes place during drying.
(2) Uniform initial temperature and moisture distribution

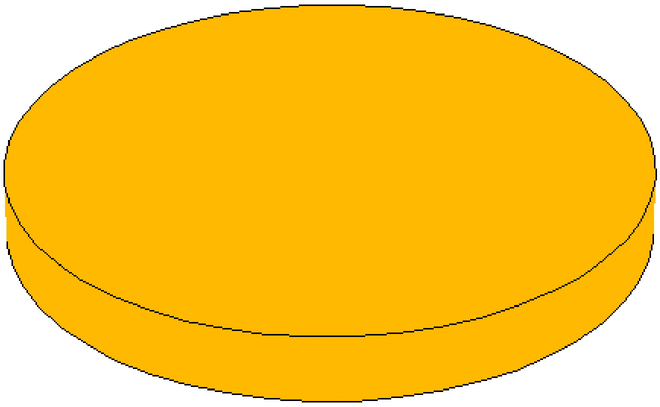

Figure 1: Actual geometry for the simulation

2D axisymmetric geometry was considered for modeling because of s symmetry and one dimensional problem. The material properties used for simulation was for banana as the data was available in the literature to validate the model.

Governing Equations:

Mass transfer equations:

$$\frac{\partial c}{\partial t} + \nabla.(-D\nabla c) + \boldsymbol{u}.\nabla c = R$$

Heat transfer equation:

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \boldsymbol{u}.\nabla T = \nabla.(k\nabla T) + Q$$

Initial and Boundary conditions:

Initial Conditions: Initial moisture content, $M_0 = 4$ kg/kg dry basis,
Initial temperature $T_0 = 25^0C$
Boundary Conditions:

For heat transfer:
At open boundaries: $\boldsymbol{n}.(k\nabla T) = h_T(T_{air} - T) - h_m\rho(M - M_e)h_{fg}$
From (Azzouz, Guizani et al. 2002) proposed $h_m\rho(M - M_e)h_{fg} = \boldsymbol{n}.(D_{ref}\lambda\nabla c)$
So the boundary condition become $\boldsymbol{n}.(k\nabla T) = h_T(T_{air} - T) - \boldsymbol{n}.(D_{ref}\lambda\nabla c)$
At symmetry and other boundaries: $\boldsymbol{n}.(k\nabla T) = 0$
For mass transfer:
At open boundaries: $\boldsymbol{n}.(D\nabla c) = h_m(c_b - c)$
At symmetry and other boundaries: $\boldsymbol{n}.(D\nabla c) = 0$

Input Parameters of the model:

However the specific heat and thermal conductivity were not considered as constant, rather the following equations of moisture dependent specific heat and thermal conductivity of banana were used (Bart-Plange, Addo et al. 2012).

$$C_s = 0.811M_w^{\ 2} - 24.75M_w + 1742 \quad (12)$$

$$K_s = 0.006M_w + 0.120 \quad (13)$$

The model was developed for air velocity $0.7 m/s$ and air temperature 60^0C drying condition (Karim and Hawlader 2005b).
Other input properties of the material are shown in table 2:

Table 2: Input properties of banana, water and air at 60^0C

Properties	Value
Density of Banana, ρ	$980\ \left(\frac{kg}{m^3}\right)$
Initial Moisture Content (dry basis), M	$4\ \left(\frac{kg}{kg}\right)$
Latent heat of Evaporation, h_{fg}	$2358600\ \left(\frac{J}{kg}\right)$
Thermal Conductivity of air, k_{air}	$0.0287\ \left(\frac{W}{mK}\right)$
Density of Water , ρ_w	$994.59\ \left(\frac{kg}{m^3}\right)$
Dynamic viscosity of air, μ_{air}	$1.78x10^{-4}\ Pa.s$
Specific heat of air, C_{pair}	$1005.04\ \left(\frac{J}{kgK}\right)$
Density of air, ρ_{air}	$1.073(\frac{kg}{m^3})$
Equilibrium moisture content, M_e	$0.29\left(\frac{kg}{kg}\right)$
Specific heat of water	$4184\ (J/kg)$
Diffusion coefficient, D	$2.41x10^{-10}\left(\frac{m^2}{s}\right)$

Effective diffusivity Calculation:

Temperature dependent diffusivity was obtained from Arrhenius type relationship with the following equation.

$$D_{eff} = D_0\, e^{\frac{E_a}{RT}} \qquad (16)$$

Activation energy for diffusion of water of the bananas was calculated to be $51.21\,\frac{KJ}{mol}$ and the integration constant to be $0.01751\,\frac{m^2}{s}$ (Islam, Haque et al. 2012).

