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Research Article

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Modeling and Investigating drying behavior of solid in a fluidize bed dryer

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ABSTRACT

In this study, the drying process of a green tea leaves is modeled in a drier. The proposed model related to single body were reviewed and validated with experimental data obtained from drying. Sample of green tea leaves at three temperatures, 35, 45, 55 ° C was dried in a laboratory dryer period of 0 to 140 minutes and moisture content, surface temperature data was extracted. The proposed model by applying mass and heat balance equations based on thermodynamic equations predicted changes of sample temperature and samples moisture. The results show that the change of air velocity has little effect on drying, but increases the diameter longer drying time. Surface temperature of samples increased rapidly at first, finally reaches to the gas temperature. Entropy generation increased rapidly at first and then will deteriorate. Comparison of model results with experimental data approved the proposed model. MRE of model and the experimental data for tea leaves at temperatures 35, 45 and 55 ° C was 1.9, 4.7, 10.2 The small amount and acceptable errors are indicative of the validity of the proposed model.

Keywords: Thermodynamic Modelling, moisture, Green Tea Leaves, Drying

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INTRODUCRION

Drying is one of the most important processes in the field of engineering and there is at least one dryer in most of the industrial units. Generally, drying a solid object is to remove a small amount of water or other liquid from it and reduce the remaining amount into an acceptable amount. Drying is usually the last step in a series of industrial processes and its product is often the final product and ready to pack. Drying is a main operation in the chemical, agriculture, biotechnology, food, polymers, ceramics, pharmaceutical, paste and paper, minerals and wood industries and it is among the oldest, most common and most diverse processes. Up to now, more than 400 types of dryers have been reported, and about 100 different types of dryers are available [1]. In this study, firstly in the process of drying, a single body is released freely inside the dryer and at different intervals; mass and surface temperature is checked. After conducting experiments with the establishment of the relevant equations, numerical simulation of drying was done and compared by using MATLAB software and the accuracy of the model was also evaluated. This study investigated the mechanism of simultaneous heat and mass transfer in the process of drying of a single body, mathematical modeling of heat and mass transfer processes in a sample by using mass energy balance, obtaining effective diffusion coefficient by solving Fick's second law, and also obtaining the function of this coefficient in terms of presented variables, predicting variations for samples' average moisture, surface temperature of samples, moisture by using mathematical models and comparing the results obtained from mentioned modeling by using analytical solving of partial differential equations and also compared with experimental results obtained from drying samples. Several studies has been made on the modeling of heat and mass transfer of fluidized and tray dryers. Here is a brief overview of empirical research and mathematical modeling work that has already been done on the dryers. Knowing the previous works will help in better understanding of these kinds of dryers.

The first practical drying was about eight thousand years ago in the north of France that a smooth rock surface was used for drying materials. They have been dried their crops by using moderates breeze or winds blew in these areas as well as the simultaneous use of sun [2]. Thomas et al (1992) proposed receding core model for synthetics drying of granular materials such as green pepper, black pepper and mustard. They show that the diffusion phenomena in particle controls drying process and dropping rate may be non-linear depending on the nature of the material [3]. Snnivasa Kannan and et al (1994) proposed a model for drying particles in dryer by considering the heat and mass transfer in the bubble, gas and solid phase [4]. Hatamipour and et al (2002) studied maize and green peas in fluid bed dryers. Their laboratory dryer contains energy carrier that examined density changes, sample size and moisture diffusion by variations of moisture content. Their presented relations for density changes, diameter and diffusion coefficient by moisture content variation with an accuracy of 98% [5]. Another research on the cubes pieces of carrot was done by Nazghelichi et al (2010). The experiment was conducted in the inlet air temperature of 50, 60 and 70 ° C and with bed depth of 30, 60 and 90 mm and size of 4, 7 and 10 mm. The amount of energy used was calculated equal to 105.0 to 949.1 kJ per second [6]. Jin and et al (2011) examined milk's spray dryer and entropy production by the second law [7].

