Drying Characteristics of Tea Leaves

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Introduction

Tea is classified into three kinds by the extent of fermentation. In Japan, green tea which is classified to non fermented tea has been consumed mainly. Eighty percent of the tea produced in Japan is the kind that is called 'sencha'. It is manufactured through six processes as shown in Fig. 1. These processes are the drying ones except for a steaming and a tea rolling process. Therefore, it is very important for tea manufacturing to know the drying characteristic of tea leaves. This paper clarified the basic drying characteristic of tea leaves and its change in a primary drying process which is important in drying.

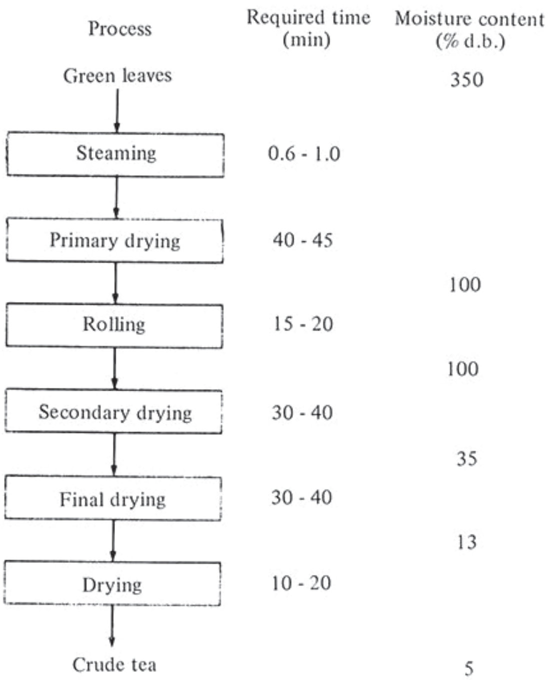


Fig. 1. Tea manufacturing process (sencha)

Equilibrium moisture content

Equilibrium moisture content is one of the important and basic characteristics in drying. However, the published data regarding tea were not sufficient to know the values in various drying conditions. Therefore, an experiment was made to obtain the data of equilibrium moisture content[7].

The tea materials are new shoots plucked from tea trees and each new shoot consists of two or three leaves and a stem. It was conjectured that the equilibrium moisture content of leaves differed from that of stems. Therefore, the equilibrium moisture content of tea leaves and that of stems were measured separately. For the experimental material, Yabukita, a standard variety of sencha in Japan, was used. The plucking was made in the best crop period of the first crop.

After the experimental materials were separated into leaves and stems, they were sealed up in desicators containing salt solution to adjust relative humidity of the air inside the desicators. Five different concentrations of salt solution were adopted to give five different degrees of relative humidity. Thus, the equilibrium moisture contents were measured at five levels of relative humidity combined with four levels of temperature.

The equilibrium moisture content curves of tea leaves and stems, shown in Fig. 2, indicated sigmoid-like curves similar to the case of other hygroscopic materials. The equilibrium moisture content of tea stems was higher than that of leaves. The difference became larger at higher moisture content.

Table 1. Coefficients of equilibrium moisture content equation

Materials	Process	a	b	c
Leaves	Drying	3.77×10^{4}	2.56×10^{-2}	4.65×10^{2}
	Adsorption	3.64×10^{2}	1.30×10^{-2}	3.92×10^{2}
Stems	Drying	1.34×10^{4}	2.33×10^{-2}	3.68×10^{2}
	Adsorption	5.90×10^{2}	1.45×10^{-2}	3.55×10^{2}

