AN ESTIMATING METHOD OF TEMPERATURE AND MOISTURE CONTENT DISTRIBUTIONS IN A CONTINUOUS COUNTER-CURRENT DRIER

Chikao ARAI, Setuo MARUTA,
Akihiko FUJII and Yoshiki SANOH

Dept. of Textile Chem. Eng., Shinshu Univ., Ueda, Japan

INTRODUCTION

Counter-current drier is one of the useful drying apparatus which has been most widely used. When such a drying apparatus is designed, temperature, moisture content, humidity and heat and mass transfer coefficients have to be estimated. Although there are so many reports concerning with heat transfer coefficient, in many cases, the mass transfer coefficients have been estimated from the heat transfer coefficient assuming that LEWIS's law is applicable.

Several authers have proposed how to estimate the temperature of solid particles and air, moisture content and humidity in a drier. In one of those methods,[6] the required values are estimated from heat and mass balance equations with some assumptions. These assumptions are obtained from the viewpoint that a drying process can be divided into three periods; pre-heat, constant drying rate and decreasing drying rate periods. In the other method,[3] the required values are estimated from humidity distribution using enthalpy-humidity chart. Sarples[4] and Garside[2] have obtained the moisture content and temperature distributions in a rotary drier using the heat and mass balance equations. However, their viewpoints of drying rate have still contained the many unsoluble problems.

The purpose of this study is to estimate moisture content and temperature distributions in a counter-current drier. In the first place, the fundamental heat and mass balance equations and heat and mass transfer rate equations have been derived. Next, we have constructed a drying apparatus in which solid particles and air were contacted with simplest process. Then, the theory was compared with the experimental results.

1 ESTIMATION OF TEMPERATURE AND MOISTURE CONTENT DISTRIBUTIONS

The model with cross sectional area A (m^2) and length l (m) shown in **Fig. 1**, makes it possible to interpret our counter-current drier. The material to be dried is supplied steadily to the drier with feed rate G_s' (kg dry solids /hr), temperature t_i (°C) and moisture content w_i (—). After the materials are dried at hold up ϕ (—), the temperature and moisture content at the outlet of the drier are varied to t_o and w_o, respectively. On the other hand, air is supplied through the outlet of the drier with feed rate G_a' (kg dry air/hr), temperature T_o (°C) and humidity H_o (—), and is exhausted from the inlet of materials with temperature T_i and humidity H_i.

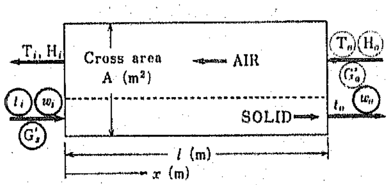

Fig. 1 The model of a counter-current drier.

When a drier is designed, the values of some parameters such as G_s', w_i, w_o and t_i (shown with sign ◎ in **Fig. 1**) should be determined. Next, the values of parameters such as G_a', T_o and H_o (signed with ○) are determined from the capacities of heater or burner and blower. Another values of the parameter, however, must be calculated by any methods.[6] In this section, both the change of temperature and moisture content in a drier and the unknown values of the parameters mentioned above are calculated.

1-1 Basic Equations

1) *Mass Balance Equation* : If moisture content and humidity are uniform at any cross section of the drier shown in **Fig. 1**, the mass balance equation is given by Eq. (1),

$$G_s'\frac{dw}{dx}=G_a'\frac{dH}{dx}. \tag{1}$$

Let G_s and G_a denote mass velocities of material and of air, respectively. Then we have

$$G_s'=A\ \phi\ G_s,\ \ G_a'=A(1-\phi)\ G_a. \tag{2}$$

Furthermore α is defined as

$$\alpha=G_s'/G_a'=\phi\ G_s\ /\ (1-\phi)\ G_a. \tag{3}$$

Using Eq. (3), Eq. (1) may be rearranged as

$$\alpha\frac{dw}{dx}=\frac{dH}{dx}. \tag{1'}$$

2) *Drying Rate Equation* : Previously, it has been widely accepted that the driving force of drying is the difference between saturated humidity at temperature of solids surface and humidity of air H_w-H. During the surface drying period, however, mass transfer mechanism on the solid surface may be approximated by a unidirectional diffusion model. Therefore, if π (atm), p_s (atm) and p are the total pressure of air, saturated water vaper pressure and vapor pressure correspond to humidity H, respectively, then $\pi\ ln\{(\pi-p)/(\pi-p_s)\}$ must be adopted for the driving force. It is the reason that at high temperature and at high humidity, the error due to using humidities instead of the unidirectional diffusion model is at least several ten percent.[5]

