J. Fac. Fish. Anim. Husb.,
Hiroshima Univ. (1977), **16**: 131~144

Studies of Drying-rate Equations based on Uniform Drying Models

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Received August 29, 1977
(Figs. 1–5, Tables 1–5, Appendix)

INTRODUCTION

The drying-rate equations have been studied dividing the drying period into constant- and falling-rate periods and the diffusion coefficients of moisture in foods which can be assumed as being infinite slab were calculated by several researchers,[1-6] but the drying mechanisms of foods are generally rather intricated. For the design of various drying apparatuses, we must take approximating drying-rate equations which are based on simple drying models.

In a previous paper,[7] we studied the drying-rate equations based on the drying-shell models and the calculation methods of the rate parameters in these equations. Later, in a following paper,[8] we took up the drying-rate equations of a agar gel and carrot based on the drying-shell model. The drying-shell model has a undrying-core and a drying-shell zones, and the former's and the latter's moisture contents are postulated as the initial and equilibrium moisture contents, respectively. These models have been used for the cooking or rice, udon and kishimen[9-11] as the cooking-shell models or the water-soaking-shell models.

In this paper, we study the another simple models (uniform drying models) which have uniform moisture content throughout the whole of the drying materials, and whose moisture content decreases from the initial moisture content to the equilibrium moisture content. In a previous paper,[12] we postulated simple idealized drying models of foods and then studied the surface-shrinkage equations. The uniform drying models in this paper are most simple models which can be adopted easily for the design of various drying apparatuses.

DRYING - RATE EQUATIONS

Fig. 1 illustrates the case of a drying spherical material. The radius, the surface area, the volume, the weight and the density of the spherical material in the intermediate state, are given as R (cm), S (cm^2), V (cm^3), w (g) and ρ (g/cm^3). The subscripts o, e and d in these symbols signify the initial, equilibrium and completely drying states, respectively.

In the intermediate state, the following equations are obtained for the spherical material.

$$S = 4\pi R^2, \quad V = (4/3)\pi R^3, \quad \rho = w/V \tag{1) – (3}$$

Thus, we obtain the following equation by combining Eqs. (1) – (3).

$$S = a\,(w/\rho)^{2/3} \tag{4}$$

where, $a = (36\pi)^{1/3} = 4.8360$. When, we assume the cubic material, a=6 is obtained. The drying-ratio x_w (–) of material is defined as follows.

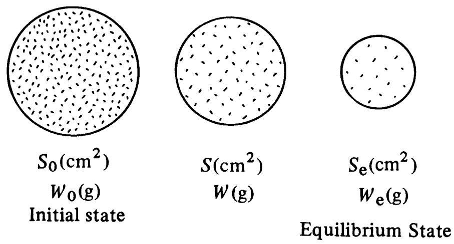

Fig. 1. Uniform drying model for sphere.

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

Next, we assumed that the density in the intermediate state could be expressed by the following equation.

$$\rho = \rho_o(1 - x_w) + \rho_e x_w \tag{6}$$

The drying-surface equation of the uniform drying models for the spherical and cubic materials can be written as follow by combining Eqs. (4) – (6).

$$S = a\,(w_o - w_e)w/((\rho_o - \rho_e)w + \rho_e w_o - \rho_o w_e))^{2/3} \tag{7}$$

In conclusion, we postulate the drying-rate equation as follows, assuming: (1) the resistance of moisture internal diffusion is negligible compared to the resistance of moisture removal from the surface, and the rate of moisture removal from the surface seems to be proportional to the drying-surface area S, (2) the internal moisture distribution is uniform, and the surface moisture content might be correlated to the exponent of $(w - w_e)$.

$$dw/d\theta = k_m S\,(w - w_e)^m \tag{8}$$

where, $dw/d\theta$: drying-rate of materials (g-H_2O/min), k_m: rate parameter of mth-order rate equation (g-H_2O^{1-m}/cm^2·min), m: order of rate equation. Thus, Eq. (8) is non-linear in terms of the unknown, we must calculate the rate parameters k_m and m with a non-linear least square method.

If the drying-surface area S may be correlated to the exponent of $(w - w_e)$, Eq. (8) becomes

$$dw/d\theta = k_n (w-w_e)^n \tag{9}$$

where, n: order of rate equation.

For the differential analysis, Eq. (9) becomes as follows.

$$\ln(-dw/d\theta) = \ln(k_n) + n\ln(w-w_e) \tag{10}$$

We can obtain the rate parameter k_n and n in Eq. (10) with a linear least square method. However, since Eq. (10) has the differentiated value $dw/d\theta$, we must first find $dw/d\theta$ from the data w vs. θ before attempting the fitting procedure. When the data are scattered, we can't reliably fine the derivatives needed in the differential method. Eq. (9) becomes as follows using the drying-ratio x_w which is a covenient variable.

$$dx_w/d\theta = k_n (w_o-w_e)^{n-1}(1-x_w)^n \tag{11}$$

For the integral analysis, Eqs. (9) and (11) become as follow.

For $n \neq 1$;

$$\begin{aligned} k_n &= ((1/(1-x_w))^{n-1}-1)/((w_o-w_e)^{n-1}(n-1)\theta) \\ &= ((1/(w-w_e))^{n-1} - (1/(w_o-w_e))^{n-1})/((n-1)\theta) \end{aligned} \tag{12}$$

For $n = 1$;

$$k_{n=1} = -\ln(1-x_w)/\theta = \ln((w-w_e)/(w_o-w_e))/\theta \tag{13}$$

In general, it is suggested that when the integral analysis is used these analitical integrated equations have to be tried out first, and, if not successful, an integral analysis by numerical integration be tried. In the numerical integral analysis a digital computer should be used and the rate parameters k_n and n should be calculated by a non-linear least square method.

