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Solar Drying in Africa

Proceedings of a Workshop held in Dakar, Senegal, 21-24 July 1986

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ABSTRACT / RÉSUMÉ / RESUMEN

Abstract -- This book presents the proceedings of a workshop on solar drying in Africa attended by 24 participants involved with solar drying research relevant to the continent. Of the papers, 17 describe research activities on socioeconomic aspects, design and testing of solar dryers, and future research needs. In addition, a summary of the discussions held during the workshop to assess the state of the art of solar drying research in Africa are outlined, focusing on progress made and on possible research and collaborative activities that are needed to overcome the technical and socioeconomic problems that limit the development and introduction of improved solar dryers.

Résumé -- Voici le compte rendu d'un colloque sur le séchage solaire en Afrique auquel participaient 24 personnes effectuant des travaux de recherche propres à ce continent. Au nombre des communications, 17 décrivent les activités de recherche sur les aspects socio-économiques, la conception et l'essai des séchoirs solaires, ainsi que les besoins futurs de recherche. En outre,le lecteur trouvera un résumé des discussions sur l'état de la recherche sur le séchage solaire en Afrique, notamment les progrès réalisés et les activités de recherche coopératives nécessaires pour surmonter les problèmes techniques et socio-économiques qui entravent la mise au point et la diffusion de séchoirs solaires améliorés.

Resumen -- Este libro contiene los trabajos presentados en un seminario sobre secamiento solar en Africa, al cual asistieron 24 participantes del área de investigación en secamiento solar referida a este continente. Diez y siete de los trabajos versan sobre actividades de investigación en aspectos socioeconómicos, diseño y prueba de secadores solares y necesidades futuras de investigación. Se describe además la discusión sostenida durante el seminario para sopesar el estado de la investigación en secamiento solar en Africa, discusión que se centró en los progresos realizados y en las posibilidades de investigación y acciones colaborativas necesarias para superar los problemas técnicos y socioeconómicos que obstaculizan el desarrollo y la introducción de secadores solares mejorados.

CONTENTS

A NUMERICAL MODEL OF A NATURAL-CONVECTION SOLAR GRAIN DRYER: DEVELOPMENT AND VALIDATION

P.H. Oosthuizen[1]

Abstract -- *This study was designed to develop a simple but reliable computer model of a natural-convection solar grain dryer, to validate this model as far as possible against existing experimental results for solar rice dryers, and to carry out a series of laboratory-scale experiments that would provide results that could be used in improving the computer model. The model is based on the assumption that all minor pressure losses are negligible in comparison with the pressure drop across the rice bed: thus, the net buoyancy force just balances the pressure drop across the rice bed. It is also assumed that the air leaving the rice bed is either saturated or at a temperature equal to the initial rice temperature and that, as a result, the buoyancy forces all effectively occur in the air below the rice bed. The model has been validated against available experimental results and good agreement between the predicted and experimental results were achieved. Some computer exploration of the effect of dryer dimensions on its performance has been undertaken. The apparatus and instrumentation to be used in a laboratory study of dryer performance are described.*

Introduction

Although the drying of rice is still accomplished in many countries by spreading it in a thin layer on the ground on a hard surface, it is widely acknowledged that significant reductions in losses during drying could be achieved by replacing this method by some form of indirect natural-convection solar rice drying. In a typical dryer of this type (Fig. 1), the rice bed is contained within a drying chamber and air, which is heated in a simple flat-plate solar collector, is drawn through the drying chamber by the buoyancy forces resulting from the temperature difference. Many attempts have been made to develop such natural-convection solar rice dryers (see, for example, Bassey 1982; Whitfield 1985; Yu Wai Man and Wong Too Yeun 1984) but the results achieved with these dryers have not generally been satisfactory. One of the reasons for the relatively poor performance is that these past studies have generally relied heavily on a purely experimental approach and no extensive theoretical investigations of the designs were undertaken before the dryers were

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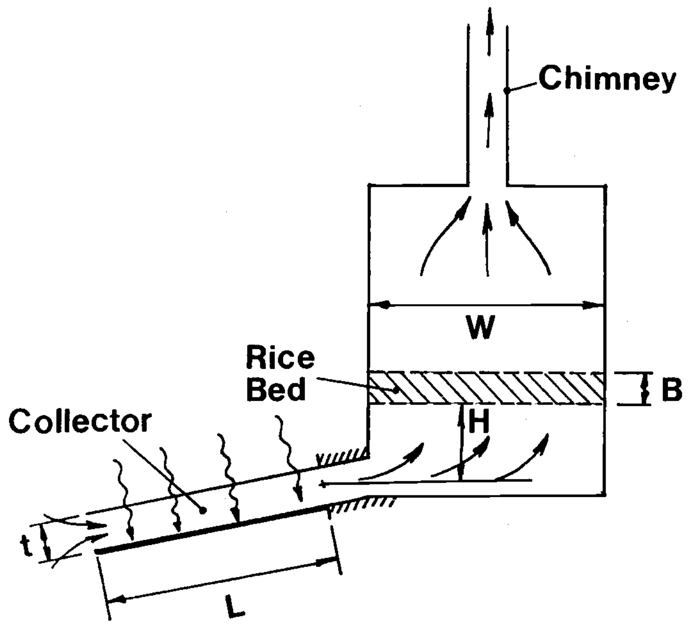

Fig. 1. Type of dryer being considered.

constructed. One consequence of this is that no clear means of improving the performance of the dryer could be deduced from the results. Another reason for the continued poor performance of these dryers is that the testing of the dryers has often been carried out in a relatively uncontrolled manner so that the reasons for the poor performance could not be clearly deduced from the results.