Let k (kg/m² hr Δp), W (kg) and S (m²) denote mass transfer coefficient based on gas phase partial pressure, weight of the solid particles to be dried and the effective drying surface area, respectively. Then surface drying rate R_c is expressed as

$$R_c=-\frac{W}{S}\frac{dw}{d\theta}=k\pi ln\frac{\pi-p}{\pi-p_s}. \tag{4}$$

Since the drying mechanism in the decreasing drying rate period is very complicate and has many unsoluble problems, the universal rate equation has not been obtained yet unfortunately. In deriving the equation for decreasing drying rate period, VAN MEEL[7] found that the ratio of decreasing drying rate to surface drying rate $f(\phi)=R_d/R_c$, is expressed by a function of moisture content of material only and does not depend upon the drying conditions. In this study, his method was used, that is, Eq. (5) was adopted as the decreasing drying rate equation.

$$R_d=R_c\ f(\phi),\quad \phi=(w-w_e)/(w_c-w_e). \tag{5}$$

In general, the effective drying surface area S in Eq. (4) may be unknown. Let ρ_s (kg/m³) and ka (kg/m³ hrΔp) denote the bulk density of particles and volumetric coefficient of mass transfer, respectively. Then Eq. (4) can be expressed as follows,

$$-\rho_s\frac{dw}{d\theta}=ka\pi ln\frac{\pi-p}{\pi-p_s}. \tag{4'}$$

Furthermore, if moving velocity of solid particles layer along a drier axis is v (m/hr), from Eqs. (4') and (5) with $v\theta=x$ and $\rho_s v=G_s$, we have

$$-G_s\frac{dw}{dx}=ka\pi ln\frac{\pi-p}{\pi-p_s}f(\phi),\quad f(\phi)=1\ (w\geqq w_c). \tag{6}$$

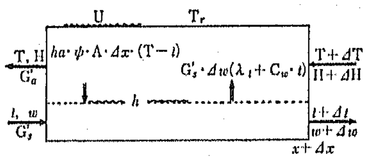

Fig. 2 Enthalpy-balance of a drier and heat-balance of solid particles layer from x to $x+\Delta x$ along a drier axis

3) *Heat Balance Equation* : The fundamental enthalpy balance equation in a drier is derived as follows. Consider an element of volume in the form of a rectangular parallel piped whose sides are parallel to the axis of coordinates and are of length Δx as shown in **Fig. 2**. The heat loss per unit length of the drier is assumed to be proportional to the circumference area of the drier A_r (m^2) and to the temperature difference between the air in the drier and the atmosphere, $T-T_r$ (°C). If over all coefficient of heat transfer is U (kcal/m^2 hr°C), the heat loss from the drier shell is equal to $UA_r(T-T_r)\Delta x$. Therefore, enthalpy balance equation is given as follows

$$\begin{aligned}&G_a'\{(C_a+C_m(H+\Delta H))\ (T+\Delta T)+\lambda_o(H+\Delta H)\}+G_s'(C_s+C_w w)t\\&=G_a'\{(C_a+C_mH)\ T+\lambda_oH\}+G_s'\{(C_s+C_w(w+\Delta w))\ (t+\Delta t)\}\\&+UA_r(T-T_r)\ \Delta x,\end{aligned}$$

where λ_o is latent heat of vaporization of water at 0°C, C is specific heat (kcal/kg°C), and subscripts s, a, w and m denote solid particles, air, water and moisture, respectively. Neglecting the second order differential terms, and substituting the next relations into the above equation

$$\begin{aligned}G_a'\Delta H(C_mT+\lambda_o)&=G_s'\Delta w(C_mT+\lambda_o),\\C_mT+\lambda_o-C_wt&=C_m(T-t)+\lambda_o+C_mt-C_wt\\&=C_m(T-t)+\lambda_t,\end{aligned}$$

the enthalpy balance is given by Eq. (7)

$$\begin{aligned}&(C_a+C_mH)\frac{dT}{dx}\\&=\alpha(C_s+C_ww)\ \frac{dt}{dx}-\alpha\{C_m(T-t)+\lambda_t\}\ \frac{dw}{dx}+\frac{UA_r}{G_a'}\ (T-T_r).\end{aligned} \tag{7}$$

4) *Heat Transfer Rate Equation* : Let ha (kcal/m^3 hr°C) denote volumetric coefficient of heat transfer as shown in **Fig. 2**. Using the heat balance equation for the solid particles layer, the heat transfer rate equation is given as

$$ha(T-t)=G_s(C_s+C_ww)\ \frac{dt}{dx}-G_s\lambda_t\frac{dw}{dx}. \tag{8}$$

Eqs. (1′), (6), (7) and (8) are the fundamental equations to estimate the temperature and the moisture content distributions in the counter-current drier.

