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Over-all Drying-rate Equations on the Drying of Potato by the Microwave Energy and of Bored One by Heated Flowing Air

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(Fig. 1–8; Table 1–3)

INTRODUCTION

In order to optimum design and operate the various drying equipments of food materials, it is necessary to determine the drying-rate equations.

In previous papers[1–3], we have been studied the over-all drying-rate and shrinking-rate equations of root vegetables under drying processes where heated air was flown through a drying chamber.

Improvement of the air-flow drying process is essential if further cost of the dehydration energy is to be lowered. Faster dehydration methods that use various heating methods or pre-treatment methods of samples are required.

The drying methods using microwave[4–8], steam[9–10] or solar [11] energy have been investigated. The drying rate by microwave energy is higher, due to different penetration characteristics, yet it is difficult to obtain a uniformly higher quality product moreover the cost of the energy is higher.

The heating proceeds by microwave energy give more rapid heat production at the inner parts of the samples and make the puffed sections softer. These can be more easily rehydrated. Pre-heating with microwave treatment for drying of food materials seems to be particularily advantageous, because this method needs a shorter drying time than in the air-flow drying and probably comes to lower energy cost. However, the study of the drying-rate equation of microwave heating is less examined[12].

The description of the conventional process for making dried potato can be found in various handbooks[4]. This process involves peeling, cutting, washing, blanching, dipping in or spraying on a sulfite solution to prevent discoloration, and then drying.

The pre-treatment methods which consist in blanching[13,14] by steam and hot or boiling water and soaking[15] in various solutions etc. have been investigated, but mechanical pre-treatment such as compressing and boring etc. have not been carried out on the drying of food materials.

In this paper, we studied the over-all drying-rate equations for the drying of the potato by microwave energy and of bored potato by heated flowing air.

EXPERIMENTAL

1. Samples

As samples, we used cylindrical potatoes. These potatoes were bought in the market. Their specific descriptions as well as their producing districts were unknown. They were made into cylindrical forms by using a cork borer and a sharp cutter.

In order to compare those with and those without the mechanical pre-treatment, cylindrical samples of the bored type were used. The bored sample and its making method are shown in Fig.1. A bored acrylic resin tube and a needle shown in Fig.1 were used for the boring operation. The comparing experiments were tested on the drying by heated flowing air.

As mechanical pre-treatmenting samples, we attempted to use a compressed sample. By the compressing operation, the water contents of the potatoes are not decreased and the cylindrical shapes ruptured. Then, the comparing tests of the samples were stoped.

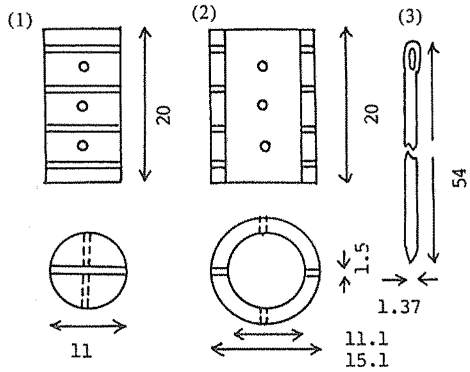

Fig.1. Making method of bored sample on the heated air-flow drying
(1) sample, (2) bored acrylic resin tube, (3) needle.

The samples of cylindrical potatoes used in this study are shown in Table 1.

Table 1. Samples

Samples: cylindrical potatoes

Run	w_0(g)	D_0(cm)	L_0(cm)
M-1~M-4*	2.291	1.11	2.18
A-1**	1.942	1.10	2.01
A-2**	1.954	1.10	2.01

Samples: Water added parafin liquid

Run	water (g)	parafin liquid (g)
W-1~W-4	3.0	0.6

where, * : average values of changed values in five-Run
** : average values of five-repeated experiments
pre-treatment: Run A-2; boring
others ; nothing
Sample on the microwave drying : M-1~M-4 and W-1~W-4
Sample on the heated flowing air drying : A-1 and A-2

In case of the other samples, we used a fixed weight of water as shown in Table 1 on the drying by microwave energy. 3.0 g water was heated in a test tube. Paraffin liquid (Nakarai Chemical Co., Extra pure reagent) weighing 0.6 g was added to the water, because the water evaporated from the surface in the higher temperature resions.

