ON DRYING OF ROUGH RICE - RECENT TRENDS IN RESEARCH AND PRACTICE IN JAPAN

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ABSTRACT

Drying of rough rice is the first step following harvesting for preservation of quality and quantity of rice as food as well as seed. Drying, in fact, is a simple operation, i.e. removing water from rice. It is not however so simple as squeezing water out of a wet towel. A little closer look reveals that drying of rough rice is quite complex and that a multitude of problems remains yet to be answered.

First, a brief historical sketch on mechanical drying of rough rice in our country is given. Then the results of the research are presented which has been made in the Laboratory of Agricultural Processing Engineering at the Department of Agricultural Engineering, University of Tokyo.

New work and new development in the same laboratory which took shape after my retirement will be presented with comments.

Comments will further be given on how soon the drying should be finished, on rewetting of test samples and on computer simulations of drying processes.

Finally some of the new features of rice driers which have been made available for farmers recently in our country will be discussed.

INTRODUCTION

Drying of rough rice, or any other grains, is the first step following harvesting for preservation of rice as food as well as seed. Drying, in fact, is a simple operation, i.e., removing water from rice. It is not, however, so simple as squeezing water out of a wet towel. A little closer look at it reveals that drying is quite complex and a multitude of problems remains yet to be answered.

Research on rice drying is roughly divided into two schools of thought. One centres around the rate of drying or how fast rice dries in relation to its drying air temperature, humidity and air volume. The rate of drying and other drying characteristics are determined experimentally. Limiting factors to raising the rate of drying are quality of rice such as milling yield and viability, energy use, labour involved or economical considerations. This approach, together with the knowledge of the method of removing foreign matters from rice or the mechanical way of handling it, aims at working out a basic design of rice driers such as selection of a proper fan, a burner and the type of driers to be constructed. Another school centres around the diffusion of water from grain kernels into their surroundings. Since direct measurement of moisture gradient in rice grain during drying has been impossible so far, various assumptions are made to suit drying characteristics. Grains are treated as spheres of a convenient diameter, and the water in the grain migrates from core to surface as either liquid or vapour. This shool concerns more in mechanism of drying than in design of driers, although the ultimate goal of both schools may be the same.

Whichever school we may be in, however, knowing on the one hand such drying characteristics of rice specific heat, heat and mass transfer rates between rice and drying air, and on the other, the drying air conditions such as its temperature, humidity, air volume and bulk density of, or air pressure loss through, the rice bed, we my be able to set up a mathematical model of rice drying. These models will enable us to predict the temperature and moisture distribution through out the bulk, the average moisture content of the rice bed at any instant of time, variation of moisture between the top and bottom layers and how soon the given amount of rice will dry and so on. Further those models enable us to simulate drying rocesses on computers in search for better drying operations. Computer simulation has become a powerful engineering tool of drying these days.

BRIEF HISTORY OF RESEARCH ON RICE DRYING IN JAPAN

Mechanical driers first entered in Japanese agriculture in later years of 1920's. Around 1935, they won government subsidies and started to spread. But the popular use of driers by farmers took place only after 1956.

After World War II, Japan suffered acute shortage of rice. The problem was at its worst in the off-season (August and September). The government encouraged earlier delivery of rice before certain dates, e.g., August 31 or September 30. Under such circumstances farmers had not enough time for sun-drying of rice, and, therefore, rice tended to be of higher moisture contents than the government specification (14% or 15% w.b.). The penalty to excess moisture more than off-set the premium. There arose a demand for simple, inexpensive mechanical driers to meet this problem.

The pioneering work on rice driers was carried out then by T. Watanabe and his colleagues at Kohnosu Agricultural Experiment Station, which lied 30 km north of Tokyo. They used several layers of trays, 15×15 cm^2 with 2 cm deep rice bed, to determine the drying characteristics of rice. Their experiments were carefully carried out and their data are highly reliable (1)*. They also gave us data on air pressure losses through the column of rough rice and the equilibrium moisture contents of it under various conditions (2, 3). These data were used for design and simulation of batch-in-bin driers with a wire-mesh floor. The holding capacity of mommon dryers was 1—2 tons and the floor area was 3.3—6.6 m^2. The depth of rice bed was 30—60 cm. Air temperature was slightly raised by putting a small charcoal or briquette stove in front of the fan. Rice at that time was harvested by hand, dried on racks and then threshed. The drier was meant to reduce the moisture content of rice from about 16–18% (w.b.) to 14–15%, at which the government purchased.

There are hundreds of research done and reported on rice drying in Japan since then, but here I only mention another minutely carried out experiments in early days. T. Ichimura of Central Electrical Power Research Institute used box trays, 19.8 × 9.1 cm^2, with 3 cm deep rice. He carefully controlled the inlet air humidity using a rather expensive humidifier (4).

After 1965, rice combines came to use. Rice was then harvested at 20–25% (w.b.) and sometimes in northern Honshu, at 25–28%. Conventional batch-in-bin driers could not handle rice with such high moisture. It took too much time to dry. Air temperature had to be raised, and air volume had to be increased. Then the bottom layers tended to overdry and to develop checks in kernels while the top layer was still wet. Vertical recirculating driers, then, were introduced. This type incorporated the idea of tempering, the upper section of the drier serving as a tempering tank. These vertical rice driers are a common sight when you visit Japanese farms to-day.

At about the same time, the US type country elecator was introduced in Japan to handle a great quantity of combine-harvested high-moisture rice at farmer's cooperatives. Especially Hachiroh-gata, Akita, the northern district of Honshu, where a lake had been drained and 6,000 ha of land had been reclaimed for wet rice field, was just going to produce rice in a year or two. One rice elevator was expected to dry 5,000 tons of rice for 25 days. The government set up a committee to look for a suitable drier to handle 200 tons of rice a day. After all, the committee decided on adaption of non-mixing columnar continuous flow drier with a pair of 20 cm screen spacings. The holding capacity of the drier was 12 tons and two driers were installed in an elevator. While I was working, as a committee member, on a model test drier, I noticed that any shape of drying curves could be obtained simply by changing combination of air temperature and humidity and the thickness of rough rice layer, as shown in Fig. 1. Then I wondered what the true drying characteristics of rice would be.

Apparently drying curves such as shown in Fig. 1 is the combined result of rice, air and rice bulk. The drying characteristics of rice is the nature of rice. It may depend upon the intensive properties of air such as its temperature and humidity, but it should be independent from such extensive properties as air volume or from the depth of the layer. These latter may be called the bulk effect rather than the rice characteristics. I thought I should divorce bulk effects entirely from the drying characteristics of rice. Then the drying characteristics, free from bulk effects, could be used for computing drying processes, regardless of the type of the drier whether it was batch-in-bin, columnar recirculation, or fluidized bed. Some researchers used a single grain layer on a wire-net. The posture of the kernel is the same and the wire effect on drying was not cleared. The only solution seemed to use a single grain as the minimum unit of bulk for determination of drying characteristics. It was not I alone that came to the similar idea. I personally know two researchers who attempted the use of a single kernel without success. It took me a year to come to the experimental apparatus shown in Fig. 2. Thus Motohashi and I set out for single grain experiments.

