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A STUDY ON EVAPORATION OF SEWAGE SLUDGE

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ABSTRACT
A large number of studies on conversion technology of sewage sludge as fuel have been investigated. The sludge consists of protein, organisms and fibrous substances and it is difficult to dehydrate mechanically. Therefore, the bottleneck of drying sewage sludge are reduction of energies for converting a sewage sludge into a solid fuel and the establishment of deodorization technology. We found the intensity of nasty smell from dried sewage sludge depended on the drying temperature.

This paper aims to make clear the drying mechanism of sewage sludge in order to increase the energy efficiency of the products and make clear the relations among drying process, particle size and surounding hot air temperature.

Tested particle diameter and drying air temperature were 10-25mm, 120-200℃ respectively and air flow rate and humidity was constant in all experiments. Initial moisture content of sludge was around of 300% (dry base).

We tried to express the evaporation curve of sludge particle theoretically to analyse its evaporation mechanizum. Drying processes of sladge occurs in falling-rate drying and moisture transfer toward to particle surface is dominant. This process can be described by the fick's law of unsteady state diffusion. As a result, we established the expression of evaporation and calculation errors of drying up time are within 10% .

1. INTRODUCTION

Sewage sludge, containing organic matter and fibrous substances, is regularly produced by purifying water at sewage disposal centre. Today, small amounts of the sludge like the melted sludge are used as building materials, but large parts of them are still incinerated and buried in the ground. Although sewage sludge have adequate calorific value in it, high moisture content of sewage sludge after extreme dehydration and additional energies to deodorize a terrible smell from the product during and after drying tend to lower the energy efficiency of product in converting. Therefore, in order to improve the energy efficiency of this converting method by drying, it is essential to make clear the relations between drying process and experimental conditions.

In this study, we conducted an experimental approach to obtain the evaporation curve in different experimental conditions like a diameter of sludge particle and temperature of drying air. Then, we determined the coefficients of the model based on the fick's diffusion law by fitting analysis, and established the calculation model of evaporation by correlating coefficients with experimental conditions.

2. THEORY

The drying process is a heat and mass transfer phenomenon. Heat is transferred from the surrounding air to the surface and simultaneously moisture transfers from the inside of the drying product to the surface.

In initial drying stages, the moisture removal is rapid since the excess moisture on the surface of products evaporates. Drying at this stage is called a constant rate period. After a certain amount of moisture has evaporated from the products, the drying rate becomes slow. The evaporation rate is reduced, and the temperature of the products tends to rise. This stage is called a falling rate period.

Several mathematical models have been proposed by researchers describing the moisture movement in various agricultural products [1]. A diffusion model based on fick's second law of diffusion has been used for modelling grains drying process. In this process, a falling rate period considering that the surface resistance to moisture transfer is negligible compared with the inside resistance.

Assuming that the internal moisture transfer mechanism is equivalent to a diffusion process, the moisture flux in the products can be written as

$$F = -D\nabla C \tag{1}$$

Where D is the diffusion coefficient and ∇C is the gradient of the local moisture concentration. In terms of local moisture content Xr, an unsteady state mass balance of an element of product is led as follows

$$\frac{\partial(\rho_s X_r)}{\partial t} = \nabla[D\nabla(\rho_s X_r)] \tag{2}$$

Where ρ_s is solid density and t time. Assuming an uniform solid density and a constant solid diffusion coefficient

$$\frac{\partial X_r}{\partial t} = D\nabla^2 X_r \tag{3}$$

Considering a spherical geometry, the last expression can be represented as

$$\frac{\partial X_r}{\partial t} = D\left(\frac{\partial^2 X_r}{\partial r^2} + \frac{2}{r}\frac{\partial X_r}{\partial r}\right) \tag{4}$$

Where, r represents the radial coordinate. The boundary conditions are [2],

$$(1)\; X_r = X_0, 0 \le r \le R, t = 0$$
$$(2)\; X_r = X_e, r = R, t \succ 0$$
$$(3)\; \frac{\partial X_r}{\partial r} = 0, r = 0, t \ge 0$$

Where, X_0, X_e R are the initial moisture content, the moisture content at equilibrium and the sphere radius respectively. Eq.(4) can be converted in the form of,

$$\frac{X_r - X_0}{X_e - X_0} = 1 + \frac{2R}{\pi r}\sum_{n=1}^{\infty}\frac{(-1)^n}{n}\sin\frac{n\pi r}{R}\exp\left(-\frac{Dn^2\pi^2 t}{R^2}\right) \tag{5}$$

Where, n represents the number of terms in the power series.