Heat and mass transfer coefficient calculation:

Average heat transfer coefficient was calculated from the following equation (Mills 1995) for laminar and turbulent flow respectively:

$$Nu = \frac{h_T L}{k} = 0.664\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \qquad (17)$$

$$Nu = \frac{h_T L}{k} = 0.0296\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \qquad (18)$$

As Fourier's law and Fick's law are identical in mathematical form the analogy is used to find mass transfer coefficient. Nusselt number and Prandtle number is replaced by Sherwood number and Schmidt number respectively as following relationship:

$$Sh = \frac{h_m L}{k} = 0.664\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \qquad (19)$$

$$Sh = \frac{h_m L}{k} = 0.0296\,\mathrm{Re}^{0.5}\,\mathrm{Pr}^{0.33} \qquad (20)$$

Where $Re = \frac{\rho_a v L}{\mu_a}$, $Sc = \frac{\mu_a}{\rho_a D}$ and $Pr = \frac{C_p \mu_a}{k_a}$

5. Materials and method

The experimental data of banana drying from Karim and Hawlader (2005a) was compared with model from to validate the model. Each sample was prepared by slicing banana into 4mm thickness and diameters vary from 30 to 36mm. More detailed about the experimental setup and procedure can be found in (Karim and Hawlader 2005a).

6. Results and discussion

The simulated results in terms of the moisture content, temperature and their spatial distribution were presented. However, only moisture profile and average temperature profile from model was compared with experimental data.

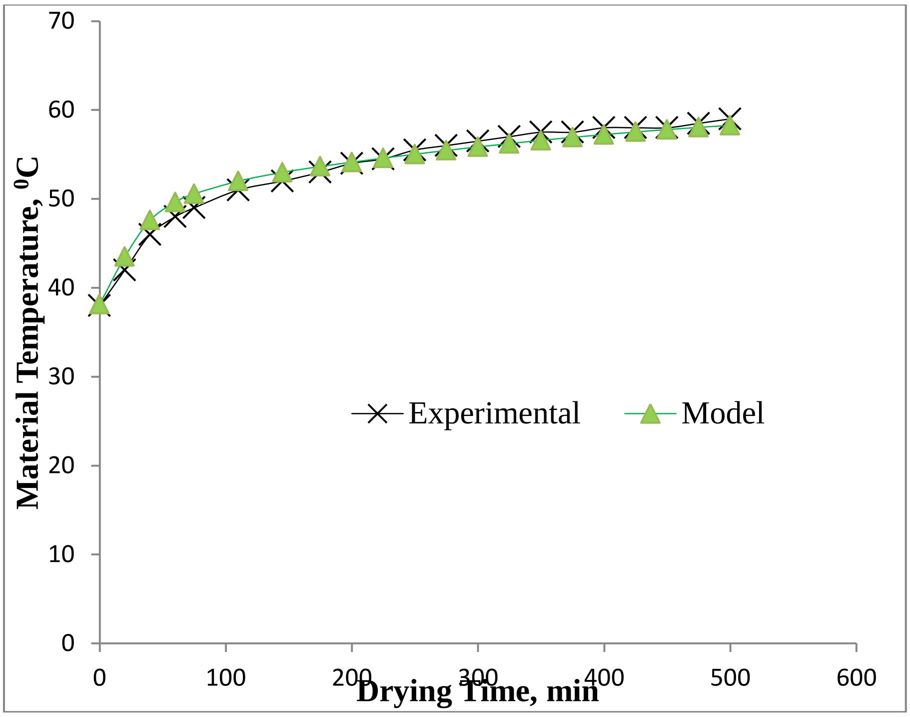

Figure 2: Temperature profile obtained for experimental and simulation with shrinkage and temperature dependent diffusivity (for drying air temp, T=60^{0}C and drying air velocity=0.5m/s)

The temperature evolution of the material is shown in Figure 2 for drying air temperature 60^{0}C and velocity 0.5m/s. The predicted temperatures agreed reasonably well with those experimental data. It can be seen that the material temperature gradually increase to drying air temperature.

