J. Fac. Appl. Biol. Sci.,
Hiroshima Univ. (1980), **19**: 147 – 154

Thermal Efficiency of Vacuum Drying in a Vibro-fluidized Bed

Asao FUJIGAMI, Kanichi SUZUKI, Kiyoshi KUBOTA and Hideaki HOSAKA

Faculty of Applied Biological Science, Hiroshima University, Fukuyama

Received: September 13, 1980
(Figs. 1–7)

INTRODUCTION

The vacuum drying has been considered as one of the most favorable drying methods for foodstuffs, though various methods for food drying have been developed according to the purposes of the drying and the properties of the products. However, the vacuum dryers actually in operation face a serious problem that the thermal efficiency of the drying is extremely low. Therefore it is very desirable for food drying, if the thermal efficiency of the vacuum drying can be improved by some suitable methods.

In this respect, thus we have tried to develop a new system of vacuum drying by utilizing a vibro-fluidized bed. The vibro-fluidized bed dryer is endowed with special features[3–7] which can be indicated as follows.

The materials in the bed circulate and mix smoothly, and thus are dried at a uniform bed moisture content in the vibro-fluidized bed even when the air velocities are lower than the minimum fluidization velocities of the materials. Furthermore, the thermal efficiency of the vibro-fluidized bed drying is much higher[4,6].

On the other hand, Gutman[1] and Kroll[2] reported that the particles in a vibro-fluidized bed could be circulated only through addition of vibration to the bed even when the air was not flowed into the bed. Thus, we were brought to the idea that vacuum drying by using a vibro-fluidized bed may be possible. Thereafter the possibility and the usefulness of this method of the vacuum drying were investigated.

In this paper, the thermal efficiency of the vacuum drying in a vibro-fluidized bed, one of the most important factors of the vacuum drying, is reported, although the results were obtained in a preliminary examination in which the heat energies for the drying were still at low regions.

EXPERIMENTAL APPARATUS AND PROCEDURES

The diagram of the experimental apparatus is shown schematically in Fig. 1. The test cylinder (1) was made of an acrylic resin tube, measuring 110 mm in inner diameter. The exterior wall and bottom of the cylinder were covered with a foaming polystyrol resin plate for heat insulation. The gas in the cylinder was evacuated by a vacuum pump (14), and the pressure was measured by a mercury manometer (4). The heat energy added to the heater (2) was calculated from the values of electric current and voltage measured

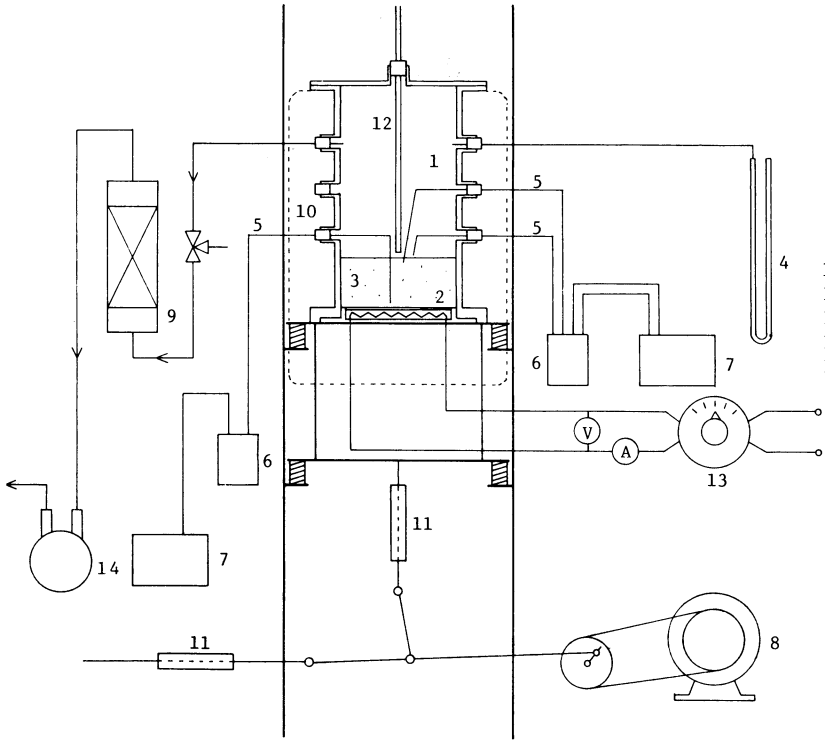

Fig. 1. Schematic diagram of experimental apparatus

by an ammeter (A) and voltmeter (V). The frequency of vibration was measured by a tachometer, and the amplitude was measured by a calibrated wedge-shaped rule having an error less than 0.025 mm.