Eq.(5) indicates the moisture content at r=r. Therefore, the moisture content of whole particle can be obtained by integrating Eq.(5) from r=0 to r=R and consequently Eq.(6) is led.

The integration of last equation between the extreme radius values, results in an expression for the dimensionless moisture content X* given by Eq.(6), in which X represents the average value of the local moisture content X_r.

$$X^* = \frac{X - X_e}{X_0 - X_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n^2\frac{\pi^2 Dt}{R^2}\right] \tag{6}$$

3. TEST SAMPLES AND METHODS

3.1 Test sample

Sample sewage sludge is extremely dehydrated by belt-press dryer at Chigasaki disposal center, Japan. Initial sewage sludge is paste-like and around 300% dry base (d.b.) of moisture content, equivalent to 3.0kg moisture /1.0kg dry matter.

Shape of sample is sphere and its diameter from 10 to 25 mm. In order to obtain a precise quantity of results, several particles are tested at the same drying experiment and the whole decrease of sludge weight is measured.

3.2 Experimental setup

The schematic arrangement of experimental set up is shown in Fig.1. The experimental drying system consists of an air provision system, a heater, measurement devices for recording the time history of weight of particles and a drying chamber that is 1m in length and 0.3m in diameter. The air is heated while flowing through the electric heater with a maximum heating capacity of 7.5kW. The air flow rate and temperature of the air are measured by a hot-wire anemometer and a thermocouple respectively at 65mm below the sample tray.

Two thin plate having lots of tiny hole is set at the entrance of drying chamber to reduce the temperature and velocity distributions of drying air. Samples are placed on the cylindrical tray connected with the electric balance by steel wire. One of the samples is connected to the thermocouple to measure the temperature at center of particle.

The values of electric balance, temperature of particle and air are recorded by PC at each 10 seconds. The drying chamber as well as all ducts is insulated to prevent from unnecessary heat losses during drying.

1. Blower
2. Electric heater
3. Drying chamber
4. Electric balance
5. PC
6. Sample tray
7. Commutator
8. Thermocouple
9. Hot wire anemometer
10. Air dampers

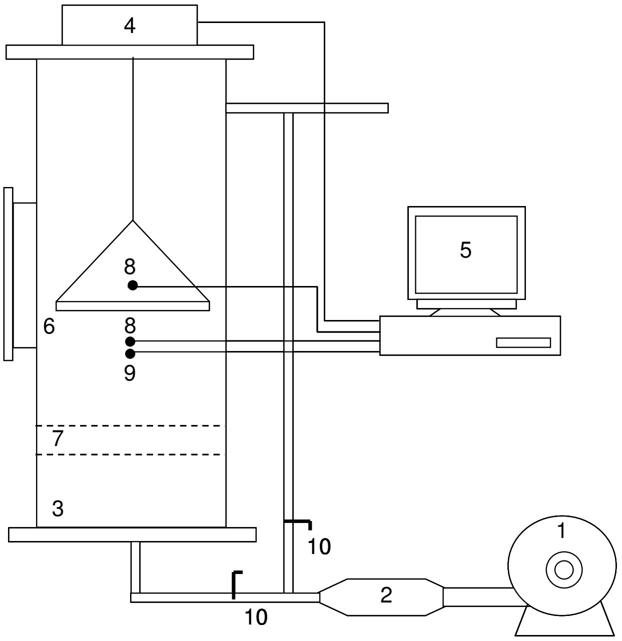

Fig.1 Experimental setup

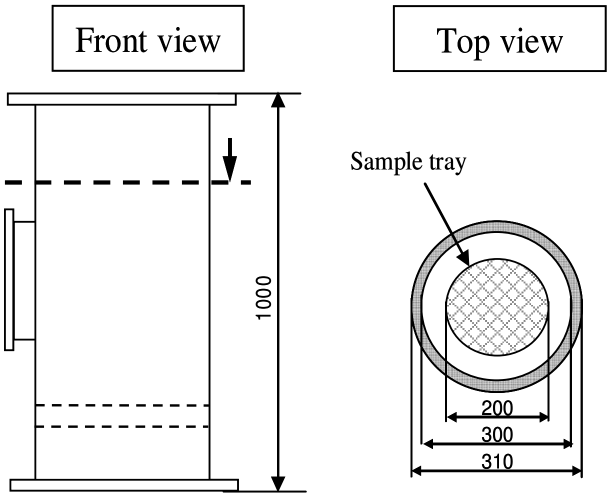

Fig.2 Drying chamber

3.3 Experimental procedure

Before starting experiment, the drier was allowed to run for at least 1-2 hours to achieve a steady state condition in drying chamber. Samples were then placed on the sample tray quickly and the starting point of the drying experiment was defined as the time that temperature of drying air reached the desired temperature.

