The Liquid Fraction of Moisture Transfer in the Drying Process of a Bed of Granular and Powdered Materials

By

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(Received October, 1, 1964)

To investigate the mechanism of the moisture transfer in the drying process of a bed of non-adsorptive granular and powdered materials, the drying experiments of a bed of such materials containing the dilute NaCl solution were performed. The liquid fraction of moisture transfer was defined and calculated from the experimental data.

The drying mechanism during the first falling rate period was deduced from these results.

1. Introduction

The drying process of bed of non-adsorptive granular and powdered materials is distinguished to three periods, i.e. constant rate period, first and second falling rate periods like the typical drying rate curve as shown in **Fig. 1.**

It is usually accepted that the moisture is transported through the bed by liquid form during the constant rate period. It was recognized that the moisture is transported by vapor diffusion through the dried-up zone of the bed during the second falling rate period.[1] But the mechanism during the first falling rate period has not yet been investigated enough.

It is necessary for the study of the drying mechanism during the first falling rate period to investigate whether the moisture is transported by liquid or vapor form. The coexistence of both can be supposed readily during this period.

Johanson[2] suggested the idea that liquid moisture transfer and vapor transfer coexist in the drying process. Recently Luikov[3] introduced the phase transformation number in his theory of heat and mass transfer for capillary porous bodies.

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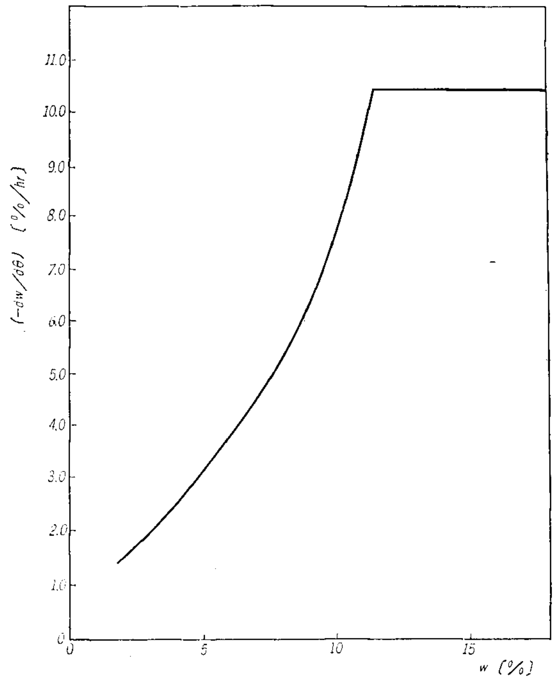

Fig. 1. Typical drying rate curve (Run S-3-95, sand 28~35#, t_a=95°C, H_a=0.0076, V_a=5.63 m/sec, L=3 cm).

There are several parameters to define the ratio of liquid moisture and vapor transfer to the total moisture transfer. The local fraction of liquid in moisture transfer f_l' and the local fraction of vapor in moisture transfer f_v' characterizing the relative intensity of internal evaporation in an infinitesimal volume are defined as follows;

$$f_v' = \frac{dc_v}{dc} = \frac{dc_v}{dc_l + dc_v} \tag{1}$$

$$f_l' = \frac{dc_l}{dc} \tag{1'}$$

$$f_v' + f_l' = 1 \tag{1''}$$

where dc_v represents quantity of vapor transfer and dc_l represents quantity of liquid moisture transfer in an infinitesimal volume.

The sectional fraction of liquid in moisture transfer f_l and the sectional fraction of vapor in moisture transfer f_v defined over the length from bottom (L) to the any section in the bed (x_i) are determined as follows;

$$f_v = \frac{R_{i_v}'}{R_i'} = \frac{R_{i_v}'}{R_{i_v}'+R_{i_l}'} \tag{2}$$

$$f_l = \frac{R_{i_l}'}{R_i'} \tag{2'}$$

$$f_v + f_l = 1 \tag{2''}$$

where R_{i_v}' is the evaporation rate over the length $x_i \sim L$ and R_{i_l}' is the liquid moisture transfer rate over the length $x_i \sim L$ and R_i' is the drying rate over the length $x_i \sim L$. The total fraction of vapor and the total fraction of liquid in moisture transfer related to the entire volume of the bed are found as follows;