If the moisture content W (g-H_2O/g-D.M.) is as follows it can be used in a similar manner as above.

$$W = (w-w_d)/w_d \tag{14}$$

$$dW/d\theta = K_n (W-W_e)^n \tag{15}$$

The rate parameter K_n in Eq. (15) is obtained from the rate parameter k_n in Eq. (9).

$$K_{\mathrm{n}} = k_{\mathrm{n}} w_{\mathrm{d}}^{n-1} \tag{16}$$

Eq. (15) is the same refered by Chin Shu Chen *et al.* [13] as empirical drying-rate equation. The empirical drying-rate equation of sausage drying is obtained as follows.[14] The theoritical and empirical drying-rate equations of grain drying have been studied under various drying conditions.[15-20] However, the simplified expressions as Eqs. (8) and (9) are adequate for our purposes.

$$\mathrm{d}W/\mathrm{d}\theta = K_{\mathrm{p}}((W - W_{\mathrm{e}})/W)^2 \tag{17}$$

EXPERIMENTAL RESULTS

The relations of the weight of drying materials w (g) vs. drying time θ (min) were measured. Tables 1 and 3–5 illustrate the experimental results. Tables 3–5 show only half of the observed values. The results of agar gel and carrot are the same as in the previous paper.[8] In this present paper, the results of cooked rice were added. The cooked rice used here as drying sample was rice ("NAKATE-SHINSENBON" in 1974) cooked for 15 min in an electric rice-cooker. The experimental apparatus was the same as for the other samples. A sample of 50 cooked rice grains was put into a sample basket made of a wire net, and was weighed under a chemical balance set up in the upper part of the dryer. The observed values used in this paper are the average values. The weights of the equilibrium and the completely drying states of the sample, w_{e} and w_{d} (g) were obtained by same methods as in the previous paper.[8]

Table 1. Experimental results

		Diameters		Weights			Dry- and Wet-bulb temperatures		Air velocity
Run	Sample	D_{o}(cm)	D_{e}(cm)	w_{o}(g)	w_{e}(g)	w_{d}(g)	t_{d}(°C)	t_{w}(°C)	$\bar{u}$(cm/min)
1	agar gel	1.20X1.20X1.30	0.392X0.761X0.761	0.950	0.0450	0.0380	40.0	25.0	3480
2	carrot	1.28X1.28X1.28	0.240X0.885X0.890	1.036	0.0858	0.0522	40.0	29.0	3480
3	cooked rice	0.790X0.346X0.239	0.676X0.315X0.175	0.0376	0.0211	0.0181	50.0	23.0	3120

Table 2. Rate parameters in Eqs.(8) and (9), and standard deviation σ_{w}(g)

Run	k_{m}	m	σ_{w}	Run	k_{n}	n	σ_{w}
1-A	0.00140	0.134	0.00649	1-B	0.00709	0.461	0.00747
2-A	0.00117	0.057	0.00820	2-B	0.00596	0.534	0.00561
3-A	0.1652	1.098	0.00024	3-B	0.1418	1.236	0.00028

Run	$k_{\mathrm{n=1}}$	σ_{w}	Run	$k_{\mathrm{n=0.5}}$	σ_{w}	Run	h_{m}^*	k_{m}^*	σ_{w}
1-C	0.01050	0.0515	1-D	0.00730	0.00858	1-E	198	497	0.0108
2-C	0.00822	0.0462	2-D	0.00582	0.00676	2-E	202	141	0.0081
3-C	0.0446	0.00046	3-D	0.00412	0.00116	3-E	250	2.05	0.00016

h_{m}^* and k_{m}^*: the rate parameters in drying-shell model in previous paper[8].

Talbe 3. Relations of weight of agar gel vs. drying time.

Drying time θ (min)	w_{obs} (g)	w_{cal} (g)				
		1-A	1-B	1-C	1-D	1-E
20	0.825	0.821	0.819	0.779	0.817	0.814
40	0.710	0.700	0.698	0.640	0.194	0.691
60	0.600	0.588	0.586	0.527	0.581	0.580
80	0.480	0.485	0.485	0.436	0.480	0.480
100	0.374	0.391	0.392	0.362	0.389	0.392
120	0.304	0.308	0.310	0.302	0.309	0.313
140	0.240	0.237	0.239	0.253	0.239	0.244
160	0.175	0.177	0.177	0.214	0.180	0.184
180	0.130	0.128	0.127	0.182	0.132	0.132
200	0.090	0.090	0.088	0.156	0.094	0.088
220	0.065	0.062	0.061	0.135	0.067	0.053
240	0.050	0.045	0.047	0.118	0.051	0.044

The above data are half of the used data N=24 (θ=10, 20, · · · , 240 min)

Table 4. Relations of weight of carrort vs. drying time.

Drying time θ (min)	w_{obs}(g)	w_{cal}(g)				
		2-A	2-B	2-C	2-D	2-E
20	0.936	0.921	0.924	0.892	0.926	0.920
40	0.831	0.814	0.819	0.770	0.832	0.814
60	0.726	0.717	0.722	0.666	0.726	0.716
80	0.636	0.628	0.632	0.578	0.637	0.627
100	0.546	0.546	0.549	0.503	0.554	0.546
120	0.471	0.473	0.474	0.440	0.477	0.473
140	0.401	0.407	0.406	0.386	0.408	0.406
160	0.346	0.347	0.344	0.341	0.345	0.347
180	0.281	0.294	0.290	0.302	0.289	0.294
200	0.236	0.248	0.242	0.269	0.240	0.247
220	0.201	0.207	0.201	0.241	0.198	0.206
240	0.176	0.171	0.167	0.218	0.162	0.171
260	0.146	0.140	0.139	0.198	0.134	0.140
280	0.116	0.114	0.117	0.181	0.112	0.115
300	0.101	0.093	0.101	0.166	0.096	0.094
320	0.091	0.082	0.091	0.154	0.088	0.086

The above data are half of the used data N=32 (θ=10, 20, · · · , 320 min).

Table 5. Relations of weight of cooked rice vs. drying time.