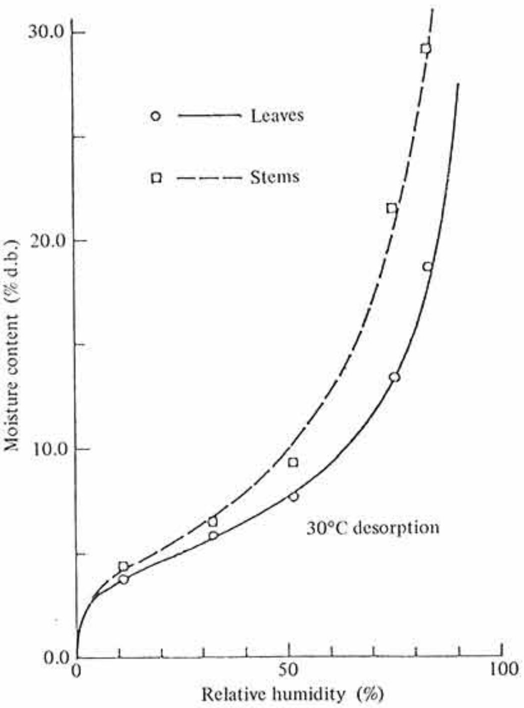


Fig. 2. Equilibrium moisture content of the leaves and stems

This difference exists in the final tea products, so that it has been utilized to separate stems with an electrostatic stalk separator. The equilibrium moisture content also varied with temperature, and became slightly low at high temperature. The hysteresis was recognized in the equilibrium moisture content curves. The equilibrium moisture content in the desorption process was higher than that in the adsorption process. The difference became small at high temperature.

Several equations regarding equilibrium moisture content were proposed so far. Five equations which have been frequently applied to farm products and indicated sigmoid in form were selected from them and their suitability to the values obtained in the present study was examined. The five equations were BET, Halsey's, Henderson's Chung-Pfost's, and Strohman-Yoerger's equations. Of these equations, Halsey's equation was considered appropriate for the equilibrium moisture equation of tea leaves. Consequently, a new equation which was based on Halsey's equation was proposed as the equlibrium moisture equation of tea leaves and stems. This equation which contains three coefficients shown in Table 1 is

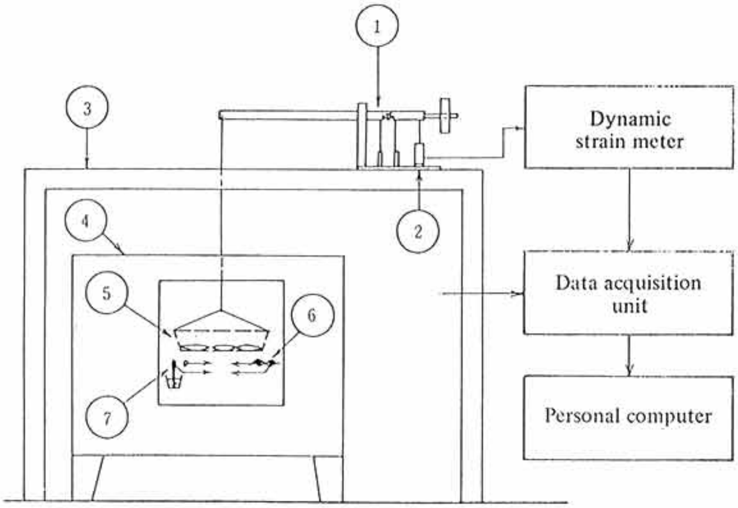
$$ln\,\phi = -a/(e^{bT}M^{c/T}) \qquad (1)$$

where ϕ : relative humidity (decimal)
T : temperature (K)
M : equilibrium moisture content (% d.b.).

It was reported that the state in which only one layer of water molecules was adsorbed on the surface of food was the most suitable to the preservation of food[4]. The moisture content in this state was calculated from BET equation. The moisture content of tea leaves in this state was 3.0% and that of stems was 4.6%. The equilibrium relative humidity was 14 and 24% respectively at 20°C. As the atmospheric humidity is usually higher than these values, dampproofing is necessary to preserve tea.

Diffusion coefficient of tea leaves

The drying characteristic of a single leaf must be firstly clarified in order to know the



1. Balance
2. Weight detector
3. Frame
4. Oven
5. Sample cage
6. Thermocouple for measuring tea leaf temperature
7. Thermocouple for measuring air temperature

Fig. 3. The experimental device

drying characteristic of tea leaves. It is especially important to know the real moisture transfer speed inside a tea leaf to obtain the moisture diffusion coefficient of a tea leaf. The moisture diffusion coefficient can be calculated from the drying rate in the falling rate drying period. Therefore, static drying experiments were made to obtain drying curves of tea leaves[9].