Two kinds of samples were examined. One was ion exchange resin particle (Amberlite, IR-120B) whose diameter ranged from 420 to 590 μm, and the initial moisture contents were prepared at about 0.4 kg-H_2O/kg-d.m., The other one was okara which was sieved by a 12-mesh sieve. Thus the sizes of the sieved okara were equal to/or less than about 1.4 mm. The initial moisture content of okara was measured to be about 4.0 kg-H_2O/kg-d.m. The charged weight of ion exchange resin particles and okara was 300 grams and 140 grams respectively. The initial bed height was 4.0 cm for all experimental runs.

In order to measure the change in moisture content, a small portion of the bed was collected by a sample collector (12)[3] at every fixed time interval. The sampling position was the center of the upper portion of the bed. The temperatures of the heater and the bed were measured by copper-constantan thermocouples at the positions shown in Fig. 2.

At the end of each run, the bed was stirred and mixed completely. Then the average moisture content of the bed was measured. The moisture contents of collected samples were determined by the drying method using a drying oven at 403 K.

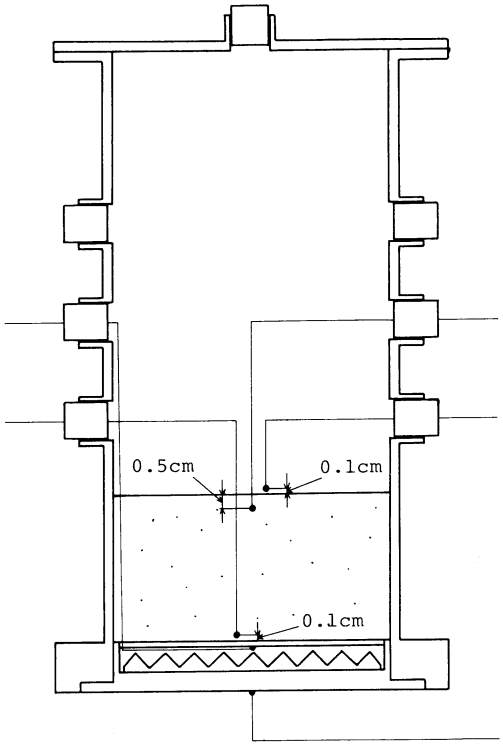

Fig. 2. Points of temperature measurement

DETERMINATION OF THERMAL EFFICIENCY AND HEAT LOSS

The thermal efficiency η_e was defined as the ratio of heat consumed for evaporation of water during the drying process to heat supplied to the heater. The value of η_e is expressed by

$$\eta_e = q_v / q_t \tag{1}$$

where q_v is the heat required for vaporization of dried water, and is calculated by the following eqation

$$q_v = (W_\circ - W_\theta)\, w_d \lambda \tag{2}$$

where W_o is the initial moisture content of the sample, W_θ is the moisture content of the sample after the drying time θ, w_d is the weight of bone dry material in the bed, and λ is the latent heat of vaporization. q_t is the total supplied heat and equal to

$$q_t = E \cdot \theta \tag{3}$$

where E is the electric power added to the heater.

On the other hand, the heat loss q_l is evaluated by the following equation

$$q_l \doteqdot q_b + q_e \tag{4}$$

where q_b is the heat loss from the bottom surface of the cylinder, and q_e is the heat loss from the exterior wall of the cylinder. The values of q_b and q_e are expressed by the following equations

$$q_b = k_1 A_1 \theta \Delta t_1 / L_1 \tag{5}$$

and

$$q_e = \frac{1}{\dfrac{L_2}{k_1 A_2} + \dfrac{L_3}{k_2 A_3}}\, \theta \Delta t_2 \tag{6}$$

where k_1 is the thermal conductivity of the heat insulator, and k_2 is that of acrylic resin, A_1 is the surface area of the bottom of the cylinder, A_2 and A_3 are the average area of side wall of the cylinder and heat insulator, L_1, L_2 and L_3 are the heat transfer distances,

and Δt_1 and Δt_2 are the temperature differences.