Drying time θ (min)	w_{obs} (g)	w_{cal}(g)				
		3-A	3-B	3-C	3-D	3-E
10	0.0307	0.0310	0.0311	0.0317	0.0327	0.0306
20	0.0274	0.0275	0.0274	0.0279	0.0287	0.0276
30	0.0256	0.0254	0.0253	0.0254	0.0255	0.0258
40	0.0244	0.0241	0.0240	0.0239	0.0232	0.0244
50	0.0234	0.0232	0,0232	0.0229	0.0217	0.0234
60	0.0228	0.0226	0.0226	0.0222	0.0211	0.0227
70	0.0221	0.0222	0.0222	0.0218	0.0211	0.0221
80	0.0218	0.0220	0.0220	0.0216	0.0211	0.0217
90	0.0214	0.0217	0.0218	0.0214	0.0211	0.0213
100	0.0212	0.0216	0.0216	0.0213	0.0211	0.0211
110	0.0212	0.0215	0.0215	0.0212	0.0211	0.0211

The above data are half of the used data N=22 (θ =5, 10, · · ·, 110 min).

DETERMINATIONS OF RATE PARAMETERS

For the calculation of the rate parameters in the drying-rate equations, we used a non-linear least square method.[21,22] We minimized the following standard deviation σ_w (g) for w.

$$\sigma_w = \sum_{i=1}^{N} (w_{obs} - w_{cal})_i^2 /N)^{1/2} \tag{18}$$

The initial values of the rate parameters k_m and k_n were given by the difference of weight values from initial drying time to 60 min for agar gel and carrot and to 30 min for cooked rice, assuming $n=m=1.0$ or $n=0.5$.

The practical program and the calculated results for the Eq. (8) are shown in Appendix (used of the Computation Center of Hiroshima University: HITAC 8700-OS7).

CALCULATED RESULTS AND DISCUSSIONS

Table 2 illustrates the calculated results of the rate parameters k_m and so on. The Runs 1-A – 3-A in Table 2 are the results for Eq. (8) which had been postulated in consideration of the drying-surface area S in the drying-rate equation. The Runs 1-B – 3-B are the results for Eq. (9) which had been postulated by assuming S being possibly correlated to the exponent of $(w-w_e)$. Thr Runs 1-C – 3-C and 1-D – 3-D in Table 2 are the results for Eq. (9) which determined $n=1$ and $n=0.5$, respectively.

The Runs 1-E – 3-E are the results which used the following drying-rate equation basded on the drying-shell model. The results of agar gel and carrot were the same as in the previous paper.[8]

$$dw/d\theta = -4\pi R^2 (c_s - c_g)/((1/h_m^*) + (R-r_c)/((r_c/R)k_m^*)) \tag{19}$$

h_m^* (cm^3-void/cm^2·min) and k_m^* (cm^3-void/cm·min) are the rate parameters related to a gas-film diffusion and a shell diffusion, respectively. c_g and c_s (g-H_2O/cm^3-void) are the moisture concentrations of the gas-film and of the undrying-core surface, and R and r_c (cm) are radius of the material and of the undrying-core.

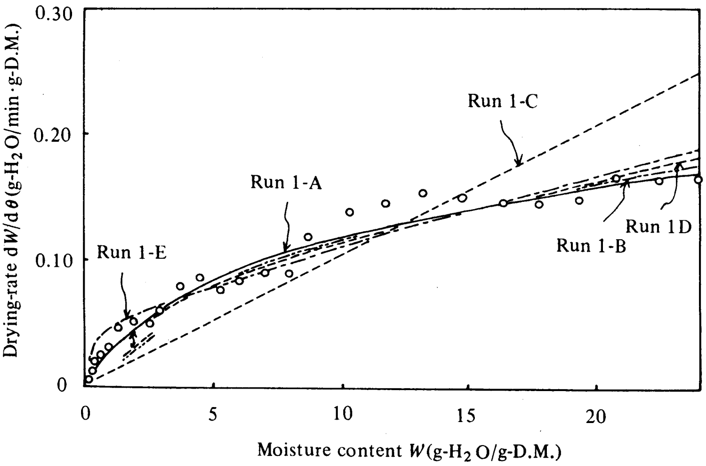

Fig. 2. Drying-rate of agar gel vs. moisture content.

The calculated values of the weight w (g) vs. drying time θ (min) for the rate parameters in Tabe 2 are illustrated in Tables 3–5, 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. 2–4.

The calculated results of Runs 1-A–3-A for Eq.(8) are similar to the results of Runs 1-B–3-B for Eq. (9). From these comparisons, we may conclude that the drying-surface area may be correlated to the exponent of $(w-w_e)$, and that the simplified Eq. (9) should be preferred for our purposes. The best approximate values of order n in Eq. (9) are 0.5 for agar gel and carrot and 1.0 for cooked rice. Then the calculated value of Run 3-C for cooked rice is satisfactory, but Runs 1-C and 2-C for agar gel and carrot are not. The values of Runs 1-D and 2-D for agar gel and carrot are satisfactory, but Run 3-D for cooked rice is not.

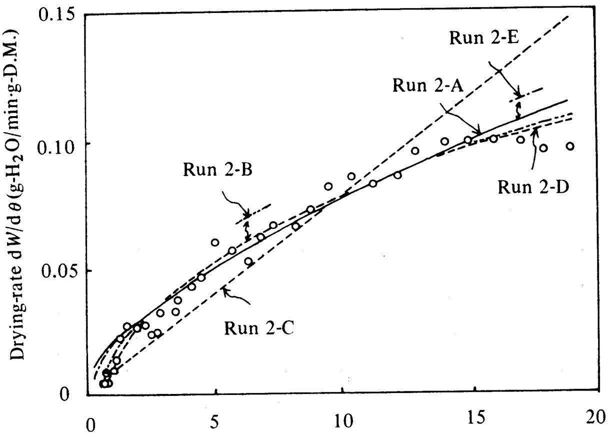

Fig. 3. Drying-rate of carrot vs. moisture content.