1-2 Calculating Method

In order to estimate the temperatures of the solid particles and air and moisture content, we had some assumptions as follows, 1) there is not mass transfer in the pre-heat period, 2) the temperature of solid particles is constant in the surface drying period and 3) $f(\phi)$ defined by Eq. (5) is proportional to the dimensionless moisture content ϕ, in the decreasing drying rate period.

In this study, without concerning these assumptions, the basic equations are solved by the numerical calculation under the initial conditions.

Integration of Eq. (1′) gives

$$H=H_i+\alpha(w-w_i). \tag{9}$$

By rearrangement of Eq. (6), the change of moisture content is given as

$$\frac{dw}{dx}=-\frac{ka}{G_s}\pi\, ln\frac{\pi-p}{\pi-p_s}f(\phi). \tag{10}$$

Let M_w and M_a denote molecular weight of water and air, respectively. The relation between partial pressure p and humidity H may be given approximately as follows

$$H=\frac{M_w}{M_a}\frac{p}{\pi-p}. \tag{11}$$

From Eq. (8), the temperature gradient of the solid particles layer is obtained as

$$\frac{dt}{dx}=\{ha(T-t)+G_s\,\lambda_t\frac{dw}{dx}\}\ /\ G_s(C_s+C_w w). \tag{12}$$

Eq. (7) gives the air temperature gradient as

$$\frac{dT}{dx}=\alpha\{(C_s+C_w w)\frac{dt}{dx}-(C_m(T-t)+\lambda_t)\frac{dw}{dx}$$
$$+L(T-T_r)\ /\ \alpha\}\ /\ (C_a+C_m H), \tag{13}$$

where $L=UA_r\ /\ G_a'$.

The latent heat of vaporization at t°C, λ_t, specific heats C_a, C_s, C_w and C_m in Eqs. (12) and (13) are functions of temperature and λ_t (kcal / kg) is approximated by the following simple equation,

$$\lambda_t \simeq a_1t^2+a_2t+a_3, \tag{14}$$

where $a_1=-1.25\times10^{-3}$, $a_2=-0.388$ and $a_3=591.4$ $(200>t>0°C)$. The maximum error due to this approximation is within 0.2 per-cent in the region from 0 to 200°C. Since temperature dependence of specific heat is very small, specific heats are treated as constants in this study.

Temperature and moisture content distributions can be calculated numerically by solving Eqs. (9), (10), (12) and (13) with the initial conditions $w=w_i$, $t=t_i$, $H=H_i$ and $T=T_i$ at $x=0$. In the first place, when the initial conditions (H_i and T_i may be arbitrarily chosen) are given and $f(\phi)$ is equal to 1 at $w \geqq w_c$, the values of t, w, H and T can be calculated numerically at the coordinate from $x=0$ to $x=l$. In general, the obtained numerical values of H and T at $x=l$ may be different from those H_o and T_o which are given at the beginning of the calculation. Therefore, the values of H_i and T_i are corrected by the obtained results and the calculations must be repeated many times until the values of H and T become equal to those of H_o and T_o at $x=l$.

Using the above method, the temperature and moisture content distributions in a drier and values of T_i, H_i and t_o can be estimated.

2 EXPERIMENTAL

2-1 Apparatus

A schematic diagram of the experimental apparatus used is shown in **Fig. 3**. The apparatus is composed of two parts, one is a counter-current band type drier (①~⑦) and the other is the section for conditioning of the air (⑨~⑭). The body of drier is a box type with 3.5 meters in length, 25 centi-meters in height and 30 centi-meters in width. It is covered with an iron plate and veneer board for insulating from heat. The both ends of the drier's body have two discal plates (④) which are opened in the form of square at their center. These plates are held over another two holding plates (⑤). Ball bearings are set between the discal and the holding plates. The

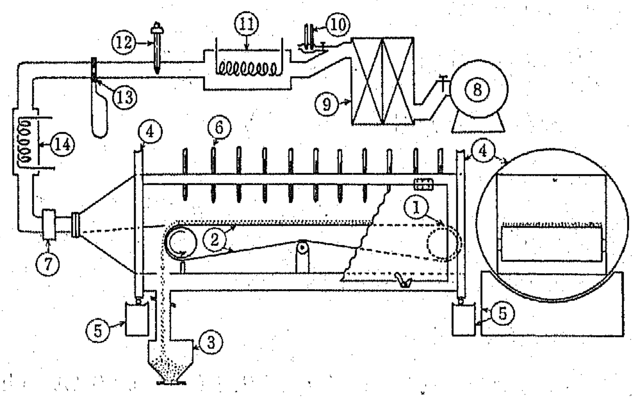

Fig. 3 Experimental apparatus.

drier's body is connected to the pipe by an expansion joint (⑦). Since the drier has the structure mentioned above, the drier's body can be rotated up to 90°. Moreover, one side of the drier wall can be opened.