EXPERIMENTAL SECTION

Mass and Energy Balance

The overall mass balance on a control volume can be expressed as follows [8]:

Accumulation= input - output (1)

$$\frac{dm_{cv}}{dt} = \sum \dot{m}_i - \sum \dot{m}_e \quad (2)$$

If the output mass flow rate of vapor expressed as $\dot{m}_e$, we have:

$$\frac{dm_{cv}}{dt} = -\dot{m}_e \quad (3)$$

Humidity variation in a slab thickness 2L is as follows [9]:

$$\frac{\bar{X}(t) - X_e}{X_0 - X_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-\pi^2 (2n+1)^2}{4} \frac{D_e t}{L^2} \right) \quad (4)$$

The first law of thermodynamics for a control volume can be written as follows [8]:

$$\frac{dE_{cv}}{dt} = \frac{dU_{cv}}{dt} = \dot{Q}_{cv} - \dot{W}_{cv} + \sum \dot{m}_i \left(h_i + \frac{1}{2} v_i^2 + g z_i \right) - \sum \dot{m}_e \left(h_e + \frac{1}{2} v_e^2 + g z_e \right) \quad (5)$$

The term of the above equation by eliminating the work and energy input with input mass and potential and kinetic energy can be summarized as follows:

$$\frac{dU_{cv}}{dt} = \frac{d(mu)_{cv}}{dt} = \dot{Q}_{cv} - \dot{m}_e h_e \quad (6)$$

Where by considering the reference temperature $T_0 = 0$ or Ignoring $\frac{d(mCT_0)}{dt}$ we have:

$$\frac{d[mC(T - T_0)]_{cv}}{dt} = \frac{d(mCT)_{cv}}{dt} = \dot{Q}_{cv} - \dot{m}_e h_e \quad (7)$$

Considering the incoming and out coming heat, heat capacity and average moisture, we have the following relations:

$$\frac{d(m_s C_P^S T + \bar{X} m_s C_P^W T)}{dt} = h A_p (T_\infty - T) + m_s \frac{d\bar{X}}{dt} \lambda \quad (8)$$

$$m_s C_P^S \frac{dT}{dt} + m_s C_P^W \frac{d(\bar{X}T)}{dt} = h A_p (T_\infty - T) + m_s \frac{d\bar{X}}{dt} \lambda \quad (9)$$

$$m_s C_P^S \frac{dT}{dt} + m_s C_P^W (T \frac{d\bar{X}}{dt} + \bar{X} \frac{dT}{dt}) = h A_p (T_\infty - T) + m_s \frac{d\bar{X}}{dt} \lambda \quad (10)$$

$$m_s (C_P^S + \bar{X} C_P^W) \frac{dT}{dt} = -T \left(m_s C_P^W \frac{d\bar{X}}{dt} \right) + m_s \frac{d\bar{X}}{dt} \lambda + h A_p T_\infty \quad (11)$$

$$\frac{dT}{dt} = \frac{m_s \frac{d\bar{X}}{dt} \lambda + h A_p T_\infty}{m_s (C_P^S + \bar{X} C_P^W)} - T \frac{m_s C_P^W \frac{d\bar{X}}{dt}}{m_s (C_P^S + \bar{X} C_P^W)} \quad (12)$$

assumed that the above This equation is differential equation of surface temperature of sample during drying. It is relationships sample temperature is uniform everywhere as a function of time.

Method of preparing green tea leaves samples and Thermodynamic Properties

Green tea leaves was selected from the tea gardens located in the city of Roudsar in Guilan with latitude and longitude 50.26 and 37.12, respectively and the leaves of the same size and shape as the homogeneity of the samples selected and then placed into plastic packages and was maintained for 24 hours in the refrigerator at 4 ° C, because moisture content in the samples to be homogeneous. Average moisture content of the tea at dry basis was 2.2. After removing the samples from the refrigerator to reach the ambient temperature, they were put in the dryer that was built for this purpose. The dryer which is used, composed of four main parts: 1- Fan that sucked air from the environment with maximum speed 5.3 $\frac{m}{s}$ leading into a electric heating. 2- Electric heaters, including heating elements with 3000 watts of power and can produce warm air up to 200 ° C. 3- The temperature controller is the heart of the system and holds inlet air temperature substrate steady at desired value with an accuracy of 1.0 ± °C and also have the capability to switch and installation of thermocouples to display temperature in other parts of the bed. 4- Dryer which is made of a cylindrical glass with 7.8 cm diameter and has a hole in the middle that can be used to control the temperature in the bed. Samples were placed inside the dryer so that in each experiment, a sample was hung in dryer with rope freely and the weight of the cotton and leaves was recorded separately and was left inside of the dryer freely. In each condition experiments were carried out on at least three samples and average of data were considered as the experimental data.