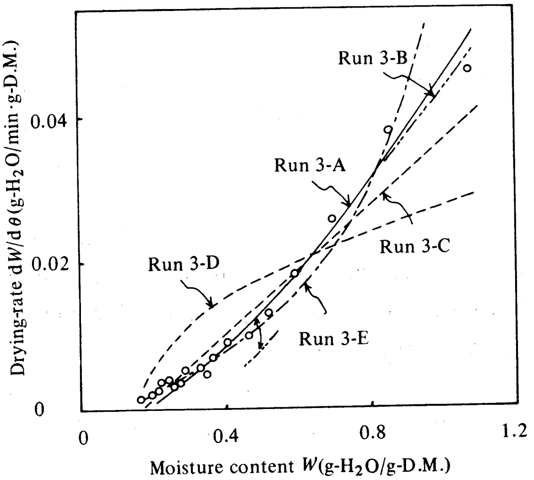

Fig. 4. Drying-rate of cooked rice vs. moisture content.

The results of Runs 1-E–2-E for Eq. (19) are similar to those of Runs 1-A – 2-A and 1-B – 2-B for Eqs. (8) and (9), respectively, but the result of Run 3-E is not similar to the results of Runs 3-A and 3-B. The drying phenomena of the samples are complicated, and can't apply exactly to the uniform drying model either.

The drying-surface area ratio $S/S_0(-)$ of agar gel for Runs 1-A and 1-E is shown in Fig. 5. The observed values of the drying-surface area in Fig. 5 were measured by photography. In Fig. 5, the calculated results of Run 1-E for the drying-shell model are better than those of Run 1-A for the uniform drying model. The reason is that Eq. (7) for the drying-surface area used in the uniform drying model is merely an assumed simple equation. While the calculated results for the uniform drying model are the same as those for the drying-shell mode, the drying-rate equations based on the former model are better than the equation based on the latter model, the former equations being simpler than the latter.

RESULTS

The drying-rate equations based on the uniform drying models were postulated, and the rate parameters in the drying-rate equations of agar gel, carrot and cooked rice were determined. From the comparison of the calculated results, we concluded that the drying-surface area S might be correlated to the exponent of undisappeared water content $(w-w_e)$, and that the order of the drying-rate equations which are postulated by assuming that S might be correlated to $(w-w_e)$, is 0.5 for agar gel and carrot and 1.0 for cooked rice.

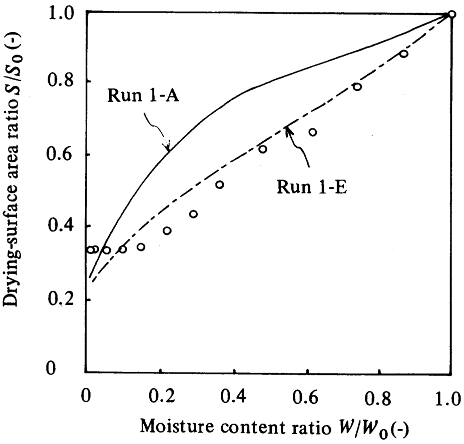

Fig. 5. Drying-surface area ratio of agar gel.vs. moisture content ratio.

The calculated results of agar gel and carrot for the uniform drying model were similar to those for the drying-shell model examined in a previous paper. For such results, the former model is better than the latter one as the former is less intricated.

SUMMARY

In order to design and automatically control various drying apparatuses, it is required to determine the simple approximated drying-rate equations and to obtain the rate parameters for the equations.

In a previous paper, we studied the drying-rate equations based on the drying-shell models. In the present paper, we postulated the drying-rate equations based on the uniform drying models, and calculated the rate parameters in the drying-rate equations of agar gel, carrot and cooked rice.

We studied the drying-rate equations which are postulated by the consideration of the drying-surface area S and by assuming that S may be correlated to the exponent of undisappeared water content $(w-w_e)$. From the comparison of the calculated results, we concluded that S might be correlated to the exponent of $(w-w_e)$, and that the order of the drying-rate equations which are postulated by assuming that S might be correlated to $(w-w_e)$, is 0.5–1.0 for the used samples.

The calculated results of agar gel and carrot for the uniform drying model were similar to those for the drying-shell model described in a previous paper. For much results, former model is better than the latter one as the former is less intricated.

NOTATIONS

k_m, K_n and k_n: rate parameters in drying-rate equations (g-H_2O^{1-m}/cm^2·min), (g-H_2O^{1-n}/min·g-D.M^{1-n}) and (g-H_2O^{1-n}/min)

m and n: order in drying-rate equations (–)

S, V, W, w and x_w : drying-surface area, volume, moisture content, weight and drying-ratio of sample (cm^2), (cm^3), (g-H_2O/g-D.M.), (g) and (–)

dW/dθ and dw/dθ : drying-rate of sample (g-H_2O/min·g-D.M.) and (g-H_2O/min)

θ : drying time (min), ρ: density of sample (g/cm^3)

Subscripts;

