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# The ultrasonic-assisted drying modeled using the reaction engineering approach (REA)

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## Abstract

Drying is a simultaneous heat and mass transfer process which involves significant energy consumption. For sustainable processing practice, ultrasonic-assisted drying is often implemented. In order to assist in process design and optimization, a physically-meaningful drying model is useful. The REA (reaction engineering approach), which has been shown to be accurate to model several challenging drying cases, is implemented here to model the ultrasonic-assisted drying with various intensities. The relative activation energy ($\Delta E_{v,b}$) generated from one accurate drying experiment is used to model the ultrasound-assisted drying with various intensities. The results of modeling match very well with the experimental data. The REA is accurate to model the ultrasonic-assisted drying under various intensities (i.e. 8, 12, 21, 29 and 31 kW/m$^3$). The mechanisms of ultrasonic-assisted drying can be explained well by the REA. A landmark for process intensification of drying process has been set up by the REA. The model can be readily adopted in industrial settings for process design and optimization.

***Keywords:*** *reaction engineering approach (REA), modeling, ultrasonic-assisted drying*

## Introduction

Drying model is useful for assisting in process design and maintaining product quality during drying. The useful model is the one which can capture the physics of drying process, require minimum sets of experiments to generate the parameters and offer simplicity in mathematical modeling and solution. For ultrasonic-assisted drying, several models have been implemented to describe the process (Garcia-Perez et al, 2007; 2009; 2011; Ortuno et al, 2010; Schossler et al, 2012). Most of the modeling implemented diffusion-based model to model the ultrasonic-assisted drying Garcia-Perez et al, 2007; 2009; 2011; Ortuno et al, 2010; Schossler et al, 2012). Crank-diffusion-based model was implemented by several researchers (Garcia-Perez et al, 2007; 2009; 2011; Schossler et al, 2012). However, this model is valid only for isothermal, negligible shrinkage and negligible external resistance (Crank, 1975; Seth and Sarkar, 2004; Doymaz, 2008; Vega-Galvez et al, 2008). The effective-diffusion model was applied by Ortuno et al (2010) and Garcia-Perez et al (2011). The model was shown to model the ultrasonic-assisted drying reasonably well but the model requires several sets of experiments followed by non-linear optimization to generate the diffusivity function (Ortuno et al, 2010; Garcia-Perez et al, 2011).
The reaction engineering approach (REA) is simple drying model proposed by X.D. Chen in 1996 and implemented in various drying systems. The REA takes advantages of simplicity, minimum number of experiments to generate the parameters and accuracy (Chen and Xie, 1997; Chen, 2008). The reaction engineering approach (REA) was applied to describe convective drying of thin layer of food materials and it was proven to be accurate and robust (Chen, Pirini, Ozilgen, 2001; Chen and Lin, 2005). The application of the REA has also been shown to be useful for non-food materials (Putranto et al, 2010[a,b]). Indeed, the REA has been proven to be able to model the cyclic drying of food materials and non-food materials well (Putranto et al, 2010[b], Putranto, et al, 2011[b-d]). The REA has also been revealed to be accurate to model the heat treatment of wood which is essentially a drying process under linearly-increased gas temperature (Putranto et al, 2011[e]). Similarly, the REA has been shown to describe baking and roasting very well (Putranto et al, 2011[f]; Putranto and Chen, 2012).

Due to the complex phenomena of ultrasonic-assisted drying, it is worthwhile to implement the REA to describe the process and apply the model to evaluate the mechanisms of ultrasound-assisted drying. Although the REA has been shown to model several challenging drying cases very well, it may be a challenge for the REA to model ultrasonic-assisted drying since the process is relatively complex. This study is aimed to investigate and assess the applicability of the REA to model the ultrasonic-assisted drying as well as use the REA to study the mechanisms of ultrasonic-assisted drying. The outline of the paper is as follows: the REA is briefly introduced followed by the brief review of the experimental details. The results of modeling and the mechanisms of ultrasonic-assisted drying are discussed subsequently.