2. Apparatuses of microwave-heat dryer

The apparatuses used in the drying experiments by microwave energy are shown in Figs. 2 and 3. The microwave generator (Model Q-38) was made by Sanyo Denki Co. with one Type 2M53/E3604 48-1B 1506 magnetron operating at 2450 megacycles. The input and output powers were 1.1 kW and 50~200 W, respectively. The wave guide is made from a copper box with a cross section of 5.9 × 10.9 cm and 77.0 cm length.

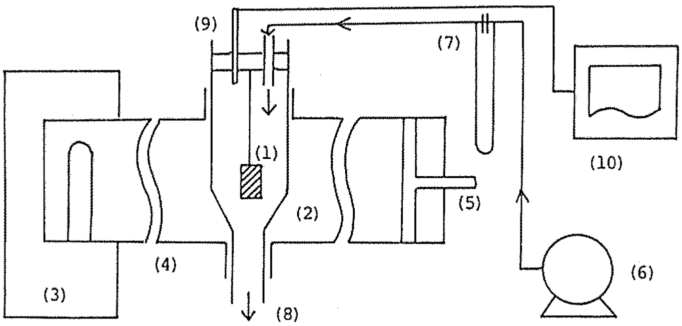

Fig.2. Experimental apparatus on the microwave-heat dryer
(1) sample, (2) drying chamber, (3) microwave generator, (4) wave guide, (5) reflux plate, (6) air pump, (7) orifice flow meter, (8) air outlet, (9) thermocouple, (10) recorder

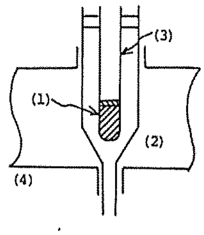

Fig.3. Structure of drying chamber for water added parafin liquid
(1) sample, (2) drying chamber, (3) test tube, (4) wave guide.

The wave distribution in the wave guide may be changed by using a movable reflux plate. The set point of the plate was fixed. Where the wave strength used to be was an interval value between the maximam and the minimum values. Instead of indicating the wave strength values, the temperature history of water which physical properties such as dielectric properties[16] and others were well known was measured at the same experimental conditions of potato's experiments.

The structure of the drying chamber for the water-added-paraffin liquid is shown in Fig.2. The test tube used had an 1.8 inside and 2.1 cm outside diameter and was 20.0 cm long.

The initial temperatures of the water added paraffin liquid in the test tube used were set at 10.0 °C by putting it in a constant temperature water bath. The water bath was provided with a thermo-heater unit with a stirrer (Taiyo Kagaku Co., Type Minder Jr) and a cooling unit (Yamato Kagaku Co., Type Neocool BD-11).

The weight changes of the water added paraffin liquid are negligible up to the boiling point of the water. The temperature changes were measured by using a chromel-alumel thermocouple. Immediately after the microwave heating, the test tube was removed from the chamber and the temperature was measured, this because the thermocouple could not be treated in the microwave chamber. The thermocouple was bought in the market. The diameter of the stainless steel sheath was 1.0 mm.

In order to except the evaporated water on the drying of potatoes, the drying chamber was made in the manner shown in Fig.1. If the vapor of water is not removed, it accumulates on the chamber wall and gives rise to a reduction of microwave strength inside the chamber. The cylindrical drying chamber was made from pyrex glass of 5.3 cm inside diameter, and the air used was flown in from an air pump.

The sample of potato was hung up in the chamber by using a tefron thread. The velocity of the air was 1.33×10^{-4} m^3/s, the average temperature and the relative humidity were 16 °C and 53%, respectively. The temperature measurements of the air were made by using a chromel-alumel thermocouple at the inlet part of the drying chamber, because the thermocouple can not be treated in the microwave chamber.

The weight changes of potatoes were measured by means of a chemical balance. Immediately after the microwave heating, the potato was removed from the chamber and the weight was taken. Measurement were made at 1 min intervals during a 10 min span. The electric current in the magnetron anode were at 10 mA intervals over a 40 mA.

The surface area changed of potatoes were measured by photography under an electric current of 40 mA only. Immediately after the microwave heating, the sample was removed and photographed on a scale, then it was enlarged. The average diameter and the length of the samples were scaled and the surface area was calculated.