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

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APPENDIX

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C       MAIN PROGRAM
C       ESTIMATIONS OF NONLINEAR PARAMETERS
C       IN ORDINARY DIFFERENTIAL EQUATIONS
C       USING SUBROUTINE HISENS BY K.KUBOTA,
C       IN SHOKUHIN KOGAKU, P.174 (KYORITSU,1975)
C       N=, L= AND K=, NUMBER OF EXPERIMENTAL POINT, PARAMETER AND ITERA-
C       TION, NT=, LT= AND KT=, MAXIMUM NUMBER OF N, L AND K
C       MY= AND MX=, NUMBER OF DEPENDENT AND INDEPENDENT VARI-
C       ABLES, MYT= AND MXT=, MAXIMUM NUMBER OF MY AND MX
C       Y(MY,N)= AND X(MX,N)=, DEPENDENT AND INDEPENDENT VARIABLES
C       A(L,K)=, PARAMETERS
C       SD(K)=, STANDARD DEVIATION
C       DYC(MY,N,K)=, DIFFERENTIAL VALUES OF YC(MY,N,K) BY X(MX,N)
C       YC(MY,N,K)=, CALCULATED VALUES OF Y(MY,N)
C       K1=KT+1, SETTING NUMBER OF INITIAL POINT
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      COMMON W0,WE,WD,R0,RE,ROU0,ROUE,YE
      DIMENSION Y(3,101),X(1,101),A(4,16),HM(16),HS(16),W(3,101),
     1DYC(3,101,16),YC(3,101,16),YCS(3,101,5),DD(4,5),SD(16),DYY(3),
     2YY(3),AA(4),Q(3),DYS(3),YS(3),DYA(3),YA(3)
      DATA HAA/0.0005/,HM(1),HS(1)/2*1.0/,HMM,HSS/2*0.5/,HST/0.0001/,
     1EPS/1.0E-50/,MYT/3/,MXT/1/,NT/101/,LT/4/,L1/5/,KT/15/,K1/16/
      EXTERNAL DIFEQA,DIFEQB
  888 READ(5,10) MY,MX,N,L
      IF(N) 999,999,777
  777 READ(5,20) ((Y(J,I),I=1,N),J=1,MY)
      READ(5,20) ((X(J,I),I=1,N),J=1,MX)
      READ(5,20) (YA(I),I=1,MY),XA,YE
      WRITE(6,50) MY,MX,N,L
      WRITE(6,60) ((Y(J,I),I=1,N),J=1,MY)
      WRITE(6,61) ((X(J,I),I=1,N),J=1,MX)
      HX=(X(1,N)-X(1,1))/100.0
      DO 40 I=1,MY
   40 DYA(I)=(Y(I,1)-YA(I))/(X(1,1)-XA)
      WRITE(6,70) (DYA(I),YA(I),I=1,MY),XA,HX,YE
      DO 100 I=1,N
      DO 100 J=1,MY
  100 W(J,I)=1.0
  555 READ(5,30) (A(I,1),I=1,L)
      IF(A(1,1)) 666,444,666
  666 WRITE(6,71)
      READ(5,30) W0,WE,WD,R0,RE
      WRITE(6,62) W0,WE,WD,R0,RE
      ROU0=W0/(4.0*3.1416*R0**3/3.0)
      ROUE=WE/(4.0*3.1416*RE**3/3.0)
      HM(1)=1.0
      HS(1)=1.0
      CALL HISENS(Y,X,A,HAA,HM,HMM,HS,HSS,HST,W,DYC,YC,YCS,DD,SD,MY,
     1MYT,MX,MXT,N,NT,L,LT,K,KT,L1,K1,EPS,DYY,YY,AA,Q,DYS,YS,DYA,YA,
     2XA,HX,DIFEQA,ILL)
      IF(ILL) 110,120,110
  110 WRITE(6,80) ILL
      GO TO 555
  120 WRITE(6,90)
      WRITE(6,92)
      WRITE(6,91) HM(K1),HS(K1),(A(I,K1),I=1,L),SD(K1)
      DO 95 J=1,MY
      WRIIE(6,93) (YC(J,I,K1),I=1,N)
      WRITE(6,93) (DYC(J,I,K1),I=1,N)
   95 CONTINUE
      WRITE(6,90)
      WRITE(6,92)
      WRITE(6,94) K,HM(K),HS(K),(A(I,K),I=1,L),SD(K)
      DO 96 J=1,MY
      WRITE(6,93) (YC(J,I,K),I=1,N)
      WRITE(6,93) (DYC(J,I,K),I=1,N)
   96 CONTINUE
      GO TO 555
  444 READ(5,10) MY,MX,N,L
      IF(N) 999,999,333
  333 WRITE(6,50) MY,MX,N,L
      WRITE(6,60) ((Y(J,I),I=1,N),J=1,MY)
      WRITE(6,61) ((X(J,I),I=1,N),J=1,MX)
      WRITE(6,70) (DYA(I),YA(I),I=1,MY),XA,HX,Y
  111 READ(5,30) (A(I,1),I=1,L)
      IF(A(1,1)) 222,888,222
  222 WRITE(6,72)
      READ(5,30) W0,WE,WD,R0,RE
      WRITE(6,62) W0,WF,WD,R0,RE
      ROU0=W0/(4.0*3.1416*R0**3/3.0)
      ROUE=WE/(4.0*3.1416*RE**3/3.0)
      HM(1)=1.0
      HS(1)=1.0
      CALL HISENS(Y,X,A,HAA,HM,HMM,HS,HSS,HST,W,DYC,YC,YCS,DD,SD,MY,
     1MYT,MX,MXT,N,NT,L,LT,K,KT,L1,K1,EPS,DYY,YY,AA,Q,DYS,YS,DYA,YA,
     2XA,HX,DIFEQB,ILL)
      IF(ILL) 130,140,130
  130 WRITE(6,80) ILL
      GO TO 111
  140 WRITE(6,90)
      WRITE(6,92)
      WRITE(6,91) HM(K1),HS(K1),(A(I,K1),I=1,L),SD(K1)
      DO 97 J=1,MY
      WRITE(6,93) (YC(J,I,K1),I=1,N)
      WRITE(6,93) (DYC(J,I,K1),I=1,N)
   97 CONTINUE
      WRITE(6,90)
      WRITE(6,92)
      WRITE(6,94) K,HM(K),HS(K),(A(I,K),I=1,L),SD(K)
      DO 98 J=1,MY
      WRITE(6,93) (YC(J,I,K),I=1,N)
      WRITE(6,93) (DYC(J,I,K),I=1,N)
   98 CONTINUE
      GO TO 111
  999 STOP
   10 FORMAT(4I4)
```