Some physical properties of samples and input gas are provided in table 1.

Table 1: Physical and thermal properties of tea leaf and the air

Property (unit)	equation	References
Latent heat ($\frac{Kj}{Kg}$)	$\lambda = 2501.3 - 2.301T(°C) - 0.00142T^2(°C)^2$	[10]
Specific heat, water($\frac{Kj}{Kg.K}$)	$C_p^w = 4.1762 - 9.0862 * 10^{-5}T + 5.4731 * 10^{-6}T^2$	[11]
Specific heat of tea($\frac{Kj}{Kg.K}$)	$C_p^{st} = 1.00926 - 0.0040403T + 6.1759 * 10^{-4}T^2$	[12]
Water activity of water at the surface of tea leaves	$x = \left(-\frac{\ln(1-A_w)}{A}\right)^{\frac{1}{B}}$	[13]
Saturation pressure (Kpa)	$P_{sat} = \exp\left(53.53 - \frac{6834.27}{T_{abs}} - 5.169\ln(T_{abs})\right)$	[14]
Specific gravity of air ($\frac{Kg}{m^3}$)	$\rho_{air} = \frac{101.325}{(0.287\,T_{abs})}$	[15]

Error Estimation in Modeling Process

In order to investigate the simple and interactive effects of process in different thermal conditions and speed and processing curves, various statistical parameters such as the correlation coefficient (R^2) and root mean square error (RMSE) were used as follows:

$$RMSE = \sqrt{\frac{1}{N}\sum_{i=0}^{N}(\bar{C}(i)_{Exp} - \bar{C}(i)_{predicted})^2} \tag{13}$$

$$R^2 = 1 - \sqrt{\frac{\sum_{i=1}^{N}(\bar{C}(i)_{Exp} - \bar{C}(i)predicted)^2}{\sum_{i=1}^{N}(\bar{C}(i)_{Exp} - \bar{C}_m)^2}} \tag{14}$$

In order to evaluate the deviation of the results of the proposed model to experimental data, percent relative error between the predictions of polynomial approximation method and experimental data and also accurate analytical predictions and experimental data, the following equation were used:

$$E(t) = 100 \times \left|\frac{\bar{C}(t)_{Exp} - \bar{C}(t)_{predicted}}{\bar{C}(t)_{Exp}}\right| \tag{15}$$

That mean relative error in total operating range is as follows:

$$MRE = \bar{E} = \frac{1}{N}\sum_{i=0}^{N} E_i \tag{16}$$

Where N is the number of time slots during the entire process over time. Software used for data analysis was MATLAB and Cftool toolbox.

RESULTS AND DISCUSSION

At first heat transfer coefficient obtained for different geometric shapes, and after calculating D_e , investigating the model and its experimental data have been done.

Calculating diffusivity coefficient of moisture in green tea leaf

In order to calculate the diffusivity coefficient of moisture of tea leaf, the green tea leaf must be firstly placed in the dryer individually and dried at different temperatures and its moisture changes is achieved during drying.

X values used in all calculations individually are the average moisture of measured samples.

The (17) equation is used to calculate diffusivity coefficient. Thus, by using the first five series of Fick's second law, we can calculate the value of De.

$$\frac{\bar{X}-X_e}{X_0-X_e}=\frac{8}{\pi^2}(exp\left(\frac{-\pi^2}{4s^2}D_e t\right)+\frac{1}{9}exp\left(\frac{-9\pi^2}{4s^2}D_e t\right)+\frac{1}{25}exp\left(\frac{-25\pi^2}{4s^2}D_e t\right)+\frac{1}{49}exp\left(\frac{-49\pi^2}{4s^2}D_e t\right)+\frac{1}{81}exp\left(\frac{-81\pi^2}{4s^2}D_e t\right) \tag{17}$$

Calculations of curve fitting and regression analysis of nonlinear equations are done by code written in MATLAB and Curve fitting toolbox. It should be noted that the diffusivity coefficients including the first five series used in Fick's second law and drawing charts of $Ln\frac{\bar{X}-X_e}{X_0-X_e}$ are obtained on the basis of t.