This time loss was disregarded because it was very short comparing to the test time.

Dying experiment was continued until the sample reached equilibrium moisture content. We defined the weight of the sample at the end of drying was equal to the solid weight of the sample. The experimental conditions are shown in Table 1.

Table 1 Experimental conditions

Item	Value
Sample product	Sewage sludge
Sample form	sphere
Diameter	10, 15, 20, 25 mm
Air temperature	120, 160, 200 mm
Air flow rate	0.7 m/s

3.4 Analysis of data

The evaporation curves of sewage sludge were fitted with moisture ratio equation. In this study, the moisture ratio (*MR*) was simplified to X/X_0 instead of $(X-Xe)/(X_0-Xe)$ since relative humidity of drying air continuously fluctuated in drying and Xe was negligible compared to X or X_0.

In general, the diffusion coefficient D in Eq.(6) is constant. However, it is conceivable that the diffusion coefficient of solid matter changes during drying process. The effective diffusion coefficient D_e is defined in this study to distinguish them. Furthermore, the term higher than second order is omitted, the following Eq.(7) is led.

$$MR = \frac{X}{X_0} = \frac{6}{\pi^2}\exp\left(-\frac{\pi^2 \cdot D_e}{R^2}t\right) \tag{7}$$

In order to normalize the deference of initial moisture ratio between each experiment, we used 300% of moisture content instead of X_0 and modification factor a correlating with X_0 was added to the right side of moisture ratio equation as shown in Eq.(8).

$$MR = \frac{X}{300} = \frac{6}{a \cdot \pi^2}\exp\left(-\frac{\pi^2 \cdot D_e}{R^2}t\right) \tag{8}$$

The parameters in Eq.(8) were obtained by non-linear regressions, using as objective function by minimizing of the deviations.

The method of determination of the effective diffusion coefficient (D_e) from the experimental data directly was also developed. For small drying times, Eq.(8) was expressed in a following logarithmic form.

$$D_e = -\frac{r^2}{\pi^2} \cdot \frac{d\left[\ln\left(MR_{\exp}\right)\right]}{dt} \tag{9}$$

The correlation factor (r) was one of the primary criteria to determine the goodness of the fitting. In this study, addition to r value, *RMS* as the root mean square of the deviations between the experimental and calculated values was used to determine the goodness of the fitting. The goodness of the fitting increases with the decrease of the *RMS* value. [3]

$$RMS = \sqrt{\frac{1}{N}\sum_{i=1}^{n}\left(MR_{\exp,i} - MR_{cal,i}\right)^2} \tag{10}$$

4. RESULT AND DISCUSSION

4.1 Characteristic of evaporation

The moisture ratio and the temperature at center of particle versus drying time are shown in Fig.3. The moisture ratio decreased slowly with drying time and finally approached to the equilibrium moisture ratio, the temperature increased gradually at first stage and is stagnant at around 80℃, after some time increased rather vigorously and closed to the drying air temperature at the final stage of drying. In Figs.4 and 5, the influence of sample diameters and drying air temperature on the moisture loss was also investigated ranging from 10 to 25mm and 120 to 200 ℃ respectively.