To assist in the design of improved solar rice dryers, the present study, therefore, sought:

- To develop a simple but accurate model of indirect natural-convection solar crop dryers that can be used in developing more efficient dryer designs;
- To validate the model, as far as possible, against existing experimental results obtained with natural-convection solar rice dryers;
- To undertake a series of controlled experimental laboratory studies of the basic characteristics of a natural-convection crop dryer and to use these results to improve the numerical model; and
- To use the final numerical model to design an improved indirect solar rice dryer.

In the study, the need to carry out both numerical studies and highly controlled experimental studies that support each other has been accepted as vital to the improvement of dryer performance.

This paper is primarily concerned with the first two points in the list. The basic approach used in the experimental study is, however, also outlined and some possible improvements in dryer design are discussed briefly. Although this paper is concerned primarily with rice drying, the computer model can be applied to the drying of some other similar crops with relatively minor modification.

Model Equations

The computer model has two basic sections. The first section determines the solar insolation and the second calculates the performance of the dryer when subjected to this insolation. If the application of a given dryer in a particular geographical area is being considered, then section 1 will generate insolation values corresponding to the selected geographical area. If, on the other hand, experimental results and the results given by the model are being compared, the insolation values used by the program will be the actual values measured during the tests. Because this paper deals basically with the second problem, that is, a comparison between experimental and numerical results, it is assumed that the insolation is a known input. If the first type of problem is being considered, however, the insolation values for a particular geographical location can be determined using the method described by Preston (1985). The model described here is essentially the same as that described by Oosthuizen (1986).

A dryer of the type shown in Fig. 1 has been considered. When the air enters the collector, there is a pressure drop due to the acceleration of the fluid. There are also pressure losses in the collector and in the chimney, at the exit of the collector, at the entrance to the chimney, and across the rice bed. These pressure losses are matched by the buoyancy forces that occur because the air in the collector and in the chamber is at a higher temperature than the ambient air. When the order of magnitude of all the losses is considered, the pressure drop across the rice bed is found to be the dominant pressure drop; thus, in the present model, all other pressure losses are assumed to be negligible compared with that across the rice bed. When this assumption is made, it is, of course, necessary that the net buoyancy forces just balance the pressure drop across the rice bed. It is assumed in the present model that the pressure drop across the rice bed (Δp) is proportional to the velocity of the air through the bed:

$$\Delta p = Ub/K \qquad [1]$$

where

U = mean air velocity in dryer
b = thickness of rice bed, and
K = bed pressure drop coefficient.

It should be noted that, because the pressure drop across the rice bed is by far the dominant pressure loss in the dryer under operational conditions, experimental studies of unloaded dryers give little information about how the dryer will actually perform.

The buoyancy forces must next be considered. These will, of course, be proportional to the difference between the mean air temperature in the section of the dryer considered and the ambient air temperature. Now, as will be discussed later, the air leaving the rice bed is at or only slightly above the temperature of the rice bed. Therefore, because the rice bed and ambient air temperatures remain close, the contribution of the buoyancy force from the air above the bed will be negligible. It should be noted that this means that the chimneys that are so often fitted to natural-convection rice dryers will have little effect on the dryer performance unless the solar heating of this chimney is significant. Because the chimneys are usually vertical, the solar heating of the chimney will usually be very small unless the dryer is being used far from the equator. This is also another reason why experimental studies that use unloaded dryers or dry rice give little information about how the dryer will actually perform because, under these conditions, all the air in the drying chamber and chimney is at a higher temperature than the ambient air. As a result of this assumption, the buoyancy forces are assumed to occur only in the collector and in the dryer chamber below the rice bed. In the collector, the air is heated from ambient temperature to that of the collector exit and the buoyancy force in the collector is given approximately by using the mean temperature in the collector. Hence, the net buoyancy force (NBF) will be given by:

$$NBF = \beta g \rho (T_c - T_a)(L \sin \theta/2 + H) \qquad [2]$$

where

β = bulk coefficient of expansion of air
g = gravitational acceleration
ρ = kinematic viscosity of air
T_c = temperature of air leaving collector
T_a = ambient air temperature
L = length of collector
θ = angle of inclination of collector, and
H = height of rice bed above collector outlet.

This buoyancy force must, in view of the assumptions above, just balance the pressure drop across the rice bed. Hence, equations 1 and 2 together give

$$Ub/K = \beta g \rho (T_c - T_a)(L \sin \theta/2 + H) \qquad [3]$$

If we consider an energy balance for the solar collector, the rate of enthalpy gain of the air in passing through the collector must just equal the rate of solar energy gain:

$$\rho U_c W_c B_c c_p (T_c - T_a) = \eta q_I W_c L \qquad [4]$$

where

U_c = mean air velocity in collector
W_c = width of collector
B_c = collector gap size
c_p = specific heat of air
η = collector efficiency, and
q_I = insolation.

