Measuring REA-based drying kinetics through temperature-moisture content relationship

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Abstract

The reaction engineering approach (REA) has been proposed and implemented for modeling a number of challenging drying cases. While the modeling is simple and accurate, it is effective to generate the drying parameters. The relative activation energy is the fingerprint of the REA which describes the changes of internal behaviors inside the materials during drying. In this paper, a new method, based on combined heat and mass balance, is proposed and implemented to retrieve the relative activation energy of flat materials. The results indicate that the new approach can be used to retrieve well the activation energy of flat materials. The relative activation energy retrieved by the new approach is independent on the external drying conditions. This new approach can also potentially be used to evaluate the change of surface area of materials during drying

Keywords: reaction engineering approach (REA); modeling; relative activation energy; mass transfer;, heat transfer.

1. Introduction

The reaction engineering approach (REA) is a 'middle path' approach to model drying in which the changes of material structure during drying is encapsulated in the relative activation energy. It has been successfully applied to model a number of challenging drying cases including intermittent drying, infared-heating drying and microwave drying [1]. While the modeling is accurate, it has been found that the REA is effective in terms of generating the drying parameters. The relative activation energy calculated based on one accurate drying run can basically be used to project drying at other conditions since the relative activation energy is independent on the drying conditions. The relative activation energy of different drying conditions would collapse to the similar profiles [2]. In these studies, the activation energy is retrieved based on the mass balance where measurements of surface area, temperature and surface area of materials being drying are required.

In this study, for the first time, a new approach based on combined heat and mass balance is proposed and implemented for retrieving the activation energy of flat materials. The study is aimed to evaluate the applicability of the new approach to generate the relative activation energy as well as assess its applicability to mode drying kinetics of flat materials. Initially, the reaction engineering approach is reviewed briefly followed up by the proposal of new approach and applications of the new approach for generating the relative activation energy and modeling of drying of flat materials.

2. Materials and Methods

The reaction engineering approach (REA) was first proposed as a lumped parameter model where the drying rate (flux multiplied by surface area) of the moist materials can be expressed as the following:

$$m_s \frac{d\bar{X}}{dt} = -N_c A = -h_m A \left(\rho_{v,s} - \rho_{v,\infty} \right) \tag{1}$$

Equation (1) is basically correct for all cases where water leaves solid in vapor form. Even in the case of the lumped approach, there is no assumption of uniform moisture content in this REA approach. It was characterized with the mean moisture content.

The surface vapor concentration ($\rho_{v,s}$) can be correlated in terms of saturated vapor concentration of water ($\rho_{v,sat}$) by the surface relative humidity (RH_s) in the following equation [3]:

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

One can see that the surface *RH* is represented in an *Arrhenius* form. *ΔE$_v$* represents the increasing difficulty to remove moisture from materials as moisture content reduces (in

addition to the free water effect). Being a semi-empirical model, ΔE_v is ideally to be the mean moisture content ($\overline{X}$) dependent. T_s is the surface temperature of the material being dried (K). For a small temperature range say from 0°C to just over 100°C, $\rho_{v,sat}$ (kg.m⁻³) can in fact be approximated with the following equation [3]:

$$\rho_{v,sat}(T) = K_v \exp\left(-\frac{E_v}{RT}\right)$$ (3)

The approach of the activation process for moisture removal is thus claimed. On the other hand, condensation is a kind of precipitation process thus is not an activation process. The activation energy of the pure water evaporation reaction is equivalent to the value of the latent heat of water evaporation, which is also in line with the classical physical chemistry.

By using the REA, equation (1) can be expressed as:

$$m_s \frac{d\overline{X}}{dt} = -h_m A\left(\exp\left(\frac{-\Delta E_v}{RT}\right)\rho_{v,sat}(T_s) - \rho_{v,\infty}\right)$$ (4)

Noting that the above equation has a parameter that is the surface temperature (T_s) for the moist porous material being dried, it can be troublesome to measure under certain circumstances.

It has been found, based on many previous practical experiences of using the REA approach, that drying experiments for generating the REA parameters need to be conducted where the air (or gas) humidity is very low in order to cover the widest possible range of ΔE_v versus $\overline{X}$.

The dependence of the additional activation energy on moisture content can then be normalized as:

$$\frac{\Delta E_v}{\Delta E_{v,\infty}} = \zeta(X - X_\infty)$$ (5)

where ζ is a function of moisture content difference (the current moisture content less the final equilibrium one), $\Delta E_{v,\infty}$ is the maximum when the moisture concentration of the sample approaches relative humidity and, for convective drying, the temperature of the drying air (gas):

$$\Delta E_{v,\infty} = -RT_\infty \ln(RH_\infty)$$ (6)

$X\infty$ is the equilibrium moisture content corresponding to $RH\infty$ and $T\infty$, which can be related to one another using the equilibrium isotherm. It is noted again that so far the experiments for gaining the relevant equation (7) has to be under the very dry condition so the final water content attained in experiments is usually fairy small.