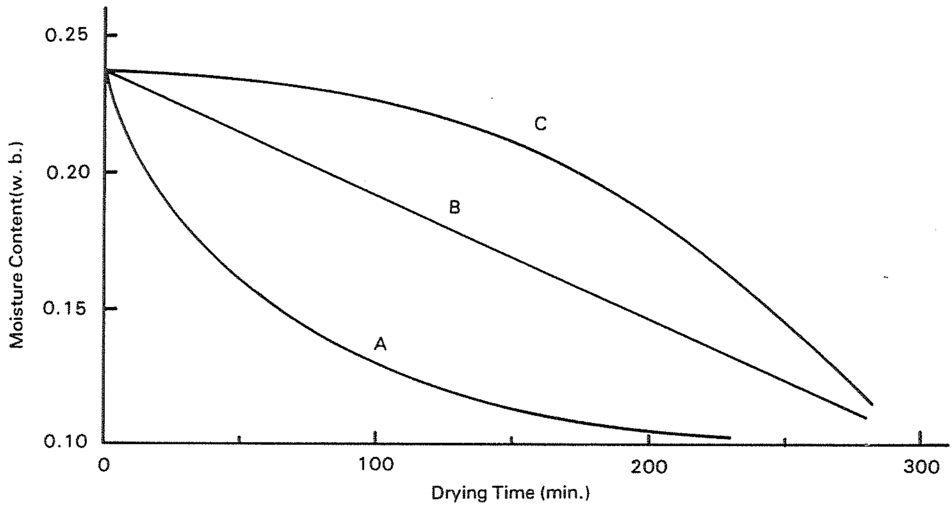

Fig. 1. Drying Curves.

SINGLE GRAIN EXPERIMENTS

The experiments were carried out during 1969—72, in the Laboratory of Agricultural Processing Engineering at the Department of Agricultural Engineering, University of Tokyo (5).

The heart of the apparatus is a slender glass beam, about 900 mm long and 0.2 mm in diameter at its hook end. A piece of Corning Pyrex glass tube, 10 mm OD and 3 mm ID, was heated red hot and then stretched by hand to form a fishing-rod shape. At the hook end a kernel of rough rice was suspended by means of a small wire hook which was bonded to rice, and the kernel was placed in a tube serving as a drying chamber, in which drying air flowed at a certain rate. The other end was attached to a vertical travelling microscope, or a cathetometer. When the rice grain dries, it becomes lighter in weight and the hook end of the beam with its mark goes off the hair line in the viewer. Then the other end was lowered to bring the mark down to the hair line. In actuality,

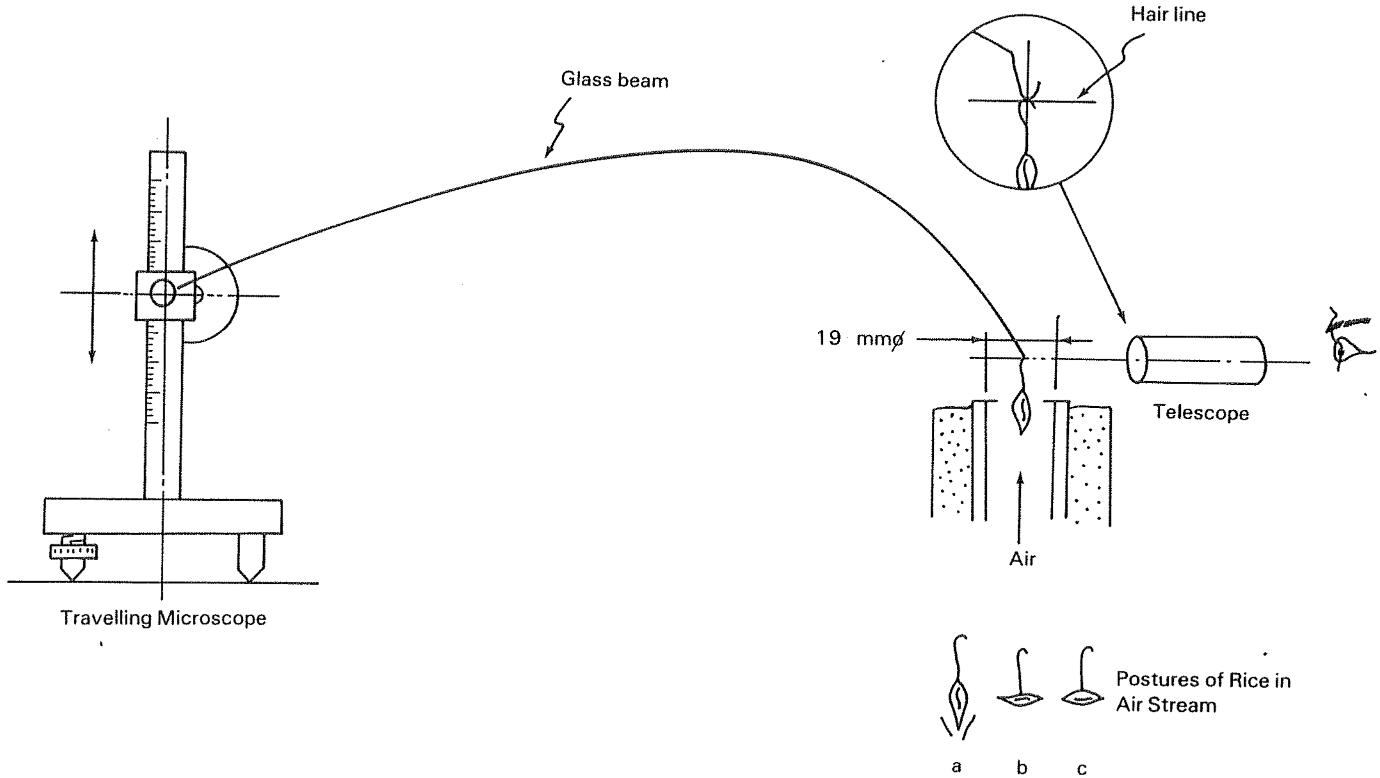

Fig. 2. Experimental Set-up.

the screw end of the beam was lowered by 0.5 mm or 0.1 mm, for instance, and the time for the grain to come up to the hair line in the viewer was measured. From the calibration curve of weight versus deflection of the beam, which was almost linear, the weight loss for a certain time interval was read off, and hence the drying curve was drawn, from which the drying characteristics were determined.