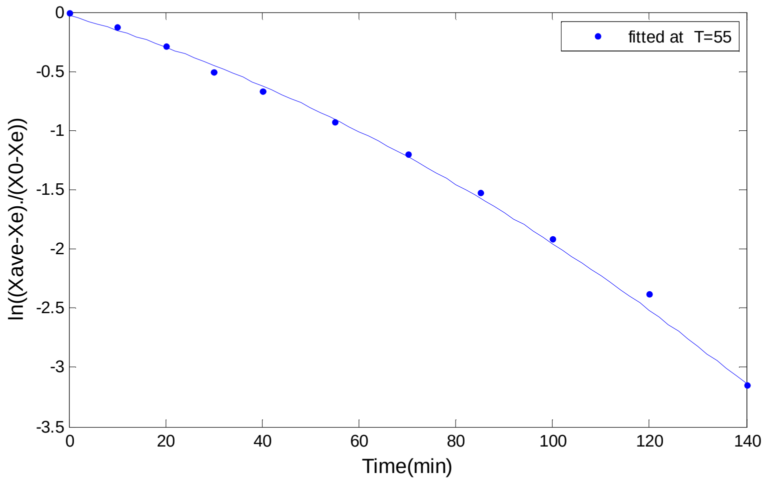

Fig. 1: Changes on the bases of $Ln\frac{\bar{X}-X_e}{X_0-X_e}$ for calculating diffusivity coefficient by using a first five series sentence at 55 °C

The values of De at different temperatures are as follows:

Table 2: diffusivity coefficient values obtained at different temperatures by using five series sentence

Temperature (°C)	Diffusivity coefficient($\frac{m^2}{sec}$)
35	1.9321×10^{-11}
45	3.1456×10^{-11}
55	5.5267×10^{-11}

The data presented in table 2 can be expressed by nonlinear regression of MATLAB software by using following equation:

$$D_e=1.14\times10^{-14}\,T^{2.132}-4.363\times10^{-12} \tag{18}$$

calculating convective heat transfer coefficient

Because of the uncertainty of the convective heat transfer coefficient of green tea leaf, the value of h must calculate firstly. For this purpose, a sheet of copper with specified percent of purity is made in the form of green tea leaf. The bottom of the leaf should be made in a way so that it can be connected to the thermocouple and can measure the temperature changes of the pieces with time. The calculation of biot's number confirms the assumption of using compact heat capacity analysis (Bi<0.1) and shows the accuracy of calculations. By using this information, we can calculate the Convective heat transfer coefficient of green tea leaf. Figure 2 shows the changes of $Ln\frac{\bar{X}-X_e}{X_0-X_e}$ in time for the copper blade at 45 degree and the speed of 0.7 m / s. In the case of blade, the number of 0.0009 is obtained.

By analyzing compact heat capacity and assuming uniform temperature in the piece of copper [16], the temperature changes of copper with the air can be obtained by using following equitation:

$$T-T_{air} / T_i - T_{air} = \exp(t/\tau), \quad \tau = mc/hA \tag{19}$$

$$T-T_{air} / T_i - T_{air} = \exp(-hA/mc \ {*}t) \tag{20}$$

Where h is the convective heat transfer coefficient, c is the heat capacity of copper, m and A are respectively the mass and surface area of copper which is made in the form of leaf, T_{air} is the air temperature, T_i is input temperature, and T is different measured temperatures.

In order to obtain the value of h, if the logarithm is calculated from two sides, the following equation will be achieved:

$$Ln(T-T_{air} / T_i - T_{air}) = -hA/mc \ {*}t \tag{21}$$

The above equation shows that if we draw $Ln\frac{\bar{X}-X_e}{X_0-X_e}$ based on t, the resulting line gradient is equal to $\frac{-hA}{mc}$. So the value of h is equal to:

