Basic Design Theory for a Simple Solar Rice Dryer

R.H.B. Exell

Asian Institute of Technology, P.O. Box 2754, Bangkok, Thailand

ABSTRACT

Details are given of the elementary theoretical calculations required for the design of a simple flat-bed grain dryer in which solar heated air rises by natural convection through the grain. Data are given for rice drying in a tropical monsoon climate where the dryer enables farmers to dry their second crop in the wet season harvest at a low cost.

1. INTRODUCTION

The staple food in monsoon Asia is rice, and the efficiencies in the various phases of its production are vital to the people of the region. The processes involved include harvesting, threshing, drying, storing and milling the grain. Drying is necessary because, while a high moisture content in the grain is desirable during harvesting to minimize losses, the moisture content must be low during storage to prevent the grain from being spoiled by fungi and insects, which thrive in warm moist conditions.

Sun drying in the open air is the traditional method used by farmers in South-East Asia for drying rice after the harvest. It can be done before or after threshing. Unthreshed paddy is sun dried by leaving small panicle bundles in the field for several days after manual cutting. Newly threshed paddy is sun dried by spreading it out on mats or on a concrete floor in a layer one or two centimetres thick. Periodic stirring is necessary to obtain uniform drying.

Considerable losses, ranging from 10% to 25%, can occur during natural sun drying in the field due to various causes, such as rodents, birds, spillage, and contamination. Moreover, rewetting and overdrying in variable weather can produce cracking of the rice grains and a poor yield of full sized kernels after the milling process.

In Thailand the second crop has to be harvested in the wet season and the farmer must sell it quickly to the rice miller or trader at a low price due to its high moisture content. It would be to his advantage to dry the rice in order to imporve its market value, or to store it for use at a later date. Traditional sun drying seems to be a hopeless method of doing this because the weather is so uncertain.

For several years the Asian Institute of Technology has been developing a simple solar dryer designed to provide the rice farmer in South-East Asia with a method of drying his second crop in the wet season harvest. The work was started in 1977, when a small prototype was tested. Since then several larger dryers, with capacities from one half to one tonne of threshed grain, have been built on farms in the surrounding rice producing area. Interest in these dryers is growing not only in Thailand but also in other parts of the world, and it seems likely that they could benefit many people. Moreover, they can be used for other crops besides rice.

Such dryers, simple though they seem to be, must be correctly designed if they are to work properly. There is always a danger that farmers, or even research workers, who try models that are the wrong size or the wrong shape will be disappointed with the results, and will then conclude falsely that the method cannot be used. The objective of this article is, therefore, to explain the principles involved in the design of these dryers so that workers in the field can apply them in the appropriate way for their own particular requirements.

2. MOISTURE CONTENT

The percentage moisture content M of a sample of grain is defined by the formula

$$M = 100\,(w-d)/w, \qquad \text{............ (1)}$$

where w is the mass of the wet sample, and d is the mass of the dry matter in the sample. This is called the *wet basis* definition.

Sometimes moisture contents are defined by the amount of moisture in a sample expressed as a percentage of the amount of dry matter present in accordance with the formula $100\,(w-d)/d$. This definition, called the *dry basis* definition, will not be used here.

A number of different methods are available for the measurement of moisture contents, two of which will be mentioned. In the laboratory the oven method is convenient. Representative samples of the grain are first weighed and are then completely dried by heating in an air-oven at 100°C for three or four days. The samples are then weighed again, and the moisture contents are calculated with the help of equation (1).

In the field one needs to measure moisture contents rapidly with easily portable equipment. A meter that measures the electrical resistance of a few grains compressed in a small cell provides a handy method since the resistance is a function of moisture content. The results obtained are not very accurate, partly because the samples used are too small.

The moisture contents of rice found in practice usually lie between 8% and 30% (wet basis). At harvest 24% might be a typical value, while for safe storage the moisture content of the grain should be about 14%.

