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Drying-rate Equations of Agar Gel and Carrot based on Drying-shell Model

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(Figs. 1–4, Tables 1–3)

INTRODUCTION

Many studies [1,2] of the drying-rate equations have been performed, dividing the drying period into constant- and falling-rate periods. However, the drying phenomena of several foods are rather complicated, and we can not determine the exact critical moisture content that markes the turning point of the two periods. In order to design various drying apparatuses, it is necessary to determine an approximating drying-rate equation which could be applied to all drying periods.

In a previous paper,[3] we studied the drying-rate equations based on the drying-shell models and the calculation methods of the rate parameters in the rate equations. Then, we determined the rate parameters in the drying-rate equations of water-absorbing sponges which were considered as simply imagined fiver-foods.[4]

In the present paper, we took up the study of the drying of agar gel and carrot, and proposed drying-rate equations which could be applied in all drying periods.

EXPERIMENTAL METHODS AND RESULTS

1. Samples

As the samples in the studies of drying-rate equations, a agar gel and a carrot were used. These samples were used in the shape of the sphere. The sample of agar gel was prepared by a sphere shape mould made of bress. Powdered agar was dissolved in hot water. The dissolved agar had a concentration of 5 wt% agar. The dissolved agar was injected into the mould, and then the injected agar and the mould were cooled in ice-water to formed as a sphere shape.

The sample of carrot was prepared in a sphere shape by a razor knife. The sampe was bought at the near market, and the center part of the carrot was used as sample.

Then each sample which had been stored in 5°C water, was transfered into drying temperature water over a 30 minutes period before the sample was used. The conditions of the samples are shown in Table 1.

2. Experimental apparatus and methods

The experimental apparatus is the same as the one for the previous paper.[4] The diameter of the air flow dryer is 10.5 cm. Temperature and humidity of the air are controled automatically by two transistor relays based on the dry- and wet-bulb temperatures in the dryer.The velocity of the air is measured by use of the orifice flow meter. In present the experiments, the center temperature of the sample was measured by a C-C thermocouple of 1.6 mm diameter.

The sample was hung on a very fine wire under a chemical balance set up in the upper part of the dryer.

3. Experimental results

Table 1 illustrates the experimental conditions. The relations of the weight w (g) and the center temperature t_c(°C) of drying material vs. drying time θ (min) were measured. The relations of w (g) and t_c(°C) vs. θ (min) for the drying of agar gel and carrot are shown in Figs. 1 and 2, respectively. The solid, broken and chain lines for the w vs. θ are the calculated values as shown latter.

Table 1. Experimental conditions

Run	Samples (sphere)	Initial values Diameters D_0(cm)	Initial values Weights w_0(g)	Volumes V_0(cm^3)	Density ρ_0(g/cm^3)	Dry- and Wet-bulb temperatures t_d(°C)	t_w(°C)	Air velocity $\bar{u}$ (cm/min)
1	agar gel	1.20X1.20X1.30	0.950	0.980	0.969	40.0	25.0	3480
2	carrot	1.28X1.28X1.28	1.036	1.098	0.943	40.0	29.0	3480

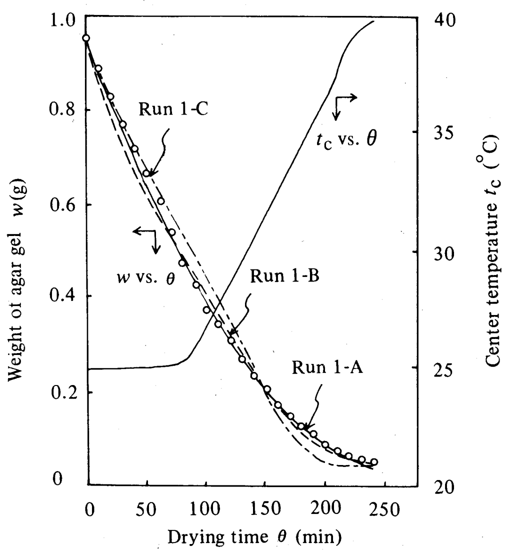

Fig. 1. Weight and center temperature of agar gel vs. drying time, t_d=40°C, t_w=25°C, $\bar{u}$=3480cm/min.