The ratio of the heat loss q_1 to the total heat supplied to the heater q_t is expressed as

$$\eta_1 = q_1 / q_t \tag{7}$$

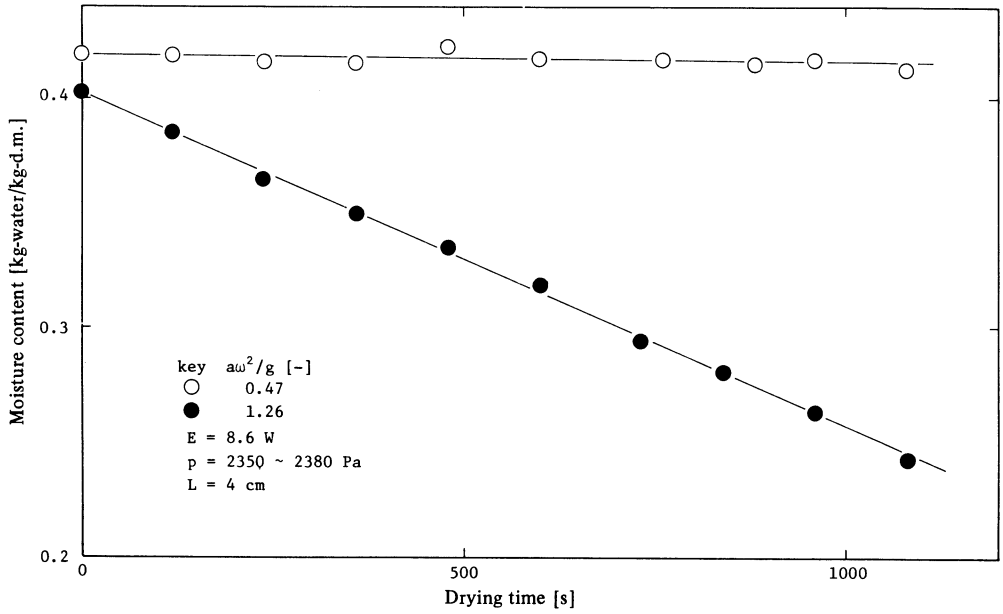

Fig. 3. Examples of drying curves for ion exchange resin particles

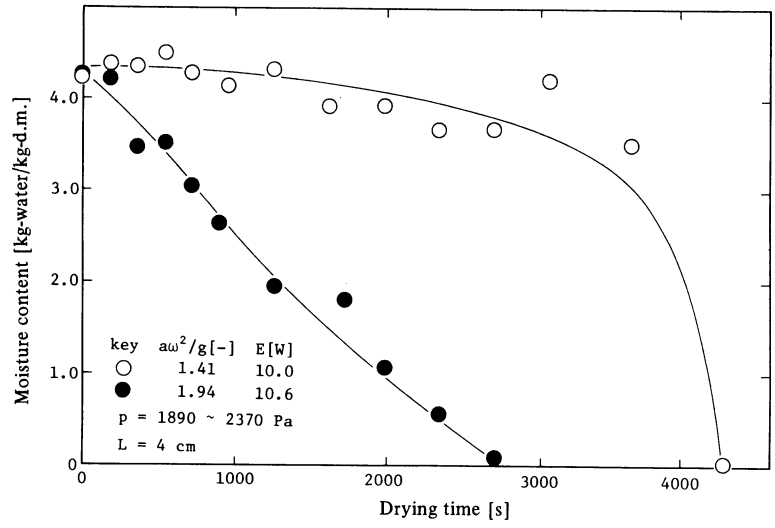

Fig. 4. Examples of drying curves for okara

EXPERIMENTAL RESULTS AND DISCUSSION

The examples of the drying curves of both samples are shown in Fig. 3 and Fig. 4. When the bed was not vibrated, or vibrated at low intensities, the moisture contents of the upper portion of the bed were maintained nearly constant until the drying process reached almost its final stage. However, when the bed was vibrated under more suitable vibrational conditions, the moisture contents of the upper portion of the bed decreased in linear relation to the drying time. These facts show that the bed was circulated and mixed, and the drying process was carried out at uniform moisture content of the bed that can be estimated by the vibro-fluidized bed drying model[3,5]. Thus, even when the air was not flowed into the bed, and the bed was in a vacuum state, the materials in the bed were circulated only adding the suitable intensities of vibration to the bed. And the mixing rate sufficient for uniform bed moisture content drying was able to be obtained.