The experimental device is shown in Fig. 3. All the measured data were recorded to a floppy disk automatically by the computer. The diffusion coefficients were also calculated immediately from these data by the computer. The drying rates of tea leaves and stems were obtained separately.

The drying characteristic curves of tea leaves and stems are shown in Fig. 4. Both tea leaves and stems showed falling rate drying curves. The drying rate of tea leaves was higher than that of stems. Therefore, it has been conceivable that the drying of tea stems is more difficult than that of tea leaves. However, it is not necessary that the real moisture transfer speed inside a stem is

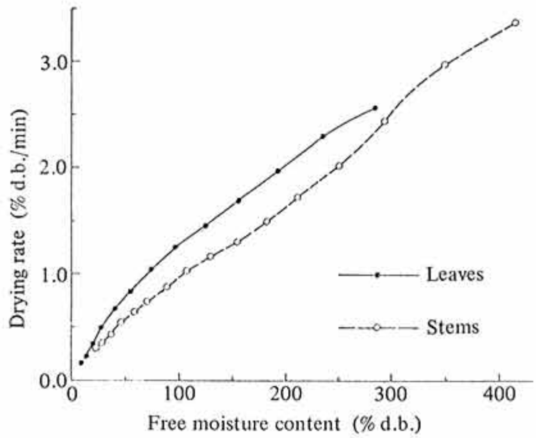


Fig. 4. Drying characteristic curves of tea leaves and stems

lower than that inside a leaf, and it can be determined only by the comparison of their moisture diffusion coefficients. The diffusion coefficient is calculated from the relation between the solution of diffusion equation and the drying constant as follows.

A tea leaf is so thin that the evaporation from the edge is negligible. Therefore, it is

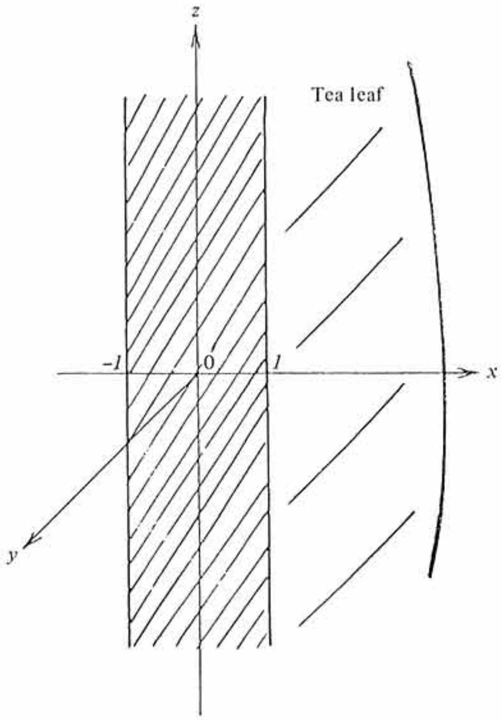


Fig. 5. The plane sheet model

sufficient to consider only one dimensional diffusion supposing the tea leaf to be a plane sheet as shown in Fig. 5. The diffusion equation is

$$\frac{\partial m_{(t,\,x)}}{\partial t}=D_l\frac{\partial^2 m_{(t,\,x)}}{\partial x^2}\quad\cdots\cdots\cdots\cdots(2)$$

where m : moisture content (decimal)
t : time (hr)
x : the distance from the center of the leaf (m)
D_l : the moisture diffusion coefficient of the leaf (m^2/hr).

The initial and boundary conditions are

$$m_{(0,\,x)}=m_0\quad\cdots\cdots\cdots\cdots(3)$$
$$m_{(t,\,l)}=m_{(t,\,-l)}=m_e\quad\cdots\cdots\cdots\cdots(4)$$

where m_0 : initial moisture content (decimal)
m_e : equilibrium moisture content (decimal)
l : the half thickness of the leaf (m).

