CHARACTERISTIC FUNCTIONS FOR THE DRYING OF NON-HYGROSCOPIC POROUS SLAB WITH A CONSTANT BODY TEMPERATURE

MASAMICHI YOSHIDA, HIRONOBU IMAKOMA AND MORIO OKAZAKI

Department of Chemical Engineering, Kyoto University,
Kyoto 606

Key Words: Drying, Characteristic Function, Non-hygroscopic Porous Material, Variable Diffusivity, Moving Boundary Problem

This paper deals with the isothermal drying process for slabs of non-hygroscopic porous material. First, the falling rate period is divided into the regular regime and the penetration period. Then the mass transfer equation involving a moving boundary is analyzed for both periods. In the regular regime, the relation between a modified flux parameter and a modified mean moisture content is characteristic of the dependence of moisture diffusivity on moisture content. On the other hand, in the penetration period, the relation between the flux parameter and the mean moisture content is not affected by the dependence of the diffusivity on the moisture content. These characteristic functions generalize the drying-rate curves, which differ with drying conditions. By using these functions, it may be possible to predict drying rate curves under any drying condition from a measured curve.

Introduction

In drying, the moisture diffusivity depends strongly upon the moisture content and the temperature, and the dependence varies with the material. The initial and boundary conditions of the mass transfer equation reflect the properties of a material and the operating conditions. Although there are many sets of equations and boundary conditions, the strict solutions of them are known in only a few cases.

The mathematically simplest system is, for example, the isothermal drying of a slab with a uniform initial moisture content and a constant surface moisture content; it corresponds to the drying of homogeneous materials such as soap and thin films. The following facts are known for this system:

1) For the beginning of the drying process, during which semi-infinite medium approximation is usable, the relation between drying rate and mean moisture content can be obtained analytically. The relation is valid even for systems with a diffusivity dependent on the moisture content.

2) For the later period, the above relation is not valid. When the diffusivity is constant, drying-rate curves with different initial conditions finally converge to a unique curve represented by an equation derived from the strict solution. Schoeber and Thijssen⁶⁾ ascertained through experiments with drying of liquid food and numerical calculations that every system has its own relation (convergence curve) between drying

rate and mean moisture content irrespective of the dependence of the diffusivity on the moisture content.

Schoeber and Thijssen⁶⁾ developed, on the basis of the above relations, a method to predict drying-rate curves for any drying conditions from only one measured curve without determining the dependence of the diffusivity on the moisture content.

Although the above relations cannot apply to materials other than homogeneous ones, the idea of generalizing the drying rate curves by such relations seems very useful and attractive. In this study, such relations are called the "characteristic functions". Characteristic functions for non-hygroscopic porous material is the subject of this paper.

1. Mass Transfer Equations

In this study, a one-dimensional drying process with a constant and uniform body temperature is investigated for slabs of non-hygroscopic porous material. The material is assumed to be isotropic and to remain unchanged in geometry during the drying process. The migrating component is water or similar moist substance.

In the constant-rate period, the drying process is described by the following equations:

$$\frac{\partial m}{\partial \tau} = \frac{\partial}{\partial \phi} \left(D_r(m) \frac{\partial m}{\partial \phi} \right) \quad (1)$$

$$\text{IC} \quad m = m_0 \quad \text{for } \tau = 0 \quad \text{and} \quad 0 \leq \phi \leq 1 \quad (2)$$

$$\text{BCs} \quad \partial m / \partial \phi = 0 \quad \text{for } \phi = 0 \quad \text{and} \quad \tau > 0 \quad (3)$$

* Received January 17, 1989. Correspondence concerning this article should be addressed to M. Yoshida.

$$-D_r(\partial m/\partial \phi) = F_0 \quad \text{for } \phi=1 \text{ and } \tau > 0 \quad (4)$$

where $\phi=1$ denotes the exposed surface of the material and $\phi=0$ the bottom. F_0 , called the drying intensity, is a dimensionless drying flux in the constant-rate period. D_r is a dimensionless moisture diffusivity defined as D_i/D_{i0} where D_{i0} is an arbitrary reference value. D_{i0} is set to be D_i at $m=1$ for calculations in this study. It is assumed that there exists a "transitional moisture content", m_b , below which the water cannot flow in liquid state and the moisture diffusivity is zero.^{7,8)} D_r for the isothermal drying of non-hygroscopic porous material is then expressed as:

$$D_r = \begin{cases} D_r(m) & \text{for } m_b \leq m \leq 1 \\ 0 & \text{for } 0 \leq m < m_b \end{cases} \quad (5)$$

The constant-rate period ceases when the surface moisture content reaches m_b .