$$f_{v_0} = \frac{R_v'}{R'} = \frac{R_v'}{R_l'+R_v'} \tag{3}$$

$$f_{l_0} = \frac{R_l'}{R'} \tag{3'}$$

$$f_{l_0} + f_{v_0} = 1 \tag{3''}$$

where R_v' is the total internal evaporation rate R_l' is the evaporation rate at surface and R' is the total drying rate. Experimental investigations about "the phase transformation number" such as f_v' and f_l' were performed by Polonskaya[4] at first. She obtained $f_v'=0.045$ at the drying of sand bed by analysing mathematically the temperature distribution through the bed during the constant rate period. But her analysis is restricted to the constant rate period and not applied to the whole period of drying. "The phase transformation number" such as f_v' and f_l' should be measured directly. Veinik and Schubin[5,6,7] have made this study using the radioisotope as tracer.

They investigated the influence of various factors on the values of the integral phase transformation numbers qualitatively rather than quantitatively.

The purpose of our paper is to investigate the influence of various factors on the values of the local and sectional phase transformation number such as f_v, f_l, f_v', f_l' at the drying process of a bed of non-adsorptive granular and powdered materials which are considered as the typical capillary porous bodies. The influence of the moisture content is investigrted particularly, which is considered as a predominant factor. In this connection, the study of liquid diffusion ratio at the drying of clay has been published by Wakabayashi[8], in which he has shown that the moisture is transported in the liquid as wall as vapor form.

2. Experimental Equipment and Procedure

The experimental equipment used for the experiment is the same as described previously[1]. The cross section of the measuring part was enlarged to 43 cm width and 13 cm height in order to eliminate the difference of the drying rate with position. The experimental procedure is carried out as follows. The material to be tested is moistened with a dilute solution (0.5~1%) of NaCl salt to a definite initial moisture content. The prepared material is packed into the containers for measuring the weight change, temperature distributions and moisture content distributions and NaCl concentration distributions.

At any desired time, one container is taken out and the container is sliced into 9 rings. The moisture content of the individual zone of the bed is measured. After that the NaCl concentration is measured. The concentration of NaCl is measured by the electrical conductivity of a solution which is prepared by dispersing the material of the individual section with the definite quantity of water. The materials used for these experiments are glass beads (50~90#), sand (15~30#, 30~60#, 60~80# and 80~120#) and a fine powder of calcium carbonate. The drying conditions are changed variously ; especially, the air temperature is changed from 50°C to 100°C.

3. Calculation of the Liquid Fraction of Moisture Transfer

The calculation method of the sectional fraction of liquid in moisture transfer is obeyed to Wakabayashi[8]. At **Fig. 2**, the transfer rate of total moisture, R_i', through the plane $x=x_i$ is given by the formula ;

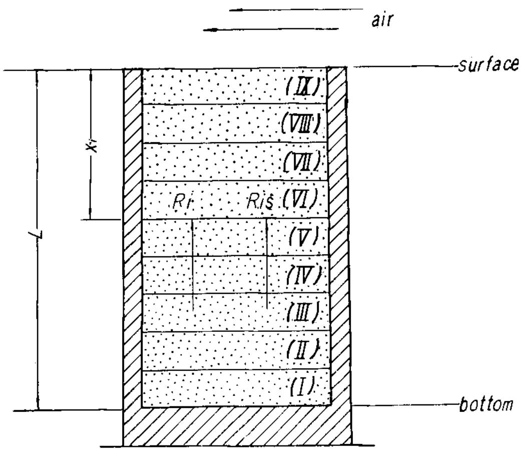

Fig. 2. Description of measuring sample.

$$R_i' = -\frac{d}{d\theta}\int_{x_i}^{L} c dx \tag{4}$$

The migration rate of NaCl, R_{is}' is given by the formula ;

$$R_{i_s}' = -\frac{d}{d\theta}\int_{x_i}^{L} c_s dx \tag{5}$$

The liquid moisture transfer can be traced by the migration of NaCl dissolved in the liquid. So the liquid moisture transfer rate through the plane $x=x_i$ can be determined by the following formula ;

$$R_{i_l}' = \left(\frac{c}{c_s}\right)_{x=x_i} R_{is}' + \left(\frac{c}{c_s}\right)_{x=x_i} D_s \left|\frac{\partial(c_s/c)}{\partial x}\right|_{x=x_i} \tag{6}$$

