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DESIGN, CONSTRUCTION AND TEST RUN OF A TWO-TONNE CAPACITY SOLAR RICE DRYER WITH RICE-HUSK-FIRED AUXILLIARY HEATER

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REFERENCE

ABSTRACT

The design and construction details of a two-tonne per batch capacity natural-circulation solar rice dryer and the highlights of the design of its rice-husk-fired auxiliary heating system which is still under construction are presented. The dryer measures approximately $17.7m$ long by $9.8m$ wide by $6m$ high. Preliminary results of a test run on the solar dryer section only is reported.

INTRODUCTION

Drying has been established as the most effective food preservation technique for most food products. In rice processing, drying is particularly a very important process. Drying may be required before par-boiling. However, after par-boiling (prio to milling), drying becomes inevitable as the moisture content of the rice must be reduced to a safe storage level that would also enhance milling. At the Adarice Production Company (a large-scale public-owned rice production company), the traditional open sun drying is still the normally utilised drying technique, where the rice is spread on a large area of concrete floor and exposed directly to solar radiation and natural air currents. For very wet days, an electric bulb heated barn is employed, where the rice is placed in bags and heated via some $1000W$ and $2000W$ electric bulbs located on the top of the barn. The traditional drying technique has numerous inherent severe limitations; high crop losses ensue from inadequate drying, fungal and insect attacks, unexpected down-pour of rain and other weathering effects, in addition to rodent and bird enchroachment. The supplemental electric bulb-heated drying in barns is costly on electric bills and frequent replacement of the bulbs. These problems associated with the rice drying operations at the Adarice Company, necessitated the design of the solar dryer in this study. The co-operation of the Board and Management of the company was obtained.

DESIGN OF THE SOLAR DRYER

There are two main rice harvest periods at the Adarice farm, namely, the wet season harvest (during the months of July and August) and the dry season harvest (during the months of December and

January). For obvious reasons, more severe practical problems are encountered in drying during the wet season than during the dry season. Thus the dryer in this study was designed bearing in mind the additional problems associated with wet season rice drying operations.

Conceptual Design Description

The dryer is of the mixed-mode natural-circulation design [1]. Thus, heat supply to the rice is via a combination of direct absorption of solar radiation on the product itself and by convection from preheated air. Accordingly, the dryer consists of two seperate drying compartments, namely, a floor dryer compartment (which also acts as the air heating solar collector of the dryer), where the rice is heated by direct absorption of solar radiation and an elevated rack dryer compartment where the rice is heated on top by direct absorption of solar radiation and from below by pre-heated air from the "solar collector". A thin layer of the wet rice spread on the floor dryer trays acts as a collector absorber plate while being dried simultaneously as in open-sun drying. The remaining portion of the rice is packed in deeper layers in the rack compartment. These two compartments are arranged on both sides of a central gangway running through the entire lenght of the dryer (see figure 1). The walls and roof of the dryer are glazed extensively. The chimney is of the ridged design, also running through the entire length of the dryer. Provision is made for an incenarator which burns rice husk to provide supplemental heating during periods of low insolation and/or high humidity. Heat from the burner exhaust is transfered to the rice through heat exchangers located below the dryer trays by natural convection.