This can be rearranged to give the temperature rise across the collector as

$$T_C - T_a = \eta q_I L \ / \ \rho U_C B_C c_p \qquad [5]$$

The mean velocities in the collector and in the drying chamber are, of course, related by mass continuity requirements so that

$$U = U_C \ (W_C B_C / W W_D) \qquad [6]$$

where

W = width of drying chamber and
W_d = length of drying chamber.

Equations 4 and 5 contain the collector efficiency (η) as a variable. For conventional types of collectors, this efficiency, as shown in standard textbooks (see, for example, Sayigh 1978), is given approximately by

$$\eta = C_1 - C_2 \ (T_p - T_a) \ / q_I \qquad [7]$$

where

C_1 and C_2 are constants and
T_p = temperature of collector plate.

Because there must be a balance between the rate at which the collector plate absorbs solar energy and the rate of heat transfer from the plate to the air passing through the collector, it follows that

$$\eta q_I W_C L = h W_C L (T_p - T_a) \qquad [8]$$

where

h = heat-transfer coefficient between collector plate and air.

It should be noted that the effective heat-transfer coefficient (h) is based on the frontal area of the collector. For a simple flat-plate collector, it will be equal to the mean heat-transfer coefficient; however, if more complex collector plates are used, it will include the effects of the increased heat-transfer area. It should also be noted that h is based on the difference between the temperatures of the plate and the ambient air. Equations 7 and 8 together give

$$\eta = C_1 h / (C_2 + h) \qquad [9]$$

Thus, the collector efficiency at which the dryer operates will depend on the value of h. If h is very large, its effect on η will be small but, at small values of h, η will be strongly dependent on h becoming directly proportional to h as h tends to zero.

The value of h will depend, in general, on the geometry of the collector, the mean velocity of the air through the collector, and the buoyancy forces in the collector. For a natural-convection dryer with a simple flat-plate collector, if the buoyancy force effects on the flow in the collector are small, the flow in the collector will tend to be laminar and of a boundary layer type and boundary layer theory then indicates that h should vary as the square root of the Reynolds number based on the mean air velocity and the length of the collector. It has, therefore, been assumed that

$$h = h_0 \ (Re_L/5000)^{0.5} \qquad [10]$$

where

h_0 = heat-transfer coefficient that would exist with a Reynolds number of 5000 and

$Re_L = U_c L/\nu$.

Once the values of the required constants are specified, these equations are sufficient to define the induced velocity through the dryer for any insolation value (q_I). An iterative solution procedure must be used because h depends on the velocity. In this procedure, a value of h is assumed and a flow rate is calculated. This allows Re_L to be found and an improved h value can then be determined and the whole procedure repeated until convergence is achieved.

So far, the generation of the hot airstream that will be used to dry the rice has been considered. The rice drying itself must now be considered. Consideration of the available experimental results and of a previous relatively unsuccessful attempt at modeling the performance of a natural-convection solar rice dryer (see Oosthuizen et al. 1985; Preston 1985) suggests that a very simple model of the drying process can be adopted. In this model, it is assumed that all the water to be removed from the rice is held in the rice in the liquid form and, therefore, that the thermal energy in the airstream entering the rice bed is used, basically, to supply the latent heat required to evaporate the water from the rice. As a result of this assumption, there will be little change in the rice-bed temperature during drying and its thermal capacity can, therefore, be ignored. As a further consequence of this assumption, the temperature of the air leaving the rice bed will be at or only slightly above the initial rice-bed temperature, which will be close to the ambient air temperature. It is this fact that allows the buoyancy forces in the air above the rice bed to be ignored.

To determine the drying rate, we must consider the drying processes indicated on a psychometric chart (Fig. 2). If the air leaving the collector and entering the drying chamber, and therefore entering the rice bed, is at the temperature indicated by a point such as b, then the drying rate will be limited by the available sensible heat of the incoming air, i.e., by the fact that the air leaving the rice bed will be at the rice-bed temperature (as indicated by point b in Fig. 2) and not fully saturated. Because the available sensible heat in the airstream will be equal to the energy it gains in the solar collector, the drying rate for this situation will be determined by