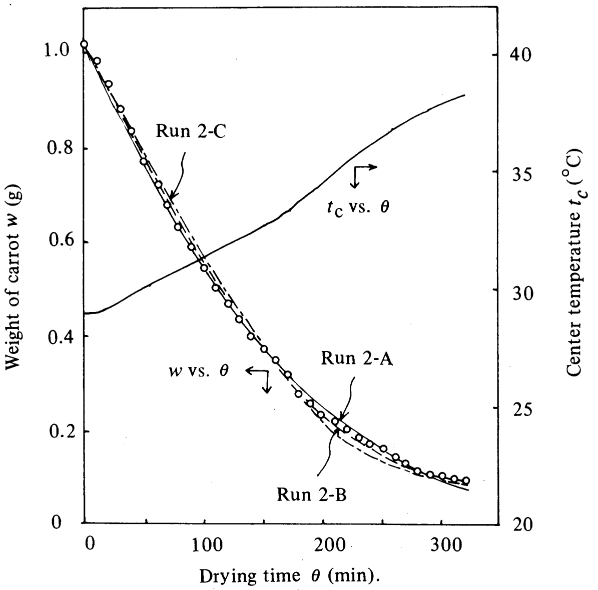

Fig. 2. Weight and center temperature of carrot vs. drying time, t_d=40°C, t_w=29.0°C, $\bar{u}$=3480cm/min.

Table 2 illustrates the experimental results which were used to calculate the rate parameters in the drying-rate equations. The weight of the equilibrium state of the sample w_e(g) was taken as being the value that kept the balance unchanged for more than 60 min. The weight of the completely drying state of the sample w_d(g) was decided as being the value that dried the equilibrium material for 2 hours at 105°C in a laboratory oven dryer.

Table 2. Experimental results

Run	Samples	Equilibrium values				Completely drying values		
		D_e (cm)	w_e(g)	V_e(cm^3)	ρ_e(g/cm^3)	w_d(g)	V_d(cm^3)	ρ_d(g/cm^3)
1	agar gel	0.392X0.761X0.761	0.0450	0.1187	0.397	0.0380	0.1187	0.320
2	carrot	0.240X0.885X0.890	0.0858	0.0990	0.867	0.0522	0.0990	0.527

Run	Vapor pressures			Humidity	Moisture concentrations		Water concentration
	P (mmHg)	P_{sd} (mmHg)	P_{sw} (mmHg)	H (g-H_2O/g-D.A.)	C_s (g-H_2O/cm^3)	C_g (g-H_2O/cm^3)	ρ_h(g-H_2O/cm^3)
1	16.8	55.3	23.8	0.014	3.30X10^{-5}	1.55X10^{-5}	0.923
2	24.9	55.3	30.0	0.021	2.87X10^{-5}	2.29X10^{-5}	0.865

The values of the moisture concentrations of a gas-film and a undrying-core surface c_g and c_s (g-H_2O/cm^3-void) are obtained from the following equations.

$$c_g = H/((H/18) + (1/29))\,((22.4 \times 10^3)\,(273.2 + t_d)/273.2) \tag{1}$$

$$c_s = 18p_{sw}/((22.4 \times 10^3)\,(760)\,(273.2 + t_w)/273.2) \tag{2}$$

The values of the water concentration of a vaporization ρ_h(g-H_2O/cm^3) were calculated using a following equation.

$$\rho_h = (w_o - w_e)/V_o \tag{3}$$

DRYING-RATE EQUATION AND DETERMINATIONS OF RATE PARAMETERS

1. Drying-rate equations

The drying-rate equations based on drying-shell models which considered the surface-shrinkage for the sphere, the long-cylinder and the infinite-slab, respectively were described in the former paper.[3)] The drying-rate equation for the spherical materials can be expressed as follows:

$$dw/d\theta = -4\pi R^2 (c_s - c_g)/((1/h_m) + (R - r_c)/((r_c/R)k_m)) \tag{4}$$

The rate parameters of gas-film diffusion and shell diffusion h_m (cm^3-void/cm^2·min) and k_m (cm^3-void/cm·min) in Eq. (4) can be calculated from the experimental results in Figs. 1 and 2.

The radius of the undrying-core r_c(cm) and material R(cm) in Eq. (4) are calculated using the following equations.

$$x_w = (w_o - w)/(w_o - w_e) \tag{5}$$

$$r_c = (1-x_w)^{1/3} R_o \tag{6}$$

$$R = (R_e^3 + (1-(R_e/R_o)^3) r_c^3)^{1/3} \tag{7}$$

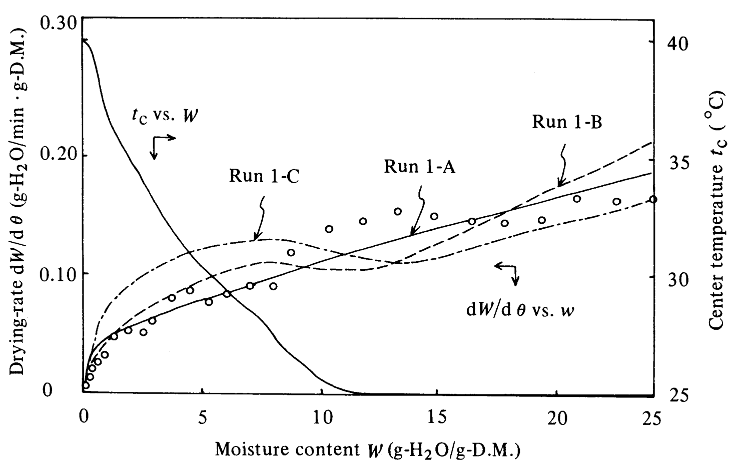

Fig. 3. Drying-rate and center temperature of agar gel vs. moisture content, t_d=40°C, t_w=25°C, $\bar{u}$= 3480cm/min.