The second term of the right hand side of eq. (6) represents the diffusion to the opposite direction due to a salt concentration gradient in the liquid. The magnitude of this term is negligibly small compared with the first term for the most part during the first falling rate period. So R_{i_l}' is determined approximately by the following formula ;

$$R_{i_l}' = \left(\frac{c}{c_s}\right)_{x=x_i} \left(-\frac{d}{d\theta}\int_{x_i}^{L} c_s dx\right) \tag{7}$$

Consequently the sectional fraction of liquid in moisture transfer over the length $L\sim x_i$ is given by the following formula ;

$$f_{l_i} = \frac{-\left(\frac{c}{c_s}\right)_{x=x_i}\frac{d}{d\theta}\int_{x_i}^{L} c_s dx}{-\frac{d}{d\theta}\int_{x_i}^{L} c dx} \tag{8}$$

The sectional fraction of vapor in moisture transfer f_{v_i} is given by

$$f_{v_i} = 1 - f_{l_i}$$

The local fraction of liquid in moisture transfer may be determined by the following formula with above approximated situation,

$$f_l'{}_{x_i+\Delta x/2} = \frac{\left\{-\left(\frac{c}{c_s}\right)_{x_i}\frac{d}{d\theta}\int_{x_i}^{L} c_s dx\right\} - \left\{-\left(\frac{c}{c_s}\right)_{x_i+\Delta x}\frac{d}{d\theta}\int_{x_i+\Delta x}^{L} c_s dx\right\}}{\left(-\frac{d}{d\theta}\int_{x_i}^{L} c dx\right) - \left(-\frac{d}{d\theta}\int_{x_i+\Delta x}^{L} c dx\right)} \tag{9}$$

The alternative formula of eq. (9) is used for actual calculation ;

$$f_l'{}_{x_i+\Delta x/2} = \frac{f_{lx_i}\left(-\frac{d}{d\theta}\int_{x_i}^{L} c_s dx\right) - f_{lx_i+\Delta x}\left(-\frac{d}{d\theta}\int_{x_i+\Delta x}^{L} c_s dx\right)}{\left(-\frac{d}{d\theta}\int_{x_i}^{L} c dx\right) - \left(-\frac{d}{d\theta}\int_{x_i+\Delta x}^{L} c dx\right)} \tag{10}$$

Eqs. (8), (9) and (10) could not be used if the deposition of salt occurs. The calculation procedure is as follows. Actually the terms of $\sum c\Delta x \fallingdotseq \Delta x \sum c$ and $\sum c_s \Delta x \fallingdotseq \Delta x \sum c_s$ were calculated instead of $\int_{x_i}^{L} c dx$ and $\int_{x_i}^{L} c_s dx$. **Fig. 3** shows the moisture distribution curves obtained at the experiment of Run No. 11 and **Fig. 4** shows the NaCl distribution curves obtained at the same experiment. **Fig. 5** and **Fig. 6** show the plotting the values of $\sum_{x_i} c$ and $\sum_{x_i} c_s$ respectively against time. From Fig. 5 and Fig. 6 the values of $-\frac{d}{d\theta}\sum_{x_i} c$ and $-\frac{d}{d\theta}\sum_{x_i} c_s$ are obtained by graphical differentiation. Then the values of f_l are calculated by eq. (8) and the values of f_l' are calculated by eq. (10) using the values of f_l. **Fig. 7** shows the relation of f_l from Run No. 11 versus

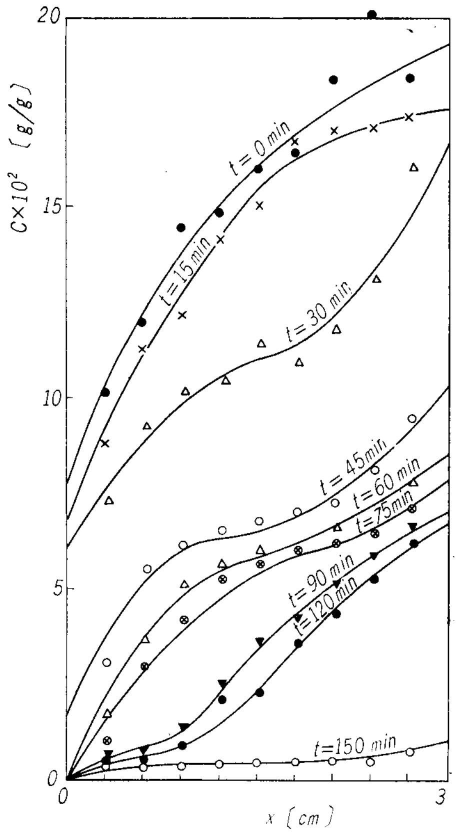

Fig. 3. Moisture distribution curves (Run 11, sand, 15~30#, t_a=100°C, H_a=0.011, V_a=2.5 m/sec, initial moisture content 15%, L=3 cm).