A single grain of rough rice weighed 30—40 mg. Variety used was Nihonbare, Japonica type. In combination with the least count of 0.01 mm of the travelling microscope, the beam gave the least reading of 2 μg. The sensitivity of the weighing apparatus, therefore, 2 μg/(30—40) or 1/17,500, allowing us to detect easily 0.1% change in moisture in the kernel. The grain buoyed up in the air stream about 1.2 mm, but this was almost constant during drying as long as the air velocity was kept constant. Grain was the air velocity was kept constant. Grain was stable in the air current when the air flow velocity was 1.5 m/s or less. One run of experiment took between 10 and 30 hrs, average being 15—20 hrs.

Air was supplied from a compressor tank. The flow was regulated by a two-stage pressure regulator. The flow rate was measured by a rotameter and could be set at any desired value between 1.5 ± 0.01 and 0.05 ± 0.005 m/s. The air was first cooled down to -40C and was removed of its moisture. Then the temperature was raised by electric heaters and a calculated quantity of water was added to the air stream by slowly pushing the piston of a hypodermic syringe. This method enabled us to control the quantity of water supply steplessely between 0.2—60 cc/hr with the maximum error of 0.02 cc/hr. Thus the relative humidity of drying air was kept with ± 1.0% accuracy.

Over 100 grains were tested under various air conditions with 3 postures of the grain in the air stream. See Fig. 2. Typical results are shown in Fig. 3. Fig. 3 (a) shows the humidity effect when air temperature is kept constant, and Fig. 3 (b), the temperature effect under constant air humidity. (1) Remarkably large rate of drying (a - b in Fig. 3) was observed in the beginning of any rice kernels which lasted 3—15 minutes, followed by a small plateau (b - c) which lasted 20—40 minutes (the plateau did not appear when the air moisture was 80%), and then the decreasing rate of drying set in (c - d), which was almost straight down to the equilibrium moisture content. Later it was explained that the first large rate (a - b) was mainly due to water evaporation from husk, the plateau (b - c) the balanced water movement from kernel to husk and from husk to air. These two stages had escaped detection in the past experiment buried in bulk effects of rice bed. (2) Three postures of rice grain in the air stream (Fig. 2) were chosen to represent the infinite possible number of postures the grain would assume in the bulk relative to air stream passing through the bulk (6). Postures, however, did not show any appreciable difference in rate in drying. Individuality of the kernel showed more pronounced difference in the rate of drying than the posture. (3) For certain reasons which I

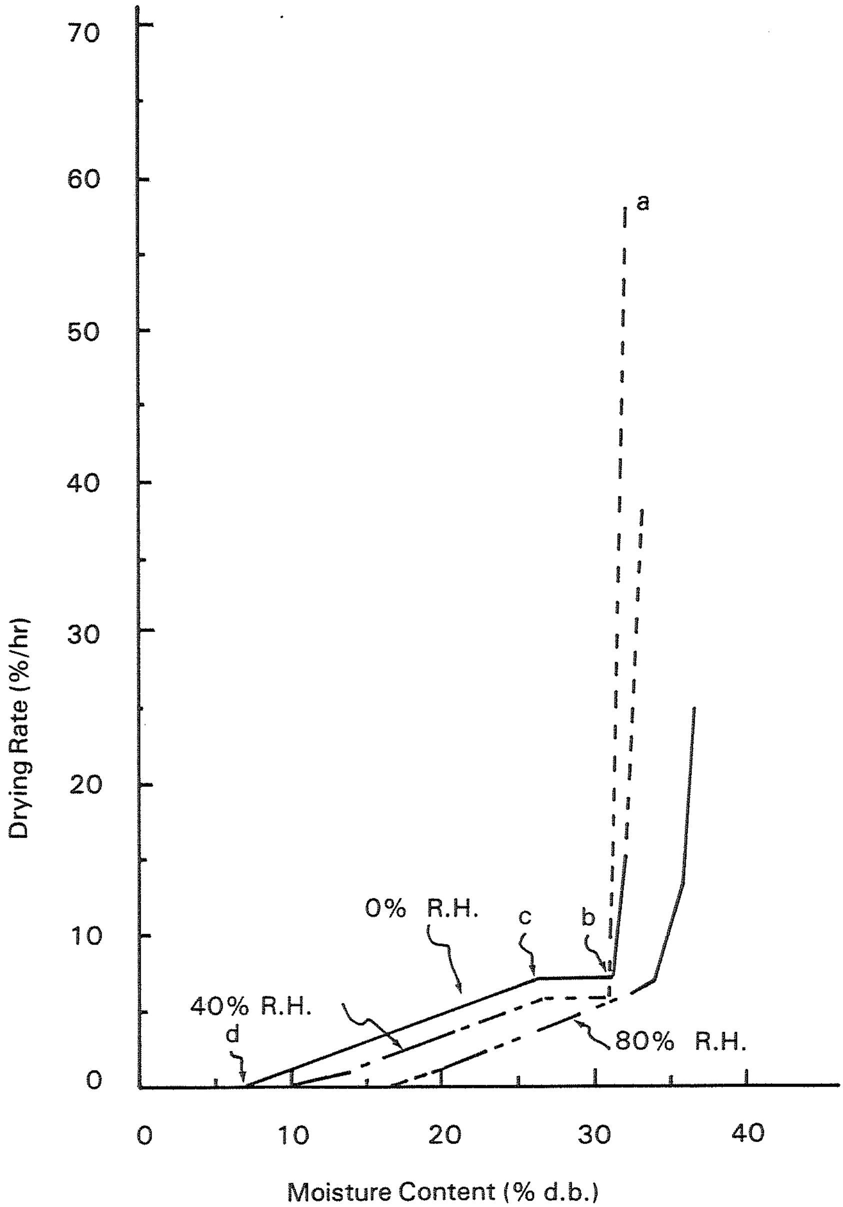

Fig. 3(a). Drying Rates (at 40C).