$$\eta q_I W_c L = m_r \ (dM/dt)\ell \qquad [11]$$

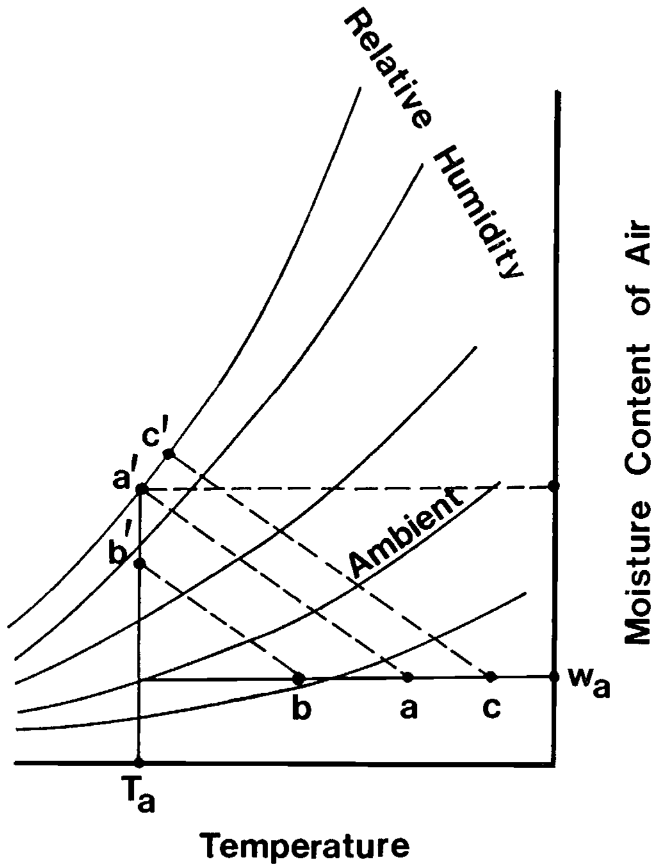

Fig. 2. Possible changes in temperature and humidity in the rice bed.

where

m_r = mass of dry rice in bed
M = moisture content of rice on dry basis
t = time, and
ℓ = latent heat of water.

The left hand side of equation 11 is, of course, the net rate at which solar energy is being absorbed by the collector and transferred to the air passing through the dryer. The right hand side is the rate at which latent heat is being supplied to the bed.

If, however, the air leaving the collector is at a point such as c (Fig. 2), the drying rate will be limited by the fact that the air leaving the bed will be saturated (i.e., the point c' must lie on the 100% relative humidity line). In this case, the drying rate is determined by noting that the energy balance for the collector gives

$$\eta q_I W_c L = m\, c_p\, (T_c - T_a) \qquad [12]$$

where

m = air mass flow rate through dryer

whereas the energy balance for the rice bed requires that

$$m\ c_p\ (T_c - T_o) = m\ (w_o - wa)\ell \qquad [13]$$

where

T_o = temperature of air leaving rice bed
w_o = moisture content at exit of rice bed, and
w_a = moisture content at ambient conditions.

It is convenient to rewrite equation 13 as

$$(c_p/\ell\ )\ [(T_c - T_a) - (T_o - T_a)] = w_o - w_a \qquad [14]$$

Because the saturation line on the psychometric chart defines w_o as a function of T_o, equations 12 and 14 together allow T_o and w_o to be determined for any value of the insolation (q_I). The drying rate is then obtained by considering a moisture mass balance for the rice bed that gives

$$m_r\ (dM/dt) = m\ (w_o - w_a) \qquad [15]$$

In all real cases, T_o will be only slightly above the rice bed temperature.

This model of the drying process will only apply, of course, as long as the moisture content in the rice bed remains well above the equilibrium moisture content for the ambient conditions. Once the moisture content drops to near the equilibrium moisture content, the drying rate will start to be limited by the moisture diffusion rate within the rice grains as well as by energy considerations and a much more complex drying model must be adopted. However, because drying can be regarded as complete when the equilibrium moisture content is reached, this is not a serious limitation. In applying the model then, these equations are used until the moisture content (M) has dropped to a value equal to the equilibrium moisture content at ambient conditions and M is then assumed to remain constant at this value.

Computer Implementation

A computer model based on these equations has been developed for an indirect natural-convection solar rice dryer of the type shown in Fig. 1. In addition to the dimensions of the dryer, this program requires, as inputs, values for the relative humidity and temperature of the ambient air, the bed pressure loss factor (K), the rice density (ρ_r), and the collector performance parameters (C_1, C_2, and h_o). In addition, the variation of the insolation (q_I) with time is required. As discussed earlier, q_I could be either given from measurements obtained during experimental studies or generated by a geographical model of the type described by Preston (1985).

In applying the model, the following values have been assumed:

$K = 0.0005\ m^2/Pa$ per second
$\rho_r = 600\ kg/m^3$
$C_1 = 0.56$
$C_2 = 4.31\ W/m^2$ per °C, and
$h_o = 8\ W/m^2$ per °C.

The values C_1 and C_2 used are typical of those observed experimentally for simple dryers with relatively poor quality glass covers (e.g., Sayigh 1978). The value of h_o used is based primarily on the flat-plate laminar boundary-layer result with rough account being taken of the effects of buoyancy forces and of fluid acceleration through the collector. Both of these effects tend to increase the convective heat transfer coefficient. The values of K and ρ_r used are taken from Excell (1980).

In the actual model, at each time for which a q_I value is specified, the equations in the previous section can be used to solve for the drying rate, dM/dt, at that time. The moisture content at time Δt later is then obtained using a simple finite difference approximation; that is,

$$M_{(t + \Delta t)} = M_t + (dM/dt)_t \Delta t \qquad [16]$$

Using this value of M, the process is repeated for the next time step and so on to give the variation of moisture content with time. As mentioned earlier, this procedure is only applied until M has dropped to the equilibrium moisture content, which is taken here to be approximately equal to 12%, and M is then assumed to remain constant at this value.