The processes that occur during the drying of grain include the movement of water through the interior of the grain, and the loss of water vapour from the grain surface. The occurrence of the latter process depends on the difference between the vapour pressure of the moisture in the grain and the vapour pressure of the drying air. The vapour pressure in the grain depends on the moisture content and the grain temperature. When it is equal to the vapour pressure of the air in contact with the grain the moisture content of the grain remains constant at a value called the *equilibrium moisture content.* If the two vapour pressures are not equal the grain will lose or gain moisture depending respectively on whether the actual moisture content is greater than or less than the equilibrium moisture content.

For practical purposes it is convenient to express the equilibrium moisture content as a function of temperature and the relative humidity of the air. Table 1 summarizes the results of measurements by a number of different workers; the accuracy of the moisture content values given is about 1%. The table shows that when the temperature is 30°C and the relative humidity is between 70% and 80% (which are typical conditions in tropical Asia) the equilibrium moisture content of rough rice is about 14% — the moisture content required for safe storage.

Table 1. Equilibrium moisture content of rough rice, per cent wet basis.

Temperature (°C)	Relative humidity of air (%)							
	20	30	40	50	60	70	80	90
10	8	9	11	12	13	14	16	19
20	7	9	10	11	13	14	15	18
30	7	8	9	11	12	13	15	17
40	6	7	8	10	11	12	14	17

3. AIR AND WATER VAPOUR

A measure of the amount of water vapour in the air is given by the *vapour pressure.* When a liquid water surface is exposed in an enclosed space the vapour pressure above the surface in equilibrium conditions has a definite value called the *saturation vapour pressure.* The saturation vapour pressure is a function of temperature only; it is independent of the amount of air in the space. Values of the saturation vapour pressure of water at different temperatures are given in Table 2.

Table 2. Saturation vapour pressure P_s of water, and humidity ratio W of saturated air at 100 kPa pressure, for various temperatures.

Temperature (°C)	P_s (kPa)	W
10	1.23	.0077
15	1.71	.0108
20	2.34	.0149
25	3.17	.0204
30	4.25	.0276
35	5.63	.0371
40	7.38	.0496
45	9.59	.0660
50	12.3	.0872
55	15.8	.1167
60	19.9	.1545

In addition to vapour pressure several other quantities are used to specify the amount of water vapour present in air. The *relative humidity* ϕ is defined to be the quotient of the mole fraction of water vapour in the air and the mole fraction of water vapour in saturated air at the same temperature. Since the water vapour behaves as an ideal gas, we have

$$\phi = P_v/P_s, \qquad \text{(2)}$$

where P_v is the actual partial pressure of the water vapour in the air, and P_s is the saturation vapour pressure of water vapour at the same temperature.

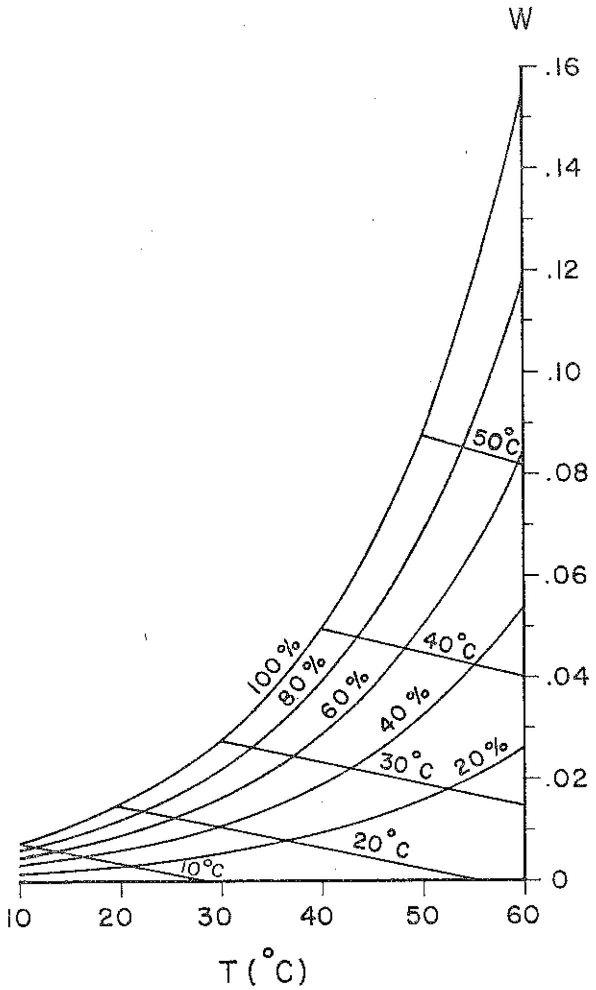

Fig. 1 Psychrometric chart for air pressure 100 kPa.