3. Apparatuses of heated air-flow dryer

The apparatuses used in the drying experiments by heated air-flow energy are shown in Fig.4. The main body is the same as in the previous paper[1]. In this study, a strain

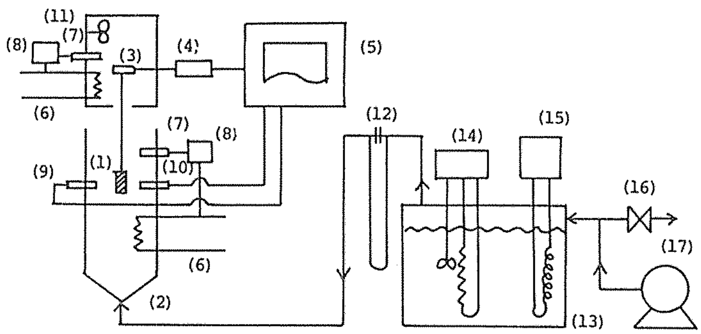

Fig.4. Experimental apparatuses on the heated air-flow dryer
(main body is same as in the previous paper[1])
(1) sample, (2) drying chamber, (3) strain gage, (4) strain amplifier, (5) recorder, (6) heater, (7) thermoregulator, (8) transister relay, (9) dry-bulb thermocouple, (10) wet-bulb themocouple, (11) fun, (12) orifice flow meter, (13) constant temperature water bath, (14) thermo-heater unit, (15) cooler unit, (16) valve, (17) blower

gage chamber set at 40 °C was added as shown in Fig.4, because the gage only was influenced by the room temperature.

The cylindrical dryer was made from acrylic resin had 11 cm inside diameter and was 60 cm long. The upper part of the dryer was open, and set up the strain gage chamber. The sample of potato was hung up in the dryer from the strain gage by using a thread. The weight change of the potato was determined by using a strain gage connected to a recorder (Yokogawa Denki Co., Type 3056-22). The heated air used was flown from a blower.

The velocity of the air was 0.25 m/s and the temperature and the relative humidity were 66.0 °C and 31.0%, respectively. The velocity was measured by means of an orifice flow meter, and the temperature and the humidity were controled by two transistor relays related to the dry- and wet-bulb thermoregulator in the dryer. The humidity control of the air was made by means of a constant temperature water bath which was provided with thermo-heater unit and a cooling unit of the same kind as the previously illustrated one.

The weight changes of potatoes were measured. The wiehgts of the equilibrium states were determined as being those values that kept the weight unchanged for more than 60 min.

RESULTS AND DISCUSSION

1. Experimental results

The relationships between the weight w (g) and the time θ (min) are shown in Fig.5. Results from this investigation indicated that microwave energy could be utilized to shorten the drying time. The temperatures of drying potatoes could not be accurately obtained, consequently, the temperature effects are not indicated in this study.

The surface area changes in drying by microwave energy are smaller than those appearing by heated air as in the previous papers[2,3]: The reason is that the inner parts of potato make the puffed sections softer due to the penetration characteristics of microwave.

When the drying continued, the coloured section appeared as shown in Fig. 6. This phenomenon appeared too when using an electronic range on the market (National

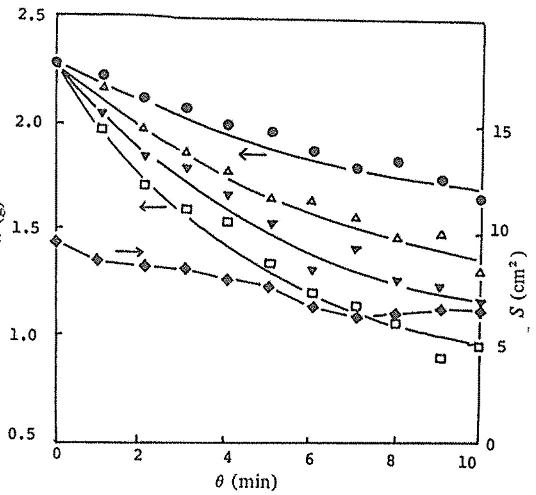

Fig.5. Relations between the weight, the surface area and the drying time on the drying potatoes by microwave energy
Observed results: Run M-1 M-2 M-3 M-4 M-4
I_A(mA) 10 20 30 40 40
● △ ▼ □ ◆
Calculated results: four curves

Denki Co., Type NE-6310, 2450 MHz, Input 1.15 kW, Output 240, 600 W) which microwave generated was stirred with a fun. Thingth which has not been discussed are the shape and the dimension of smaple, the position of the reflux plate and so on. Long and careful consideration should be given to these countermeasures. The coloured section did not appear in the initial drying region.