In a drier's body, a band of wire net (②), whose sizes are 3.3 meters in length and 26 centi-meters in width, is set up to carry the materials. The band is moved by a moter. Wet materiales are supplied at the one end of drier ①), moved contacting with air, and discharged in the hopper (③) after dried. As results of some considerations, the air is blown only on the surface of the band in the drier. In order to measure the temperature distribution of the air in the drier, the eleven thermometers (⑥) are set up at the equal intervals along a center of upper wall of the drier.

Air is blown from a blower (⑧) to a dehumidification tower (⑨) in which granular silica-gel is packed, through a control valve. A part of air is carried into a dry- and wet-bulb hygrometer (⑩), and humidity is measured. After the dehumidificational operation, air is heated to the desired temperature by heater (⑪), and is blown in the drier through the orifice meter (⑬) and heater (⑭).

2-2 Experimental Methods

The air, coditioned at desired temperature and humidity, is blown into the drier. When the each thermometer shows the constant temperature, the feed of wet materials is started. At this time, the air temperature is decreased because the materials are supplied. After the air temperature shows constant value again, the inside of the drier can be regarded as the steady state. Then, the temperatures of solid particles and air and moisture content are measured.

2-2-1 Supplying Method of the Materials

The feed materials are previously immersed in water at the constant temperature. The definite volume of the particles with the constant size are taken out from the water to a vessel with wire net at the bottom. Water absorbed on the surface of solid particles is dropped through the net for a definite time. After the feed materials are poured into another vessel, whose size is 10.7 centi-meters in length, 24 centi-meters in width and 0.6 centi-merers in depth, they are supplied on the moving band at a definite time intervals. The moisture content of feed materials can be nearly constant.

2-2-2 Measurement of Moisture Content

The experiments were carried out by measuring of the weight of the solid materials.

Moisture content distribution along a drier axis was measured as follows.

When the steady state had been achieved, supply of the materials was stopped. At the same time, one side of a drier wall was opened, and a drier was rotated to 90°. Then solid particles in a drier were fallen down into the many weighing bottles arranged on a table under the drier. The weight of the each of them was weighed, and the moisture content distribution was calculated.

2-2-3 M3asurement of Temperature of Solid Particles

It is very difficult directly to measure the temperature of solid particles surface in a drier. In many cases, previously, temperature of solid particles has been measured by a thermocuple immersed in solid particles layer.

In this study, temperature of solid particles was determined using a calorimeter. With the assumption that there was no temperature distribution inside a particle, it was regarded that the temperature of solid particles was equal to the temperature at the solid surface.

The temperature distribution along a drier axis at steady state was measured as follows. When the solid particles were fallen down into the weghing bottles, another part of solid particles was poured into a calorimeter filled by 1000 ml of water. The temperature elevation of water in the calorimeter was measured by a BECKMANN's thermometer. The temperature of the solids was calculated from the values of weight of the solid and water, their specific heats, the moisture content of the solids and water equivalent of the calorimeter.

2-2-4 Measurement of Temperature of Air

Temperature distribution of air along the drier axis was measured by the eleven thermometers that had been calibrated. Before the solid particles were supplied into the drier, the apparatus was heated for about five hours. After every thermometers indicated constant tempereture respectively, the temperature of air was measured. Using this data, the heat loss from the drier was calculated. Moreover, after starting of material feed, the each thermometer indicated constant value again. These values have been taken as temperature of the air.

2-3 Materials

When the method mentiond in the previous section is used, the experimental materials must satisfy the following conditions. 1) The heat of wetting of the materials must be very small or negligible. If the heat is large, the error of measurement due to use the wetted particles may be large. Therefore, silica-gel or active carbon, which have been widely used, is not suitable as the sample. 2) The particle size must be small so as not to show the temper-

Table 1 The properties of Soma Sand

Particle size	(mesh)	5~6
Density	(kg/m^3)	2620
Bulk density	(kg/m^3)	1500
Specific heat	(kcal/kg°C)	0.18

ature distribution inside of a particle. For this reason, Soma Standard Sand of 5 to 6 mesh was used.