The relative humidity is usually expressed as a percentage. Its value is important in drying theory because it is the main parameter determining the equilibrium moisture content of grain, as explained in Section 2, and also because it determines how effectively the air can dry the grain.

The *humidity ratio* W of air containing water vapour is defined to be the quotient of the mass m_v of water vapour in a given volume air and the mass m_d of the dry air in the same volume, thus

$$W = m_v/m_d.$$

Again, since the water vapour and air behave as ideal gases, we have

$$W = M_v P_v / M_d P_d, \qquad \text{............ (3)}$$

where M_v is the molecular weight of water (18.015), M_d is the mean molecular weight of air molecules (28.97), and P_d is the partial pressure of the dry air. A relation connecting humidity ratio and relative humidity, obtained from equations (2) and (3) is

$$W = 0.622 \ \phi \ P_s/P_d. \qquad \ldots\ldots\ldots\ldots \ (4)$$

The humidity ratios of saturated air for different temperatures at a total atmospheric pressure $P = 100$ kPa calculated from equation (4) by putting $\phi = 1$ and $P_d = P - P_s$ are also shown in Table 2.

The properties of moist air are commonly displayed on a *psychrometric chart.* Figure 1 shows such a chart covering the conditions found in the rice dryers described in this article. The horizontal axis of the chart represents the air temperature T, and the vertical axis represents the humidity ratio W. Curves are drawn on the chart through points having the same relative humidity ϕ.

A *psychrometer* is an instrument for measuring air humidity. It consists of two liquid-in-glass thermometers, one of which has its bulb covered by a clean cotton wick wetted with distilled water. When the two thermometers are exposed to a stream of air the temperature shown by the thermometer with the uncovered bulb, called the *dry-bulb temperature,* is simply the temperature of the air. The temperature shown by the thermometer with the wetted wick, called the *wet-bulb temperature,* is generally lower than the dry-bulb temperature due to cooling by the evaporation of water from the wick. The temperature of the wetted bulb is steady when the heat transfer rate from the warmer surroundings to the thermometer bulb is equal to the rate at which latent heat is absorbed in the evaporation of the water.

When the air is saturated no evaporation from the wick can take place and the wet-bulb temperature is equal to the dry-bulb temperature. The humidity of unsaturated air can be found from the wet-bulb and dry-bulb temperatures with the help of standard psychrometric tables. Lines through points having the same wet-bulb temperature are plotted on the psychrometric chart in Figure 1.

4. THE DRYING PROCESS

During the drying of rice the latent heat of vaporization of the water in the grains is exchanged for sensible heat of the grains and the drying air. This causes the grains and the air to cool just as the wet-bulb thermometer in a psychrometer is cooled below the temperature of the dry-bulb thermometer. The resulting changes in the temperature and humidity of the air are represented on the psychrometric chart by a line parallel to the wet-bulb lines as shown in Figure 2.

The initial point of a drying line represents the temperature and humidity of the air as it first comes into contact with the grain. The final point of a drying line, where the maximum possible amount of moisture has been absorbed by the drying air, represents the temperature and humidity at which equilibrium with the moisture content of the grain occurs, as shown in Table 1.

If unmodified ambient air is used in a climate typical of the wet season in South-East Asia the initial temperature will be about 30°C and the humidity will be about 80%; and if the moisture content of the rice is 20% wet basis the equilibrium relative humidity will be between 90% and 100% at a temperature of about 27.5°C. Under these conditions the humidity ratio of the air would change during the drying process only from 0.022 to 0.023, and a large volume of air would have to be passed through a bed of grain to dry it.