During the falling-rate period, the material can be divided into dry and wet zones. At their boundary, called the evaporating plane, the water changes its phase. The mass transfer equation for the wet zone is the same as that for the constant-rate period. Boundary conditions for this period are:

$$m = m_b \quad \text{for } \phi = \eta \text{ and } \tau > \tau_e \quad (6)$$

$$-D_r(\partial m/\partial \phi) = F + m_b(d\eta/d\tau) \quad \text{for } \phi = \eta \text{ and } \tau > \tau_e \quad (7)$$

where F , called the flux parameter, corresponds to the drying rate, $-dm/d\tau$. The assumption that the dry zone is quasi-stationary yields the following relation between the drying rate and the location of the evaporating plane (**Appendix 1**):

$$F = \frac{F_0}{1 + Bi(1 - \eta)} \quad (8)$$

The dry zone is then regarded as an additional mass transfer resistance to that in the wet zone.

The mass transfer equation of the falling-rate period is difficult to solve numerically because of its moving boundary. A new spatial variable $\xi = \phi/\eta$ is hence introduced to transform the equation into that of a fixed boundary:

$$\eta^2 \frac{\partial m}{\partial \tau} - \eta \frac{d\eta}{d\tau} \xi \frac{\partial m}{\partial \xi} = \frac{\partial}{\partial \xi} \left(D_r \frac{\partial m}{\partial \xi} \right) \quad (9)$$

$$\text{ICs} \quad m = m_e(\xi) \quad \text{for } \tau = \tau_e \text{ and } 0 \leq \xi \leq 1 \quad (10)$$

$$\eta = 1 \quad \text{for } \tau = \tau_e \quad (11)$$

$$\text{BCs} \quad \partial m/\partial \xi = 0 \quad \text{for } \xi = 0 \text{ and } \tau > \tau_e \quad (12)$$

$$m = m_b \quad \text{for } \xi = 1 \text{ and } \tau > \tau_e \quad (13)$$

$$-D_r(\partial m/\partial \xi) = F\eta + m_b\eta(d\eta/d\tau) \quad \text{for } \xi = 1 \text{ and } \tau > \tau_e \quad (14)$$

Table 1. Various moisture diffusivities examined

Number	Moisture diffusivity
D-1	$D_r = 1$ [$m_b = 0, 0.2$]
D-2	$D_r = (m - m_b)^a / (1 - m_b)^a$ [$a = 0.6, 2, 3; m_b = 0, 0.2$]
D-3*	$D_r = \exp\{a(m - 1)\}$ [$a = 2, 4; m_b = 0, 0.2$]
D-4**	$D_r = \exp\left\{\sum_{n=0}^6 a_n m^n\right\}$ [$m_b = 0.2$]
	a_n ($n = 0, 1, \dots, 6$): $-20.07, 112.0, -252.8, 244.6, -83.73, 4.937 \times 10^{-4}, -6.751 \times 10^{-4}$

* loam, clay³⁾; sand, brick²⁾ ** unglazed alumina⁵⁾

Fig. 1. Change of moisture content profile with time; $D_r = \exp\{4(m - 1)\}$ and $m_b = 0.2$; (a) $F_0 = 0.1$, $Bi = 10$; (b) $F_0 = 10$, $Bi = 1000$. Numbers indicate τ .

2. Direct Numerical Solutions

The drying equations, Eqs. (1)–(4) and Eqs. (9)–(14), for which strict solutions are not known, have been solved numerically by a Crank-Nicolson finite difference method. The resultant numerical solutions are used to examine validity of the proposed theory. The types of dependence of moisture diffusivity on moisture content used for calculations are listed in **Table 1**.

Figure 1 shows typical numerical results for the changes of moisture content profiles with time. The calculation conditions for the two figures are the same, except for the material length; the material for Fig. 1-b is 100 times thicker than that for Fig. 1-a. Considering the shape of the moisture content profile, the falling-rate period may be divided into the

following two periods:

1) The period during which the moisture content at the bottom remains unchanged is called the "penetration period (PP)".⁴⁾

2) The period during which the moisture content at the bottom decreases is called the "regular regime (RR)".⁶⁾ In this period, the initial distribution of the moisture content has little effect on the profile.