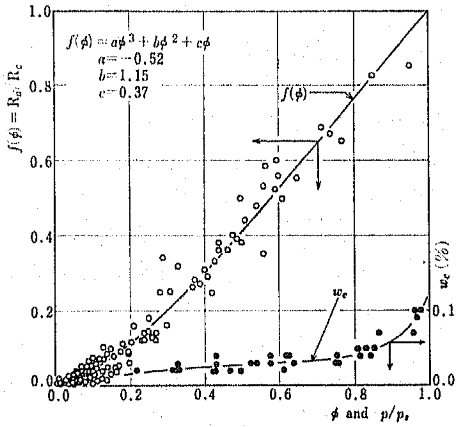

Fig. 4 Decreasing drying rate characteristic and equilibrium moisture content from 10 to 50°C.

Some properties of the Sand are shown in **Table 1.** The characteristics of the decreasing drying rate period $f(\phi)$ and the equilibrium moisture content of Soma Sand are shown in **Fig. 4.** As shown in **Fig. 4,** the equilibrium moisture content is very small and no affected by temperature. Therefore in this study, it is assumed that the equilibrium moisture content is equal to zero.

Details for a characteristics of decreasing drying rate period and equilibrium moisture content should be reported in the separate paper.

3 RESULTS AND DISCUSSIONS

3-1 Experimental Conditions

Each experiment was carried out under the almost equal conditions which are shown in **Table 2.**

Table 2 Experimental conditions

		Average value	Standard deviation
Feed rate of solids : G_s'	(kg/hr)	14.5	0.76
Feed rate of air : G_a'	(kg/hr)	37.1	0.62
Temperature of inlet solid : t_i	(°C)	22.0	0.13
Inlet moisture content : w_i	(-)	0.034	0.001
Temperature of inlet air : T_o	(°C)	98.3	1.5
Inlet air humidity : H_o	(-)	0.0092	0.0007
Surrounding temperature : T_r	(°C)	21.9	1.5
Velocity of solids : v	(m/hr)	7.92	0.38

According to the experimental method shown in the previous section, the parameters are divided into the two groups. One is easy to control experiementally such as the temperature of feed materials, and the other is difficult to do such as the surrounding temperature of a drier. Therefore, in principle, the experimental conditions are changed slightly in each run. One of the index of fluctuation in the experimental conditions may be the standard deviation of the experimental parameters calculated by Eq. (15),

$$\sigma=\sqrt{1/N\sum(X_i-\bar{X})^2}. \tag{15}$$

3-2 Results

The distributions of solid moisture content and of temperature of solid

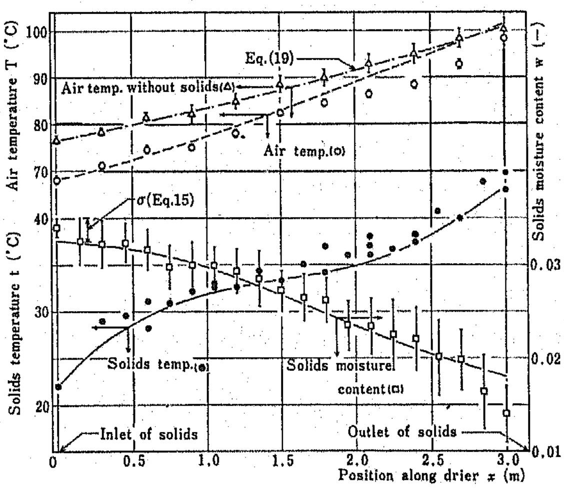

Fig. 5 Air and solid particles temperatures and moisture content distributions.

particles and air are shown in **Fig. 5**. Every plots for moisture content and temperature of air are the average values of 78 or 26 measurements, respectively. The standard deviation for the obtained values are shown with the average values in the same figure. The curves shown in **Fig. 5** were calculated by the method mentioned in the Section 1.

3-2-1 Moisture Content Distribution along a Drier

Moisture content of solid particles at 20 points along a drier axis were measured. The average values and the standard deviations for these measurements are shown in **Fig. 5**. The moisture content at the inlet ($x=0$) was obtained from the weight of solid particles which were sampled at the beginning of the feed. From **Table 2** and **Fig. 5**, it is clear that the moisture content decreased so rapidly with an increase in x–axis to $x=0.15$ (m). On the other hand, the standard deviation of the moisture content was increased from about 3 per-cent to 8 per-cent when the position in the drier varried from $x=0$ to $x=0.15$. Considering the fact that, when a cloth band was used, the moisture content was decreased by approximately one-half between the above-mentioned positions, this phenomenon was considered to be due to the transfer of a part of water adsorbed from the surface of particles to the wire net of the band.