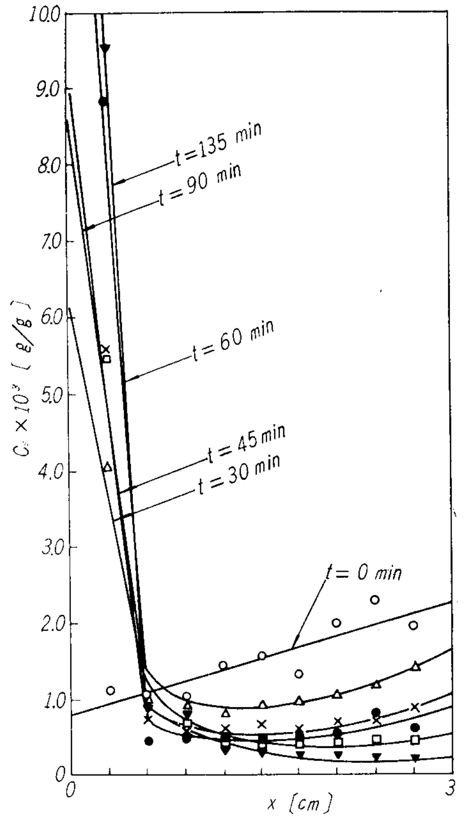

Fig. 4. NaCl distribution curves (Run 11).

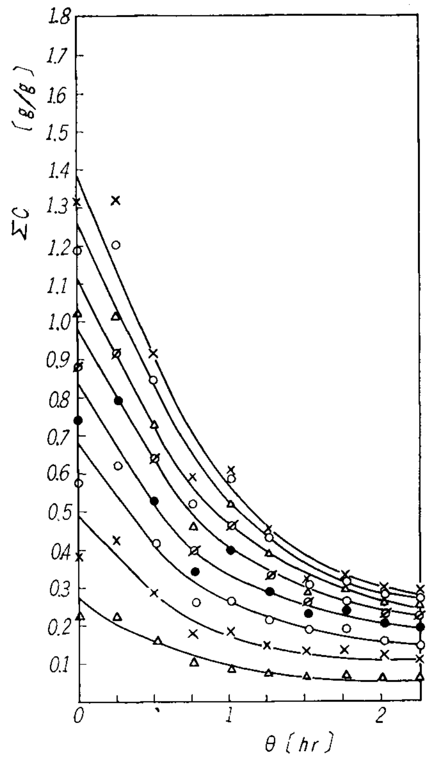

Fig. 5. $\sum c$ vs. θ (Run 11).

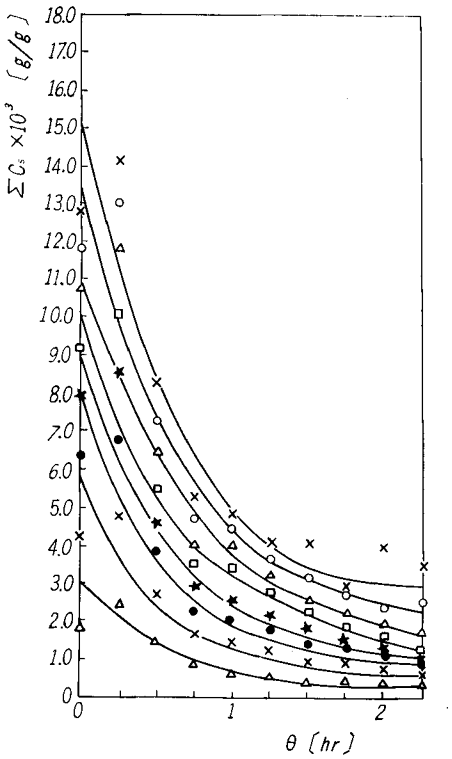

Fig. 6. $\sum c_s$ vs. θ (Run 11).