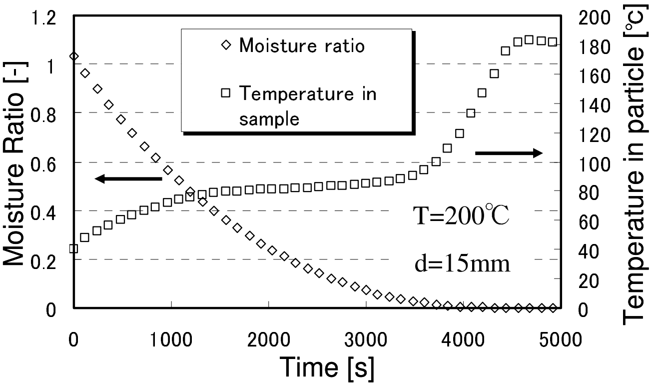

Fig.3 Moisture ratio and temperature at center of particle versus drying time

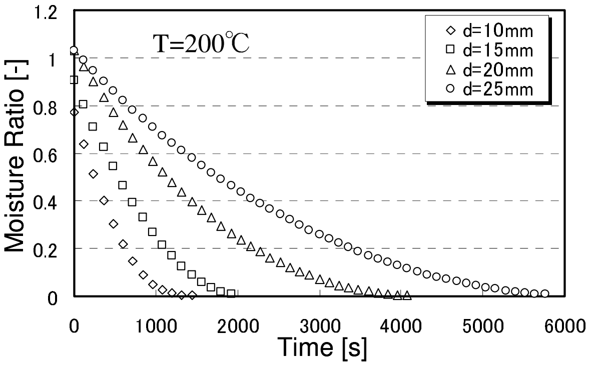

Fig.4 Influence of sample diameter on moisture loss

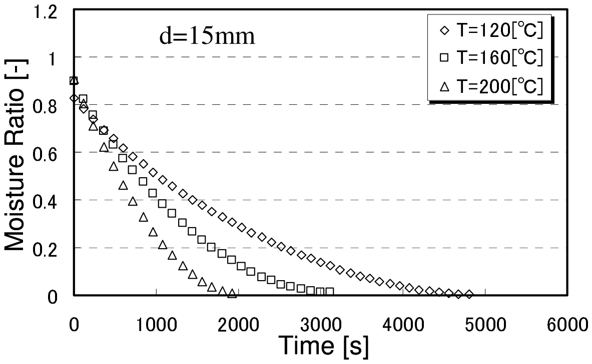

Fig.5 Influence of drying air temperature on moisture loss

These results showed that the particle diameter and air temperature were significant parameters concerning the evaporation. The difference of sample diameter changed the surface area to volume ratio, thus the larger sample caused to delay the evaporation rate at same air temperature. In same sample diameter, the higher air temperature promoted the rapid establishment of equilibrium moisture content on the sample surface and the gradient of moisture content became larger.

The evaporation rate versus moisture ratio is shown in Figs.6 and 7. These figures showed that the constant rate drying was absent in sewage sludge drying because the evaporation rate started to decrease at the beginning of the drying. Thus, the drying process took place in only the falling rate period.

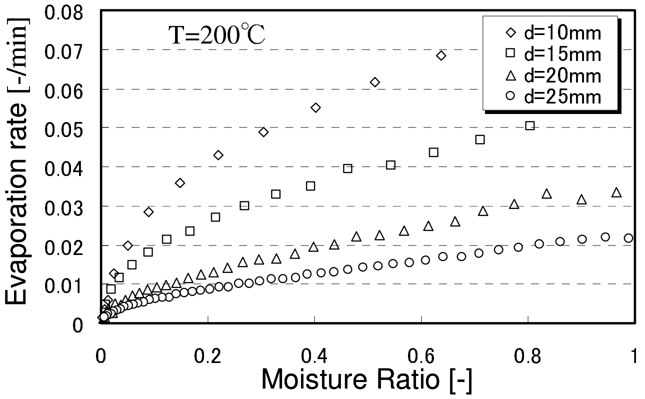

Fig.6 The evaporation rate versus moisture ratio

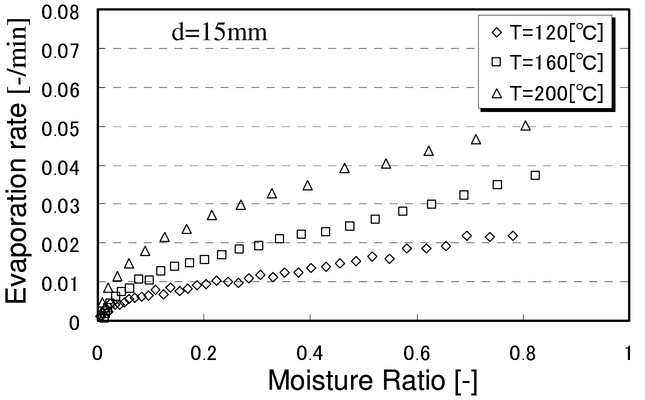

Fig.7 The evaporation rate versus moisture ratio

Evaporation rate continuously decreased with moisture content. Evaporation rate was larger at smaller diameter of sample in same drying air temperature, and it was also larger at higher drying air temperature in same sample diameter. These results clearly show that sample diameter and drying air temperature were significant factors of evaporation rate.