The decrease in moisture content was a little from $x=0$ to $x=0.4\sim0.6$ along x–axis in the drier (this section corresponds to "pre-heat period"). After passing through the preheat period, the moisture content decreased with nearly constant rate. The last two points of measurement evidently suggest the end effect of the apparatus appeared.

In this study, the standard deviation was used as a expression of the fluctuation of moisture content of any cross-section of a drier. Increase of the standard deviation is due to the two causes; one is the difference of experimental conditions as shown in **Table 2**, and the other is the vertical fluctuation of moisture content in a cross-section of drier. Therefore, as is evident from **Fig. 5**, the increase of standard deviation of moisture content with the proceeding of drying process might be due to the fact that the drying of solid particles has been carried out un-uniformly.

In a rotary drier, generally, mixing of solid particles in cross-section is carried out sufficiently. In a band type drier, as mixing of solid particles is difficult, drying of particles may be done un-uniformly. This phenomenon is one of the weak points of this type drier.

3-2-2 Solids Temperature Distribution

As a calorimeter was used for measurements of temperature of solid particles, the only one value of temperature could be obtained at every run. Rapid raising of temperature of solid particles was observed in the vicinity of inlet of feed. Passing through the region, the temperature of the solid particles gradually increased with an increase in x-axis in the drier. In the region of $x>1.6\sim2$ (m), the raising of the temperature of solid particles was remarkable again.

3-2-3 Air Temperature Distribution

The air temperature distribution along the x-axis in the drier at steady state is also shown in **Fig. 5**. The standard deviation of air temperature were calculated by Eq. (15). A little differences of the conditions of each run may produce the such fluctuation of the values.

3-3 Some Characteristic Values of the Apparatus

3-3-1 Volumetric Coefficient of Mass Transfer : ka

In a counter-current drier, the drying process is unsteady. Therefore, as the driving force of drying is varied, the surface drying rate calculated by Eq. (4) is not constant. However, assuming that mass transfer coefficient k is constant, volumetric coefficient of mass transfer ka is calculated by using Eq. (4′) and the experimental results of moisture content in the surface drying period.

From Eq. (4′), we have

$$ka\int_{\theta_1}^{\theta_2} d\theta = -\rho_s\int_{w_1}^{w_2}\frac{dw}{\pi\ ln\{(\pi-p)\ /\ (\pi-p_s)\}}.$$

Eq. (1′) reads

$$\alpha\ dw = dH.$$

From these two equations, ka is shown as

$$ka = \frac{\rho_s}{\alpha(\theta_2-\theta_1)}\int_{H_2}^{H_1}\frac{dH}{\pi\ ln\{(\pi-p)\ /\ (\pi-p_s)\}}. \qquad (16)$$

The relation between p and H in Eq. (16) is given by Eq. (11). The integration of the right hand side of Eq. (16) must be done by a graphical method. Of cause, the range of the integration must be the surface drying period.

As shown in **Fig. 5**, a boundary between the surface and the decreasing drying rate periods is not so clear. However, from the experimental data of the critical moisture content of Soma Sand obtained by the packed bed type drier, the surface drying rate period may be extended up to about $x=1.5$. Futhermore, since the change of moisture content from $x=0$ to $x=0.4$ (m) was so small, the integration region in Eq. (16) was adopted from $x=0.6$ to

1. 5(m).

Using the values shown in **Table 2** and the result of graphical integration of Eq. (16), the volumetric coefficient of mass transfer ka is obtained as follows,

$$ka = 2700 \quad (\text{kg/m}^3\text{hr}\Delta\text{p}).$$

If $k'a$ is a volumetric coefficient of mass transfer based on humidity difference ΔH, the values of $k'a$ is calculated approximately as

$$k'a \doteqdot 29/18ka = 4350 \quad (\text{kg/m}^3\ \text{hr}\Delta\text{H}).$$

3-3-2 Volumetric Coefficient of Heat Transfer : ha

Relations among volumetric coefficient of heat transfer ha, moisture content and temperature of solid particles and air are given by Eq. (8). If change of moisture content and temperature of solid particles is small in length Δx along the axis in the drier, Eq. (8) can be written approximately as

$$ha(T-t) = G_s(C_s + C_w\overline{w})\frac{dt}{dx} - G_s\overline{\lambda_t}\frac{dw}{dx},$$

where $\overline{w}$ and $\overline{\lambda_t}$ are average values of moisture content and latent heat of vaporization in the small ragion Δx. Then, we have

$$ha = \frac{G_s}{\Delta x(T-t)_{lm}}\{(C_s + C_w\overline{w})\,\Delta t - \overline{\lambda_t}\Delta w\}. \tag{17}$$

The volumetric coefficient is calculated as follows. The surface drying period ($x = 0.6$ to 1.5) is devided in equal distance ($\Delta x = 0.3$m) and the value of ha in each region is calculated from Eq. (17). The volumetric coefficient of heat transfer is the average value of the ha's value in each Δx,

$$ha = 1020 \quad (\text{kcal/m}^3\ \text{hr}^\circ\text{C}).$$

The ratio of ha and $k'a$ calculated in the previous section is $ha / k'a = 0.23 \simeq C_H$. From this value, it is considered that LEWIS's law is valid in the surface drying rate period.