Model Validation

Before the computer model can be used with any confidence to design an improved rice dryer, its ability to adequately predict the performance of a dryer must, of course, be proven, i.e., the model must be validated. This has been done by comparing the results given by the model with the experimental results obtained with loaded dryers that are presented by Bassey (1982) and Whitfield (1985). One of the difficulties encountered in undertaking this comparison arose from the fact that, in Bassey's paper, the variation of the insolation with time was only partially specified for some of the days over which the tests were performed and, in Whitfield's, although some insolation values were given for all days over which the tests were undertaken, these values are for only a portion of each day. In specifying q_I, then, some assumptions concerning the form of its variation during the day had to be made. It was assumed that, in all cases, a 10-hour drying day occurred, i.e., that there was significant insolation for 10 hours/day. Using this assumption and whatever measured values of q_I were given, assumed insolation variations were derived (Fig. 3). For the test results given by Bassey, the same isolation variation was assumed for each day on all days on which tests were undertaken (Fig. 3, broken line). However, because more extensive measurements of q_I are given by Whitfield, it was possible to describe separate insolation variations for each of the days over which the test was undertaken (Fig. 3, solid line).

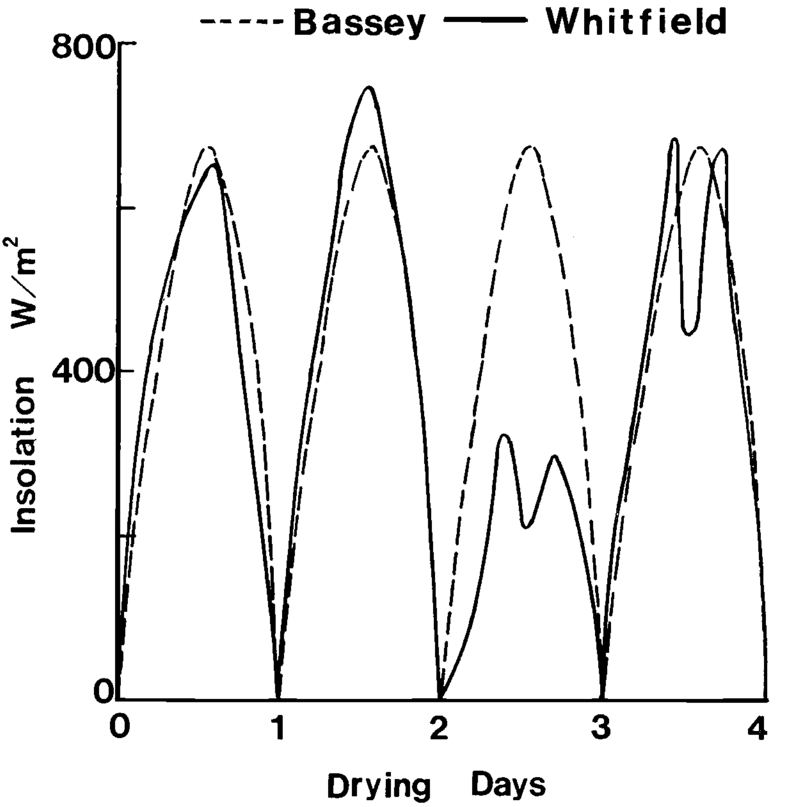

Fig. 3. Assumed daily variation of insolation based on data from Bassey (1982) and Whitfield (1985).

In carrying out all of the model validations, average constant values of 30°C for ambient air temperature and 50% for relative humidity were assumed and the rice-bed temperature was assumed equal to this mean ambient air temperature. The initial moisture content of the rice was deduced in each case from the experimental results. Rewetting of the rice during the night was neglected.

Using these assumptions, the computer model has been used to predict the variation of the moisture content with time for the four loaded dryer tests for which results are given by Bassey (1982) and for the single loaded dryer test for which results are given by Whitfield (1985). Comparisons between these predicted variations and the measured results are shown in Figs 4-7 (the full set of results are given elsewhere, Oosthuizen 1986).

In assessing the agreement between the predicted and experimental results, it must be realized that there appear to be occasional problems with the moisture content determination in the experimental studies. Whether this was caused by the sampling procedure used, as suggested by Bassey et al. (this volume), the method used to store the samples before the moisture content was measured, or with the method

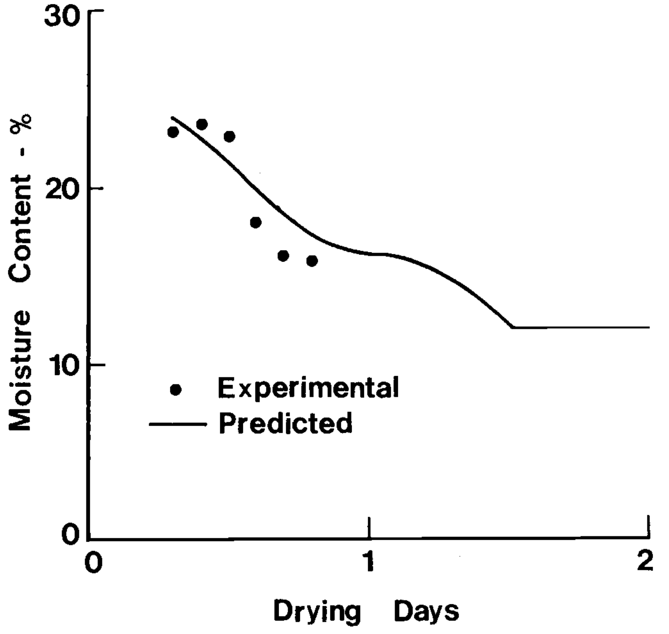

Fig. 4. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 25 mm.