Strictly speaking, two transitional periods may appear between the PP and the RR, and between the constant-rate period and the PP (or the RR in cases where the PP is absent). In this study, however, such transitional periods are not considered. Two characteristic functions, one for the PP and the other for the RR, will be formulated in the following sections.

3. Regular Regime in Falling Rate Period

3.1 Approximate solution for constant moisture diffusivity

This section deals with the regular regime of a constant moisture diffusivity ($D_r = 1$). Figure 2 shows typical numerical results of the relation between $\eta(d\eta/d\tau)$ and $\hat{m}$. To the left of the circled points, at which the moisture content at the bottom reaches 90% of its initial value, each curve is almost flat. It is hence assumed that the following equation is valid in the regular regime of $D_r = 1$:

$$\eta(d\eta/d\tau) = D_r \alpha = \text{const.} \quad (15)$$

where α is a constant depending on the drying condition. With and only with this assumption, Eqs. (9)–(14) can be solved analytically to yield:

$$\hat{F} = \frac{\pi^2}{4} D_r (\hat{m} - m_b) \quad (16)$$

where $\hat{F}$ is the modified flux parameter defined as $\hat{F} = F\eta + (\hat{m} + m_b\eta)(d\eta/d\tau)/2$ and $\hat{m}$ the modified mean moisture content defined as $\hat{m} = \bar{m}/\eta$ (Appendix 2).

The relation between $\hat{F}$ and $\hat{m} - m_b$ for $D_r = 1$ from direct numerical calculations are drawn in Fig. 3 for some drying conditions. Soon after the moisture content at the bottom reaches 90% of its initial value, all curves converge to a straight line expressed by Eq. (16). This is true for all the drying conditions and values of m_b examined here.

It can be concluded that when the moisture diffusivity is constant the relation between $\hat{F}$ and $\hat{m} - m_b$ of the regular regime is unique and independent of drying conditions. This is the characteristic function of the regular regime for a constant moisture diffusivity.

3.2 Characteristic function of regular regime for variable moisture diffusivity

For cases with a variable moisture diffusivity, it is generally difficult to derive a characteristic function analytically from the mass transfer equation. The

Fig. 2. Relation between $\eta(d\eta/d\tau)$ and $\hat{m}$ for constant diffusivity.

Fig. 3. Characteristic function of regular regime for constant moisture diffusivity

Fig. 4. Characteristic function of regular regime for variable diffusivities; D-2, 3 and 4 correspond to those in Table 1.

validity of the $\hat{F}$ vs. $\hat{m} - m_b$ plots is therefore examined for variable moisture diffusivities.

It is found from numerical results that curves of $\hat{F}$ vs. $\hat{m} - m_b$ with the same Bi/F_0 ratio converge in the regular regime. Figure 4 shows numerical results of $\hat{F}$ vs. $\hat{m} - m_b$ for some types of diffusivity, where only the parts of the curves corresponding to the regular regime are plotted (cf. Fig. 3). In these cases, curves with the same diffusivity are so close to each other that they can be regarded as a unique curve. The above applies to all the types of moisture diffusivity examined. This fact implies that even when the diffusivity depends upon the moisture content the

relation between $\hat{F}$ and $\hat{m}-m_b$ of the regular regime is independent of drying conditions and unique for the dependence of the diffusivity on the moisture content. The characteristic function of the regular regime can be thus defined by this unique relation, expressed generally as:

$$\hat{F} = \text{func.}(\hat{m}-m_b; D_r) \quad (17)$$

It is called the regular regime function hereafter. This function and Eq. (8) compose a set of ordinary differential equations in $\bar{m}$ and η . Once this function is obtained, the drying rate curves of the regular regime under any drying condition can be predicted by solving the set in some appropriate manner.

4. Penetration Period in Falling Rate Period

4.1 Semi-infinite medium approximation

Figure 5 shows numerical results of the relation between η and $\bar{m}$ for the case of $D_r = \exp\{4(m-1)\}$ and $m_b = 0.2$. At each white circle in the figure the moisture content at the bottom reaches 90% of its initial value. In the penetration period, which corresponds to the range of each curve between the white circle and the black one, η may be expressed as a linear function of $\bar{m}$ as $\eta = \beta\bar{m}$ where β is the constant of proportionality. Equation (8) can then be rewritten in the form:

$$\{1 + Bi(1-\eta)\}(d\eta/d\tau) = -\beta F_0 \quad (18)$$

This equation holds good in the penetration period for all the drying conditions and types of moisture diffusivity examined.