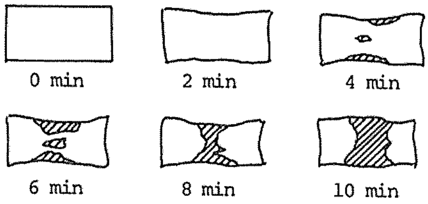

Fig.6. Cross sections of dryed potatoes by microwave energy
I_A=40 mA
lined area : coloured section

If the on-off of microwave energy can be operated on the sample, we may infer that the coloured section is can be removed by decreasing the temperature of the samples. From the results in these investigations, we may infer that as a pre-treatment method microwave energy may be usuful.

When the water content of sample had decreased until a very small value, an electric discharge happened in the wave guide. Experiments in longer drying time were not made, in order to avoid wave strength increasion, colouring of the sample, electric discharge and magnetron breakage in the microwave generator. If the experiments have to be continued until a very small value of water content in the samples, we must absorb the excess energy by adding water to it, or use a lower electric current in magnetron anode for decreasing.

The relationship between the temperature increase ΔT (°C), the time θ (min) and the microwave strength which are defined by the electric current in the magnetron anode are shown in Fig. 7. Results from these investigations indicate that the temperature increase changed proportionaly to the microwave strength in the shorter heating time region at a lower strength. In the longer heating time region, the release of heat energy affects the temperature increase.

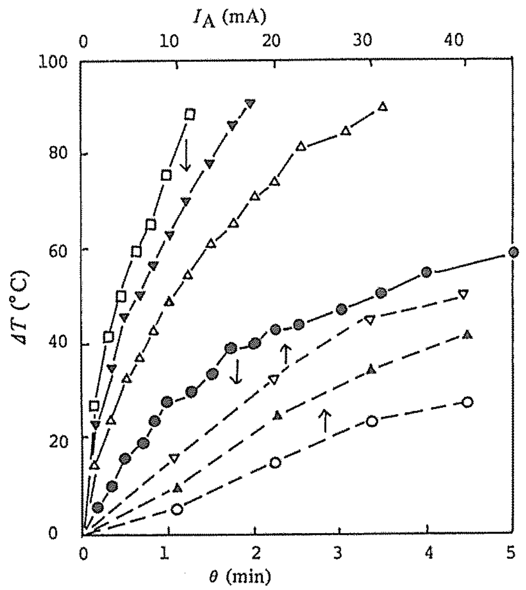

Fig.7. Relations between the temperature increase and the heating time, the microwave strength on the heating of water added parafin liquid by microwave energy

Observed values:

Run	W-1	W-2	W-3	W-4
I_A(mA)	10	20	30	40
	●	△	▼	□
θ (min)	0.07	0.33	0.50	
	○	▲	▽	

If calculation of energy efficiency is needed, we must use the results in the shorter heating region, and take into cosideration the heat capacity of the test tube and the paraffin liquid. In this paper, we did not consider these facters, since the coloured section appeared.

The relationships between the drying ratio x (–), the drying rate $dx/d\theta$ (min^{-1}) and the drying time θ(min) are shown in Fig. 8. The drying ratio is a value that will be shown later. Results from this investigation indicated that there is no notable difference in the samples with and without bore on the drying potatoes by heated flowing air energy.