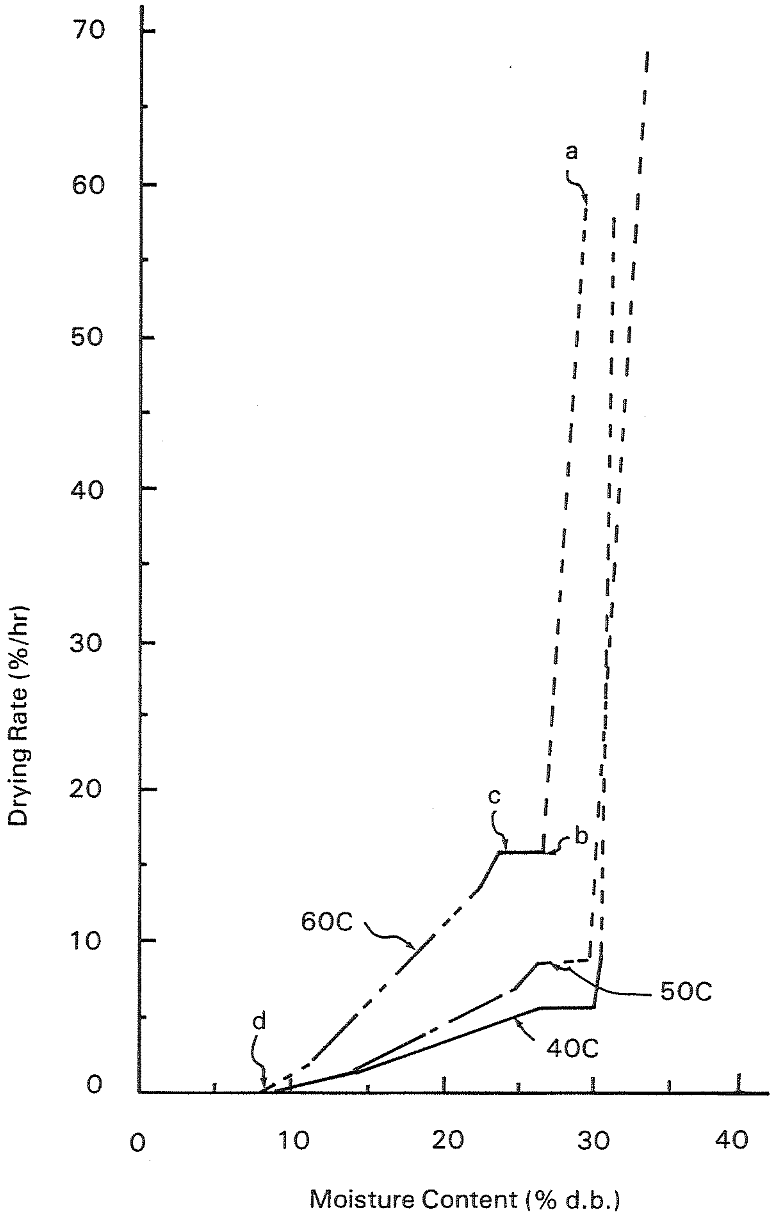

Fig. 3(b). Drying Rates (at 40% R.H.).

have not space to mention, constant rate of drying of a rough rice grain was measured (7). The sample grain was well moistened in water so that the surface of it was covered with thin water film. The constant rate of drying is, by definition, the rate of water vaporization from free water surface. It depends on air conditions and also air velocity passing on the water surface, but there should be no such distinction between the constant rate of free water and of grain. Therefore the constant rate of drying we measured is not a rice characteristic.

One run of experiment finished in 1—3 minutes, during which 6—10 readings were taken. The amount of water removed from rice surface during this period was well summarized in the following Ranz-Marshall form

$$Nu = 2.0 \pm 0.74\, Pr^{1/3}\, Re^{1/2}$$

which was very close to the Ranz-Marshall equation for a sphere,

$$Nu = 2.0 \pm 0.60\, Pr^{1/3}\, Re^{1/2}.$$

This result, together with the one from (2), assured us to treat rice grains in the bulk as spheres. Many researchers had treated rice as spheres without these warrants.

(4) When our drying characteristics were presented as Fig. 4, the drying constant for the period I (a - b), K_I, and for the period II (c - d), K_{II}, were given, as

$$K_I = 0.0339ta - 0.346$$
$$K_{II} = 0.0153ta - 0.215$$

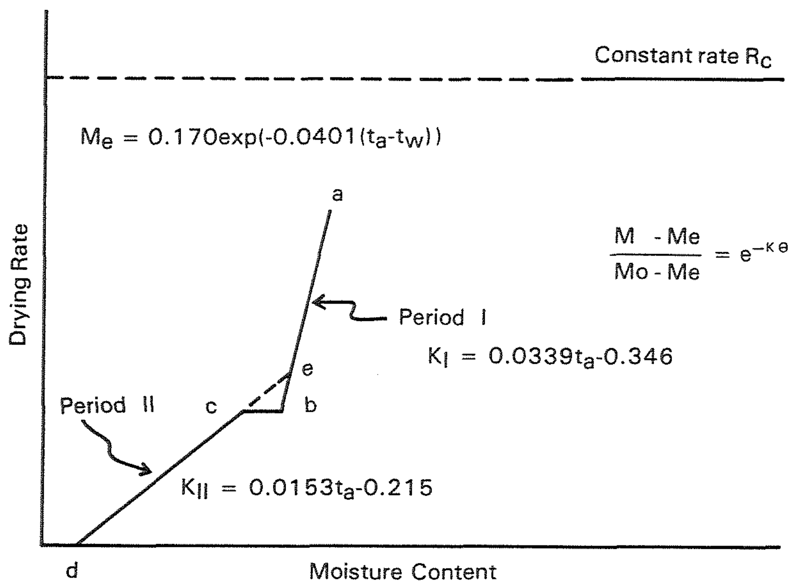

Fig. 4. Drying Characteristics.

where K is defined as

$$\frac{M - Me}{Mo - Me} = e^{-KO}$$

(5) When no more reduction of weight was observed for 2—4 hours towards the end of the experiment, the experiment was terminated. The final moisture content of the grain was taken as the equilibrium moisture content at the air conditions under which the experiment was made. This is what is called the dynamic equilibrium moisture content and was given as

$$Me = 0.170e^{-0.0401(ta - tw)}$$

APPLICATION OF SINGLE GRAIN DRYING CHARACTERISTICS TO BULK

Professor Toei of Department of Chemical Engineering, Kyoto University developed an analytical method of calculating drying processes taking place in through-air drying of a granular bed during a 1965—1966 period (8), as if he would offer us a proper method for our rice drying calculations. He approximated the drying characteristics of granular materials to two line segments as shown in Fig. 5. This approximation, he claimed, was valid for most granular materials of 3—5 mm sizes in diameter. Further assumptions are needed in calculation as follows.

(1) The initial moisture content and temperature of the granules were the same and uniform throughout the bed.

(2) The inlet air conditions should remain constant throughout during drying.

(3) The problem was treated as one dimensional in the direction of air flow, Fig. 6.

(4) No shrinkage of particle sizes would occur during drying.

(5) Drying process through the bulk is adiabatic.

Our drying characteristics of rough rice could be approximated to df in Fig. 7 to conform to Toei's assumption by extending dc, and assuming that drying would begin at g. This neglect of the first period of large drying rate (a - b) may throw us off with errors but may not be seriously wrong because the first period took only 1—2% of the total drying time. We used Toei's equations and calculated local moisture content and the average rate of drying of the bed as regards to drying time (9).

Fig. 8 shows one of the examples. At that time deep bed calculation resorted usually to layer by layer method in which the deep layer was divided into several thin enough layers with whose depth the drying characteristics had been experimentally determined. We demonstrated, now, that the direct analytical method could be used in deep bed calculation.