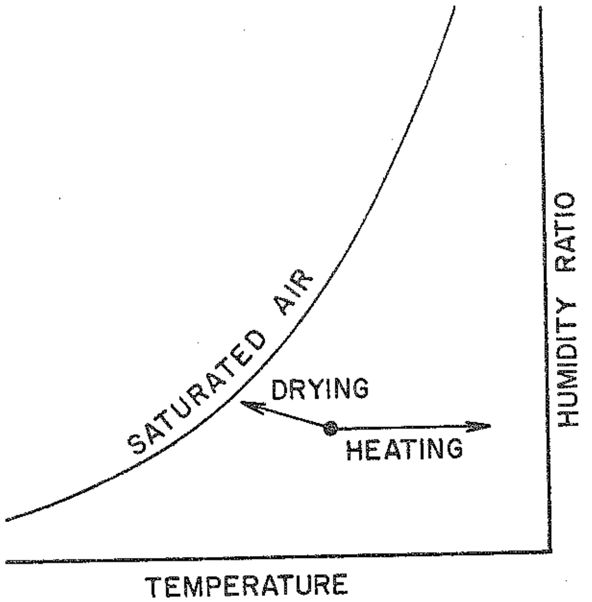

Fig. 2 Processes on the psychrometric chart.

If moist air is heated without the addition or removal of water, so that its humidity ratio remains constant, its relative humidity will be reduced. This is represented on the psychrometric chart by a horizontal line as shown in Figure 2. A given quantity of heated air is capable of removing more moisture from a bed of grain than the same quantity of unheated air.

If ambient air at a temperature 30°C and with relative humidity 80%, as in the previous example, is heated to 45°C, its relative humidity is reduced to 35%. If this heated air is then used to remove moisture from a bed of rice having a moisture content of 20% wet basis and the equilibrium relative humidity between 90% and 100% is reached, the temperature of the drying air will be reduced to 31°C and the humidity ratio will change from 0.022 to 0.028. This change in the humidity ratio, and hence the drying capability of the heated air, is about six times greater than it would have been if the air had not been heated.

The paths AB and ACD drawn to scale on the psychrometric chart in Figure 3 compare the two preceding examples.

5. THE ENERGY BALANCE FOR DRYING

Let m_w denote the mass of water evaporated from a given quantity of rice and absorbed by a mass m_a of drying air; let L denote the specific latent heat of vaporization of the water from the grain; let C_p denote the specific heat capacity of the air at constant pressure; and let T_i and T_f denote the initial and final temperatures of the drying air respectively. Then the basic energy balance equation for the drying process is

$$m_w L = m_a C_p (T_i - T_f). \qquad \ldots\ldots\ldots\ldots (5)$$

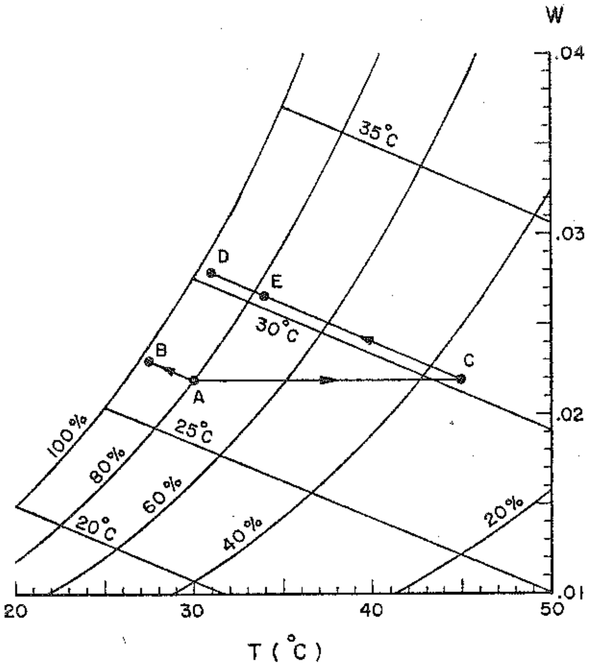

Fig. 3 Paths on the psychrometric chart illustrating the examples in Sections 4 and 6.

The problem in designing a rice dryer is to determine a suitable initial temperature T_i and the correct quantity of air m_a necessary to remove a specified amount m_w of water from the rice. It is assumed that L and C_p are known, and that T_f can be found from the ambient conditions with the help of the psychrometric chart as explained in Section 4. The solution of this problem is difficult, partly because the parameters in equation (5) are changing continuously during the drying, and partly because resistances to heat and mass transfer slow down the process and may prevent the theoretical amount of drying from taking place.