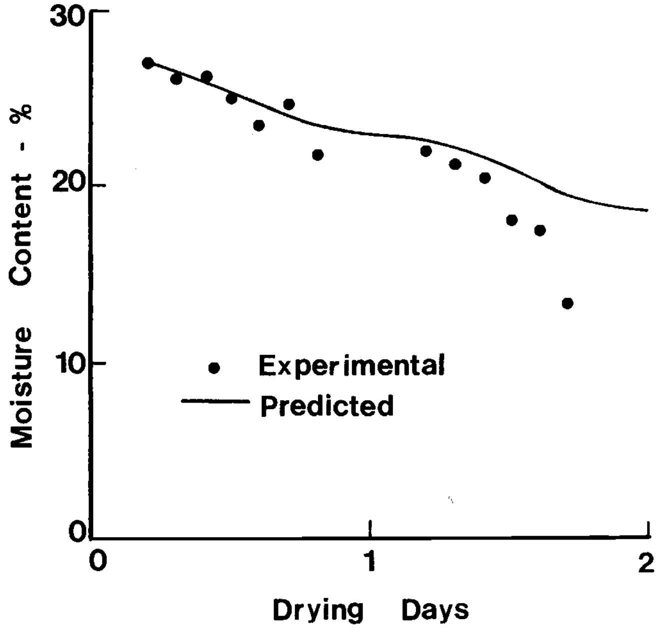

Fig. 5. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 50 mm.

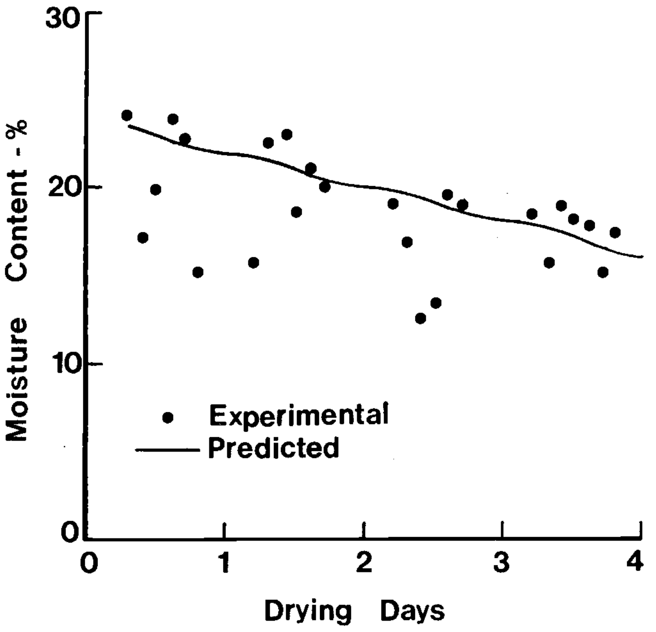

Fig. 6. Comparison of predicted and experimental results (Bassey 1982) for a rice bed thickness of 100 mm.

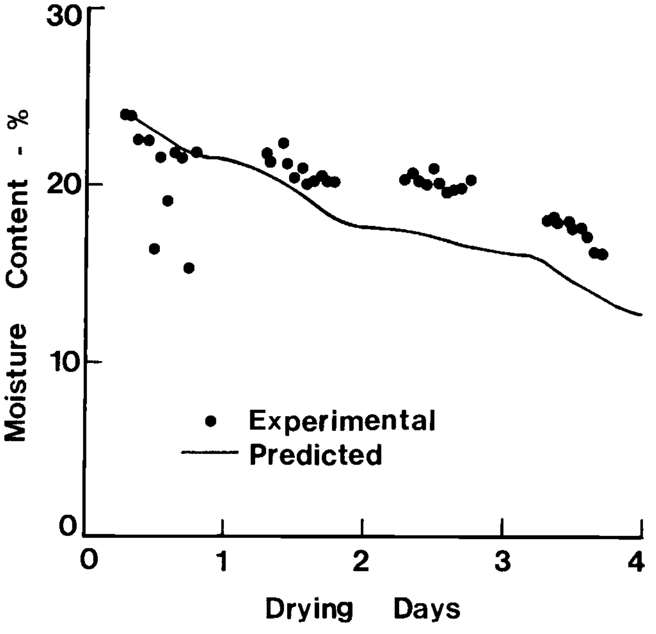

Fig. 7. Comparison of predicted and experimental results (Whitfield 1985).

used to determine the moisture content cannot be determined. However, the very low moisture content values periodically observed in the experimental studies, some of them being close to the equilibrium moisture content, are obviously in error. If these points are ignored, the agreement between the model and the experimental results is quite good. Thus, although the results from some much more controlled experiments are required to refine the model, it does appear capable, even in its present form, of indicating some improvements that can be made in existing dryer designs.