Since the moisture content at the bottom remains unchanged during the penetration period, the thickness of the material has no effect on the moisture content profile and hence this process is identical to that of a semi-infinite medium. By introducing a new independent variable, $\zeta = \{\eta(1-\xi)\}/\{1 + Bi(1-\eta)\}$, and using Eq. (18), Eqs. (9)–(14) are transformed into an ordinary differential equation problem of m depending on ζ :

$$\frac{d}{d\zeta} \left(D_r \frac{dm}{d\zeta} \right) + \beta F_0 (1 + Bi\zeta) \frac{dm}{d\zeta} = 0 \quad (19)$$

$$\text{BCs } m = m_0 \quad \text{for } \zeta = \infty \quad (20)$$

$$dm/d\zeta = 0 \quad \text{for } \zeta = \infty \quad (21)$$

$$m = m_b \quad \text{for } \zeta = 0 \quad (22)$$

$$-D_r(dm/d\zeta) = F_0 + m_b\beta F_0 \quad \text{for } \zeta = 0 \quad (23)$$

Equations (20) and (21) are derived by use of a semi-infinite medium approximation. Equation (23) is obtained from Eqs. (14) and (18).

4.2 Characteristic function of penetration period

For the case of $D_r = 1$, a strict solution of Eqs. (19)–(23) can be obtained in the form:

Fig. 5. Relation between location of evaporating plane and mean moisture content

$$m(\phi, \tau) = m_0 - (m_0 - m_b)h(\zeta) \quad (24)$$

where the function $h(\zeta)$ monotonously decreases with increasing ζ and should satisfy conditions $h(0) = 1$ and $h(\infty) = 0$.

Even when D_r depends on the moisture content, the profile change can be given as a function of ζ only, and is then expressed in the same form as Eq. (24), because Eq. (19) is an ordinary differential equation. On the basis of this fact, the following equation is obtained (Appendix 3):

$$F \left(m_0 - m + \frac{m_0}{Bi} \right) = \gamma = \text{const.} \quad (25)$$

where γ is a constant determined by the drying condition and the dependence of moisture diffusivity on moisture content, but which usually cannot be evaluated in analytical ways. Once γ is determined in some manner, which is discussed later, drying-rate curves for the penetration period can be drawn from Eq. (25).

Differentiating Eq. (25) with respect to $\bar{m}$ leads to an important relation which does not include the unknown constant γ :

$$G = \frac{\bar{m}}{m_0 - \bar{m} + (m_0/Bi)} \quad (26)$$

where

$$G \equiv d(\ln F)/d(\ln \bar{m})$$

Numerical results of the relation between G and $\bar{m}$ are plotted in Fig. 6 for two types of diffusivity. In the penetration period, which corresponds to the range of each curve between the white and black circles, Eq. (26) is approximately valid irrespective of the type of diffusivity. It is confirmed that the above is true for all the drying conditions and types of moisture diffusivity investigated here. The relation between G

Fig. 6. Characteristic function of penetration period

and $\bar{m}$ of the penetration period is not influenced by the dependence of moisture diffusivity on moisture content but is determined only by drying conditions, Bi and m_0 . This is the characteristic function of the penetration period and is called the penetration period function here.

The constant γ can be determined in the following way. The penetration period function is readily available from Eq. (26). A curve of G vs. $\bar{m}$ for the regular regime can be plotted if the regular regime function is known. The curve of G vs. $\bar{m}$ for the whole process is then obtained by connecting those two curves at their intersection where the transition occurs. Since both F and $\bar{m}$ of the penetration period are equal to the same quantities for the regular regime at that point, γ can be evaluated by substituting those values into Eq. (25).

Conclusion

In the isothermal drying process of a non-hygroscopic porous slab, the falling-rate period can be divided into the regular regime and the penetration period. For both periods, the characteristic functions are derived by analyzing the mass transfer equation involving a moving boundary problem. Their mathematical forms and features are summarized below.