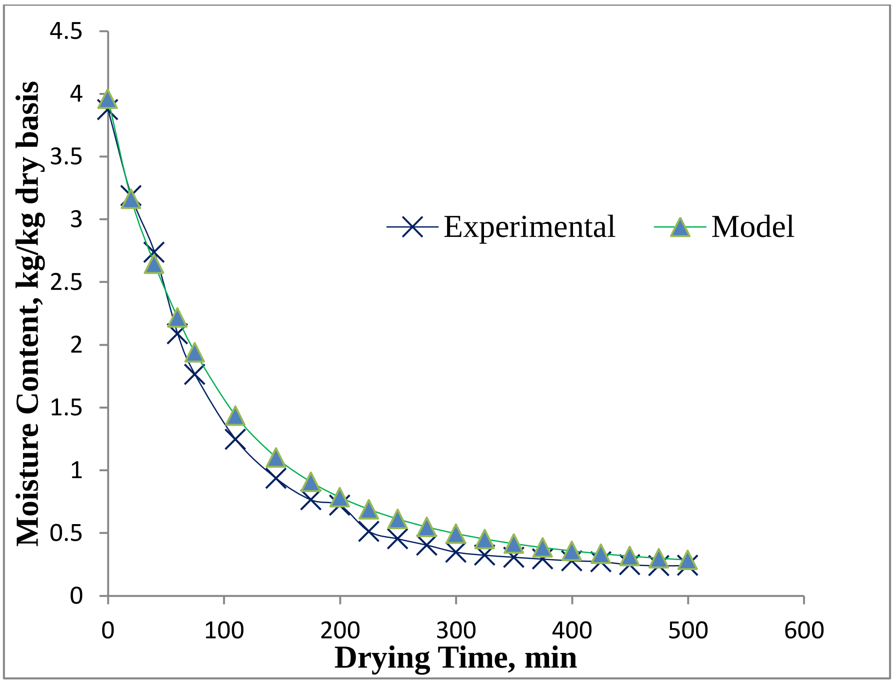

Figure 3: Moisture profile obtained for experimental and simulation with shrinkage and temperature dependent diffusivity (for drying air temperature=60^{0}C and drying air velocity, V=0.7m/s).

Figure 3 presents change of moisture content with time. It can be seen that moisture content prediction with model closely agrees with the experimental moisture content data. The comparison of predicted and experimental data of temperature and moisture indicate that the model can predict those values quite accurately. From figure 3 it is clear that the drying rate is higher during the initial period of the drying and then it decreases gradually. The drying rate curve from the model is shown in figure 4.