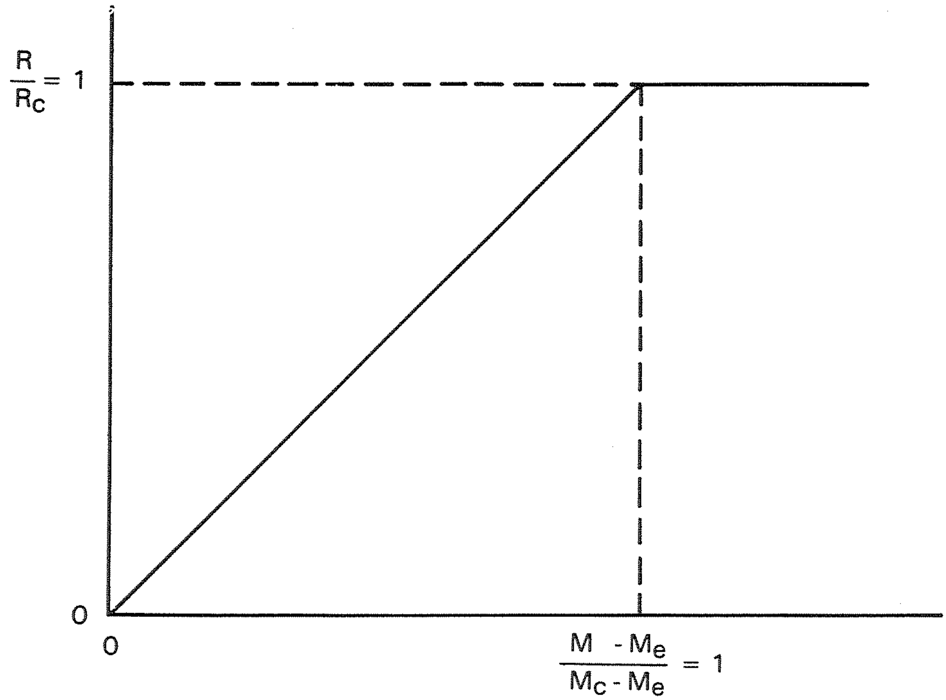

Fig. 5. Non-dimensional Drying Characteristics.

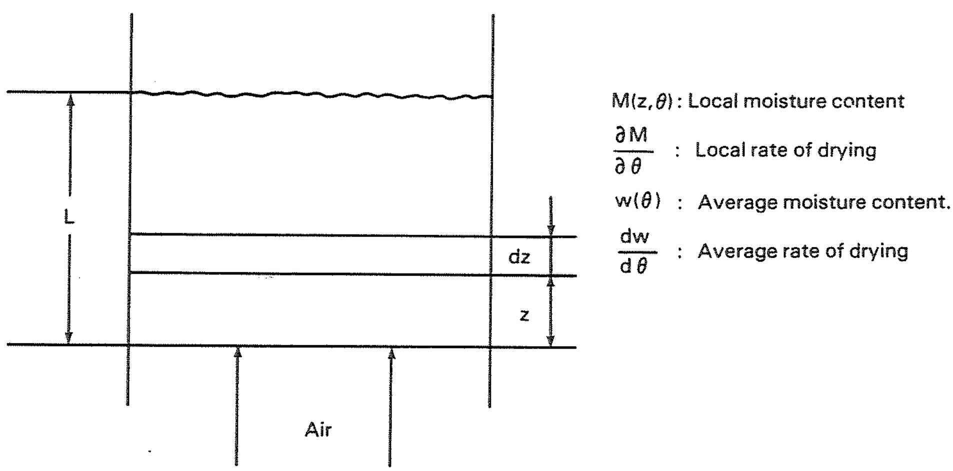

Fig. 6. Deep bed of rough rice.

The results for deep beds were quite satisfactory but it turned out that the results of our equations for drying with tempering were rather off the experimental data. Drying with tempering is a process is which a pass consisting in drying and tempering is repeated 3 to 6 times to complete drying in such a ray that half an hour's drying with rather high temperature air and high air volume is followed by tempering, viz., storing rice in a tank for at least 4 hours. The overall rate of drying including tempering time is 0.5—1.5% (w.b.)/hr, but the drying itself takes place with a rate as high as 3—6%/hr in a columnar continuous flow drier.

Because one drying pass terminated in half an hour, Motohashi thought it necessary to take the first large rate of drying into account. He modified the drying characteristics to a-e-c-d in Fig. 7, and also incorporated both Period I and Period II into Toei's equation. Then he showed that the modified equations could successfully calculate the tempering drying process as shown in Fig. 9 (10). There were a few investigators who tried to explain the tempering process by water diffusion models through a sphere, but Motohashi was the first who offered a satisfactory way of calculating the drying with tempering based totally upon his experimentally determined drying characteristics of rough rice.

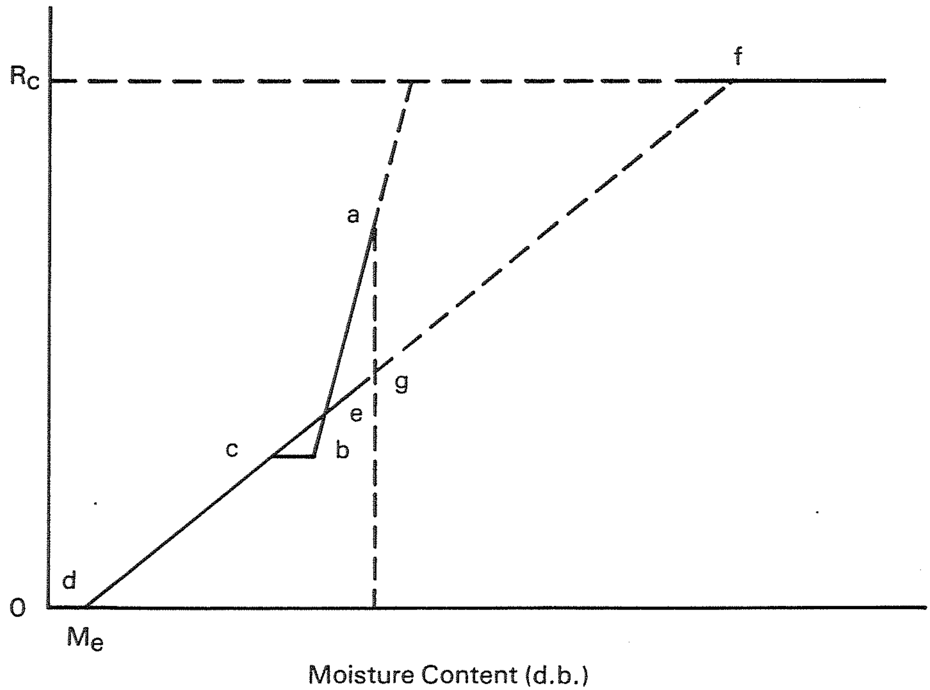

Fig. 7. Our Experimental Drying Characteristics.