1) In the regular regime of a constant moisture diffusivity, $\hat{F}$ is a linear function of $\hat{m} - m_b$ with no parameter. Even for a variable moisture diffusivity, the relation between $\hat{F}$ and $\hat{m} - m_b$ is independent of the drying condition and is characteristic of the dependence of moisture diffusivity on moisture content.

2) In the penetration period, G is expressed as a function of $\bar{m}$ with parameters Bi and m_0 . This function is not affected by the dependence of moisture

diffusivity on moisture content.

The characteristic functions are generalized forms of the drying-rate curves, which differ with drying conditions. This implies that by using these functions drying-rate curves under any drying conditions may be predicted from a measured curve.

Appendix 1

The mass flux of the vapor across the dry zone can be estimated as that for the steady-state diffusion process. The intruded amount of air is so small that the mass flux of the vapor is formulated as¹⁾:

$$n_v = \frac{M_v \bar{D}_{ev} (p_s - p_i)}{RTL(1 - \eta)} \quad (\text{A-1})$$

where p_s is vapor pressure at the evaporating plane, evaluated as the saturated value at the material temperature. The effective diffusivity of vapor, $\bar{D}_{ev}$, is defined as:

$$\bar{D}_{ev} = \frac{D_{eav}}{c(y_s - y_i)} \ln \left(\frac{1 - cy_i + D_{av}/D_{kv}}{1 - cy_s + D_{av}/D_{kv}} \right) \quad (\text{A-2})$$

where $c = 1 - \sqrt{M_v/M_a}$ and D_{eav} is the effective air-vapor diffusivity defined as:

$$D_{eav} = (\varepsilon/q)D_{av} \quad (\text{A-3})$$

The vapor flux across the film on the material surface is given as:

$$n_v = k_g(p_i - p_a) \quad (\text{A-4})$$

Elimination of p_i from Eqs. (A-1) and (A-4) yields Eq. (8), in which dimensionless parameters F and Bi , are introduced.

Appendix 2

Analysis begins with the assumption that Eq. (9) has the solution of the form:

$$m(\xi, \tau) = m_b + f(\tau)g(\xi) \quad (\text{A-5})$$

Substitution of Eq. (A-5) into Eq. (9) yields

$$\frac{1}{D_r f} \frac{\eta^2}{\tau} \frac{df}{d\tau} = \frac{1}{g} \left(\frac{1}{\eta} \frac{d\eta}{d\xi} \xi \frac{dg}{d\xi} + \frac{d^2 g}{d\xi^2} \right) \quad (\text{A-6})$$

Since Eq. (15) holds in the regular regime, Eq. (A-6) can be separated into two ordinary differential equations. The equation with respect to τ has a strict solution. The other with respect to ξ is approximately solved by the perturbation method. An approximate solution of the mean moisture content is then expressed as:

$$\bar{m} = m_b \eta + \eta \sum_{n=1}^{\infty} C_n \exp \left(-\lambda_n^2 D_r \int_{\tau_e}^{\tau} \frac{d\tau}{\eta^2} \right) \quad (\text{A-7})$$

where C_n should be determined by the initial conditions. λ_n is an eigen value expressed as:

$$\lambda_n = l_n + \alpha/(4l_n), \quad l_n = (2n-1)\pi/2$$

When time is large enough, terms in Eq. (A-7) with n larger than 1 are negligible since λ_n increases and C_n decreases with n . The mean moisture content is then approximately expressed as:

$$\bar{m} = m_b \eta + C_1 \eta \exp \left(-\lambda_1^2 D_r \int_{\tau_e}^{\tau} \frac{d\tau}{\eta^2} \right) \quad (\text{A-8})$$

Differentiation of this equation with respect to τ yields an equation in F :

$$F = -m_b \frac{d\eta}{d\tau} + C_1 \left(\lambda_1^2 \frac{D_r}{\eta} - \frac{d\eta}{d\tau} \right) \exp \left(-\lambda_1^2 D_r \int_{\tau_e}^{\tau} \frac{d\tau}{\eta^2} \right) \quad (\text{A-9})$$

Elimination of unknown parameters from Eqs. (A-8) and (A-9) yields Eq. (16).

Appendix 3

For cases with a variable diffusivity, the functional form of $h(\zeta)$ is usually unknown because of the difficulty in solving Eqs. (19)–(23) analytically.