The quantity m_w is calculated from the initial moisture content M_i of the rice and the desired final moisture content M_f with the help of equation (1), thus

$$m_w = w_i (M_i - M_f)/(100 - M_f), \qquad \text{............ (6)}$$

where w_i is the initial mass of wet rice to be dried.

The specific latent heat of vaporization of free water at 30°C is about 2.4 MJ/kg. If, however, the water is to be evaporated from grain instead of from a free water surface, more heat is required. The actual amount needed is a function of the temperature and the moisture content of the grain. It decreases as the temperature increases, and as the moisture content increases. However, over the range of conditions that occur in our rice dryers the variation in the specific latent heat L of vaporization of water from grain will not vary more than about 10%. For approximate calculations its value can be taken to be 2.8 MJ/kg.

Quantities of air are usually expressed in terms of the volume V at atmospheric pressure P and temperature T instead of in terms of the mass m_a. The volume of air with humidity ratio

0.025, which is a typical value for the examples of Section 4, can be calculated from the equation

$$PV = m_a RT, \qquad \ldots\ldots\ldots\ldots (7)$$

where $R = 0.291$ kPa m^3/kg K. The effect on R caused by departures of the humidity ratio from 0.025 that occur in practice may be neglected.

The specific heat capacity at constant pressure of the drying air depends on the humidity ratio and on the temperature. For the present purpose we may assume it to be constant at $C_p = 1.02$ kJ/kg°C.

Note that equation (5) assumes that the rice grains are already at the temperature T_f, and only the air is cooled. If the cooling of the rice has to be taken into account the specific heat capacity of rice can be estimated from the formula $1.1 + 0.0448\,M$ kJ/kg°C, where M is the moisture content.

6. THE QUANTITY OF AIR NEEDED FOR DRYING

The quantity of air needed for drying by means of a specified process may be estimated from the psychrometric chart, or from the energy balance equation (5). Consider as an example the amount of air needed to dry 1 kg of rough rice from an initial moisture content of 22% wet basis to a final moisture content of 14%. Assume, as in the second example treated in Section 4, that the ambient air has a temperature 30°C and a relative humidity 80%, and that it is heated to 45°C before being used for drying.

The psychrometric chart in Figure 3 shows that at the beginning of the process the humidity ratio of the air can be expected to increase from 0.022 to 0.028 as it passes through the rice bed. However, the end of the process will be represented by the point E with temperature 34°C and humidity ratio 0.0266, since here the relative humidity of 75% is in equilibrium with rice having moisture content 14%. On the average, therefore, the humidity ratio of the drying air can be expected to rise about 0.005.

The amount of water to be extracted from 1 kg of rice calculated from equation (6) in this example is 0.093 kg. It follows from the definition of the humidity ratio that the mass m_a of air needed is approximately $0.093 \div 0.005 = 18.6$ kg. Equation (7) now shows that the volume of air needed when $P = 101.3$ kPa and $T = 308$ K (35°C) is about 16.5 m^3.

The calculation of the volume of air needed for drying from the energy balance equation (5) in the above example is as follows. We already have $m_w = 0.093$ kg, $L = 2.8$ MJ/kg, and $C_p = 1.02$ kJ/kg°C. Next, assuming $T_i = 45$°C and taking a mean value of 32°C for T_f we obtain from equation (5) $m_a = 19.6$ kg. The corresponding volume of air calculated as before from equation (7) is 17.3 m^3. In view of the approximate nature of the calculations, this is in satisfactory agreement with the value 16.5 m^3 determined from the psychrometric chart.

7. AIR MOVEMENT THROUGH A RICE BED

The flow of air through a bed of rice depends on the air pressure gradient dP/dx in the bed. For small pressure gradients the flow is laminar and directly proportional to dP/dx. This is the kind of flow that occurs in solar rice dryers where the movement of air is by natural convection. In such cases dP/dx is less than 50 Pa/m and one may calculate the flow through rough rice from the equation

$$v = k\, dP/dx, \qquad \ldots\ldots\ldots\ldots \quad (8)$$

where v is the velocity of air entering and emerging from the bed, and $k = 0.03$ m^2/Pa min.