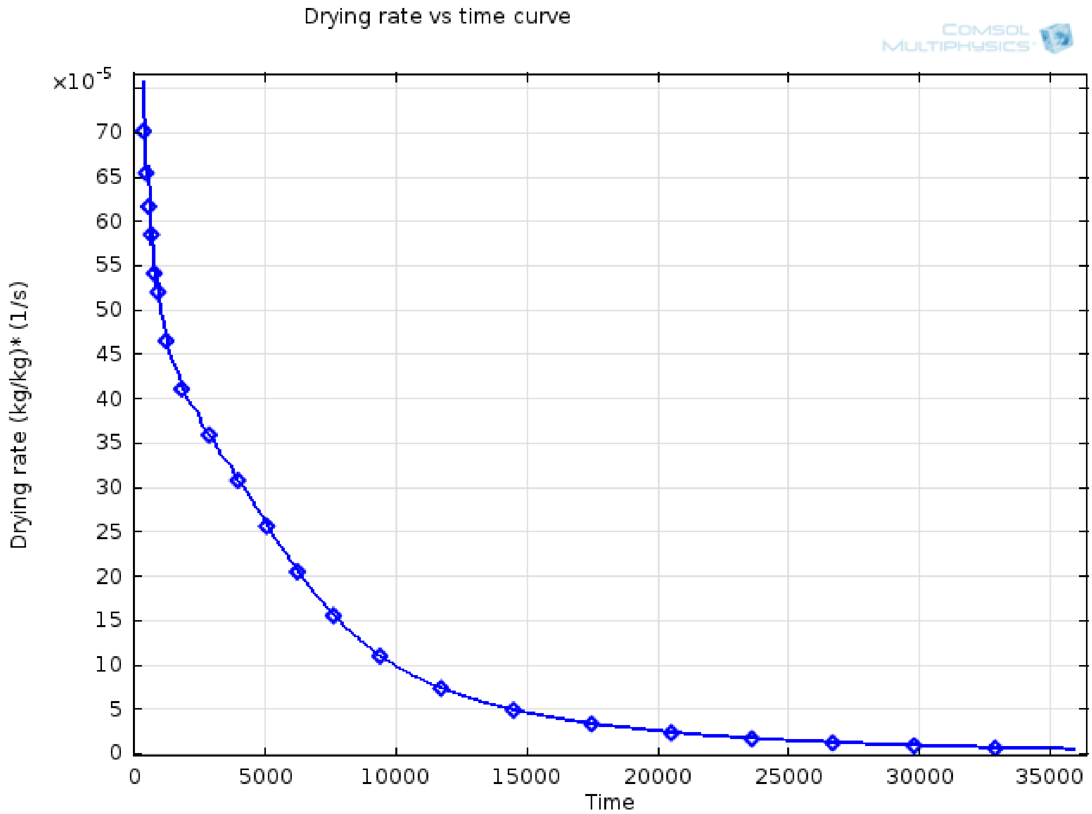

Figure 4: Drying rate vs time curve for drying air temperature=600C and drying air velocity, V=0.7m/s.

From the model temperature and moisture distribution at any time can be easily obtained. For example, figure 5 and figure 6 shows the temperature and moisture distribution at 60mins of drying.

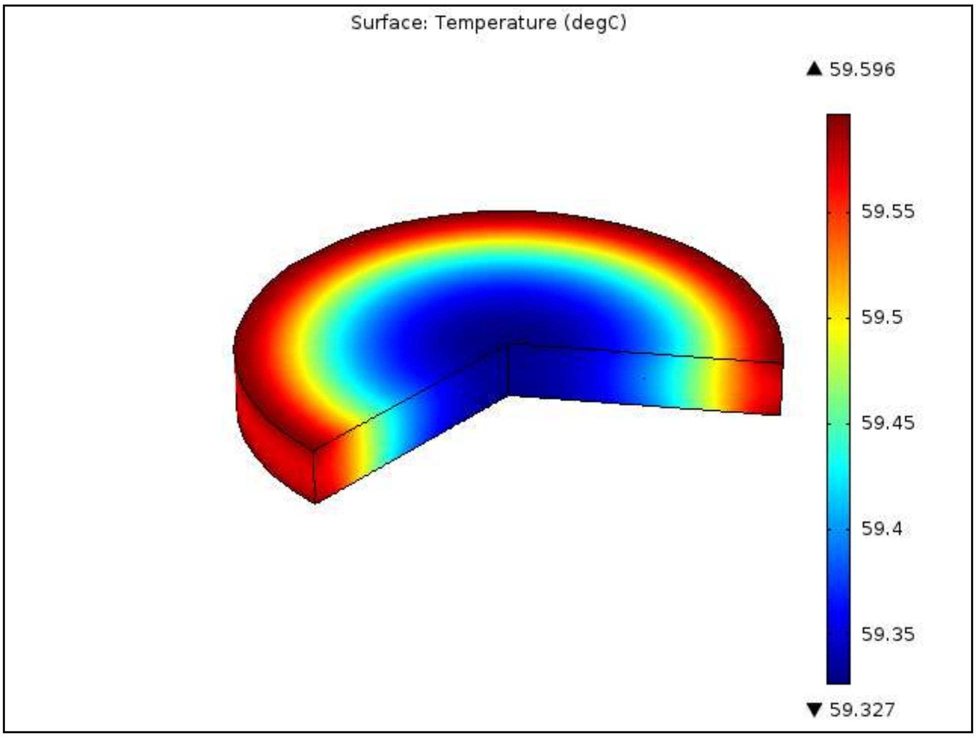

Figure 5: Temperature distribution inside the product after 60 mins of drying

From figure 5 it is clear that the temperature gradient is minimal inside the product this is because the thickness of the material is small.