**Review of the reaction engineering approach**

The general REA is an application of chemical reaction engineering principles to model drying kinetics which was firstly reported in 1996-1997 (Chen and Xie, 1997; Chen, 2008). A summary of the development of the REA was presented previously (Chen, 2008). Generally, the drying rate of a material can be expressed as:

$$m_s \frac{d\overline{X}}{dt} = -h_m A(\rho_{v,s} - \rho_{v,b}) \tag{1}$$

Equation (1) is a basic mass transfer equation. The mass transfer coefficient ($h_m$) is determined based on the established Sherwood number correlations for the geometry and flow condition of concern or established experimentally for the specific drying conditions involved. The surface vapor concentration ($\rho_{v,s}$) is then scaled against saturated vapor concentration ($\rho_{v,sat}$) using the following equation (Chen and Xie, 1997; Chen, 2008):

$$\rho_{v,s} = \exp\left(\frac{-\Delta E_v}{RT_s}\right)\rho_{v,sat}(T_s) \tag{2}$$

where $\Delta E_v$ represents the additional difficulty to remove moisture from the material beyond the free water effect. This $\Delta E_v$ is moisture content ($X$) dependent. $T_s$ is the surface temperature of the material being dried (K) and $\rho_{v,sat}$ for water vapor can be estimated by:

$$\rho_{v,sat} = 4.844\times10^{-9}(T_s-273)^4 - 1.4807\times10^{-7}(T_s-273)^3 + 2.6572\times10^{-5}(T_s-273)^2 - 4.8613\times10^{-5}(T_s-273) + 8.342\times10^{-3} \tag{3}$$

based on the summarized data (Keey, 1992) where $T_s$ is the surface sample temperature (K) used in equation (2). When material is ‘thermally’ thin, the surface temperature is the same as the sample temperature (Chen and Peng, 2005).

The mass balance (equation 1) is then neatly expressed as:

$$m_s \frac{d\overline{X}}{dt} = -h_m A\left[\exp\left(\frac{-\Delta E_v}{RT_s}\right)\rho_{v,sat}(T_s) - \rho_{v,b}\right] \tag{4}$$

From equation (4), it can be observed that the REA is expressed in the first order ordinary differential equation with respect to time and the model may be called L-REA (lumped reaction engineering approach). The REA does not assume uniform moisture content but it evaluates average moisture content of the samples during drying.

The activation energy ($\Delta E_v$) is determined experimentally by placing the parameters required for equation (4) in its rearranged form:

$$\Delta E_v = -RT_s \ln\left[\frac{-m_s \frac{d\overline{X}}{dt}\frac{1}{h_m A} + \rho_{v,b}}{\rho_{v,sat}}\right] \tag{5}$$

where *dX/dt*, average moisture content, surface area and temperature is experimentally determined. The dependence of activation energy on moisture content on a dry basis ($X$) can be normalized as:

$$\frac{\Delta E_v}{\Delta E_{v,b}} = f\left(\overline{X} - \overline{X}_b\right) \tag{6}$$

where $f$ is a function of water content difference, $\Delta E_{v,b}$ is the ‘equilibrium’ activation energy representing the maximum $\Delta E_v$ under the relative humidity and temperature of the drying air:

$$\Delta E_{v,b} = -RT_b \ln\left(RH_b\right) \tag{7}$$

$RH_b$ is the relative humidity of drying air and $T_b$ is the drying air temperature (K).

In order to generate the relative activation energy ($\Delta E_v/\Delta E_{v,b}$) shown by equation (6), the activation energy ($\Delta E_v$) is evaluated by equation (5) from one accurate drying experiment. The activation energy is divided by the equilibrium activation energy ($\Delta E_{v,b}$) indicated by equation (7) to yield the relative activation energy during drying.