The velocity of the air inside the bed in contact with the rice grains is greater than the value of v calculated from equation (8) because only the void spaces between the grains are available for the flow. Consequently, the flow v is usually expressed in terms of volume of air per unit time through unit area perpendicular to the flow, or m^3/min per m^2.

The value of k given above is for loosely filled clean and relatively dry grain. It increases with increasing moisture content, and decreases if the bed is packed. Foreign material contaminating the rice can increase or decrease k depending respectively on whether the material is coarser or finer than the grain.

As dP/dx increases above 50 Pa/m the value of k progressively decreases, the flow gradually becomes turbulent, and equation (8) ceases to apply.

In a flat bed dryer the rice bed rests on a perforated floor through which the drying air passes. It is important for the perforations to be about the same size as the spaces between the rice grains, and for the area of the spaces to be at least 10% of the total floor area, otherwise the floor will create an additional resistance to the air flow.

8. THE DESIGN CONCEPT

The idea underlying the design of the type of rice dryer described in this article is to heat a body of air in the sun and then let this air pass through a flat bed of rice by natural convection. Figures 4 and 5 show the type of dryer that has been developed at the Asian Institute of Technology. It consists of a solar air heater, a box for the rice bed, and a chimney giving a tall column of warm air to increase the convection effect. Clear plastic sheet covering the rice bed allows it to be heated from above by the sun while protecting it from rain.

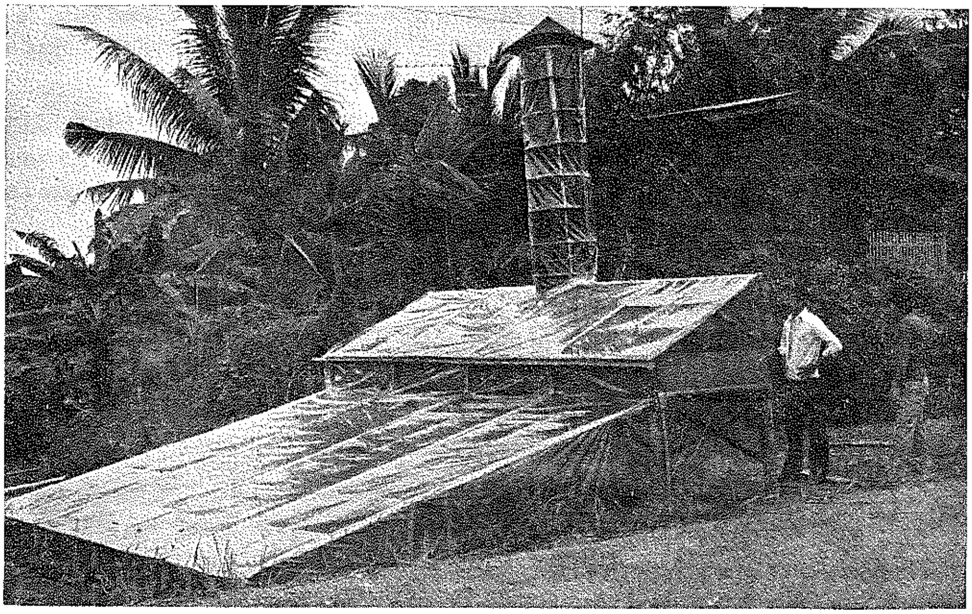

Fig. 4 Photograph of dryer.

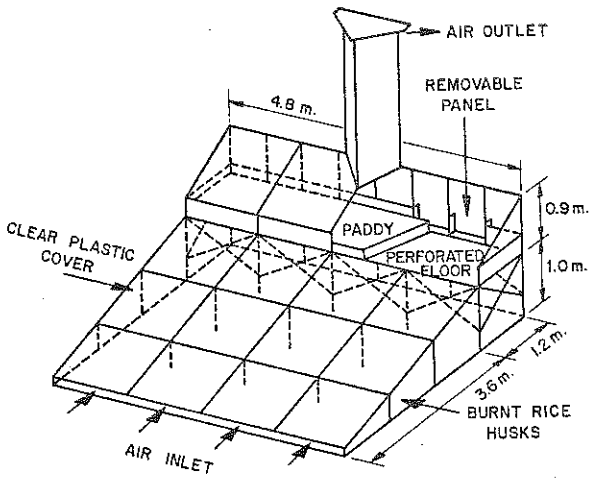

Fig. 5 Design of dryer for $\frac{1}{2}$ tonne of rice.