For convective drying, the lumped energy balance can be represented as:

$$mC_p \frac{d\overline{T}}{dt} = hA\left(T_\infty - \overline{T}\right) + H_{drying}m_s \frac{d\overline{X}}{dt}$$ (7)

The relative activation energy is usually found by rearranging equation (4) into:

$$\Delta E_v = -R\overline{T}\ln\left[\frac{-\dfrac{m_s\dfrac{d\overline{X}}{dt}}{h_m A} + \rho_{v,\infty}}{\rho_{v,sat}\left(\overline{T}\right)}\right]$$ (8)

If the surface area A and the mass transfer coefficient h_m are known, or measured by separated experiments, one good run of drying experiment under the same drying air (gas) condition is sufficient for establishing equation (6), which is the core of the REA approach.

Here, now, we introduce *another kind* of approach based on the temperature-moisture content relationship. The lumped energy balance can be written as:

$$m_s\left(1+\overline{X}\right)\left(C_{pw}\frac{\overline{X}}{1+\overline{X}} + C_{p,s}\frac{1}{1+\overline{X}}\right)\frac{d\overline{T}}{dt} = hA\left(T_\infty - \overline{T}\right) + H_{drying}m_s \frac{d\overline{X}}{dt}$$ (9)

On both sides, we now divide them with the rate of drying, incorporating equation (9), we can obtain:

$$\left(C_{pw}\overline{X} + C_{p,s}\right)\frac{d\overline{T}}{d\overline{X}} = -\left(\frac{h}{h_m}\right)\frac{h\left(T_\infty - \overline{T}\right)}{\exp(\dfrac{-\Delta E_v}{R\overline{T}})\rho_{v,sat}\left(\overline{T}\right) - \rho_{v,\infty}} + H_{drying}$$ (10)

For flat sample geometry and parallel flow, one may have:

$$Nu = \frac{hL}{k_f} = C\mathrm{Re}^m\mathrm{Pr}^n$$ (11)

$$Sh = \frac{h_m L}{D_f} = C\mathrm{Re}^m Sc^n$$ (12)

Combining equations (10) and (12) results in the expression of relative activation energy retrieved by the new approach:

$$\Delta E_v = -RTln\left[\frac{\frac{D_f}{k_f}\left(\frac{Pr}{Sc}\right)^n(T_b-T)}{\rho_{v,sat}(\Delta H_v-(XCp_W+Cp_s)\frac{dT}{dX}}+\frac{\rho_{v,b}}{\rho_{v,sat}}\right] \quad (14)$$

3. Results and discussion

The new method (based on equation (14)) is implemented to generate the relative activation energy of a mixture of polyvinyl alcohol (PVA) during drying at 35 and 55 ºC [4-5]. The experimental details are presented previously [4-5] and reviewed briefly here in order to better understand the modeling framework. Materials used in this experiment were a mixture of equal proportion of partially hydrolyzed polyvinyl alcohol (80 wt%) and glycerol which has 88 wt% of water. 8 mL of the mixture was poured into a 90 mm diameter of Petri dish so that the initial thickness of sample was 1.3 mm. The velocity of the drying medium was set to 1 m.s^{-1}. The experiments were undertaken at drying air temperature of 35°C and 55°C.

Figure 1 indicates the relative activation energy of polyvinyl alcohol (PVA) during drying at drying air temperature of 55 ºC. By using the new method (combined heat and mass balance, equation (14)), the relative activation energy of drying at drying air velocity of 1 and 2.8 m s^{-1} collapses to the similar profiles. As expected, similar profiles are also produced based on the calculation using the mass balance only (equation (6)). Comparing the relative activation energy retrieved using the heat and mass balance with the mass balance only indicates that the profiles are very similar. The results suggest that the new method can produce well the relative activation energy of polyvinyl alcohol at drying air temperature of 55 ºC.

Figure 2 shows the relative activation energy of polyvinyl alcohol (PVA) during drying at drying air temperature of 35 ºC. The new method generates the very similar profiles of the relative activation energy for drying at drying air velocity of 1 and 2.8 m s^{-1}. In addition, the profiles of relative activation energy generated using the combined heat and mass balance collapse to those retrieved using the mass balance only.