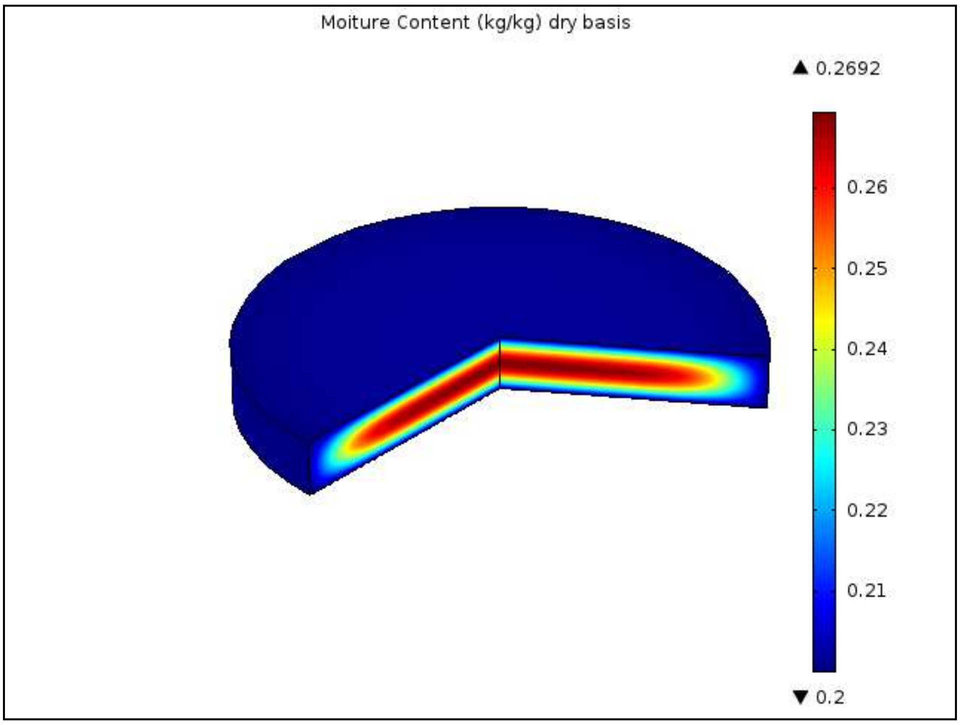

Figure 6: Moisture distribution after 60 min of drying

This is interesting that although the moisture content in the outer region is small but inner core of the product has higher moisture content which can be seen from figure 6. To know the moisture distribution in dried product is important because spoilage can start from higher moisture content region.

Parametric analysis:

Once the model is developed and validated then it can be used to investigate the effect of drying air temperature and drying air velocity on moisture profile. Figure 7 show the effect of different drying air temperature on drying rate. It shows that the increasing drying air temperature reduces the dying time significantly. Hoevver increasing drying air temperature decrease the product quality (e.g. nutrients). Therefore drying process has to be optimized and product quality should be investigated along with drying kinetics. Figure 8 show the effect of drying air velocity on moisture profile. It shows increasing drying air velocity increases drying rate but in it is not significant compared with the effect of temperature.