```
   20 FORMAT(10F8.0)
   30 FORMAT(8F10.0)
   50 FORMAT(1H1,3HMY=,I4,5X,3HMX=,I4,5X,2HN=,I4,5X,2HL=,I4)
   60 FORMAT(1H0,8HY(MY,N)=/(1H ,5E13.5))
   61 FORMAT(1H0,8HX(MX,N)=/(1H ,5E13.5))
   62 FORMAT(1H0,15HW0,WE,WD,R0,RE=/1H ,5E13.5)
   70 FORMAT(1H0,24HDYA(MY),YA(MY),XA,HX,YE=/(1H ,5E13.5))
   71 FORMAT(1H0,31HDY(MY)=-A(1)*S*(Y(MY)-YE)**A(2))
   72 FORMAT(1H0,25HDY(MY)=-A(1)*S*(Y(MY)-YE))
   80 FORMAT(1H0,4HILL=,I8)
   90 FORMAT(1H0,2HK=/1H ,25HHM(K),HS(K),A(L,K),SD(K)=)
   91 FORMAT(1H ,4H   0/(1H ,5E13.5))
   92 FORMAT(1H ,11HYC(MY,N,K)=/1H ,12HDYC(MY,N,K)=)
   93 FORMAT(1H ,5E13.5)
   94 FORMAT(1H ,I4/(1H ,5E13.5))
      END

      SUBROUTINE HISENS(Y,X,A,HAA,HM,HMM,HS,HSS,HST,W,DYC,YC,YCS,
     1DD,SD,MY,MYT,MX,MXT,N,NT,L,LT,K,KT,L1,K1,EPS,DYY,YY,AA,Q,
     2DYS,YS,DYA,YA,XA,HX,DIFEQ,ILL)
      METHOD OF NONLINEAR LEAST SQUARE
      DIMENSION Y(MYT,NT),X(MXT,NT),A(LT,K1),HM(K1),HS(K1),W(MYT,NT),
     1DYC(MYT,NT,K1),YC(MYT,NT,K1),YCS(MYT,NT,L1),DD(LT,L1),SD(K1),
     2HA(20),AS(20),DDS(20),DYY(MYT),YY(MYT),AA(LT),Q(MYT),DYS(MYT),
     3YS(MYT),DYA(MYT),YA(MYT)
      IF(KT.GE.1.OR.MY.GE.1.OR.MX.GE.1.OR.N.GE.L.OR.L.GE.1.OR
     1.L.LE.20.OR.L.LT.L1.OR.KT.LT.K1.OR.EPS.GE.0.0) GO TO 200
      ILL=30000
      GO TO 999
  200 K=1
      HM(K1)=HM(1)
      HS(K1)=HS(1)
      SDS=0.0
      DO 10 IA=1,L
   10 A(IA,K1)=A(IA,1)
  888 CALL SUB(DYC,YC,X,A,MY,MYT,MX,MXT,N,NT,L,LT,K,KT,K1,DYY,YY,
     1AA,Q,DYS,YS,DYA,YA,XA,HX,DIFEQ,ILL)
      IF(ILL) 300,400,300
  300 IF(SDS) 999,999,700
  400 D=0.0
      DO 20 I=1,N
      DO 20 J=1,MY
   20 D=D+((Y(J,I)-YC(J,I,K))*W(J,I))**2
      SD(K)=SQRT(D/(N*MY))
      IF(SDS) 999,500,600
  500 SDS=SD(K)
      SD(K1)=SD(K)
      DO 30 I=1,N
      DO 30 J=1,MY
      YCS(J,I,L1)=YC(J,I,K)
      DYC(J,I,K1)=DYC(J,I,K)
   30 YC(J,I,K1)=YC(J,I,K)
      DO 21 IA=1,L
   21 A(IA,K1)=A(IA,1)
      GO TO 777
  600 IF(SDS-SD(K)) 700,800,800
  700 HS(K)=HS(K)*HSS
      IF(HST-HS(K)) 666,999,999
  800 IF(KT-K) 999,999,900
  900 K=K+1
      HM(K)=HM(K-1)*HMM
      HS(K)=HS(1)
      SDS=SD(K-1)
      DO 40 IA=1,L
   40 A(IA,K)=A(IA,K-1)
      DO 50 I=1,N
      DO 50 J=1,MY
   50 YCS(J,I,L1)=YC(J,I,K-1)
  777 DO 60 IA=1,L
      AST=A(IA,K)
      HA(IA)=A(IA,K)*HAA
      A(IA,K)=A(IA,K)+HA(IA)
      CALL SUB(DYC,YC,X,A,MY,MYT,MX,MXT,N,NT,L,LT,K,KT,K1,DYY,YY,
     1AA,Q,DYS,YS,DYA,YA,XA,HX,DIFEQ,ILL)
      IF(ILL) 999,1000,999
 1000 DO 70 I=1,N
      DO 70 J=1,MY
      YCS(J,I,IA)=YC(J,I,K)
   70 YCS(J,I,IA)=(YCS(J,I,IA)-YCS(J,I,L1))/HA(IA)
   60 A(IA,K)=AST
      LP=L+1
      DO 80 IA1=1,L
      DO 80 IA2=1,L
      DD(IA1,IA2)=0.0
      DO 80 I=1,N
      DO 80 J=1,MY
   80 DD(IA1,IA2)=DD(IA1,IA2)+YCS(J,I,IA1)*YCS(J,I,IA2)
     1*W(J,I)**2
      DO 90 IA=1,L
```

```
      DD(IA,IA)=DD(IA,IA)*(1.0+HM(K))
      DD(IA,LP)=0.0
      DO 90 I=1,N
      DO 90 J=1,MY
   90 DD(IA,LP)=DD(IA,LP)+YCS(J,I,IA)*(Y(J,I)-YCS(J,I,L1))
     1*W(J,I)**2
      IF(L-1) 999,333,222
  222 CALL GAUYOS(DD,L,LP,LT,L1,EPS,ILL)
      IF(ILL) 999,1100,999
  333 DD(1,2)=DD(1,2)/DD(1,1)
      ILL=0
 1100 DO 110 IA=1,L
      AS(IA)=A(IA,K)
  110 DDS(IA)=DD(IA,LP)
  666 DO 120 IA=1,L
      DD(IA,LP)=DDS(IA)*HS(K)
  120 A(IA,K)=AS(IA)+DD(IA,LP)
      GO TO 888
  999 RETURN
      END