The relative activation energy generated by the new method can be represented as:

$$\frac{\Delta E_v}{\Delta E_{v,b}} = \exp[-1.0794(X-X_b)^{1.6874}]$$

The similar expression is also shown for the relative activation energy retrieved by the mass balance only [6]. This is also supported by the profiles of relative activation energy generated by both methods as show in Figures 1 and 2. Therefore, the expression of the relative activation energy is independent on the retrieving method.
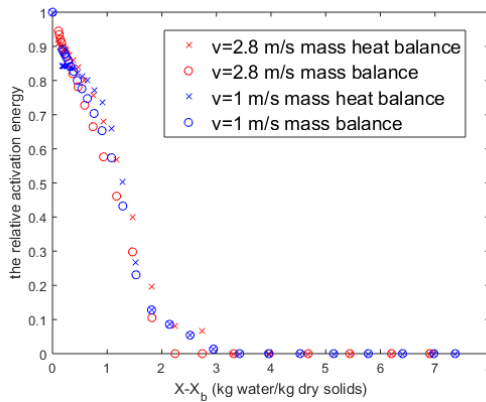
Figure 1. The relative activation energy of PVA mixture during drying at 55 ⁰C
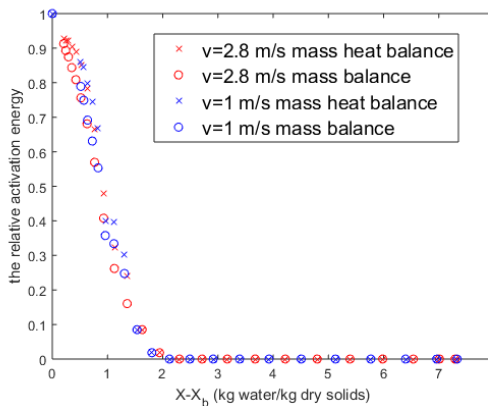

Figure 2. The relative activation energy of PVA mixture during drying at 35 ⁰C

Based on the generated relative activation energy, the new method can also be used to evaluate the change of surface area of materials during drying. Measurements of areas of materials (such as dairy droplets, fruits and leafy vegetables) can sometimes be difficult due to highly deformation during drying and irregularity of the materials. The accuracy of the measurements is needed in order to project the drying kinetics accurately. This new approach offers advantage of ability to measure the surface area during drying by combining the generated relative activation energy of specific materials with the mass balance or heat balance. Nevertheless, it is still uncertain whether the new approach can be implemented to generate the relative activation energy for spherical or cylindrical materials where the heat and mass transfer correlations are more complex.

4. Conclusions

In this study, the new approach to generate the relative activation energy of the reaction engineering approach (REA) is proposed and implemented. In the new approach, the heat

and mass balance is combined to yield the activation energy. Only a set of experimental data of moisture content and temperature during drying time is required to generate the relative activation energy. The results indicate that the new approach is applicable to retrieve the relative activation energy of flat materials. Different drying conditions result in the similar profiles of the relative activation energy. It is independent on external drying conditions which has also been highlighted for the relative activation energy retrieved using the mass balance only. The relative activation energy retrieved using combined both heat and mass balance gives the similar profiles of that evaluated based on mass balance only. Implemented in the REA, the relative activation energy evaluated by the new approach projects well the drying kinetics of flat materials.

5. Nomeclature

X	Moisture content on dry basis, kg.kg^{-1}
$\overline{X}$	Mean moisture content on dry basis, kg.kg^{-1}
N	Drying flux, kg.m^{-2}.s^{-1}
A	Surface area of single droplet or particle, m^2
Bi	*Biot* number (for heat transfer $Bi = hL/k$)
$Ch\text{-}Bi$	*Chen-Biot number*
D	Diffusivity, m^2.s^{-1}
D_v	Vapor diffusivity in air, m^2.s^{-1}
E	Activation energy, J.mol^{-1}
f	Relative drying rate function
g	Gravitational acceleration, m.s^{-2}
H_{drying}	Heat of drying/wetting, J.kg^{-1}
h	Heat transfer coefficient, W.m^{-2}K^{-1}
h_m	Mass transfer coefficient, m.s^{-1}
k	Thermal conductivity, W.m^{-1}.K^{-1}
M	Molecular weight, g.mol^{-1}
m_s	Mass of solids, kg
Nu	*Nusselt* number ($Nu = hL/k$)
Pr	*Prandtl* number
R	Ideal gas law constant
Re	*Reynolds* number ($Re = \rho uL / \mu$)
RH	Relative humidity
Sc	*Schmidt* number ($Sc = v/D$)
Sh	*Sherwood*
T	Temperature, K
t	Time, s
T_s	Surface temperature, K

T_{sat}	Adiabatic saturation temperature of drying air, K
u	Gas velocity, m.s^{-1}
X_∞	Equilibrium moisture content on dry basis, kg.kg^{-1}

Symbols

ρ	Density or concentration, kg.m^{-3}
μ	Dynamic viscosity, Pa.s
δ	Thickness, m
τ	Dimensionless time
ρ_v	Vapor concentration, kg.m^{-3}
Φ	Dimensionless water content
ς	Relative activation energy function
ξ	Relative rate of drying

6. References

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