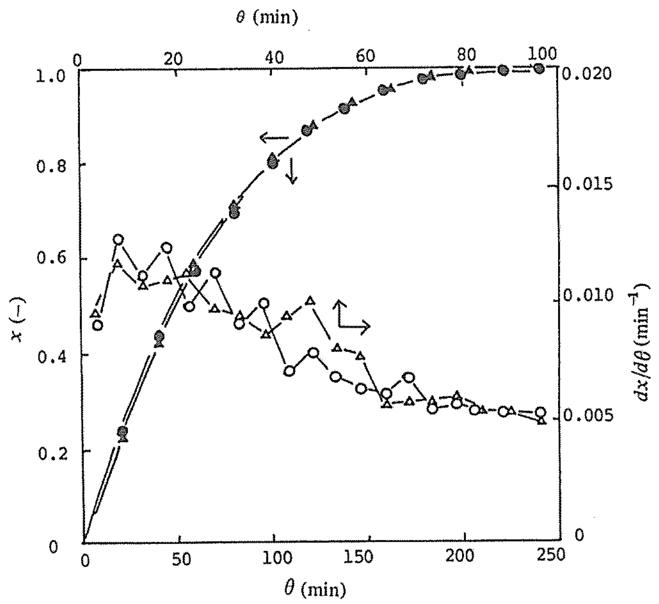

Fig.8. Relations between the drying ratio, the drying rate and the drying time on the drying potatoes by heated flowing air

Observed results: Run A-1 ● ○ A-2 ▲ △

Calculated results: two curves

2. Over-all drying-rate equations

Over-all drying-rate equations have been used by us[1~3] as the following equations. These drying-rate equations are characterized by the convenience when constant- and falling-rate periods are not rearly observed such as on the drying by microwave energy.

$$dx/d\theta = k_n (1-x)^n \tag{1}$$

$$dx/d\theta = k_n S (1-x)^n \tag{2}$$

where, $x = (w_0 - w)/(w_0 - w_e)$

$$= (W_0 - W)/(W_0 - W_e) \tag{3}$$

$$W = (w - w_d)/w_d \tag{4}$$

where, x (–) is the drying ratio, θ (min) is the drying time, S (cm^2) is the surface area, and w (g) and W (g-H_2O/g-dry material) are the weight and the water content of sample. The subscripts 0, e and d signify the initial, equilibrium and completely drying states, respectively.

Thus, we may express the drying surface area by the following equation[2,3].

$$S = S_0(1-x) + S_e x \tag{5}$$

The drying-rate parameters k_n and n are given by the relations of the weight or the drying ratio vs. the drying time. The rate parameters are non-linear, and therefor must be calculated by a non-linear least square method[17] using an electronic computer. The values of the following standard deviation σ (–) for the x were minimized.

$$\sigma = \left[\sum_{i=1}^{N} (x_{obs} - x_{cal})_i^2 \Big/ N\right]^{0.5} \tag{6}$$

where, x_{obs} and x_{cal} are the observed and calculated values of x, and N is the total number of the experimental points. For the calculation of k_n and n, we used the digital electronic computer "FACOM M-20" in the Computation Center of Nagoya University.

The rate parameters in Eq. (1) on the drying of potatoes by microwave energy are shown in Table 2. The equilibrium values w_e can not be obtained from the experimental data of Fig.5. Therefore, we assumed the value of 0.330 g on the results by the air-flowing data[18] which were obtained at 66 °C temperature and 8.6% relative humidity. If the value is not obtained accurately and it seems to be not quite all right, we may consider it as one of the parameters with the other parameters of k_n and n.

Table 2. Rate parameters on the drying of potatoes by microwave energy

Over-all drying-rate equation (1) ;

Samples	n-th order			n=1.5 order		n=2.0 order		n=1.8 order	
	k_n	n	σ	$k_{n=1.5}$	σ	$k_{n=2}$	σ	$k_{n=1.8}$	σ
M-1	0.0396	1.54	0.0155	0.0394	0.0155	0.0423	0.0158	0.0411	0.0156
M-2	0.0872	2.11	0.0172	0.0752	0.0198	0.0849	0.0173	0.0809	0.0179
M-3	0.1279	1.93	0.0240	0.1109	0.0265	0.1307	0.0240	0.1224	0.0242
M-4	0.1620	1.51	0.0273	0.1613	0.0273	0.1988	0.0327	0.1830	0.0294

The values of n in Table 2 and found to be from 1.5 to 2.0, so they are unified as n = 1.8 as shown in Table 2. The calculated values using the rate parameters of Table 1 compared to the observed values are illustrated by the solid lines in Fig.5. All of the calculated results were satisfactory.

The values of n are much larger than the values obtained to be from 0.60 to 0.65 on the heated air-flowing data[1]. Thus, we may infer that the drying rates of potatoes by microwave energy at initial drying time are much larger than the ones by heated flowing air.