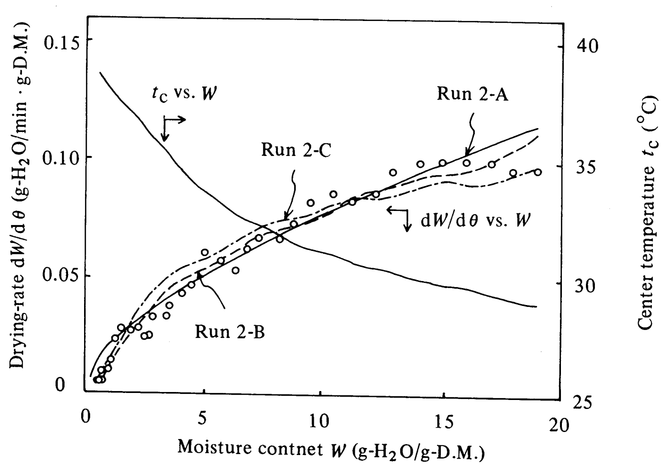

Fig. 4. Drying-rate and center temperature of carrot vs. moisture content, t_d=40°C, t_w=29.0°C, $\bar{u}$=3480cm/min.

The relations of the drying-rate $dW/d\theta$ ($g\text{-}H_2O/min\cdot D.M.$) vs. the moisture content W($g\text{-}H_2O/g\text{-}D.M.$) for the drying of agar gel and carrot are shown in Figs. 3 and 4, respectively. The calculated values of W and $dW/d\theta$ in Figs. 3 and 4 were obtained from w and $dw/d\theta$ using the following equations.

$$W = (w - w_d)/w_d \tag{8}$$

$$dW/d\theta = (dw/d\theta)/w_d \tag{9}$$

2. Determinations of rate parameters

For the calculation of the rate parameters in the drying-rate equation, we used a non-linear least square method. The programs for the calculation are the same as in the previous paper.[3] In the previous paper, we minimized the standard deviation σ_r(cm) for r_c, but in this paper we minimized the following standard deciation σ_w(g) for w.

$$\sigma_w = \left(\sum_{i=1}^{n} (w_{obs} - w_{cal})_i^2 / n \right)^{1/2} \tag{10}$$

The initial values of the rate parameters h_m and k_m were given the average values obtained from the integrated equations. These have been illustrated in the previous paper assuming gas-film or shell diffusion controlling. The FACOM 230-75 digital computer in the Computation Center of Nagoya University was used for these calculations.

CALCULATED RESULTS AND DISCUSSIONS

Table 3 illustrates the calculated results of the rate parameters h_m and k_m. The surface temperatures of the undrying-core can not be measured, so we took up with the wet-bulb temperatures or the center temperatures of the samples rather than with the surface temperatures. The Runs 1-A and 2-A in Table 3 are the results which used the values of c_s for the wet-bulb temperatures t_w(°C) as shown in Eq. (2). The Runs 1-B, 1-C, 2-B and 2-C are the results which used the values of c_s for the center temperatures of samples t_c(°C) instead of the wet-bulb temperatures t_w(°C). The Runs 1-C and 2-C in Table 3 are the results which used the fixed values of h_m at the initial drying time.

Table 3. Rate parameters h_m (cm^3-void/$cm^2\cdot$min) and k_m (cm^3-void/cm $\cdot$ min), and standard deviation σ_w (g).

Run	Initial values			Number of iteration	Calculated values		
	h_m	k_m	σ_w		h_m	k_m	σ_w
1–A	191	4.32	0.1702	15	198	497	0.0108
1–B	120	1.75	0.2376	13	224	11.6	0.0186
1–C	(170)	1.75	0.1975	11	(170)	44.6	0.0401
2–A	193	3.50	0.1717	15	202	141	0.0081
2–B	97.6	1.23	0.2370	11	193	5.93	0.0044
2–C	(171)	1.23	0.1707	8	(171)	7.82	0.0136

( ): fixed values at initial drying time.

The calculated values of the weight w(g) vs. drying time θ (min) for the rate parameters in Table 3 are shown in Figs. 1 and 2, and the relations of the drying-rate $dW/d\theta$ (g-H_2O/min·g-D.M.) vs. moisture content W (g-H_2O/g-D.M.) are shown in Figs. 3 and 4.