The basic calculations in the design of the dryer must allow one to determine the depth of the rice bed, the height of the chimney, and the area of the solar air heater that will provide a sufficient flow of air to dry a given quantity of newly harvested and threshed rice in a few days during the wet season. The temperature of the drying air should not exceed 45°C otherwise cracking of the rice kernels may occur.

9. THE REQUIRED AIR FLOW

Suppose that the dryer is required to dry 1000 kg of rice from an initial moisture content of 22% wet basis to a final moisture content of 14% with ambient air at 30°C and 80% relative humidity. Suppose also that the air is heated to 45°C in the solar air heater. The calculations in Section 6 show that the total volume of air required is about 17000 m^3.

Suppose also that we expect the drying to be complete in 30 hours. This might be achieved through solar drying for 3 days with 10 hours of drying per day, or 4 days with 7.5 hours of drying per day. (We cannot expect any drying to occur at night). The air flow rate should therefore be 9.44 m^3/min.

The volume of a 1000 kg rice bed is calculated from the bulk density of rough rice. This depends on the variety of rice, the moisture content of the rice, and the packing. For approximate calculations it can be assumed to be 600 kg/m^3. The volume of 1000 kg of rice is therefore 1.667 m^3.

Combining the results of the last two paragraphs we obtain a required flow of 5.7 m^3/min per m^3 of grain or 5.7 complete air changes in the bed per minute.

10. THE PRESSURE DIFFERENCE ACROSS THE BED

The convection of air through the rice bed is caused by a pressure drop across it resulting from the difference between the density of the relatively cool ambient air and the warm air inside the dryer.

Let ρ be the density of the ambient air, and let ρ' be the density of the warm air inside the dryer. Let h_1 be the height between the inlet to the solar air heater and the rice bed, and let h_2 be the height between the rice bed and the top of the chimney. Since the depth of the rice bed will be small, the height of the top of the chimney above the air inlet is $h_1 + h_2$. Also let P_1 be the air pressure inside and outside the dryer at the level of the air inlet, let P_2 and P_3 be the pressures inside the dryer at the bottom and top of the rice bed respectively, and let P_4 be the air pressure inside and outside the dryer at the top of the chimney (see Figure 6). Then the following equations hold:

$$P_2 = P_1 - h_1 \rho' g,$$
$$P_3 = P_4 + h_2 \rho' g,$$
and
$$P_4 = P_1 - (h_1 + h_2) \rho g,$$

where g is the acceleration of gravity 9.8 m/s^2. Eliminating P_1 and P_4 we obtain for the pressure difference across the bed the equation

$$P_2 - P_3 = (h_1 + h_2)(\rho - \rho')\, g, \qquad \text{............ (9)}$$

The difference in the air densities calculated from equation (7) at atmospheric pressure 101.3 kPa and temperatures 30°C and 45°C outside and inside the dryer respectively is

$$\rho - \rho' = 0.05419 \ \text{kg/m}^3.$$

If $h_1 + h_2$ is 4 m, then the pressure difference across the bed calculated from equation (9) is 2.1 Pa.

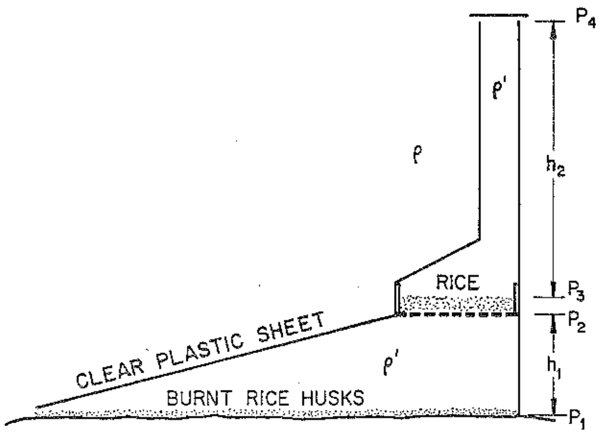

Fig. 6 Cross-section of dryer showing heights h_1 and h_2, air densities ρ and ρ', and pressures inside dryer at different heights.