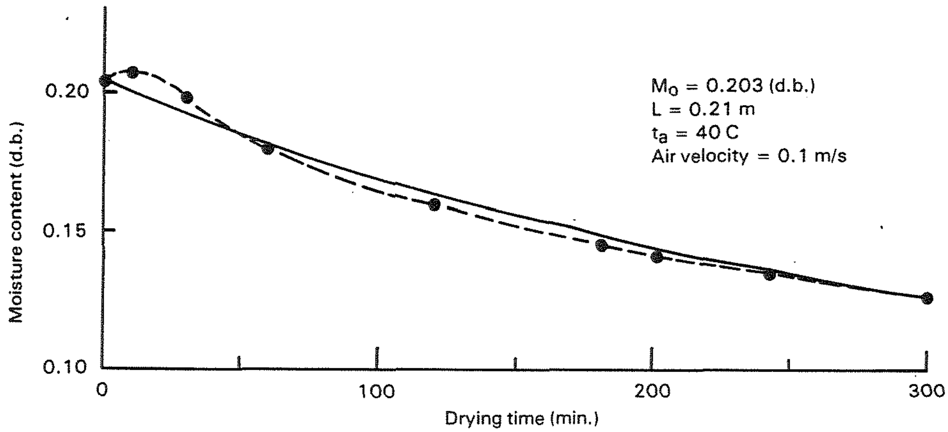

Fig. 8(a). Drying curves.

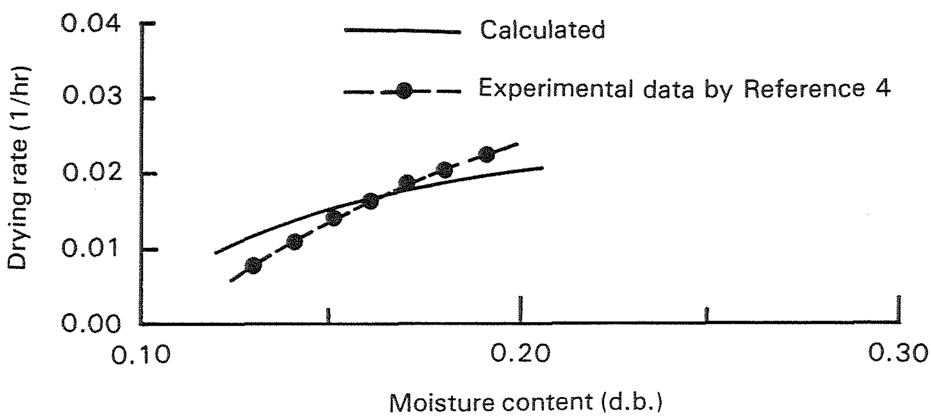

Fig. 8(b). Drying rate.

Unfortunately this method has not enjoyed popular acceptance in drying of rice yet. One reason is that these results are fairly new, published only four years ago. Another factor may be that our data are rather limited in their applicable temperature range of 30—60C, lacking especially in lower ranges between 20—30C, which became increasingly useful since the repeated oil crises. The equations are rather complicated but any desk top or hand-held calculators for engineers can handle them easily. We are hoping that our method will be used in general calculation of drying of rough rice in the near future. At present we are leaving such matters as comparing our method with layer by layer methods for its advantages and disadvantages and improvement of our results for further investigation.

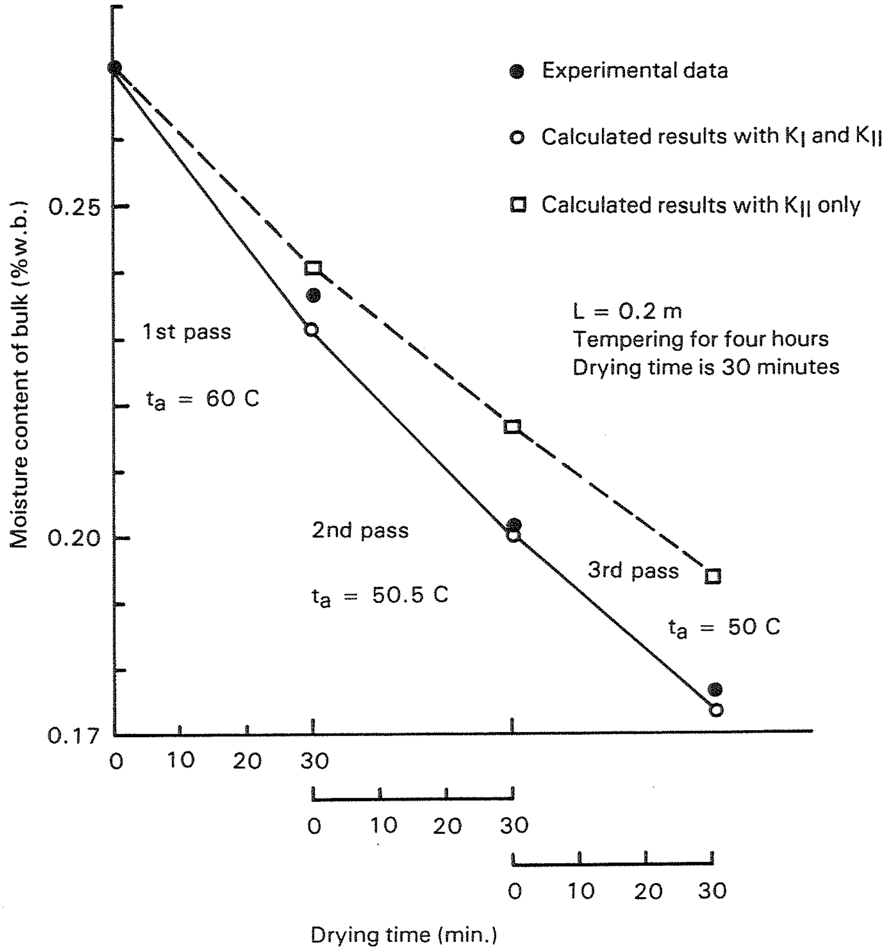

Fig. 9. Drying curves with tempering drying.

RECENT DEVELOPMENT BY DR. KAMEOKA

Kameoka started his doctor's work on drying of rough rice under me in 1980, did not of his experiments while I was in University of Tokyo, and completed and presented his dissertation this last February under the guidance of Prof. Morishima (11). His basic approach to the drying problem is of water diffusion through a sphere. He made comprehensive experimental work on such basic matters as bulk thermal conductivity of rough rice, equilibrium moisture contents of rough rice as a whole, brown rice and husk separately at various temperature and relative humidity conditions. He carried out experiments on thin layer drying as well as deep bed drying. Based upon his own data, he set up a mathematical model of water diffusion through the starch core of rice kernel to husk and from husk into passing air in each of a series of thin layers of a deep bed. From his work a few topics of interest may be offered.