3-3-3 Heat Loss from the Drier Shell

Before suppling materials, the drier is heated by air. Because of the heat loss from the drier shell, the temperature distribution of air is as shown in **Fig. 5.** At that time, since the feed materials is not supplied in the drier, Eq. (7) becomes as follows,

$$G'_a(C_a + C_m H)\frac{dT}{dx} = UA_r(T - T_r).$$

Integration the above equation with the relation $C_a + C_m H = C_H$ gives

$$U=\frac{G'_a\ C_H}{A_r(x_2-x_1)}\ ln\frac{T_2-T_r}{T_1-T_r}. \tag{18}$$

The over-all heat transfer coefficient U is calculated by the same method as ha is done,

$$U=2.0\ \ (\text{kcalm}^2\ \text{hr}^\circ\text{C}).$$

Since air temperature T is equal to exhausted air temperature T_i at inlet of solid particles ($x=0$), air temperature distribution along x-axis in the drier is shown as follows,

$$T=T_r+(T_i-T_r)\ \exp(UA_r\ x\ /\ G'_a\ C_H). \tag{19}$$

In **Fig. 5**, the numerical value calculated by Eq. (19) is shown by the dotted line.

3-4 Discussions

3-4-1 Comparison of Calculated Results with Experimentals

The numerical results, calculated by Eqs. (9), (10), (12) and (13) under the initial conditions shown in **Table 3**, and the experimental results are shown in **Fig. 5**.

Table 3 Initial conditions in calculation

G_s	(kg/m²hr)	12000
t_i	(°C)	22.0
w_i	(-)	0.0325
T_i	(°C)	67.9
H_i	(-)	0.018
T_r	(°C)	21.9
w_c	(-)	0.025
ka	(kg/m³hr)	2700
ha	(kcal/m³hr)	1020
L	(kcal/kg°C)	0.018
α	(-)	0.39
π	(atm)	0.95

In these calculation, $f(\phi)=1$ for $w\geqq w_c$ and $f(\phi)=a\phi^3+b\phi^2+c\phi$ for $w<w_c$. Since the moisture content is equal to the critical value w_c at $x=1.76$ (m), this point is regarded as the boundary between the surface and decreasing drying rate period.

The calculation values of the moisture content and particles temperature distributions along a drier are in fair agreement with the experimental values. While the calculated values of air temperature also agreed fairly with the experimental values in the surface drying period, the calculated values of those are a little larger than those observed in the decreasing drying rate period. This difference between the calculated values and the observed may be said to result from the following facts. Although the temperature gradient of the air along the coordinate of the drier is calculated by Eq. (13), Eq. (13) contains the many assumptions in the derivation for the gradient of moisture content and of temperature of solid particles and heat loss. And so the values calculated contain the considerable errors.

3-4-2 Comparison of the Present Method with the Previous Study

The experimental values and the calculated values in this study are compared with those calculated by the method appeared in the literature.[6] The results is shown in **Fig. 6**. The solid lines in **Fig. 6** show the values calculated by the literature's method. Those values were calculated by using Eqs. (9), (10), (12) and (13) under the following assumptions. 1) The driving force of drying process is H_w-H, 2) the mass transfer does not take place in the pre-heat period, 3) the temperature of solid particles is constant in the surface drying period and 4) the decreasing drying rate is proportinal to the

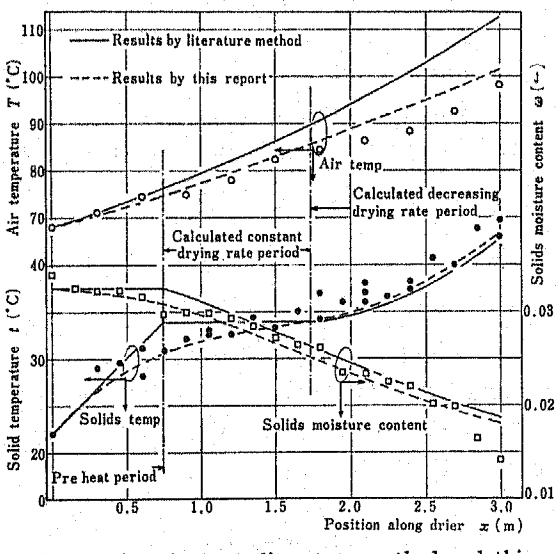

Fig. 6 Comparrison between literature method and this report.