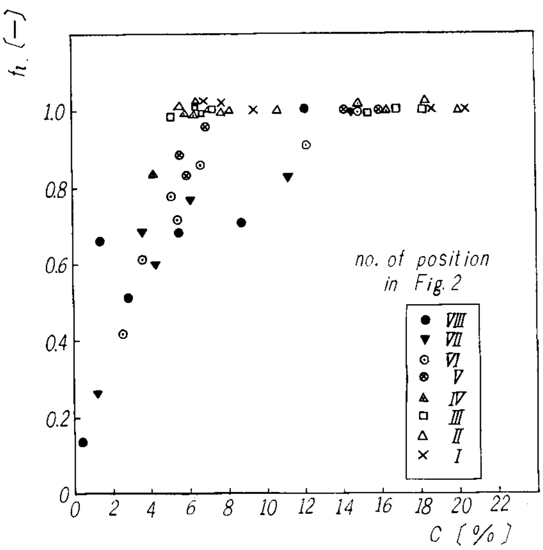

Fig. 7. f_l vs. c (Run 11).

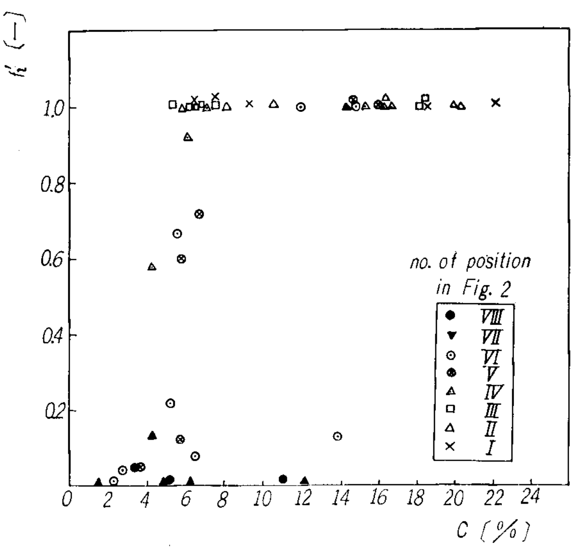

Fig. 8. f_l' vs. c (Run 11).

the moisture content and **Fig. 8** shows the relation of f_l' from Run No. 11 versus the moisture content.

4. Experimental Results

It is observed from Fig. 7 and Fig. 8 that the value of f_l or f_l' is maintained at the value of one in some range of moisture content. This fact means that all of the moisture is transfered in liquid form above the critical moisture content, c_{f_l} at which the values of f_l or f_l' being to decrease from one. As the experiment of Run No. 11 is performed at high initial moisture content, the experimental data at low moisture content is not reliable by the deposit of salt. So most experiments are performed at low initial moisture content in order to obtain the values of f_l and f_l' at the neighbourhood of c_{f_l} as truly as possible. The results described in **Fig. 9** and **Fig. 10** are the examples of such experiments.

Fig. 10 shows that the values of f_l' decrease steeply with decreasing moisture content and decrease immediately from one to zero. The dependencies of f_l' with c are nearly the same for any depths of bed and each value of f_l' at any depths decreases from the same critical moisture content c_{f_l} with the exception of the value at suface. A similar fact is recognized in the other experiments. **Fig. 11** and **Fig. 12** show an example of the relation f_l and f_l' with c in the experiment of the glass beads and **Fig. 13** and **Fig. 14** show an example of the same relation in the experiment of $CaCO_3$ (fine powder).

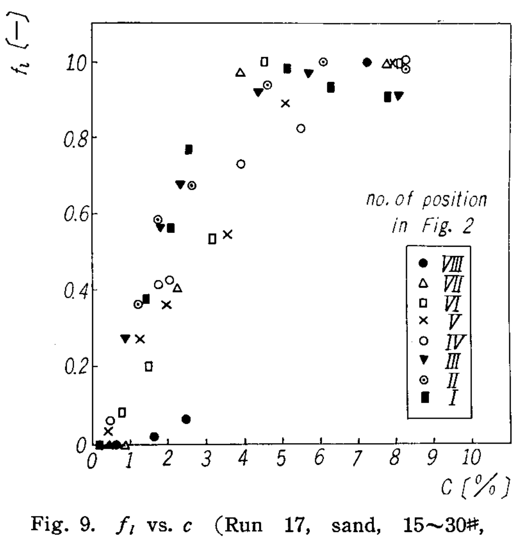

Fig. 9. f_l vs. c (Run 17, sand, 15~30#, t_a=61°C, H_a=0.023, V_a=3.3 m/sec initial moisture content 8%, L=3 cm).