For similar drying condition and initial water content, it is possible to obtain the necessary REA parameters (apart from the equilibrium isotherm), expressed in the relative activation energy ($\Delta E_v/\Delta E_{v,b}$) as indicated in equation (6), in one accurate drying experiment. The relative activation energy ($\Delta E_v/\Delta E_{v,b}$) generated can then be implemented to other drying conditions provided same material and similar initial moisture content since the relative activation energy would collapse to the similar profile (Chen, 2008).

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**Review of experimental details**

The meaningful experimental data for study of ultrasound-assisted drying is derived from the previous published work of Garcia-Perez et al (2009). For better understanding of the modeling implemented here, the experimental details of Garcia-Perez et al (2009) are reviewed briefly here. The raw materials of lemon were obtained from Javea, Spain in the end stage of ripeness. The lemon-peel was separated from the pulp by hand and the samples of lemon-peel were cut into slabs with thickness of 7 mm (Garcia-Perez et al, 2009). The convective dryer equipped by the ultrasound power generator was used to study the drying kinetics of lemon-peel. The details of the equipment were presented previously (Garcia-Perez et al, 2006). The ultrasonic generator produced a high intensity ultrasonic field and reached an average sound pressure level of 154.3 dB. The digital power meter was used to monitor the voltage, intensity, power, phase and frequency of the electric signal (Garcia-Perez et al, 2009). Convective drying experiments were conducted at drying air temperature of 40 °C and air velocity of 1 $m.s^{-1}$. For ultrasonic-assisted drying, various levels of energy were applied to give various power densities. This was conducted by adjusting several electric powers to the ultrasonic transducer. The load density of lemon-peel of 36 $kg.m^{-3}$ was used for the experiments. During drying, the air velocity and temperature were controlled by a PID controller and the weight of the samples was monitored by a balance wired to the sample load chamber (Garcia-Perez et al, 2009).

**Mathematical modeling**

In order to model the convective and ultrasonic-assisted drying of lemon-peel using the reaction engineering approach (REA), the relative activation energy ($\Delta E_v/\Delta E_{v,b}$) is generated from one accurate drying experiment which is the convective drying of lemon-peel at drying air temperature of 40 °C. The activation energy during drying is evaluated using equation (5) and divided with the equilibrium activation energy represented in equation (7) to yield the relative activation energy as mentioned in equation (6). The relationship between the relative activation energy and average moisture content can be represented by simple mathematical equation obtained by least square method using Microsoft Excel® (Microsoft Corp, 2011). The relative activation energy can be represented as:

$$\frac{\Delta E_v}{\Delta E_{v,b}} = \left[1 - 0.217(X - X_b)^{0.881}\right]\exp\left[0.163(X - X_b)^{0.322}\right] \qquad (8)$$

The good fit of the relative activation energy is shown in Figure 1 ($R^2$ of 0.998). The format of equation (8) can be varied but in this case equation (8) seems to be sufficient to describe the relative activation energy of drying of lemon-peel.

The heat balance of convective drying of lemon-peel can be expressed as:

$$\frac{d\left[m_s(1+X)C_pT\right]}{dt} \approx hA(T_b - T) + m_s\frac{dX}{dt}\Delta H_v \qquad (9)$$

where $m_s$ is sample mass (kg), $C_p$ is the heat capacity of the sample ($J.kg^{-1}.K^{-1}$), $T$ is the temperature of the sample (K), $h$ is the heat transfer coefficient ($W.m^{-2}.K^{-1}$), $\Delta H_v$ is vaporization heat of water ($J.kg^{-1}$), $T_b$ is the gas temperature (K). The drying rate $dX/dt$ is negative when drying occurs.

while the heat balance of the ultrasound-assisted drying of lemon-peel can be written as:

$$\frac{d\left[m_s(1+X)C_pT\right]}{dt} \approx P + hA(T_b - T) + m_s\frac{dX}{dt}\Delta H_v \qquad (10)$$

where $P$ is the ultrasonic power received by the sample (W).