      SUBROUTINE GAUYOS(A,N,N1,NT,NT1,EPS,ILL)
C     GAUSS-JORDAN METHOD
      DIMENSION A(NT,NT1)
      DO 10 K=1,N
      BIG=ABS(A(K,K))
      IP=K
      K1=K+1
      IF(K1.GT.N) GO TO 14
      DO 11 I=K1,N
      IF(ABS(A(I,K)).LE.BIG) GO TO 11
      BIG=ABS(A(I,K))
      IP=I
   11 CONTINUE
   14 IF(BIG.GE.EPS) GO TO 12
      ILL=1000
      GO TO 999
   12 IF(IP.EQ.K) GO TO 15
      DO 13 J=1,N1
      TEMP=A(K,J)
      A(K,J)=A(IP,J)
   13 A(IP,J)=TEMP
   15 W=A(K,K)
      DO 20 J=K1,N1
   20 A(K,J)=A(K,J)/W
      DO 30 I=1,N
      IF(I.EQ.K) GO TO 30
      W=A(I,K)
      DO 40 J=K1,N1
   40 A(I,J)=A(I,J)-W*A(K,J)
   30 CONTINUE
   10 CONTINUE
      ILL=0
  999 RETURN
      END

      SUBROUTINE SUB(DYC,YC,X,A,MY,MYT,MX,MXT,N,NT,L,LT,K,KT,K1,DYY,
     1YY,AA,Q,DYS,YS,DYA,YA,XA,HX,DIFEQ,ILL)
C     CALCULATION OF EQUATIONS FOR SIMULATION
      DIMENSION DYC(MYT,NT,K1),YC(MYT,NT,K1),X(MXT,NT),A(LT,K1),
     1DYY(MYT),YY(MYT),AA(LT),Q(MYT),DYS(MYT),YS(MYT),DYA(MYT),YA(MYT)
      XX=XA
      DO 100 I=1,L
  100 AA(I)=A(I,K)
      DO 200 I=1,MY
      DYY(I)=DYA(I)
      YY(I)=YA(I)
  200 Q(I)=0.0
      DO 300 I=1,N
      IF(XX-X(1,I)) 400,500,500
  400 DO 600 J=1,MY
      DYS(J)=DYY(J)
  600 YS(J)=YY(J)
      CALL URKGS(DYY,YY,XX,AA,Q,HX,MY,MYT,L,LT,DIFEQ,ILL)
      IF(ILL) 999,700,999
  700 IF(XX-X(1,I)) 400,500,500
  500 DO 300 J=1,MY
      DYC(J,I,K)=DYY(J)-(DYY(J)-DYS(J))*(XX-X(1,I))/HX
  300 YC(J,I,K)=YY(J)-(YY(J)-YS(J))*(XX-X(1,I))/HX
  999 RETURN
      END

      SUBROUTINE URKGS(DY,Y,X,A,Q,HX,MY,MYT,L,LT,DIFEQ,ILL)
C     RUNGE-KUTTA-GILL METHOD
      DIMENSION DY(MYT),Y(MYT),A(LT),Q(MYT),T(20),R(20),P(6),B(4),C(4)
      DATA P(1),C(1),C(4)/3*0.0/,B(1)/1.0/
      DATA B(2)/0.2928932/,B(3)/1.707107/
      PX=X
      P(2)=0.5*HX
```

```
      P(3)=0.5*HX
      P(6)=0.5*HX
      P(4)=HX
      P(5)=HX
      B(4)=1.0/3.0
      C(2)=0.7071068*HX
      C(3)=-C(2)
      DO 100 J=1,4
      X=PX+P(J)
      CALL DIFEQ(DY,Y,X,A,MY,MYT,L,LT,ILL)
      IF(ILL) 999,200,999
  200 DO 100 I=1,MY
      T(I)=P(J+2)*DY(I)-Q(I)
      R(I)=B(J)*T(I)
      Y(I)=Y(I)+R(I)
  100 Q(I)=3.0*R(I)-T(I)+C(J)*DY(I)
  999 RETURN
      END

      SUBROUTINE DIFEQA(DY,Y,X,A,MY,MYT,L,LT,ILL)
C     CALCULATION OF ORDINARY DIFFERENTIAL EQUATIONS
C     DY(MY)= DIFFERENTIAL VALUES OF Y(MY) BY X
C     Y(MY)= DEPENDENT VARIABLES
C     X= INDEPENDENT VARIABLE
C     A(L)= PARAMETERS
C     CALCULATION OF DY(MY)=-A(1)*S*(Y(MY)-YE)**A(2)
      COMMON W0,WE,WD,R0,RE,ROU0,ROUE,YE
      DIMENSION DY(MYT),Y(MYT),A(LT)
      XX=Y(1)-YE
      IF(XX) 100,200,200
  100 XX=1.0E-10
  200 SS=Y(1)/((ROU0-ROUE)*Y(1)+ROUE*W0-ROU0*WE)
      IF(SS) 300,300,400
  300 S=4.0*3.1416*RE**2
      GO TO 500
  400 S=4.8360*((W0-WE)*SS)**(2.0/3.0)
  500 DY(1)=-A(1)*S*XX**A(2)
      ILL=0
  999 RETURN
      END