The effective diffusion coefficients versus moisture ratio were shown in Fig.8. The value of D_e increased with the drying air temperature and increased rapidly at later drying stage (below 0.2 of moisture ratio).

It is said that the D_e of a vegetable or fish is nearly constant or slightly decreases with drying process because of the formations of resistance of moisture transfer on the product surface [4]. These results suggest that the same processes are surely occurred in sewage sludge evaporation but the structure of dried sewage sludge changes and make the resistance of moisture transfer easier. As a result, D_e increased with drying process.

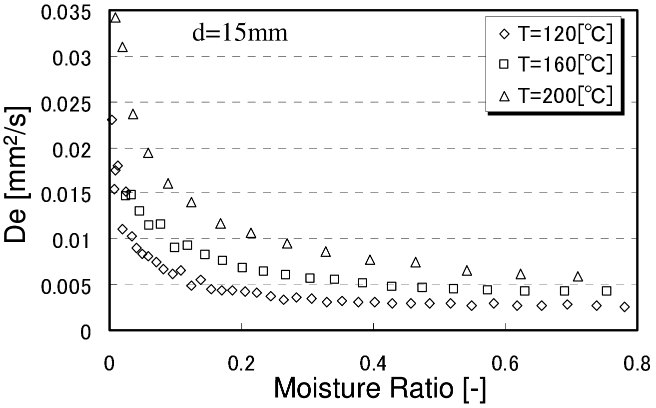

Fig.8 Effective diffusion coefficients versus moisture ratio

In the initial stage of drying, the inner structure of sample is uniform. However, the shell structure is formed on the sample surface by hot air and it prevents the sample particle from shrinkage. The inner structure of the sample changes into porous state during drying. This fact suggests that the moisture transfers easily at later drying stage.

The temperature at center of particle stagnates once and approaches to the air temperature as explained in Fig.3. These stagnation points of the temperature are located at around 90℃ and the temperature starts rising again at around 0.1 of moisture ratio in all experimental conditions.

4.2 Proposal of evaporation formula for sewage sludge

We analyzed the several kind of model expressing the evaporation process of sewage sludge, i.e. Eq.(8) with constant D_e, one with variable D_e, one with correction term, etc. were discussed. As a result, *RMS* by the equation that D_e changes with moisture content and temperature shows the smallest value and this equation can express the behaviour of sewage sludge drying over wide conditions.

The relation between D_e and moisture ratio could be indicate by Eq.(11).

$$De = De_0\left[1 + b \cdot \exp(c \cdot MR_i)\right] \tag{11}$$

The relation between D_e and temperature could be expressed by introducing a simple Arrhenius-type relationship as Eq.(12), i.e. De_0 is replaced by a function of the reciprocal of the temperature.

$$De = \alpha \cdot \exp(-\beta/T)\left[1 + b \cdot \exp(c \cdot MR_i)\right] \tag{12}$$

These equations contain the coefficients of α, β, a, and b, and they were obtained by linear regression of the sample diameter because they were the function of only diameter. Thus, D_e was defined as a function of drying air temperature, moisture ratio and sample diameter.

Relation between D_e, drying air temperature and moisture ratio was shown in Fig.9. The white dots show the experimental values of D_e and the black surface show the calculated values by using Eq.(12).

According to the figure, D_e tended to rise at higher temperature and lower moisture ratio.