11. THE DIMENSIONS OF THE RICE BED

In the design of the rice bed the most important dimension is the depth x. It must be so chosen that the pressure difference across the bed causes the right amount of air to flow through.

Since the pressure drop across the bed as calculated in Section 10 is 2.1 Pa, the pressure gradient dp/dx in the bed is 2.1 Pa/x. Therefore from equation (8) we find that the air velocity v through the bed is (0.063 m^2/min)/x.

Let the airflow through the grain be expressed in terms of the number N of complete air changes per unit time. Then we have the relation

$$N = v/x. \qquad \text{(10)}$$

The calculations in Section 9 show that N must be 5.7/min. Substituting for N and v in equation (10) we find that the depth x of the rice bed should be 105 mm.

Experimental tests have confirmed that rice can actually be dried satisfactorily in beds of this depth. In fact, since the design of the dryers allows the sun to dry the rice by heating the top of the bed as well as by the passage of warm air from below, beds of depth up to 150 mm can be used.

If A_b is the area of the rice bed, then using the bulk density of rough rice given in Section 9 for a bed containing 1000 kg we have $A_b x = 1.667\ m^3$. Putting $x = 150$ mm we find that A_b should be about 12 m^2.

12. THE AREA OF THE SOLAR AIR HEATER

In order to determine the area A_h of the air heater required to collect sufficient solar energy to dry the rice we must know the mass m_w of water to be evaporated from 1000 kg of the wet rice, the specific latent heat L of vaporization of this water, the quantity Q of global solar radiation falling on unit horizontal area per day, and the efficiency ε of the solar collector.

The calculations in Section 6 show that $m_w = 93$ kg, and in Section 5 we gave $L = 2.8$ MJ/kg. Hence the amount of heat required to evaporate the water in the drying process is 260.4 MJ.

The daily global solar radiation in a tropical monsoon climate is highly variable, especially in the wet season. It ranges from 5 MJ/m^2 per day to 25 MJ/m^2 per day 95% of the time, and 15 MJ/m^2 per day may be taken as an average value. The efficiency of the solar collector is not known with certainty. As a conservative estimate we shall assume it to be 0.25. The amount of heat provided by the collector per unit area in 3 days is therefore estimated to be 11.25 MJ/m^2 on the average.

It follows from the results in the last two paragraphs that a collector area of 23 m^2 is required. However, in the solar rice dryers developed in the Asian Institute of Technology a larger collector area than this has been used. The dryers can then be operated when the daily solar radiation is less than average, and in fine weather the bed of rice can be dried in one or two days. The simple rule of making the collector area three times the area of the rice bed gives satisfactory results. Thus for a dryer of capacity 1000 kg the collector area should be about 36 m^2.

13. PRACTICAL CONSIDERATIONS

It is beyond the scope of this article to discuss in detail the practical construction of the dryer, or to present the results of experimental tests. However, a few remarks on these topics will be made in this section for the sake of completeness.

The clear plastic sheet used to cover the dryer is PVC 0.15 mm thick. This lasts about one year, but is easily damaged. Thicker sheet would be better. The sheet is supported by a frame of bamboo poles and wire. Burnt rice husks cover the ground underneath the sheet to absorb the solar radiation for the heating of the drying air.

The bottom of the box holding the rice bed is made of bamboo matting with a fairly open structure to allow the drying air to pass through easily. It is covered with nylon netting to prevent the rice grains from falling through.

The chimney consists of a bamboo frame covered with plastic sheet, which should be dark in colour to absorb heat from the sun and keep the air inside warm. A cover over the chimney keeps out rain.

Experience shows that if the bed is left untouched during drying the rice at the bottom is liable to be overdried while the rice within the bed just below the top is underdried. This problem can be overcome by stirring the rice in the bed from time to time.

ACKNOWLEDGEMENTS

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