      SUBROUTINE DIFEQB(DY,Y,X,A,MY,MYT,L,LT,ILL)
C     CALCULATION OF ORDINARY DIFFERENTIAL EQUATIONS
C     CALCULATION OF DY(MY)=-A(1)*S*(Y(MY)-YE)
      COMMON W0,WE,WD,R0,RE,ROU0,ROUE,YE
      DIMENSION DY(MYT),Y(MYT),A(LT)
      XX=Y(1)-YE
      IF(XX) 100,200,200
  100 XX=1.0E-10
  200 SS=Y(1)/((ROU0-ROUE)*Y(1)+ROUE*W0-ROU0*WE)
      IF(SS) 300,300,400
  300 S=4.0*3.1416*RE**2
      GO TO 500
  400 S=4.8360*((W0-WE)*SS)**(2.0/3.0)
  500 DY(1)=-A(1)*S*XX
      ILL=0
  999 RETURN
      END
```

```
MY=   1      MX=   1      N=  24      L=   2

Y(MY,N)=
  0.89000E 00  0.82500E 00  0.76500E 00  0.71000E 00  0.65500E 00
  0.60000E 00  0.54000E 00  0.48000E 00  0.43000E 00  0.37400E 00
  0.34000E 00  0.30400E 00  0.27000E 00  0.24000E 00  0.21000E 00
  0.17500E 00  0.15000E 00  0.13000E 00  0.11000E 00  0.90000E-01
  0.75000E-01  0.65000E-01  0.55000E-01  0.50000E-01

X(MX,N)=
  0.10000E 02  0.20000E 02  0.30000E 02  0.40000E 02  0.50000E 02
  0.60000E 02  0.70000E 02  0.80000E 02  0.90000E 02  0.10000E 03
  0.11000E 03  0.12000E 03  0.13000E 03  0.14000E 03  0.15000E 03
  0.16000E 03  0.17000E 03  0.18000E 03  0.19000E 03  0.20000E 03
  0.21000E 03  0.22000E 03  0.23000E 03  0.24000E 03

DYA(MY),YA(MY),XA,HX,YE=
 -0.60000E-02  0.95000E 00  0.00000E 00  0.23000E 01  0.45000E-01

DY(MY)=-A(1)*S*(Y(MY)-YE)**A(2)

W0,WE,WD,R0,RE=
  0.95000E 00  0.45000E-01  0.38000E-01  0.61620E 00  0.30490E 00

K=
HM(K),HS(K),A(L,K),SD(K)=
YC(MY,N,K)=
DYC(MY,N,K)=
   0
  0.10000E 01  0.10000E 01  0.22020E-02  0.10000E 01  0.85854E-01
```

```
  0,86084E 00  0.78227E 00  0.71294E 00  0.65174E 00  0,59749E 00
  0,54934E 00  0.50655E 00  0.46837E 00  0.43426E 00  0,40373E 00
  0,37630E 00  0.35162E 00  0.32937E 00  0.30924E 00  0,29101E 00
  0,27446E 00  0.25938E 00  0.24564E 00  0.23308E 00  0.22157E 00
  0.21102E 00  0.20131E 00  0.19236E 00  0.18411E 00
 -0,83649E-02 -0.73711E-02 -0.65074E-02 -0.57576E-02 -0,51043E-02
 -0,45350E-02 -0.40387E-02 -0.36046E-02 -0.32247E-02 -0,28918E-02
 -0,25991E-02 -0.23415E-02 -0,21145E-02 -0.19137E-02 -0,17360E-02
 -0.15784E-02 -0.14380E-02 -0.13131E-02 -0.12014E-02 -0,11015E-02
 -0,10119E-02 -0.93135E-03 -0.85876E-03 -0.79333E-03

K=
HM(K),HS(K),A(L,K),SD(K)=
YC(MY,N,K)=
DYC(MY,N,K)=
   15
   0,61035E-04  0.62500E-01  0.14044E-02  0.13367E 00  0,64944E-02
   0,88478E 00  0.82138E 00  0.75989E 00  0.70044E 00  0,64307E 00
   0.58791E 00  0.53506E 00  0.48458E 00  0.43660E 00  0,39121E 00
   0,34847E 00  0.30847E 00  0.27128E 00  0.23691E 00  0,20543E 00
   0.17682E 00  0.15103E 00  0.12806E 00  0.10779E 00  0,90120E-01
   0,74969E-01  0.62201E-01  0.51779E-01  0.44926E-01
  -0,64330E-02 -0.62452E-02 -0.60486E-02 -0.58427E-02 -0,56275E-02
  -0,54026E-02 -0.51680E-02 -0,49239E-02 -0.46704E-02 -0,44080E-02
  -0,41377E-02 -0.38606E-02 -0.35781E-02 -0.32922E-02 -0,30049E-02
  -0,27189E-02 -0.24367E-02 -0.21611E-02 -0.18946E-02 -0.16390E-02
  -0,13950E-02 -0.11597E-02 -0.91703E-03 -0.75369E-04
```

均一乾燥モデルに基づく乾燥速度式に関する研究

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各種の食品乾燥装置を設計し，制御化などを行なっていくためには，簡単な乾燥モデルに基づいた乾燥速度式を設定し，それに含まれる速度パラメータを求めていくことが必要である。

既報[7)]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てきた。本報は，均一乾燥モデルに基づく乾燥速度式を設定する研究を行ない，寒天，にんじんならびに炊飯米を例として速度パラメータを算出して，両乾燥モデルの適用性について検討したものである。

均一乾燥モデルに基づく乾燥速度式として，乾燥表面積を簡単な近似式で仮定して表わした場合と，それが未消失含水量のべき乗で関係づけられるとした場合とを仮定した。両者の計算結果はよく似た結果になり，乾燥装置の設計などに対しては簡単なだけ後者が有用と考えられた。乾燥速度は，寒天とにんじんでは，未消失含水量のほぼ 0.5 乗に，炊飯米ではほぼ 1.0 乗に比例する結果が得られ，乾燥速度式におけ未消失含水量のべき乗値は試料により著しく異なる結果になることが分った。

既報の殻状乾燥モデルと本報に示した均一乾燥モデルによる計算結果を比較した結果，寒天およびにんじんでは大変よく似た結果が得られた。乾燥機構が明確でなく，よく似た結果が得られる場合には，取り扱いが簡単となる後者が有用と考えられる。