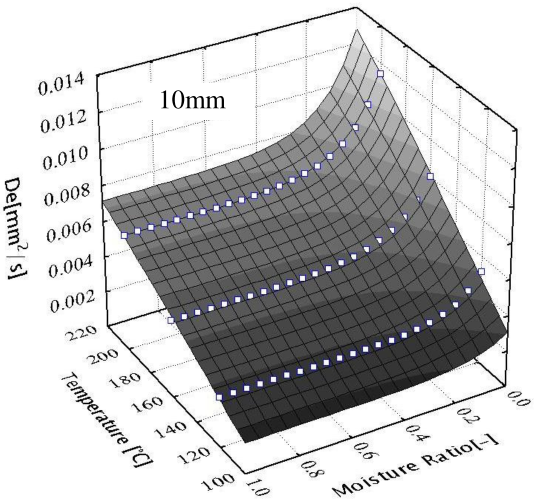

Fig.9 Relation among D_e, drying air temperature and moisture ratio

As a result, the expression to calculate an evaporation process of sewage sludge was shown in Eq.(13).

$$MR = \frac{6}{a(MR_0)\cdot\pi^2}\exp\left(-\frac{\pi^2\cdot D_e(T,d,MR_i)}{R^2}t\right) \tag{13}$$

4.3 Comparison of experimental and calculated value

In order to evaluate the accuracy of calculated evaporation curve, comparison of experimental data and calculated value by formulating a terminal drying time and *RMS* was analyzed.

The relations between calculated and experimental values of the terminal drying time were shown in Fig.10. The terminal drying time was defined as a time moisture ratio approached to 0.03. The error of calculated terminal drying time was defined as Eq.(14). In all experiment, the mean of error between experimental value and calculated one was 5.5%.

$$Error[\%] = \frac{t_{term,\exp} - t_{term,cal}}{t_{term,\exp}} \times 100 \tag{14}$$

The *RMS* was also obtained as shown in Table 2 in all experimental conditions, and *RMS* values were correlated to the error values.

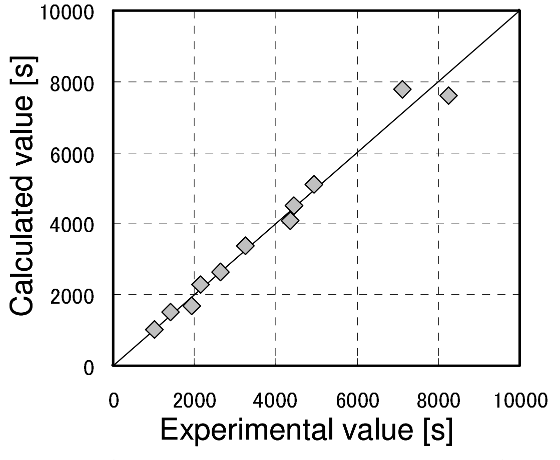

Fig.10 Relations between calculated and experimental values of the terminal drying time.

Table 2 RMS values for all experimental conditions

No	d [mm]	T [℃]	Error[%]	RMS
1	10	120	6.96	0.0344
2	15		6.62	0.0193
3	20		8.70	0.0253
4	10	160	5.96	0.0352
5	15		0.38	0.0135
6	20		1.33	0.0212
7	25		8.61	0.0373
8	10	200	1.94	0.0179
9	15		13.53	0.0291
10	20		3.85	0.0210
11	25		2.94	0.0307

5. CONCLUSION

In order to make clear the drying mechanism of sewage sludge and establish the calculation model of evaporation, we conducted a hot air drying and analyzed the evaporation data based on Fick's diffusion model by non-linear regressions. From this study, the following conclusions can be made

- The moisture ratio of a sewage sludge decreases rapidly at initial drying stage and then slowly approaches to the equilibrium moisture content.
- The temperature at the center of particle increase slightly increased, stagnated once at around 80℃ in any drying air temperature, and rises again towards the drying air temperature at the final stage of drying.
- The evaporation rate of sewage sludge started to decrease from the beginning of the drying. Thus, the drying process took place in only the falling rate period.
- The effective diffusion coefficient D_e increased gradually with the drying air temperature at the early stage and rapidly at less than 0.2 of moisture ratio.
- The formula expressing the evaporation process of sewage sludge was proposed. The mean of error between experimental value and calculated one was 5.5%.

6. NOMENCLATURE

Symbol	Quantity	Unit
F	moisture flux	kg / m^2 s
C	local moisture concentration	kg / m^3
D	diffusion coefficient	mm^2 / s
D_e	effective diffusion coefficient	mm^2 / s
a	modification factor	-
X	moisture content (d.b.)	%
MR	moisture ratio	-
ρ_s	solid density	kg / m^3
t	time	s
T	temperature	℃
r	radius coordinate	mm
R	radius of sphere	mm
n	number of terms of power series	
∇	gradient operator	

Subscribe

r	local
i	at time
e	equilibrium
0	initial
*	dimensionless
b,c,α,β	model coefficient

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