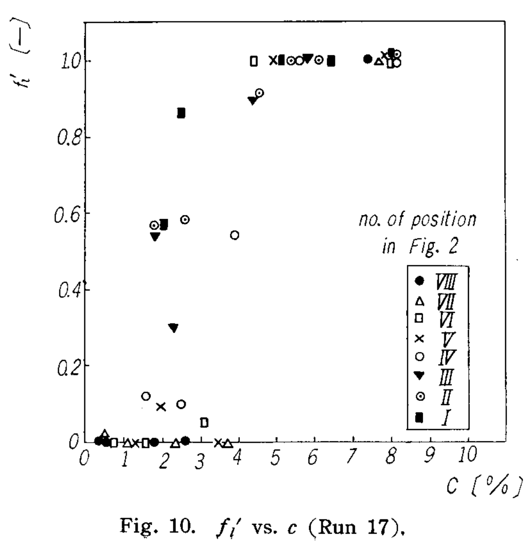

Fig. 10. f_l' vs. c (Run 17).

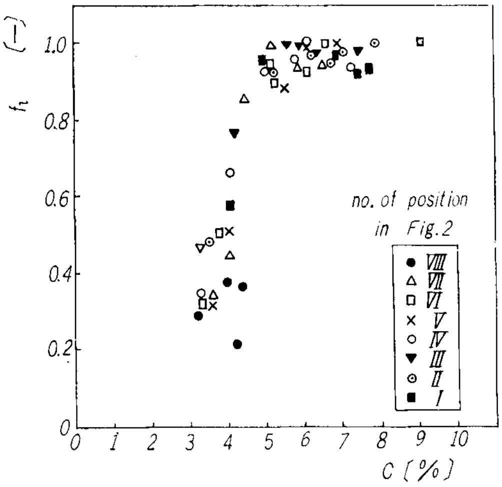

Fig. 11. f_l vs. c (Run 1, glass beads, 50~90#, t_a=50°C, H_a=0.012, V_a=5.5 m/sec, initial moisture content 7%, L=3 cm).

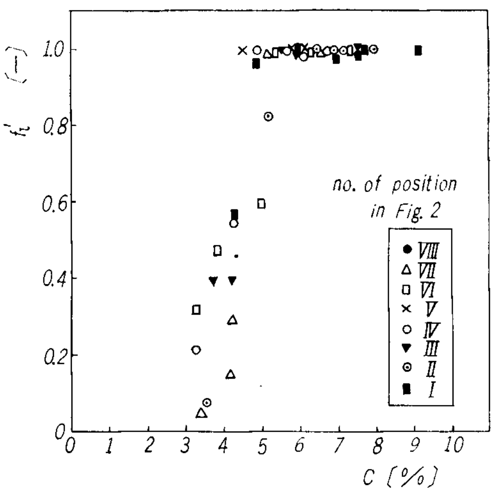

Fig. 12. f_l' vs. c (Run 1).

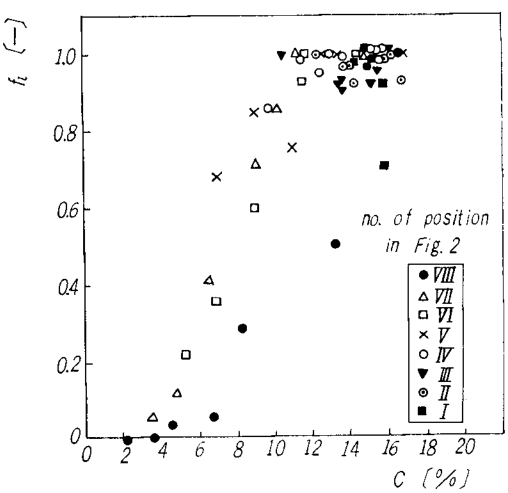

Fig. 13. f_l vs. c ($CaCO_3$, t_a=60°C, H_a=0.017, V_a=2.9 m/sec, initial moisture content 15% L=3 cm).