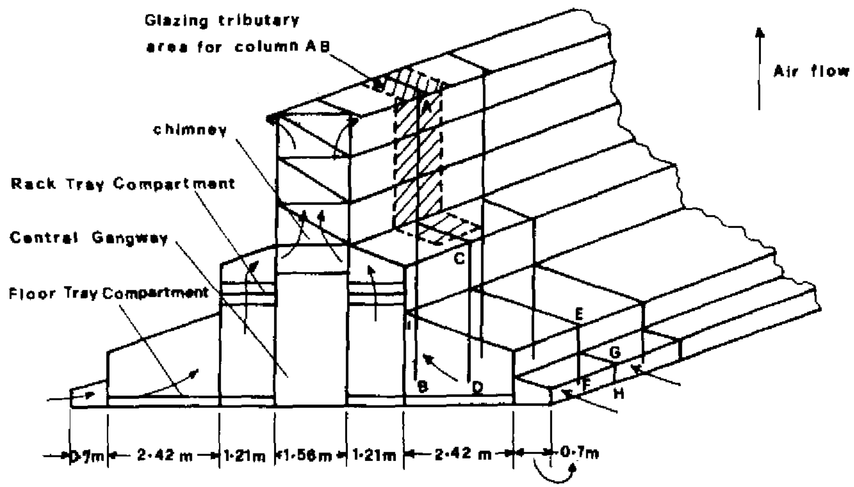

FIGURE 1 Schematic Illustration of the Solar Rice Dryer.

Design Parameters

Quantity of rough rice to be dried (w_i)	$= 2000kg$
Initial moisture content of the wet rice (M_i)	$= 25\%db$
Desired final moisture content (M_f)	$= 14\%db$
Mean ambient air temperature (T)	$= 30^oC$
Mean ambient air relative humidity	$= 85\%$
Maximum allowable drying air temperature	$= 45^oC$
Typical drying air temperature (T')	$= 40^oC$
Mean daily global radiation (I)	$= 11MJm^{-2}$
Bulk density of rough rice	$= 600kgm^{-3}$ [2]
Latent heat of vapourization of water from rough rice, H,	$= 2.8MJkg^{-1}$ [2]
Assumed overall dryer system efficiency (η)	$= 20\%(0.2)$
Rack dryer (thick layer) maximum packing thickness	$= 0.06m(6cm)$
Floor dryer (thin layer) maximum packing thickness	$= 0.01m(1cm)$

Dryer Floor Area and Drying Time

From the dryer tray widths in fig. 1, and considering a floor and rack packing thickness of $0.01m$ and $0.06m$ respectively and a bulk density of rough rice of $600kgm^{-3}$[2], the dryer length to contain $2000kg$ of rough rice can be obtained from,

$$l(2.42\times0.06+7.26\times0.01) = 2000/600 = 3.33m^3 \qquad (1)$$

hence, l, dryer length $= 15.3m$.
Effective solar energy collection area (A) $= 7.26 \times 15.3 = 111.88m^2$
Thus the maximum volume of rice on the rack $=15.3 \times 2.42 \times 0.06 = 2.22m^3$
and the maximum volume of rice on the floor $= 15.3 \times 7.26 \times 0.01 = 1.11m^3$.

Mass of water, m_w, to be evaporated from fresh rough rice of initial mass, w_i, of $2000kg$ from an initial moisture content, M_i of $25\%db$ to a final moisture content, M_f, of $14\%db$ is given by,

$$m_w = w_i(M_i-M_f)/(100-M_f) \qquad (2)$$

$$\Rightarrow m_w = 255.82kg$$

If m_wH is the total energy requirement to evaporate $255.82kg$ of moisture from the rice surface and $nIA\eta$ is the total amount of solar energy available to evaporate that mass of moisture, then,

$$nIA\eta = m_wH \qquad (3)$$

Thus number of drying days $n = 2.93days \approx 3days$ (assuming $\eta = 20\%$).
At 8 hours of sunshine per day this corresponds effectively to $24hours$ of drying.

Dryer Overall Height

Assuming a mean ambient air temperature of 30^oC, a mean ambient air relative humidity of 85%, drying air temperature of 40^oC, and mean exhaust air relative humidity of 90%, then, from the psychrometric chart; an absolute humidity change of 0.0038 is obtained on the average. The mass of air required to carry $255.82kg$ of water for this humidity ratio change $= 6.73 \times 10^4kg$. This corressponds to $5.96 \times 10^4m^3$ of air by volume, given,

$$PV = M_aRT \qquad (4)$$

where, P and V are pressure (Nm^{-2} or Pa) and volume (m^3) respectively of air of mass M_a at temperature T while R is the universal gas constant ($Jmol^{-1}K^{-1}$). Thus the air flow rate over the $24hour$ drying period $= 0.69m^3s^{-1}$ and the volume of complete air exchanges N, per second per m^3 of the rack dryer rice bed (of volume $2.22m^3$) or air flow rate per unit volume of rice bed$=$ $0.31m^3/s/m^3$.