$$slope = \frac{-hA}{mc} \Rightarrow h = \frac{slope \times mc}{-A} \tag{22}$$

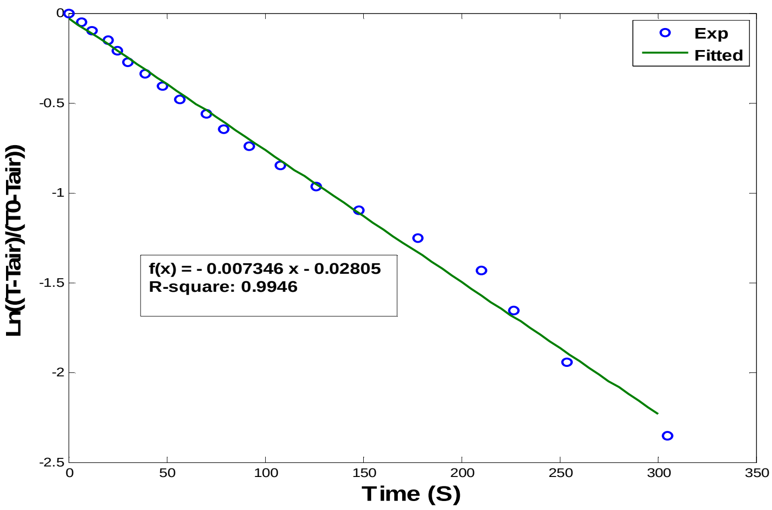

Fig. 2: Chart ln($T-T_{air} / T_i - T_{air}$) of changes based on time to calculate convective heat transfer of copper blade with the speed of 0.7 m / s and at 45 (^{o}C)

If we put the unknown values as well as the slope obtained from drawing chart in the slope= $\frac{-hA}{mc}$equation, the value of h at the speed of 0.7 m / s is equal to: h=131.4 $\frac{w}{k.m^2}$ .Also, for copper blade in the air at a speed of 5.0 meters per second, convective heat transfer coefficient values are obtained as 90.5 .

The value of *h* with an error for the blade is shown in Table 3.

Table 3: Obtained values of convective heat transfer coefficient for blade in different conditions

$v_{air}(\frac{m}{s})$	0.5	0.7
h $(\frac{w}{m^2k})$	90.5	131.5
R^2	0.993	0.994
RMSE	0.021	0.05

Moisture Investigation

After calculating the heat and mass transfer coefficients and effective diffusion coefficient of moisture in tea, the values were used in the model and the results of the model were compared with experimental data. Figure 3 shows variation of moisture content versus time for tea. The results indicated an acceptable fit with the experimental values of moisture and model, thus validated the proposed model. Figure shows that tea drying in all period of the drying of was performed at falling rate zone where indicates the internal moisture diffusion of sample controls the drying. The mean relative error (MRE) between experimental data and model For tea at air temperatures of 35, 45 and 55 ° C was 1.9, 4.7 and 10.2. Low and acceptable levels of errors indicate reliability and validity of the proposed model. Error rate increased that with increasing diameter of the model prediction accuracy will be reduced thus the proposed model is accurate for objects with small diameter or thickness. Figure 4, shows the effect of velocity (flow) of drying gas on the drying rate and drying curve. Figure shows that although increased air velocity resulting in increased heat and mass transfer coefficients, but the velocity increase did not noticeable effect on the drying. This was confirmed the fact that controlling mechanisms of drying foods such as tea related the moisture within the samples.

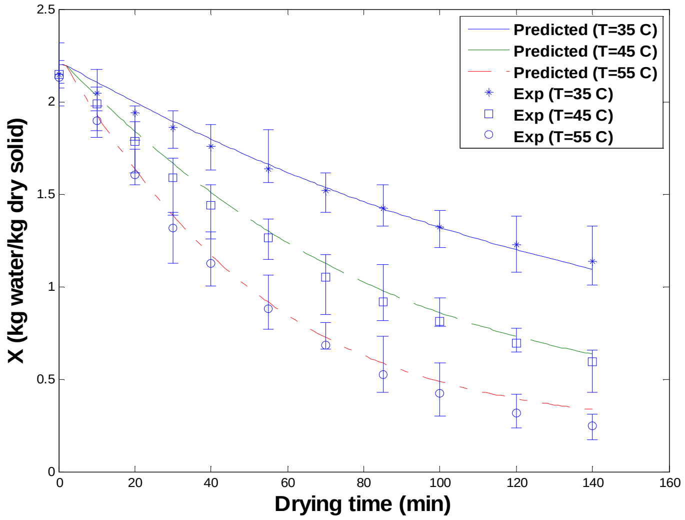

Fig. 3: variation of moisture content for green tea leaves at 0.7 m/s gas velocity and at different temperatures