The rate parameters h_m must be used to fix the values at the initial drying time, but the calculated values of Runs 1-C and 2-C are less satisfactory than those of the other ones. The reasons are that the drying data of these samples are not sufficient to discuss the drying-shell model, and that the rate parameters k_m can not keep up a constant value throughout all the drying time.

The results of Runs 1-B, 1-C, 2-B and 2-C in Figs. 3 and 4 are more complicated than the results of Runs 1-A and 2-A, and show a similar tendency of the experimental waved lines, but we can not figure them out with accuracy. One of the reasons is that the surface temperatures of the undrying-core is not assumed with accuracy.

The Runs 1-A and 2-A are not the exact theoritical model, but the standard deviations σ_W in Table 3 are lower than the others, and these results is not require to measure the sample temperatures. We adopt these results for the design of various drying apparatuses, but the theoritical meaning of the rate parameters is less clear than the other Runs.

RESULTS

The rate parameters in the drying-rate equations of the agar gel and carrot were calculated, replacing the surface temperatures of the undrying-core by the wet-bulb tempeeratrures or the center temperatures of the samples. The standard deviations for the results which used the wet-bulb temperatures were smaller than those which used the center temperatures of the samples.

The rate parameters for the fixed values of h_m at the initial drying time were calculated too. The rate parameters h_m must be used for the fixed values at initial drying time, but the standard deviations were not smaller than the other ones. One of the reasons is that the rate parameters k_m can not be a constant value throughout the whole drying time.

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SUMMARY

In the previous paper, we studied the drying-rate equations based on the drying-shell models and the calculation methods of the rate parameters in the rate equations. In the present paper, the drying-rate equations of a agar gel and carrot based on the drying-shell model have been studied.

The surface temperatures of the undrying-core can not be measured, so we took up with the wet-bulb temperatures and the center temperatures of the samples instead of the surface temperatures. The calculated results which used the center temperatures showed a similar tendency in the experimental results, but the over-all relationships were less satisfactory than the results which used the wet-bulb temperatures.

From the comparisons of the calculated results described above, we may conclude that the drying-rate equations which used the wet-bulb temperatures instead of the surface temperatures of the undrying-core in order to simplify the calculations were better than the other, and more adequate for the design of various drying apparatuses.

NOTATIONS

c_g and c_s: moisture concentrations of gas-film and undrying-core surfaces (g-H_2O/cm^3-void)

h_m and k_m: rate parameters of gas-film diffusion (cm^3-void/cm^2·min) and shell diffusion (cm^3-void/cm^2·min)

p, p_{sd} and p_{sw}: vapor pressure and saturated vapor pressures at t_d and t_w(mmHg)

R and r_c: radius of sample and the undrying-core (cm)

t_c, t_d and t_w: center temperature of sample, and dry- and wet-bulb temperatures (°C)

V, W, w and x_w: volume, moisture content, weight and drying-ratio of sample (cm^3), (g-H_2O/g-D.M.), (g) and (−)

$dW/d\theta$ and $dw/d\theta$: drying-rate of sample (g-H_2O/min·g-D.M.) and (g-H_2O/min)

θ: drying time (min)

Subscripts;

o, e and d: initial, equilibrium and completely drying states

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殻状乾燥モデルに基づく寒天とにんじんの乾燥速度式

久保田清・小畠秀樹・鈴木寛一・保坂秀明

既報において，殻状乾燥モデルに基づく乾燥速度式の設定について報告し[3]，含水スポンジを仮想食品として考えて速度パラメータを算出して，各種形状について比較検討をしてきた。[4] 本報は，球状の寒天とにんじんを試料として，乾燥実験を行ない，殻状乾燥モデルの適用性について検討したものである。

乾燥進行に伴なう未乾燥核の表面温度の変化を測定することが不可能であるため，試料の中心温度の測定を行なった。未乾燥核の表面温度として，中心温度と湿球温度をそれぞれ仮定した場合について速度パラメータを算出した。また，ガス境膜の拡散に関する速度パラメータh_mを乾燥初期の値に固定した場合についての計算も行なった。

以上の計算結果の比較から，当面する各種の乾燥装置の設計などに対しては，反理論的とはなるが，ガ

ス境膜および乾燥殻状部拡散に関する2つの速度パラメータ h_m および k_m を相関させて非線形最小二乗法で同時計算し，未乾燥核の表面温度として湿球温度を仮定する場合が，総括的に実験データとの一致がよく，取り扱いも簡単でよいことが分った。尚，本実験条件下において，寒天およびにんじんの乾燥は，殻状部から乾燥をする現象を示したが，未乾燥核の部分の乾燥も進行していたことから殻状乾燥モデルを満足的に適用できるものではなかった。簡単な乾燥速度式を得る目的に対しては，均一乾燥モデルに基づいた乾燥速度式との比較検討も必要と考えられる。