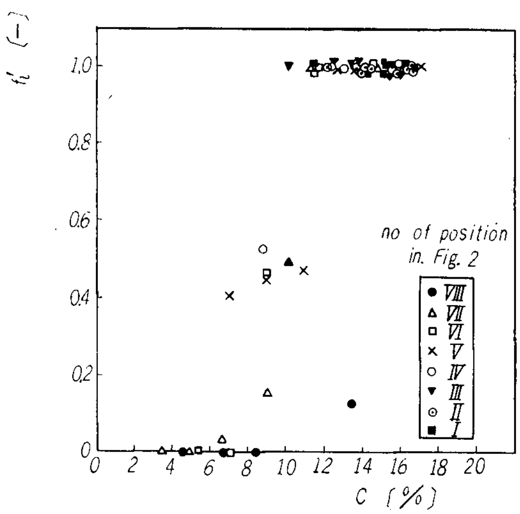

Fig. 14. f_l' vs. c ($CaCO_3$, the same exp. of Fig. 13).

The moisture content c_{f_l}' at which the value of f_l' reaches to zero is defined as the critical moisture content for the vapor transfer. The vapor transfer only occurs below c_{f_l}'.

The values of c_{f_l} and c_{f_l}' are not influenced by the change of the external drying conditions ; for example, c_{fl} and c_{fl}' change scarcely by increasing the

Table I. The exprimental values of c_{f_l} and c_{f_l}'.

Material	t_a (°C)	H_a (kg/kg)	V_a (m/sec)	w_0 (%)	L (cm)	c_{f_l} (%)	c_{f_l}' (%)
sand 15～30#	100	0.011	2.5	15	3	6.0 } av. 5.4	3.5
sand 15～30#	61	0.023	3.3	8	3	4.5	2.0
sand 30～60#	62	0.021	2.9	7	3	6.0	3.0
sand 80～120#	62.5	0.020	2.9	7.5	3	5.0	2.5
glass bead 50～90#	50	0.012	5.5	7	3	4.5	3.0
$CaCO_3$ (fine powder)	60	0.017	2.9	15	3	11.0	7.0

air temperature from 50°C to 90°C. Then it can be recognized that the influence of the moisture content to f_l and f_l' is predominant in the range of the experimental conditions. The values of c_{f_l}' and c_{f_l} are tabulated in **Table I.** **Fig. 15** shows the schematical curve of f_l' vs. local moisture content c. This curve is not dependent on the external drying conditions and is characterized by the two critical values of c_{f_l} and c_{f_l}'. The values of f_l' is maintained at the value of one above the moisture content c_{f_l}. Then f_l' decreases suddenly and reaches to zero at the moisture content c_{f_l}'. This means that only the liquid moisture transfer occurs above c_{f_l} and only the vapor transfer occurs below c_{f_l}'. In the range between c_{f_l} and c_{f_l}' the both transfer coexists, but this range is sufficiently small.

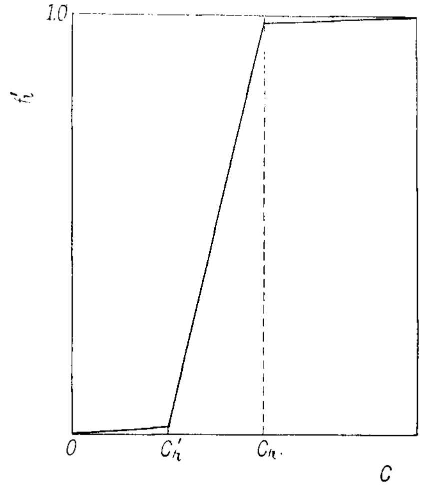

Fig. 15. Schematic curve for f_l' vs. c.

5. Consideration of Drying Mechanism

We try to compare the value of c_{f_l} with the moisture content characterizing the drying process such as the surface moisture content c_{sc} at the critical moisture content w_c. The surface moisture content at drying of a bed moistening with NaCl solution is not reliable by the deposition of NaCl. So the values of the surface moisture content c_{sc} at the critical moisture content w_c are obtained from the other drying experiments of bed not containing NaCl. The values of c_{sc} for sand are tabulated in **Table II.** The values of c_{sc} are not dependent on the particle diameter and the experimental conditions,

Table II. The experimental value of c_{sc}

Material	t_a (°C)	H_a (kg/kg)	V_a (m/sec)	L (cm)	c_{sc} (%)
sand 10~16#	70.5	0.012	3.30	3	5.0
sand 16~32#	70.7	0.012	1.80	3	6.1
sand 28~35#	70.0	0.0076	5.63	3	6.0
sand 35~60#	70.2	0.011	2.25	3	6.5
sand 60~80#	70.3	0.0102	4.5	3	5.0
sand 60~80#	80.8	0.0086	5.5	3	4.0
				average value of c_{sc}	5.4

and are found 5.4% on average. By comparing the values of c_{sc} with the values of c_{f_l} in Table I, the agreement of both is fairly good. These results are consistent with the fact that during the constant rate period above the critical moisture content the moisture is transfered by liquid form and consequently the surface evaporation takes place, because the local moisture contents of all depths are maintained above c_{sc} ($\fallingdotseq c_{f_l}$). Below the critical moisture content the surface moisture content decreases from c_{sc} and the plane of the moisture content c_{sc} ($\fallingdotseq c_{f_l}$) retreats into the bed. In the region between this plane and surface, the value of f_l' is below one. So the vapor transfer appears and soon after becomes predominant in this region. This region increases continuously as the drying proceeds.