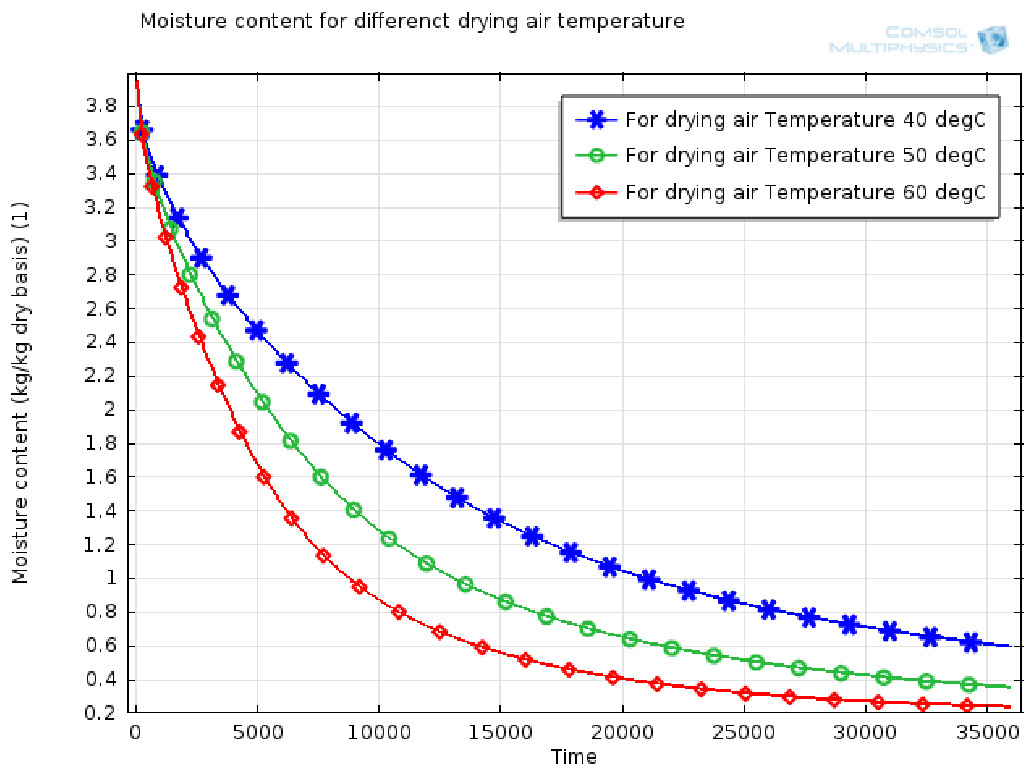

Figure 7: Effect of drying air temperature on moisture profile for constant velocity 0.7m/s

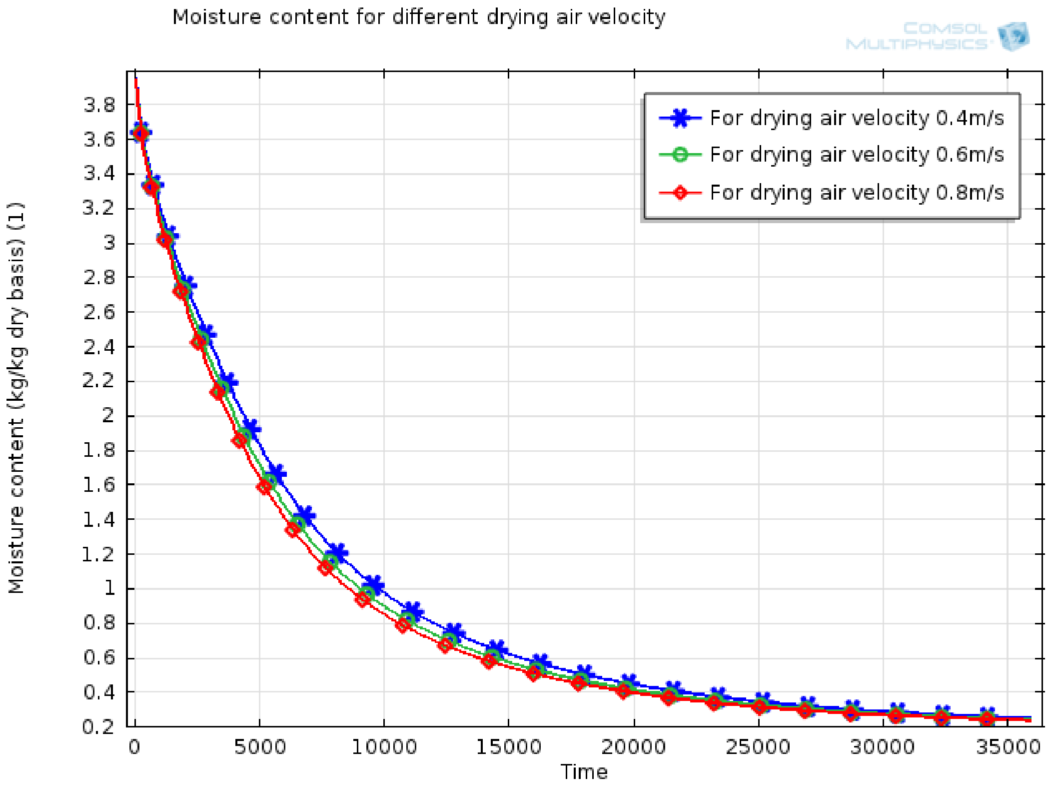

Figure 8: Effect of drying air temperature on moisture profile for constant temperature 60^0C

7. Conclusion

Drying models are necessary to optimize the drying process and develop better strategies for the control of the system. The model should be able to predict temperature and moisture distribution to ensure safe storage of dried product. In this article, a multyphysics based model was developed using COMSOL multiphysics. The simulated result were compared with experimental data from literature and found conformed. Temperature and moisture distribution of the model was presented. It was observed that the temperature gradient is negligible because of small thickness of the material and moisture content was higher at the center. The effect of different drying air temperature and drying air velocity has been investigated with the aid of the model. This model can easily be adapted to new material and extra physics can be added without significant effort and also can easily be simulated for different shape.

8. References

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