(1) In his thin layer experiments in which be used 7, 17, 27 mm thicknesses, he observed the initial large rate of drying, as shown in Fig. 10, which was almost identical with Fig. 3. Kameoka took readings every 10 minutes for the first one hour of his drying, every 20 minutes in the following 4 hours and after that every half an hour, and with this frequency of observation, he could detect the initial period of large drying rate. Watanabe (1) took his first, second and third reading 10 minutes, 30 minutes and 50 minutes after the start of the experiment with a 2 cm layer respectively and Ichimura (4), 5, 15, 25 minutes with a 3 cm layer respectively, but both of them failed to observe the first period. I should like to know why Kameoka was successful in arresting the first period, whereas others failed.

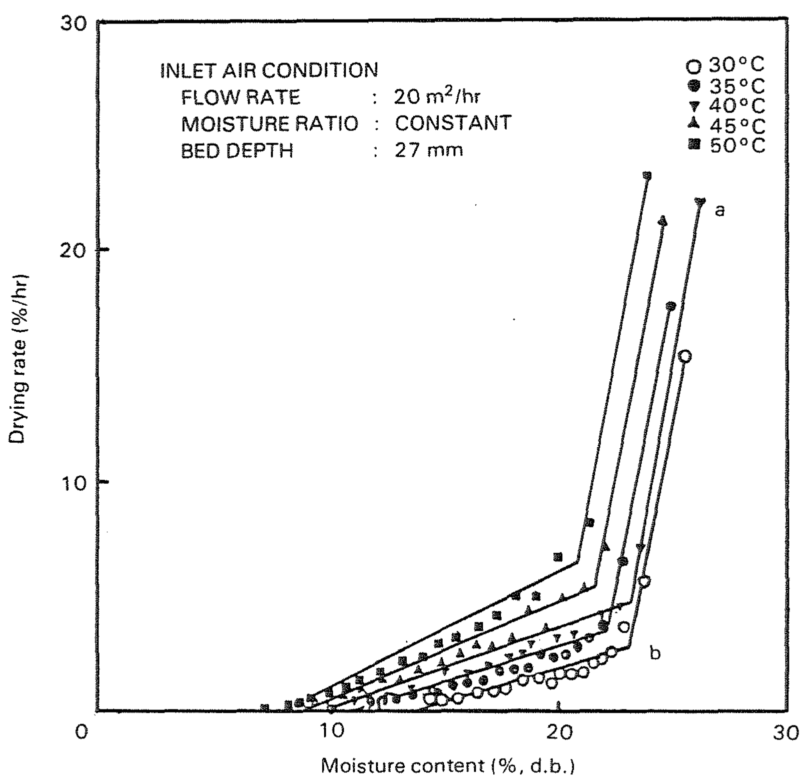

Fig. 10. Drying rate from thin layers.

Kameoka took one and plus readings for the first period with the maximum rate of 18–25% (d.b.)/hr, whereas Motohashi took 6–15 readings with the maximum rate of 55–68% as can be seen in Fig. 3. Also Kameoka lacks in humidity effects. Even though he wants information that correlates thin layer data with ones of a single grain, he way have demonstrated a possibility of replacing rather difficult single grain experiments with thin layer experiments.

(2) It was well known that the heat of water desorption was greater than the heat of evaporation of water and a good discussion on this topic could be found in old textbooks (12). Detailed data on rice, however, were unknown. Here Kameoka presented a good experimental result with theoretical considerations, Fig. 11. In our drying range of rice moisture, the ratio is 1.0–1.2. The data will certainly be used with benefit in our computation.

(3) Shrinkage of rice during drying has been quite obvious but no one ever gave quantitative relations on this phenomenon. Kameoka gave he following from his deep bed drying experiment.

$$\frac{L}{Lo} = 0.132 \times \frac{M}{Mo} + 0.868$$

where M and Mo are in d.b..

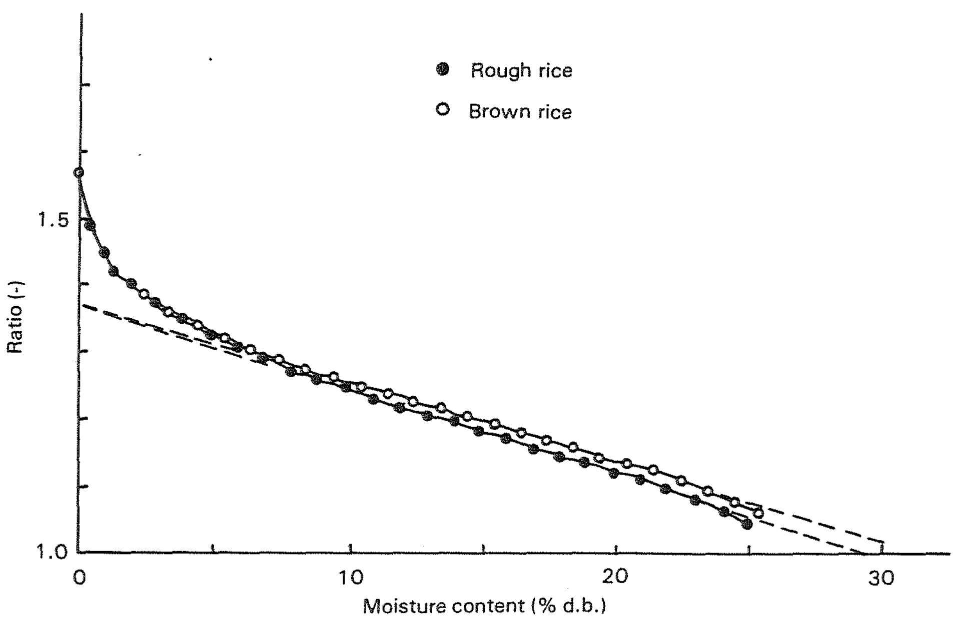

Fig. 11. The ratio of desorption heat to eveporation heat.

SOME OTHER TOPICS

How Soon Should Rough Rice be Dried?

Fifty-five percent of the rice are harvested by combine these days in Japan with moisture contents of about 20–25%. The government recommends to start drying within 4 hours after harvest, before microorganisms start their activities, especially when the outdoor temperature is above 20C. You will certainly feel heat and smell due to incidence of fermentation when you put your hand in a sack of high moisture rice 4 or 5 hours after harvest. It is our common practice to finish up drying in a drier within 24 hours for the next batch of rice that will be harvested the next day. In country elevators people reduce the moisture down to 17–18% before the rice goes to temporary storage. But I know a case reported that in deep bed of 83 cm, the top layer got moulded in 5 days before the entire bed dried. In batch-in-bin drying, deep rice as 2.5 m may require 20 days to dry under favourable weather and sometimes more during bad weather.