The mean moisture content is obtained from Eq. (24) as:

$$\bar{m} = m_0\eta - (m_0 - m_b)\{1 + Bi(1 - \eta)\} \int_0^{\zeta_1} h(\zeta) d\zeta \quad (\text{A-10})$$

where $\zeta=0$ denotes the evaporating plane and $\zeta=\zeta_1$ the bottom. In the entire range of $\zeta > \zeta_1$, which is a fictitious one, the moisture content remains unchanged and hence $h=0$. Consequently, the definite integral in the above equation with time-dependent unknown boundary ζ_1 is equivalent to the following definite integral:

$$I = \int_0^\infty h(\zeta) d\zeta \quad (\text{A-11})$$

where the value of this equation is a constant depending on the drying condition. The elimination of η in Eq. (A-10) by using Eq. (8) after replacing the definite integral in Eq. (A-10) with I yields

$$F\left(m_0 - \bar{m} + \frac{m_0}{Bi}\right) = \frac{F_0 m_0}{Bi} + (m_0 - m_b)F_0 I = \text{const.} \quad (\text{A-12})$$

The value of the above equation is indicated by γ in Eq. (25).

Nomenclature

a	= parameter	[—]
Bi	= Biot number of mass transfer ($= k_g L / (M_v \bar{D}_{ev} / RT)$)	[—]
D_{av}	= air-vapor diffusivity	[m ² /s]
D_{eav}	= effective air-vapor diffusivity	[m ² /s]
$\bar{D}_{ev}$	= effective diffusivity of vapor	[m ² /s]
D_{Kv}	= Knudsen diffusivity	[m ² /s]
D_l	= moisture diffusivity	[m ² /s]
D_r	= dimensionless moisture diffusivity ($= D_l / D_{l0}$)	[—]
F	= flux parameter ($= nL / (D_{l0} \rho_m^*)$)	[—]
F_0	= drying intensity ($= n_0 L / (D_{l0} \rho_m^*)$)	[—]
$\hat{F}$	= modified flux parameter ($= F\eta + (\bar{m} + m_b\eta)(dn/d\tau)/2$)	[—]
k_g	= film mass-transfer coefficient	[kg/(Pa · s · m ²)]
L	= thickness	[m]
M	= molecular weight	[kg/mol]
m	= moisture content ($= \rho_m / \rho_m^*$)	[—]
$\bar{m}$	= modified mean moisture content ($= \bar{m} / \eta$)	[—]
n	= mass flux, drying rate	[kg/(m ² · s)]
P	= atmospheric pressure	[Pa]
p	= partial pressure of vapor	[Pa]

q	= tortuosity factor	[—]
R	= gas constant	[J/(mol · K)]
T	= absolute temperature	[K]
t	= time	[s]
x	= distance from bottom	[m]
y	= molar fraction of vapor	[—]
ε	= porosity	[—]
ζ	= independent variable ($= \eta(1 - \xi) / \{1 + Bi(1 - \eta)\}$)	[—]
η	= location of evaporating plane from bottom	[—]
ξ	= independent variable ($= \phi / \eta$)	[—]
ρ	= mass concentration	[kg/m ³]
τ	= dimensionless time ($= D_{l0} t / L^2$)	[—]
ϕ	= dimensionless distance ($= x / L$)	[—]

<Subscripts>

a	= air
b	= transitional
e	= end of constant-rate period
i	= interface
l	= liquid
s	= evaporating plane
v	= vapor
0	= initial, constant-rate period

<Superscripts>

*	= saturation
—	= mean value

Literature Cited

- Asaeda, M., M. Nakano and R. Toei: *J. Chem. Eng. Japan*, **7**, 37 (1974).
- Endo, A., I. Shishido, M. Suzuki and S. Ohtani: *AIChE Symp. Ser.*, **73** (163), 57 (1977).
- Gardner, W. R. and M. S. Mayhugh: *Soil Sci. Soc. Amer. Proc.*, **22**, 197 (1958).
- Higbie, R.: *Annln Phys.*, **53**, 959 (1894).
- Imakoma, H., M. Okazaki and R. Toei: *J. Chem. Eng. Japan*, **18**, 184 (1985).
- Schoeber, W. J. A. H. and H. A. C. Thijssen: *AIChE Symp. Ser.*, **73** (163), 12 (1977).
- Toei, R., S. Hayashi, S. Sawada and T. Fujitani: *Kagaku Kogaku*, **29**, 525 (1965).
- Wyckoff, R. D. and H. G. Botset: *Physics*, **7**, 325 (1936).