The solution is[1]

$$\frac{m_{(t,\,x)}-m_e}{m_0-m_e}=\frac{2}{l}\sum_{n=0}^{\infty}e^{-\lambda_n^2 D_l t}\frac{(-1)^n}{\lambda_n}\cos(\lambda_n x)\quad\cdots\cdots\cdots\cdots(5)$$

The average moisture content is

$$\frac{m_{(t)}-m_e}{m_0-m_e}=\frac{2}{l^2}\sum_{n=0}^{\infty}\frac{1}{\lambda_n^2}exp\left(-\frac{\pi^2}{4l^2}D_l t\right)\cdots(6)$$

However, this equation can be approximated with the only first term when t is large.

$$\frac{m_{(t)}-m_e}{m_0-m_e}=\frac{8}{\pi^2}exp\left(-\frac{\pi^2}{4l^2}D_l t\right)\cdots\cdots\cdots(7)$$

On the other hand, the drying curve of tea leaves is also expressed by the following exponential function.

$$\frac{m_{(t)}-m_e}{m_0-m_e}=Ae^{-\kappa t}\quad\cdots\cdots\cdots\cdots(8)$$

The drying constant K is determined from the experimental data using the least square method. The relationship between the moisture diffusion coefficient and the drying constant which is expressed by the following equation was reduced by the equations (7) and (8). Thus the moisture diffusion coefficient of tea leaf can be calculated from the following equation.

$$D_l=\frac{4l^2}{\pi^2}K=0.406\,l^2K\quad\cdots\cdots\cdots\cdots(9)$$

On the other hand, the diffusion equation of a tea stem is obtained based on the assumption that a tea stem is an infinite cylinder. The moisture diffusion coefficient is

$$D_s=\frac{a^2}{\alpha_1^2}K=0.173a^2K\quad\cdots\cdots\cdots\cdots(10)$$

where D_s : the moisture diffusion coefficient of stem (m^2/hr)
a : the radius of stem (m)
α_1 : the positive root of Bessel's function.

As the moisture diffusion coefficient depends upon the temperature[3], the diffusion coefficients were obtained in the conditions of five different temperatures. The results are shown

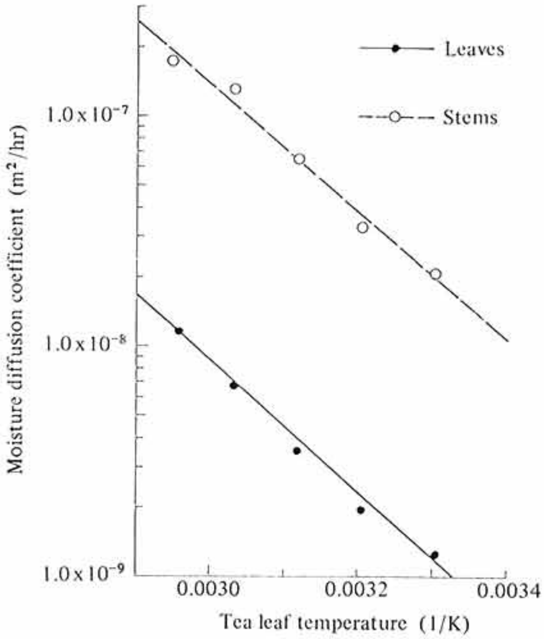


Fig. 6. Moisture diffusion coefficient of a tea leaf and a stem

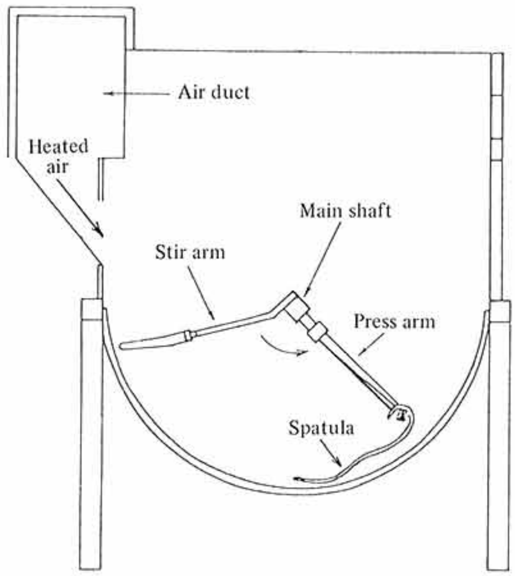


Fig. 7. The structure of a primary drying tea roller

in Fig. 6. The relationship between the diffusion coefficient and the temperature was expressed by the following equations which were based on Arrhenius' law.