The thermal efficiencies and the heat losses evaluated from the results of the experiments performed under various conditions of vibration and electric power supplied to the heater are shown in Fig. 5 and Fig. 6. The values shown in these figures are the average values of two experiments under each condition. The results indicate that the sums of η_e and η_1 were nearly equal to unity, and thus the values of η_e and η_1 calculated by Eqs.(1) and (4) were applicable. The sums of η_e and η_1 became slightly larger than unity as the intensities of vibration increased. The reason for this may be the influence of the heat generated by the vibration[1] on the drying rate.

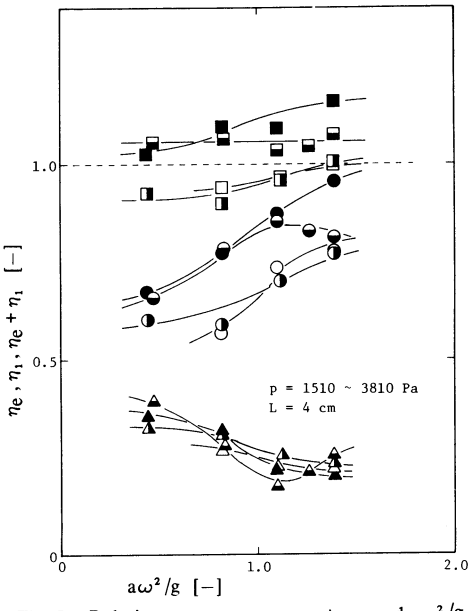

Fig. 5. Relations among η_e, η_1, $\eta_e + \eta_1$, and $a\omega^2/g$ for ion exchange resin particles

E =	6.9 W	8.6 W	10.6 W	13.3 W
η_e :	●	◒	◑	○
η_1 :	▲	◭	◮	△
$\eta_e + \eta_1$:	■	◒	◨	□

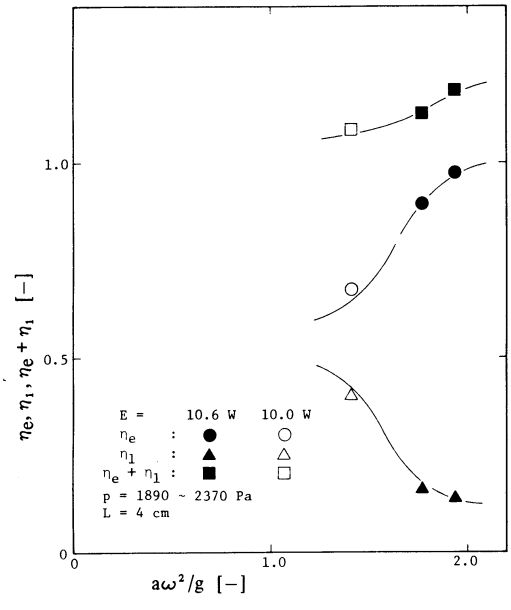

Fig. 6. Relations among η_e, η_1, $\eta_e + \eta_1$, and $a\omega^2/g$ for okara

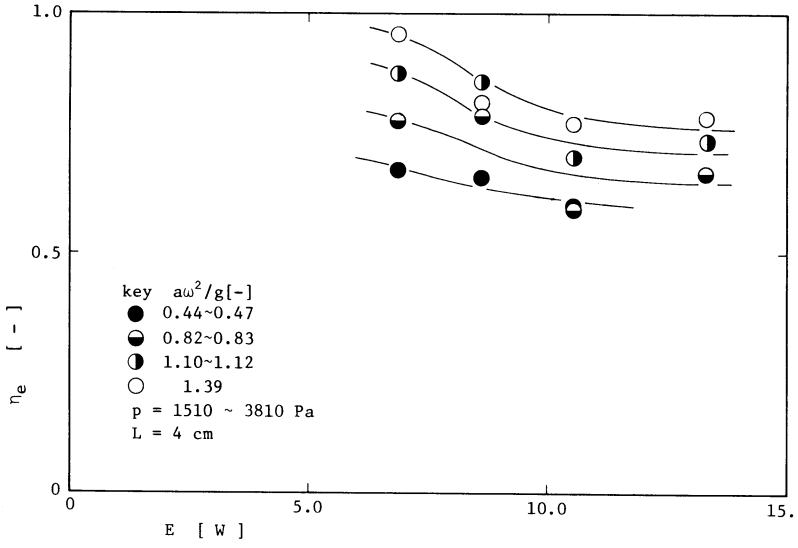

Fig. 7. Relations among thermal efficiency η_e, electric power supplied to heater E, and intensity of vibration $a\omega^2/g$ for ion exchange resin particles