Aflatoxin development must be carefully avoided. Corn (maize) seems particularly susceptible to contamination by aflatoxin producing microorganisms. I noticed that a good number of research was going on in the ASEAN countries in this line, when I attended the Postharvest Workshop at Puncak last year. Ross (13) developed a model to specify the necessary time within which drying should be finished to avoid aflatoxin production in corn. It is fortunate that rice is much less attacked by aflatoxin producing fungi (14), but I know a case in imported rice from one of the Southeast Asian countries in postwar years which caused a serious political trouble at that time. Similar work to Ross's on rice seems very necessary, especially for tropical regions, to inform us how soon we should complete the drying of rice.

Rewetting of Sample Rice

It is an unwritten code in Japan that for determination of drying characteristics of rice, we should not rewet rice samples. We do not know when it started and how. It is true that rewetted rice dries faster, but we do not know how fast. Our drying constant, K_{II}, was only 13% greater than that by Watanabe at 40C who used fresh rice, but 27% less than one and 50% more than another. Both of the latter came from rewetted samples. The discrepancy may be due to difference in experimental methods rather than to rewetting itself, but it seems wise to avoid rewetting of rice in drying experiments. There is a carefully carried out experiment by Hustrulid on corn (maize) showing us the effect of rewetting on drying (15). Here again similar work on rice will free us from trouble of storing naturally moist rice currently procticed in Japan.

Computer Simulation

Computer simulation is, as I mentioned, a powerful engineering tool for us. Experiment on a computer for different set of air conditions and other data is much quicker in time with less labour. It is also economical. It allows us to repeat hundreds of runs of experiment. Because our goal is pretty clearly set, such as obtaining the most desirable drying curve, or reconstructing our experimental data, when our computation goes awry we simple make changes in time interval or thickness of the layer, until our results become reasonable. Actually however I myself experienced that the drying curve had a hump like of a camel. Both Kameoka and Nishiyama told me that they had cases in which the computational result diverged. But I have not come across with reports on computational failures. If we had a rule in our computer simulation that assured us proper convergence and appropriate accuracy, we would be able to conduct our computer experiment with more confidence.

(a) First, we may have to find out whether such a principle exists or not as to ensure us the proper result of simulation.

(b) Then, we may be able to find a guide to assure us the convergence of computational results.

(c) Thirdly we may be able to find a rule to govern how closely our computation results approach the true experimental data, or to give us something like the confidence interval (with probability) in which the true drying curve may likely to fall.

RECENT TRENDS IN DRIERS

Environmental Pressures on Rice Driers

Creeping urbanization into rural areas has blurred the demarcation between residential and farming areas throughout Honshu. In many places wet rice fields are surrounded by houses. The dust coming out of driers is a source of complaints and troubles to neighbouring houses. The dust stains laundry in the sun or accumulates on window frames. It gets into rooms or onto tables. Fan and burner noises are disturbing to neighbours's sleep at night then otherwise the world is silent.

Makers are elaborating on dust collectors of individual small driers as well as of big driers in country elevators. Especially in country elevators of rice centres, a huge wet type dust collector is installed into which is connected a number of dust collecting pipes distributed through the plant. The dust collector sometimes amounts to 5—10% of total construction costs.

One maker of rice driers installed a timer to small driers for farmers. The timer cuts off the fan and the burner during the night when air temperature is relatively low, requiring more fuel to heat the drying air than during the day time, and also neighbours are asleep, and starts up the drier automatically in the morning. The drier uses the 4—8 hour night time for tempering.

These measures for well-being of neighbouring people are costly but so far there seems no other ways of getting along with them except these somewhat costly measures. Environmental pressures are increasing these days.

Large Vertical Recirculating Driers

Capacities of vertical recirculating driers have been 1—5t, 1—2t capacity being most popular. In the last few years, large vertical recirculating driers of 20t holding capacity are partly replacing vertical columnar driers, without clear-cut reasons or advantages.

Air gates are vertically arranged, and when the loading rice reaches to the lowest gate, is lets the air in and the drying begins. When the rice reaches the second gate, the depth up to the second gate will be on drying, and so on. Gate operation is automatic. In fact the incoming rice is weighed by an automatic weighing hopper, and while it is weighed, the moisture content of the 50 kg of hopper rice is determined by a dielectric meter installed in the hopper. The results are stored in memories of a small computer and used for automatically adjusting drying conditions and automatically shutting up the drier.

Automatic controls are fancy, but the provision of the drier with many air gates or shutters, and sometimes many air ducts in order to incorporate the reversing direction airflow drying method, which will come in the next section, make the drier very complex. The appearance of the drier gives me an impression that this new type is somewhat against the basic principles of drier design; simplicity and balanced proportion.

Several makers are manufacturing similar driers. These driers will have to demonstrate their operational and especially economical advantages over the conventional ones.

Reversing Direction Airflow Drying

Four years ago one company installed a reversing direction air flow drier in an country elevator. Rice bed is sandwitched between two air chambers and the thickness of the rice layer is 750 mm. Air is alternated but the frequency depends up the initial moisture. The company recommends an interval of 5—6 hours for 25—26% initial moisture rice.

The same company now manufactures circular bin driers of 20 t capacity with double walls so that the reversing direction airflow drying may be possible.

One of the reasons the columnar drier uses 15—20 cm thin layers is to avoid the use of reversing direction air flow through the layer. Therefore the new reversing direction airflow drying is a reversal of not only the air flow but the conventional drying concept and practice.

There is a recent report on this topic (16). They used 30.5 cm deep fixed bed consisting of 6 aluminium square trays with wire mesh at the bottom. They reported that the reversing direction airflow drying was effective in reducing the differences in the final grain moisture gradient for better quality with a 10% increase in energy consumption and corresponding decrease in drying efficiency. They recommend low temperatures (35—43.3C) and high air volume (0.69—0.92 m^3s^{-1} t^{-1}) with reversing airflow only once during their complete drying period of 8 hours.

To achieve uniform drying through the bed, we either move rice continuously or intermittantly or we can change the air direction. Comparative studies among various methods seem neccessary again for better quality of rice and for improving economy of drying.

NOMENCLATURE

K : Drying constant, 1/hr
K_I : Drying constant for period I, 1/hr
K_{II} : Drying constant for period II, 1/hr
L : Depth of bed, m
Lo : Initial depth of bed, m
M : Local moisture content, %(d.b.)
Me : Equilibrium moisture content, % (d.b.)
Mo : Initial moisture content, % (d.b.)
Nu : Nusselt number, -
Pr : Prandtl number, -
R : Rate of drying, 1/hr
Rc : Constant rate of drying, 1/hr
Re : Reynolds number, -
ta : Dry bulb air temperature, C
tw : Wet bulb air temperature, C
w : Average moisture content of bed, % (d.b.)
z : Vertical coordinate, m
θ : Time, hr or min.

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