Assuming h_1 is the height between inlet and bottom of rice bed on the rack and h_2 is the height between top of rice bed and chimney top (see fig. 2) and that 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 cool ambient air and the warm air inside the dryer and if $h_1 + h_2 >> $ the rice bed thickness, x, then $h_1 + h_2 \approx$ height of the chimney top above air inlet.
Thus,

$$P_2 = P_1-h_1\rho'g \qquad (5)$$

$$P_3 = P_4+h_2\rho'g \qquad (6)$$

$$P_4 = P_1 - (h_1 + h_2)\rho g \quad (7)$$

where P_1, is the air pressure inside and outside the dryer at the air inlet, P_2 and P_3 are the dryer air pressures at the bottom of the rice bed and at the top of the rice bed in the rack section respectively, P_4 is the air pressure inside and outside the dryer at the chimney top while g, ρ and ρ' are acceleration due to gravity, ambient air density and drying air average density respectively.

Eliminating P_2 and P_4, the pressure difference across the bed would be

$$P_2 - P_3 = (h_1 + h_2)(\rho - \rho')g \quad (8)$$

Rearranging (4),

$$M_a/V = P/RT \quad (9)$$

At pressure, P of $101.3kPa$, ambient temperature, T of $30^oC(303K)$ and dryer temperature, T' of $40^oC(310K)$,

$$\Rightarrow (\rho - \rho') = P/R(1/T - 1/T') = 0.0367kgm^{-3} \quad (10)$$

Since N = the air flow rate per volume of the rice bed[2],

$$\Rightarrow N = v/x \Rightarrow v = Nx = 0.31 \times 0.06 = 0.0186ms^{-1} \quad (11)$$

where v and x are the air velocity through the rice bed in the rack (ms^{-2}) and the rice bed depth. From[2],

$$v = kdP/dx \quad (12)$$

where k is a dimensional constant = $0.0005m^2Pa^{-1}s^{-1}$ for rough rice[2]

$$\Rightarrow dP/dx = v/k = 37.24Pam^{-1} \quad (13)$$

Thus the pressure difference across the bed = $dP/dx \times x = 2.23Pa$ and from (7),

$$P_2 - P_3 = (h_1 + h_2)(\rho - \rho')g = dP \quad (14)$$

Thus height of the dryer above air inlet

$$(h_1 + h_2) = dP/(\rho - \rho')g = 6.2m \quad (15)$$

A chimney overall height above air inlet of $6m$ was used for construction.

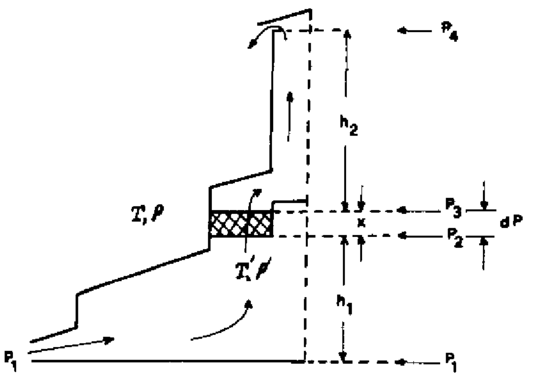

FIGURE 2 Illustration of Pressure Differences within the Solar Dryer Chamber.

Dryer Space Configuration

The space design and some material selection and sizing were guided by experience and standard sizes of available materials. The widths of the various sections of the dryer are shown on the cross-sectional plane of fig. 1. The floor dimensions were adjusted to fit space considerations and construction constraints to $17.7m$ long by $9.8m$ wide. Air enters the dryer through louvred openings (for flow control) on either side, passes over the floor trays and is forced to flow through the rack trays to the chimney by a transparent ceiling and a wall over the gangway. There are three layers of rack trays of $50mm$ depth each. A heated space, $0.7m$ wide, seperates the floor trays from the outside to protect the former from splashes of rain water. The $1.5m$ height above the floor trays was chosen to allow an operator to stir the rice and lift the trays with relative convinience. Axially, there are 8 tray compartments on each side of the gangway, $2.2m$ long and seperated by support columns. With this, small farmers may use one or more compartments, simultaneously, to suit their individual sizes of operation.