In order to yield the profiles of moisture content and temperature during convective drying of lemon-peel, the mass balance implementing the REA shown in equation (4) is solved simultaneously with the equilibrium activation energy, relative activation energy and heat balance shown in equations (7), (8) and (9) respectively. The ordinary differential solver *ode23s* available in Matlab® (Mathworks Inc, 2012) is used to solve these equations simultaneously. Similarly, for ultrasound-assisted drying, the mass balance implementing the REA, equilibrium activation energy and heat balance presented in equations (4), (7), (8) and (9) are solved simultaneously using *ode23s* available in Matlab® (Mathworks Inc, 2012). The results of the modeling are validated against the experimental data of convective and ultrasonic-assisted drying from the previous published work of Garcia-Perez et al (2009).

**Results and Discussion**

Results of modeling using the REA are shown in Figures 1 to 4. Figures 1 and 2 present the results of modeling of convective drying and ultrasonic-assisted drying at intensity of 4 $kW.m^{-3}$ using the REA. A good agreement between the predicted and experimental data is observed. Table 1 indicates that the good agreement is supported by $R^2$ of higher than 0.995 and *RMSE* lower than 0.086. In addition, the profiles of temperature during

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drying are shown in Figure 2. Compared to the diffusion-based modeling implemented by Garcia-Perez et al (2009), the REA yields advantages of generating temperature profiles during drying; not shown by the other model.

The results of implementation of the REA for ultrasonic-assisted drying at intensity of 8 and 12 kW.m$^{-3}$ are presented in Figures 3 and 4. Figure 3 shows the profiles of moisture content during drying. The REA describes the profiles of moisture content during drying very well. The good agreement is indicated by $R^2$ of higher than 0.996 and *RMSE* lower than 0.071 (refer to Table 1). Figure 4 reveals the profiles of temperature during drying. Again, the REA yields the advantages of generating the temperature profiles during drying; not shown by the modeling applied by Garcia-Perez et al (2009). The REA can model the ultrasonic-assisted drying with intensity of 8 and 12 kW.m$^{-3}$ well.

It has been shown that the REA models the convective and ultrasonic-assisted drying of lemon-peel very well. The relative activation energy generated from one accurate convective drying can be used for modeling of ultrasonic-assisted drying at various intensities. The accuracy of the REA could be because of applicability of the relative activation energy to capture the physics of ultrasonic-assisted drying. Ultrasound wave implemented may alter the internal and external resistance of mass and heat transfer (Scarborough et al, 2006). The ultrasound was postulated to cause "sponge effect" i.e. expansion and compression in the material which facilitates water removal (Garcia-Perez et al, 2007). Application of ultrasonic wave resulted in change of microstructure at the surface and inside the materials. At the surface, the pores were obstructed by wax component scattering (Ortuno et al, 2010) and the ultrasonic wave may result in pressure variation, oscillation and microstreaming which reduces the thickness of boundary layer (Gallego-Juarez et al, 1999). Inside the materials, the ultrasound wave was shown to make the cellular structure were more compressed and destroyed with large air intercellular spaces (Ortuno et al, 2010).

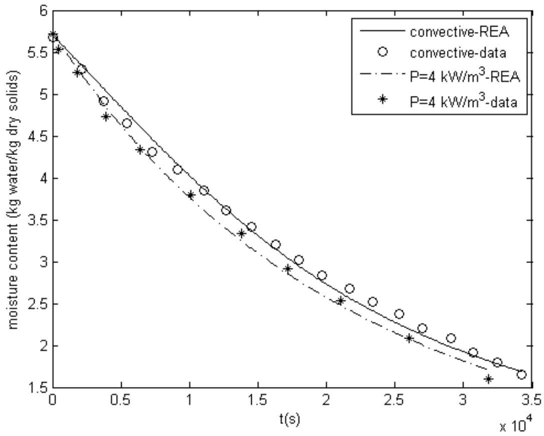


**Figure 1. Profiles of moisture content of convective drying at drying air temperature of 40 °C and ultrasonic-assisted drying at intensity of 4 kW.m$^{-3}$**