Improved Dryer Design

An assessment of the results obtained during the model validation strongly suggests that the most important factors that limit the performance of the existing dryers were

- The size of the collector and
- The height of the rice bed above the collector outlet.

The dryers used in the experimental studies described by Bassey (1982) and Whitfield (1985) had, basically, a collector that was 0.7 x 0.7 m with the gap between the collector plate and the glass cover of about 40 mm and a dryer chamber that was about 0.9 x 0.9 m in cross section with the rice bed roughly 0.12 m above the collector plate.

In assessing the effect of changes on the dryer's performance in the two dryer parameters mentioned above, calculations were undertaken for the following fixed values: dryer chamber cross-sectional size, 1 x 1 m; collector gap, 40 mm; rice-bed thickness, 75 mm (about 45 kg of rice); ambient temperature, 30°C; ambient relative humidity, 50%; and initial rice moisture content, 25%. The insolation values used were the same as those given in Fig. 3 for Bassey (1982). It has been assumed that the collector length and width are, in all cases, equal. The height of the rice bed above the collector outlet has, for reasons discussed later, been taken as 1 m.

As is to be expected, the dryer performance is considerably improved as the collector size increases (Fig. 8) and, with a 1 x 1 m collector, successful drying is accomplished in just over 2 days: this would be satisfactory in most applications. These, and other calculations, suggest that a rough design guide is to make the collector area equal to the area of the rice bed.

A study of the effect of the height of the rice bed above the collector outlet (H) on dryer performance (Fig. 9), using a 1 x 1 m collector, showed significant improvements in dryer performance with increasing H up to values of 1 m. However, relatively little improvement in performance was found for H values greater than 1 m.

In conclusion, then, it is suggested as a preliminary design guide that for dryers with rice-bed thicknesses up to about 100 mm:

- The area of the collector be set equal to the rice-bed area;
- The rice bed be placed 1 m above the collector outlet; and
- No chimney be fitted to the dryer.

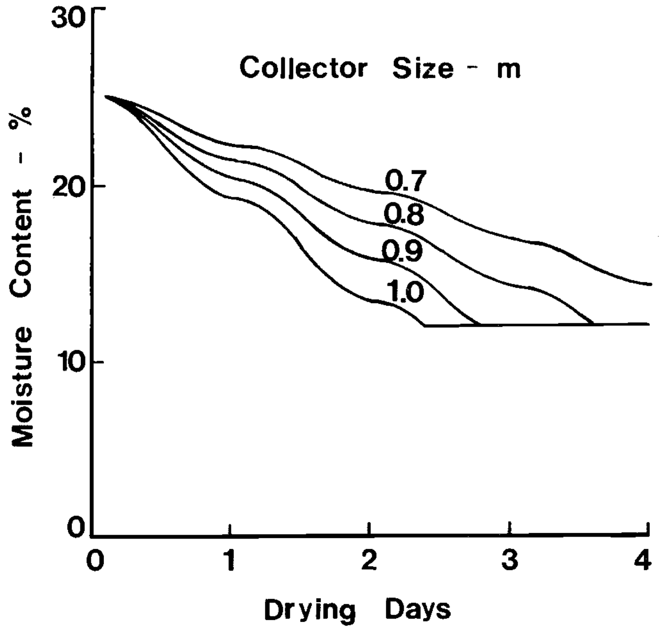

Fig. 8. Effect of collector size on dryer performance.

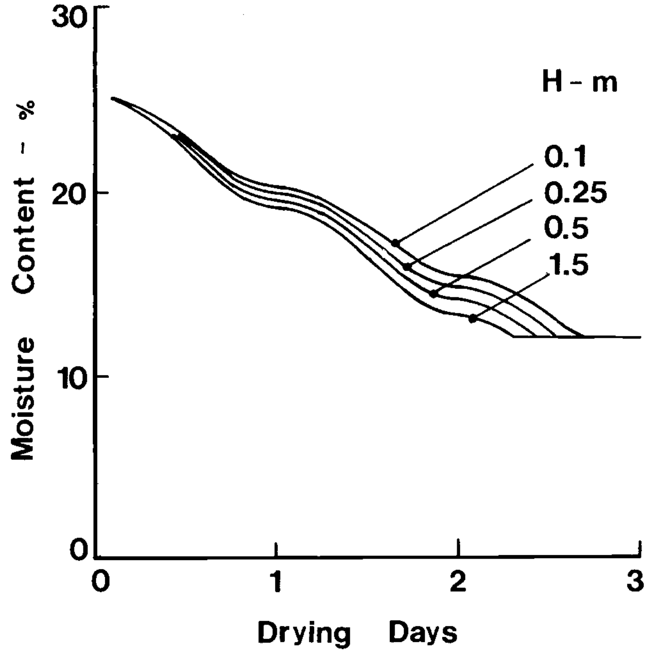

Fig. 9. Effect of rice bed height on dryer performance.

Experimental Study

Although the results given by the computer model agree quite well with the experimental results, there are some significant differences that may be the result of deficiencies in the model. It is suspected that, if such deficiencies exist, they are most probably due either to errors in the assumed heat-transfer coefficient in the collector or to deficiencies in the rice-drying model used.