These results show that the thermal efficiency of the drying increased as the vibrational intensities increased. However, when the electric power became large, the influence of vibration on the thermal efficiency was decreased. These relations were rearranged as shown in Fig. 7. As is evident from this figure, the appropriate intensities of vibration have to be determined experimentally according to the electric power supplied to the heater and the properties of the materials to be dried in order to obtained the desired thermal efficiency. Nevertheless, the possibility and the usefulness of the vacuum drying in a vibro-fluidized bed were recognized, though further investigations have to be performed in order to verify the applicability of this vacuum drying method to the conditions for actual drying processes.

SUMMARY

We tried to develop a new system for vacuum drying by using a vibro-fluidized bed. The thermal efficiency of the apparatus which is the most important factor of the vacuum drying was investigated in this paper. Two kinds of samples were examined. One was ion exchange resin particle (Amberlite, IR-120B), and the other was okara,

When the bed was vibrated under suitable vibrational intensities, the materials in the bed were circulated and mixed even though the air was not flowed into the bed, and the bed was in vacuum state. Thus, the drying processes were able to be carried out at uniform bed moisture content even in such conditions.

The thermal efficiencies obtained were nearly equal to 100 % for both samples under suitable conditions of vibration, although the heat energies supplied to the heater were very low. When the vibrational intensities were constant, the thermal efficiencies decreased as the heat energies supplied to the heater increased. As a results of this study,

the possibility of the vacuum drying in a vibro-fluidized bed was recognized.

NOMENCLATURE

A_1	= area of bottom of cylinder	(m^2)
A_2	= average area of side wall of cylinder	(m^2)
A_3	= average area of heat insulator of side wall	(m^2)
a	= amplitude of vibration	(cm)
D_p	= diameter of sample	(μm)
d.m.	= bone dry material	
E	= electric power supplied to heater	(W)
g	= gravitational acceleration	(cm/s^2)
k_1	= thermal conductivity of heat insulator	(W/m·k)
k_2	= thermal conductivity of acrylic resin	(W/m·K)
L	= height of bed	(cm)
L_1, L_2, L_3	= heat transfer distance	(m)
p	= pressure in drying chamber	(Pa)
q_b	= heat loss from bottom surface of cylinder	(W·s)
q_e	= heat loss from exterior side wall	(W·s)
q_1	= $q_b + q_e$	(W·s)
q_t	= total heat supplied to heater	(W·s)
q_v	= heat required for vaporization of water	(W·s)
W_o	= initial moisture content	(kg-H_2O/kg-d.m.)
W_θ	= moisture content after θ	(kg-H_2O/kg-d.m.)
w_d	= weight of bone dry materials in bed	(kg)
$\Delta t_1, \Delta t_2$	= temperature difference	(K)
η_e	= q_v/q_t	(—)
η_1	= q_1/q_t	(—)
θ	= drying time	(S)
λ	= latent heat of vaporization	(W·s/kg)
ω	= angular frequency	(1/s)

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振動流動層を用いた真空乾燥における熱効率の研究

藤上朝生・鈴木寛一・久保田清・保坂秀明

振動流動層を用いた新しい形の真空乾燥法の開発を試みた。本研究ではその予備試験として，真空乾燥における最も重要な問題である装置の熱効率について考察を加えた。実験には2種類の試料を用いた。一つはイオン交換樹脂球（Amberlite，IR－120 B）であり，他の一つはおから（卯の花）である。

層に空気を吹き込まず，真空状態にしても層を適当な振動強度で振動させれば，層内の材料は移動，混合した。それ故，そのような真空下であっても，層全体にわたり均一含水率で乾燥を行うことができた。ヒーターに加えた熱量はまだ非常に少ない範囲であるが，得られた熱効率はほぼ100％であった。振動強度が一定の場合には，ヒーターに加える熱量が増加するにつれて熱効率は減少した。

本研究の結果，振動流動層を用いた真空乾燥の可能性が認められた。