$$D_l = 2.74\ exp(-6.53\times10^3/T) \quad \cdots\cdots\cdots\cdots(11)$$
$$D_s = 24.3\ exp(-6.33\times10^3/T) \quad \cdots\cdots\cdots\cdots(12)$$

The moisture diffusion coefficient of a stem was greater than that of a leaf in each temperature. Therefore, the inner transfer rate of the moisutre in the stem is greater than that of the leaf. According to this fact, it is considered that the reason why the static drying rate of stems was lower than that of leaves was that the distance for the moisture transfer in the stem was longer than that of the leaf. Because the diameter of stem becomes closely 2.0 mm while the thickness of leaf is about 0.2 mm.

Drying characteristics of tea leaves in a primary drying process

A prmiary drying process is the first drying process in sencha manufacturing processes

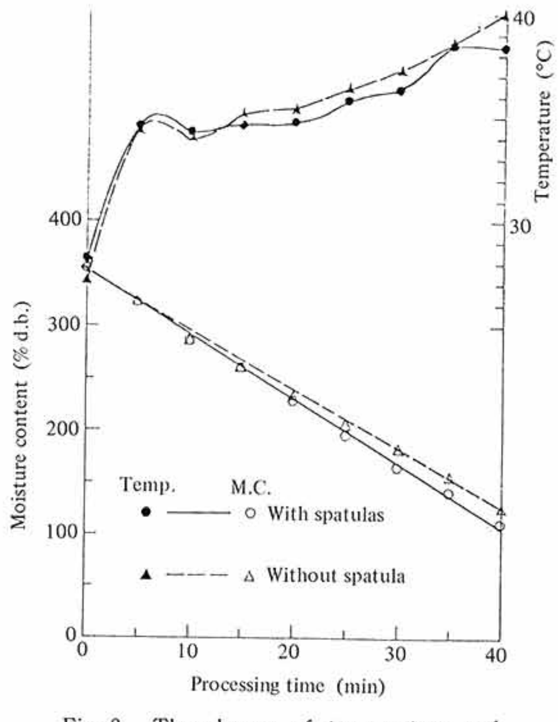


Fig. 8. The change of temperature and moisture content of the leaves in the primary drying process

Table 2. Changes of moisture diffusion coefficients due to the mechanical action of a primary drying tea roller

Material	Spatula*	Processing time (min)	Thickness (mm)	Drying constant (/hr)	Diffusion coefficient (m^2/hr)
Leaf	○	0	0.21	0.785	3.52×10^{-9}
		20	0.18	1.514	4.98×10^{-9}
		40	0.14	3.084	6.14×10^{-9}
	×	20	0.18	1.647	5.42×10^{-9}
		40	0.15	2.794	6.38×10^{-9}
Stem	○	0	1.64	0.406	4.72×10^{-8}
		20	1.62	1.182	1.34×10^{-7}
		40	1.41	3.246	2.79×10^{-7}
	×	20	1.71	1.123	1.42×10^{-7}
		40	1.40	2.739	2.32×10^{-7}

○ : With spatula, × : Without spatula.

and 2/3 of the moisture that should be removed is eliminated here. A particular drying machine called primary drying tea roller which is shown in Fig. 7 is used in this process. As it has stir arms that agitate tea leaves and press arms that oppress them, it can dry tea leaves effectively. While tea leaves indicate the falling rate drying period in static drying process, they indicate the constant rate drying period in the early stage of the primary drying process as shown in Fig. 8[8]. Therefore, the quality is not deteriorated because the temperature of tea leaves is maintained low.