To check whether these aspects of the model do, in fact, need improvement, a series of controlled laboratory-scale experiments is being undertaken. These experiments use a model of a typical natural-convection solar rice dryer, but with a simulated solar collector. This simulator consists of an aluminum plate with a series of electrical heaters beneath it (Fig. 10). The following measurements are taken during the test with the instrumentation indicated:

- The average temperature of the collector plate measured using a series of copper-constantan thermocouples attached to the back of the plate;
- The air temperature before and after the rice bed measured with thermocouple probes inserted into the airstream;
- The pressure drop across the rice bed measured using pressure taps in the dryer wall in conjunction with a Barocel electronic manometer system;
- The weight of the dryer with the rice measured by mounting the entire dryer on three load cells; and
- The ambient air temperature and relative humidity.

The measurements are obtained automatically using a Sciemetric Data Acquisition unit in conjunction with a Zenith Z-150 microcomputer.

It was felt that an adequate comparison between the numerical model and the experimental results could only be made if the pressure drop factor (K) for the actual rice being used in the dryer was known. For this reason, separate tests are undertaken in which air is blown at a known rate through a rice bed of known thickness. With the K value accurately determined in this way, the measured pressure drop across the rice bed in the dryer tests can be used to find the flow rate through the dryer. With the flow rate known, using the measured air temperatures before and after the collector and the mean plate temperature, the heat-transfer coefficient for the collector can be found using:

$$m\, c_p\, (T_c - T_a) = hA_p\, (T_p - T_a) \qquad [17]$$

where

A_p = area of collector plate.

Using the measured variation of total dryer weight with time and the known mass of rice on a dry basis, the variation of rice moisture content with time can be found.

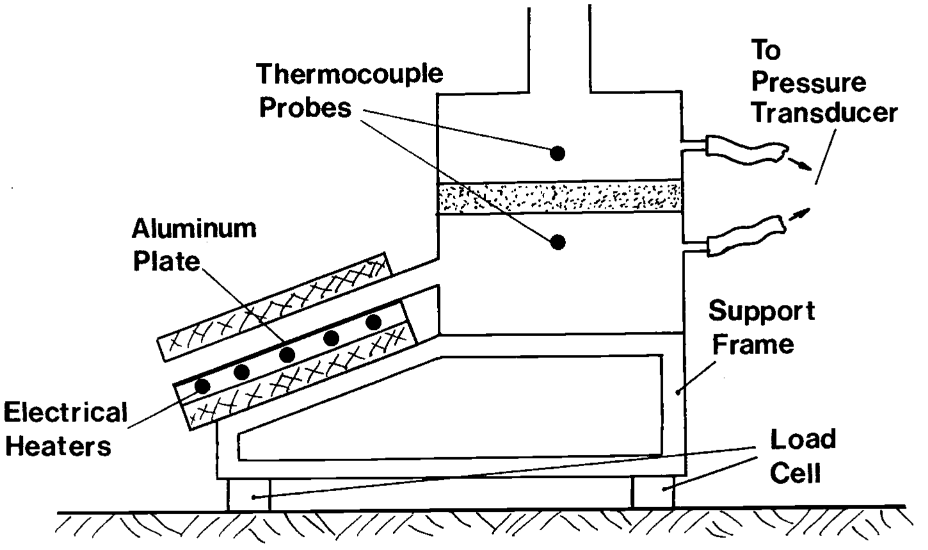

Fig. 10. Layout of experimental apparatus.

Conclusions

On the basis of the model validation tests, five main conclusions were reached. First, the collector area should be set equal to the area of the rice bed in the dryer; second, the dryer bed should be placed at a height of roughly 1 m above the collector outlet; third, tests with no load in the dryer give little information about dryer performance; fourth, a chimney is not likely to produce much improvement in dryer performance; and, fifth, all of the basic rice dryer performance parameters can be measured automatically using a simple microcomputer-based data-acquisition system.

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Appendix

A_p = area of collector plate
B_c = collector gap size
b = thickness of rice bed
C = constants in collector equation
c_p = specific heat of air
g = gravitational acceleration
H = height of rice bed above collector outlet
h = heat-transfer coefficient between collector plate and air
h_o = value of h at Re_L = 5000
K = bed pressure drop coefficient
L = length of collector
ℓ = latent heat of water
M = moisture content of rice on dry basis
m_r = mass of dry rice in bed
m = air mass flow rate through dryer
q_I = insolation
Re_L = $U_c L/\nu$
T_a = ambient air temperature
T_c = temperature of air leaving collector
T_p = temperature of collector plate
T_o = temperature of air leaving rice bed
t = time
U = mean air velocity in dryer
U_c = mean air velocity in collector
W = width of drying chamber

W_c = width of collector
W_D = length of drying chamber
w_a = moisture content at ambient conditions
w_o = moisture content at exit of rice bed
β = bulk coefficient of expansion of air
Δp = pressure drop across rice bed
η = collector efficiency
θ = angle of inclination of collector
υ = kinematic viscosity of air
ρ = density of air
ρ_r = density of rice in bed