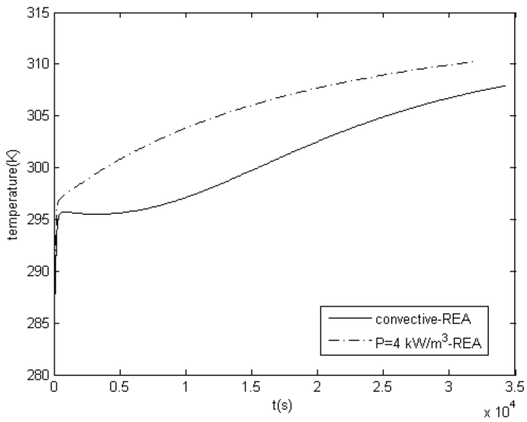


**Figure 2. Profiles of temperature of convective drying at drying air temperature of 40 °C and ultrasonic-assisted drying at intensity of 4 kW.m$^{-3}$**

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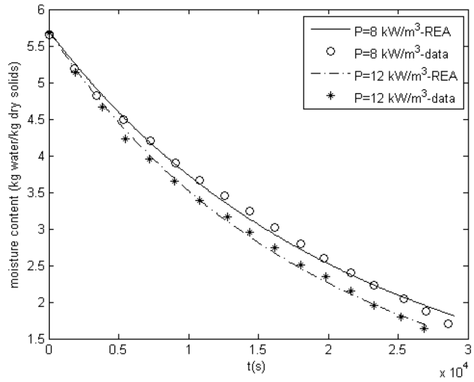


**Figure 3. Profiles of moisture content of ultrasonic-assisted drying at intensity of 8 and 12 kW.m$^{-3}$**

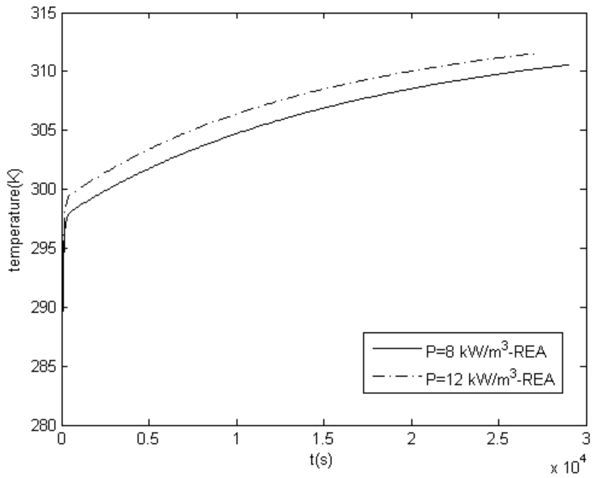


**Figure 4. Profiles of temperature of ultrasonic-assisted drying at intensity of 8 and 12 kW.m$^{-3}$**

It can be said that the REA is accurate to model the ultrasonic-assisted drying. While the results are accurate, the modeling itself is still simple and requires minimum number of experiments for generate the drying parameters. It can also explain the mechanisms of ultrasonic-assisted drying well. This has extended the application of the REA significantly and revealed that the REA can be used to explain the physics of ultrasound-assisted drying. It has followed the accuracy of the REA to several challenging cases of drying, baking and roasting as well as the ability of the REA to explain the physics of these processes (Putranto et al, 2010[a,b]; Putranto et al, 2010[a-f]; Putranto and Chen, 2012).

## Conclusion

In this study, the REA is applied to model the ultrasonic-assisted drying at various intensities. The relative activation energy is generated from one accurate drying experiment is implemented to describe the change of internal behavior inside the materials during ultrasound-assisted drying at various intensities. The results of modeling match well with the experimental data. The REA is accurate to model the ultrasound-assisted drying. The REA can model the ultrasound-assisted drying very well. The mechanisms of ultrasonic-assisted drying can be explained well also by the REA. While the results are accurate, the modeling is still simple. Another significant landmark of the REA on process intensification of drying has been shown here.

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