It has been conceivable that the reason why the tea leaves indicated the constant rate drying period in the primary drying process was that the spatulas of the press arms pushed out the water in tea leaves. However, the constant rate drying period was also observed without using the spatula in the primary drying tea roller. Accordingly, it is considered that another reason is the agitation by the stir arms, as described as follows[8].

Every tea leaf is not dried simultaneously because the tea leaves become a lump and stick each other. Therefore, the tea leaves are exposed to the hot air and dried only when they are on the surface of the lump. The lump is remade by agitation, and the other leaves come out to the surface next time. Thus individual leaf is dried intermittently, and the inner moisture gradient of the tea leaf inside the lump is relaxed during the pause. Therefore, the surface of a tea leaf is always getting wet, and the constant rate drying is maintained.

While the drying rate of leaves is higher than that of stems in static drying, the drying rate of stems is higher than that of leaves in the primary drying process. It is considered that the surface area of the twisted tea leaves became small and the moisture diffusion coefficient of the stem became great due to the mechanical action of a primary drying tea roller[9]. The changes of moisture diffusion coefficients of a leaf and a stem are shown in Table 2. The diffusion coefficients of a leaf and a stem became great with progression of the primary drying process. This change was also given in the case of using the primary drying tea roller without the spatula. Therefore, it is considered that this phenomenon was also induced by the agitation with the stir arms.

Discussion and conclusion

The real moisture transfer speed in the

Table 3. Comparison of moisture diffusion coefficients among different treatments

Material	Treatment	Thickness (mm)	Drying constant (/hr)	Diffusion coefficient (m^2/hr)
First leaf	Steamed by a steamer	0.169	1.740	5.04×10^{-9}
Third leaf	Steamed by a steamer	0.222	0.703	3.52×10^{-9}
	Steamed by a steaming machine	0.232	0.725	3.96×10^{-9}
	Rubbed after steaming	0.196	1.079	4.21×10^{-9}
Stem	Steamed by a steamer	1.97	0.289	4.85×10^{-8}
	Steamed by a steaming machine	1.76	0.481	6.45×10^{-8}
	Rubbed after steaming	1.70	0.620	7.75×10^{-8}

material should be compared by the moisture diffusion coefficient. The moisture diffusion coefficients of a tea leaf and a stem were smaller than those of cereals. From this point of view, the drying of tea leaves were more difficult than that of cereals. The reason why the diffusion coefficients of a tea leaf and a stem were very small is considered that they have cuticle layers[9]. The diffusion coefficient of the first leaf which had no cuticle layer and that of the third leaf which had well grown cuticle layer[2] are shown in table 3[9]. The diffusion coefficient of the first leaf was greater than that of the third leaf. It showed that the cuticle layer contributed to the resistance for moisture transfer.

The cause of the change of moisture diffusion coefficient of a leaf during the primary drying process is considered that the cuticule layer on the surface of a tea leaf was broken down by the mechanical action exerted upon the leaves in the primary drying process[9]. When the steamed tea leaves were rubbed by hands or steamed by the tea steaming machine with agitating hands, the diffusion coefficient also became great by the same reason.

In this paper, the moisture diffusion coefficients were calculated by assuming that a tea leaf was homogeneous. Therefore, the decrease of the resistance of moisture transfer by the breakdown of the cuticle layer showed the increase of the diffusion coefficient of the tea leaf. The diffusion coefficient in this paper means the overall diffusion coefficient.

A primary drying tea roller and the other tea manufacturing machines simulated the actions of hands in the conventional method of hand-made sencha. Especially, the stir arms in the primary drying tea roller are very important, and the motion of tea leaves induced by these stir arms affected the drying of tea leaves. The motion of tea leaves was analyzed theoretically and several factors affecting the trajectory were reported[5,6]. Consequently, the mechanism of the primary drying tea roller is not only traditional but also reasonable.

The basic drying characteristics of tea leaves which were reported in this paper will be useful for improvement and development of tea manufacturing process and machines.

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