dimensionless moisture content, *viz.*, $f(\phi)=\phi$. Because of these assumptions, the solid lines contain a little artificial points as shown in **Fig. 6**. However the significant differences between the solid lines and the dotted lines can not be observed for the moisture content and the temperature of solid particles. On the contrary, the values of air temperature, calculated by the method appeared in the literature, are larger than those calculated by the present method.

In the method proposed in this paper, the some assumptions have been included in deriving of the fundamental equation. Therefore, the many unsoluble problems are left and they need to be invesigated further.

SUMMARY

In order to estimate the moisture content, the solid particles temperature and air temperature distributions in a counter-current drier, a band type drier has been constructed and a series of drying experiments have been carried out with Soma Sand.

The heat and mass transfer rate equations and the heat and mass balance equations have been derived based on the mathematical model for drying process in the counter-current drier. From the results and the discussions, we obtained the following conclusions.

1) The change of moisture content in the pre-heat period is very little.

2) In the surface drying rate period, the temperature of solid particles increases gradually with an increase in x-axis and LEWIS's law between heat and mass transfer process is valid.

3) In the calculation of moisture content and the temperature distributions along a drier, the agreement between the experimental and calculated values obtained by the present method is better than that obtained by the conventional method.

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Nomenclature

A=cross-sectional area of drier (m^2)

A_r=circumference area per unit length of drier (m^2)

C=specific heat (kcal/kg°C)

C_H=specific heat of wetted air (kcal/kg°C)

f=function appeared in Eq. (5) (–)

G=mass velocity of solid particles or air (kg/m^2 hr)
G'=feed rate of solid particles or air (kg/hr)
H=humidity of air (–)
ha=air / solid volumetric heat transfer coefficient (kcal/m^3 hr°C)
k=mass transfer coefficient (kg/m^2 hr ΔP)
ka=air / solid volumetric mass transfer coefficient based on partial pressure (kg/m^3 hr Δp)
$k'a$=air / solid volumetric mass transfer coefficient based on humidity (kg/m^3 hr ΔH)
L=constant for heat loss appeared in Eq. (13)
p=partial pressure of moisture in air (atm)
p_s=saturated vapor pressure at solids surface temperature (atm)
R_c=surface drying rate (kg/m^2 hr)
R_d=decreasing drying rate (kg/m^2 hr)
S=effective solids surface area for drying (m^2)
T=air temperature in a drier (°C)
T_r=temperature of surrounding drier (°C)
t=temperature of solid particles (°C)
U=over-all heat transfer coefficient of drier shell (kcal/m^2 hr°C)
W=weight of solids (kg)
w=moisture content of solid particles (–)
w_c=critical moisture content (–)
w_e=equilibrium moisture content (–)
x=length along x-axis in the drier (m)
α=constant defined by Eq. (3) (–)
θ=dring time (hr)
λ_t=latent heat of vaporization of water at t°C (kcal/kg)
π=atmospheric pressure (atm)
ρ_s=bulk density of solid particles (kg/m^3)
σ=standard deviation defined by Eq. (15) (–)
ϕ=dimensionless moisture content appeared in Eq. (5) (–)
ψ=hold up of solid particles in drier (–)

<Subscripts>

a=air
c=critical state
e=equilibrium state
i=initial state
m=moisture

o=final state
s=solid particles
w=water

Literature cited

1) C. ARAI and Y. SANOH : Preprint of the 39th Annual Meeting of the Soc. Chem. Engrs., *Japan*, B210 (1974)
2) J. GARSIDE : Chem. Eng. Sci., **25**, 1133 (1970)
3) M. KAWABUCHI : *Kagaku Kogaku* (Chem. Eng., Japan), **20**, 223 (1956)
4) K. SARPLES, P. G. GLIKIN and R. WARNE : Trans. Insten. Chem. Engrs., **42**, T 275 (1964)
5) T. SATO and A. YAMAZAKI : *Kagaku Kogaku*, **18**, 553 (1954)
6) R. TOEI : "*Kagaku Kogaku Binran*", 3th ed., Maruzen Co. Ltd., (1968)
7) D. A. van MEEL : Chem. Eng. Sci., **9**, 36 (1958)