Surface temperature investigation

The values of samples' surface temperature are shown at three temperatures. Figure 5 shows the temperature variations of tea with time. Figure show the temperature predicted by the model matched the experimental temperature measured at the surface of the material. The mean relative error (MRE) between the experimental data and the results predicted by the model for tea at temperatures of 35, 45 and 55 degrees Celsius was equal to 2.3, 2.8 and 4. Figure show that tea leaves according to the thickness of the sample rapidly reached up gas temperature. More matching between model and experimental data for green tea because of low thickness of leaves and assuming a uniform temperature at all surface of samples

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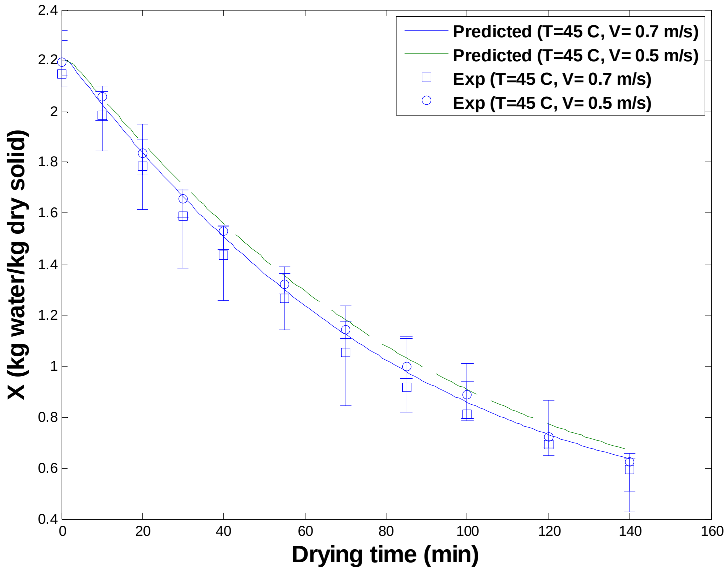

Fig. 4: The effect of gas velocity on the drying curve of green tea leaves drying at 45 ° C

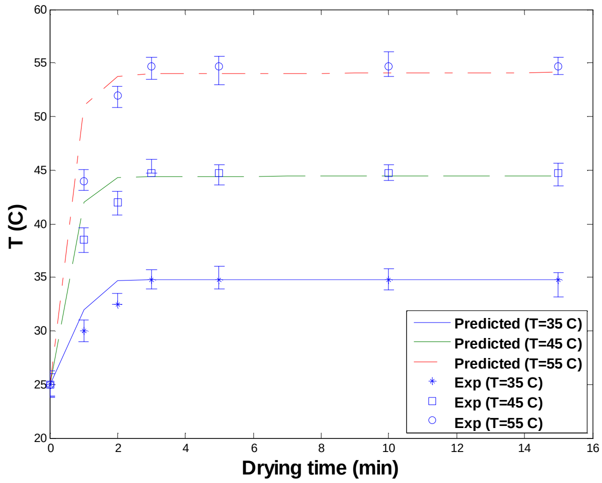

Fig. 5: Comparison between predicted temperatures by the model with experimental data for green tea leaves drying with a velocity of 0.7 m/s and different temperatures

CONCLUSION

Laboratory data shows that during the drying process, drying rate is not constant and drying has been dropping from the beginning. This means that immediately after the particles are exposed to air due to low external resistance against heat and mass transfer, surface moisture of particles will be excreted quickly. After the drying process is completed in time, moisture disposal reduced significantly. This process suggests that for this type of material, the primary rate of drying is high and after some time, due to the emergence of a layer of dry (low humidity outside), the rate of drying reduced very quickly. According to curves it was observed that the thermodynamic model for objects with low thickness will be closely predicted for both surface temperature and moisture content of sample, but for thick samples there was difference between the predicted and experimental moisture content. It was observed that drying rate was independent or low dependent of flow rate because by the change of velocity, the values of h increase and its effect is not so much in the equation.

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