The rate parameters on the drying of potatoes by heated flowing air energy are shown in Table 3.

Table 3. Rate parameters on the drying of potatoes by heated flowing air

Over-all drying-rate equation (1);

Samples	n-th order			n=0.5 order		n=0.6 order		n=0.7 order	
	k_n	n	σ	$k_{n=0.5}$	σ	$k_{n=0.6}$	σ	$k_{n=0.7}$	σ
A-1	0.0125	0.699	0.00576	0.0112	0.0198	0.0118	0.0112	0.0125	0.0058
A-2	0.0125	0.661	0.00771	0.0114	0.0177	0.0121	0.0099	0.0128	0.0087

Over-all drying-rate equation (2);

Samples	n-th order			n=0.5 order		n=0.15 order		n=0.2 order	
	k_n	n	σ	$k_{n=0.5}$	σ	$k_{n=0.15}$	σ	$k_{n=0.2}$	σ
A-1	0.00156	0.169	0.0109	0.00193	0.0374	0.00154	0.0106	0.00159	0.0121
A-2	0.00153	0.157	0.0136	0.00189	0.0390	0.00152	0.0137	0.00157	0.0148

In the drying by heated flowing air, the equilibrium values w_e can be obtained from the experimental data. The compared results of Run A-1 and A-2 not differ from each other. So, we may infer that the bored effect can be neglected.

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SUMMARY

In order to design various drying equipments of food materials, it is necessary to determine the drying-rate equations.

In a former paper[1~3], we studied the over-all drying-rate equations of root vegetables under the heated air-flow dryer. To improve the process, a faster dehydration method by using various heating methods or pre-treatment methods of samples is required.

In this paper, we studied the over-all drying-rate equations on the drying of potatoes by microwave energy and of bored ones by heated flowing air. In the drying-rate equation on the drying by microwave enegy, we obtainéd it in the initial drying region only. The values of the orders in the rate equation are much larger on the drying by microwave energy than the ones obtained by heated flowing air.

The results for the unbored and bored potatoes on the drying by heated flowing air did not differ from each other in these experimental conditions.

The results of the microwave drying obtained are usuful for later promising experiments of the pre-treatment of potato using microwave energy.

NOTATION

D : diameter of sample (cm)

I_A : microwave strength (electric current in magnetron anode) (mA)

k_n and n : rate parameters

L : length of sample (cm)

S : surface area of sample (cm^2)

ΔT : temperature increase of sample (°C)

W : water content of sample (g–H_2O/g-dry material)

w : weight of sample (g)

θ : drying or heating time (min)

σ : standard deviation (–)

Subscripts;

0, e, d : initial, equilibrium and completely drying states

obs and cal : observed and calculated values

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Over-all Drying-rate Equations on the Drying of Potato by the Microwave Energy and of Bored One by Heated Flowing Air

ジャガイモのマイクロ波乾燥と穴あけ処理をしたものの熱風乾燥における総括乾燥速度式

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金藤浩昭・鈴木寛一・江坂宗春

各種食品の各種乾燥装置を設計するためには，各種乾燥における乾燥速度式を設定しておくことが必要となる。前報[1~3]において，熱風乾燥における食品の総括乾燥速度式の設定に関する研究を根菜類食品を例として行なってきた。

食品乾燥工程における熱効率向上を進めることを目的として，試料の前処理方法とか加熱方法とかを検討していくことは，熱エネルギー資源を有効利用し，食糧資源を保存利用していくのに役立つ研究と考えられる。本報では，ジャガイモを例とし，マイクロ波利用と試料に穴あけする方法で乾燥速度を増大させる試みをする実験を行ない，それぞれに対し総括乾燥速度式の設定を行なった。

マイクロ波利用の乾燥は，試料の褐変化などのために低乾燥域の実験しか行なうことができなかった。また，熱風乾燥において，試料に穴あけする方法による熱効率向上の試みに対しては，本実験条件下では期待した結果が得られないことがわかった。本研究成果を参考とし，マイクロ波利用における均一化加熱の検討を進めるなどし，マイクロ波加熱による組織破壊の前処理試料を作製し，それを熱風乾燥していく研究を進めていくことによって，熱効率向上ができる結果が得られるのではないかと期待できる。