Fig. 16 shows the schematic model of drying mechanism of bed during the first falling rate period. It is considered that the rate controlling steps during the first falling rate period are the vapor transfer resistances at surface air film and in the region of $0 \sim x'$ as shown on Fig. 16. The mechanism continues until the surface moisture content reaches

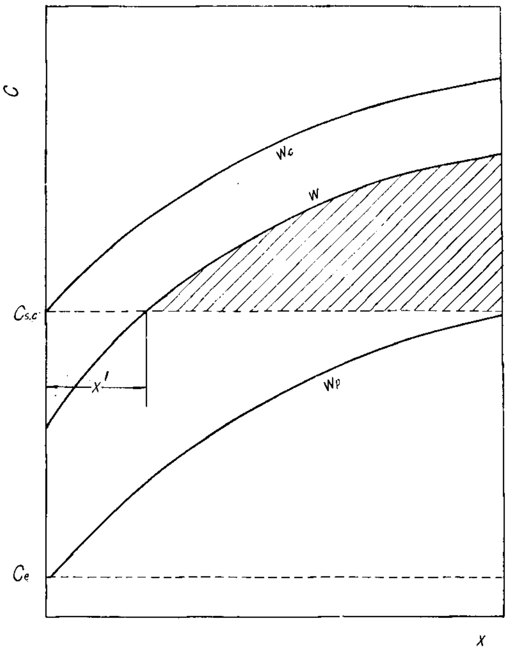

Fig. 16. Schematic model of drying mechanism of bed during the first falling rate period

to the equilibrium moisture content, namely, the average moisture content reaches the second critical moisture content w_p. The drying mechanism during the first falling rate period will be analysed by the authors based on the present conclusion in the succeeding paper.

Acknowledgement

The authors wish to express their appreciations to Mr. S. Sawada and Mr. T. Fujitani for their assistances in conducting the experiments and also to Hattori Hokokai to their financial assistance in this work.

Normenclature

c	:	local moisture content	[% or g/g-dry solid]
c_{f_1}	:	critical moisture content for the liquid moisture transfer	[% or g/g-dry solid]
c_{f_l}'	:	critical moisture content for the vapor transfer	[% or g/g-dry solid]
c_s	:	NaCl concentration in solid	[g/g-dry solid]
c_{sc}	:	surface moisture content at critical moisture content w_c	[% or g/g-dry solid]
D_s	:	diffusion coefficient of NaCl in bed	[cm^2/hr]
f_l	:	sectional fraction of liquid in moisture transfer	[−]
f_l'	:	local fraction of liquid in moisture transfer	[−]
f_{l_0}	:	total fraction of liquid in moisture transfer	[−]
f_v	;	sectional fraction of vapor in moisture transfer	[−]
f_v'	:	local fraction of vapor in moisture transfer	[−]
f_{v_0}	:	total fraction of vapor in moisture transfer	[−]
L	:	depth of bed	[cm]
R'	:	total drying rate	[cm/hr]
R_i'	:	moisture transfer rate over the length $x_i \sim L$ of the bed	[cm/hr]
R_{i_l}'	:	moisture transfer rate due to liquid moisture transfer over the section ($x_i \sim L$) of the bed	[cm/hr]
R_{i_s}'	:	quantity of moving NaCl through a plane $x=x_i$ per unit time	[cm/hr]
R_{i_v}'	:	moisture transfer rate due to vapor transfer over the section ($x_i \sim L$) of the bed	[cm/hr]
R_l'	:	evaporation rate at the surface	[cm/hr]
R_v'	:	total internal evaporation rate	[cm/hr]
w_c	:	critical moisture content	[% or g/g-dry solid]
w_p	:	second critical moisture content	[% or g/g-dry solid]
x	:	distance from surface	[cm]

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