STRUCTURAL DESIGN AND DRYER CONSTRUCTION

The entire glazing and rack support structure is of "Iroko" hardwood. The glazing is of corrugated transparent PVC sheets. There are 9 main, intermidiate, subsidiary and minor vertical columns, AB, CD, EF and GH, respectively (fig.1), at each axial row of columns. The upper half of each pair of main columns are braced with four horizontal and three diagonal braces. Each main column and the adjacent intermidiate columns are joined by three braces which also act as support and guides for the rack trays. The tray base is of expanded metal and wire mesh. Due to the height of the main columns, two joists are joined together with flat steel bar braces ($75mm \times 610mm \times 6mm$) and bolts. Longitudenal girts and roof purlines are used to support the glazing and brace the columns against lateral wind loads. The dryer, alinged in the North–South axis, is glazed on all surfaces execpt for the $1m$ high dwarf walls and the entrace doors at the ends. The side glazing slope is 7^o. During construction, the floor area was specially prepared with stone and concrete overlay for strength and to prevent moisture migration from the ground. The foundations for the walls and columns were treated with chemicals to prevent ants destruction of the woodwork. The main, intermediate and subsidiary columns were embedded in concrete to a depth of $0.6m$.

Sizing of Members

Selected sizes of the main, intermediate and subsidiary columns were $100 \times 150, 75 \times 100$ and $75 \times 100(mm)$, respectively. All other joists were of $50 \times 50mm$ size. The critical structural members such as AB and CD, were verified for strength against vertical and wind loads, using the concept of tributary area to distribute the load. The tributary area for AB is shaded in fig. 1. The weights per unit length of the joists and sheeting were calculated to be

$100 \times 150mm \rightarrow 79.5N$
$75 \times 100mm \rightarrow 39.75N$
$50 \times 50mm \rightarrow 13.25N$
sheeting $\rightarrow 30.5Nm^{-2}$

Wind speeds, v_w, average about $2m/s$ over the year. However at start and end of the wet season, they are strong enough to break off branches. This is a stong gale with rated speeds of $21 - 24m/s$ [3]. For the design, it is assumed to act pependicularly on the east or west face of the dryer (actual direction of maximum projected area of dryer is 12.9^o NE or SW). At 30^oC ambient temperature, $6m$ dryer height and $24m/s$ wind speed, free stream Reynolds Number = 8.11×10^6, which is turbulent. Drag coefficient C_D for turbulent flow over a box-type house is given as 1.4 [4]. Hence, wind force per unit projected area of dryer is given by,

$$p_w = C_D 1/2 \rho v_w^2 = 470Nm^{-2} \quad (16)$$

where v_w and ρ are wind speed and air density respectively.

For columns AB, dead or gravity load within its tributary area = weights of (1/2 roof truss + roof girder + girts + intermediate roof purline + glazing) = $(1.685 + 2.2 + 6.6 + 0.605) \times 13.25 + 9.706 \times 30.5N = 443N$. Similarly, allowing an overload of rack trays with rice by a factor of 2, the weight of trays and rice is estimated to be $2238N$. Minimum roof live load for normal wooden building design with low roof slope is $20lbf/ft^2$ [5]. For the columns tributary roof area, this translates to $2965N$. Because little transient loads are expected on the dryer roof, 1/3 of this value (or $1000N$) is used. Thus, total roof vertical load = $443 + 1000 = 1443N$
Lateral wind load = $430 \times 2.2 \times 3.284N = 3395.7N$ or $1132N$ per unit height of bearing area. The simplified loading diagram for the column is shown in fig. 3. The rack tray loads which act $0.6m$ off the column centreline, is equivalent to a couple of $1343Nm$ and a vertical load of $2238N$ along column axis.

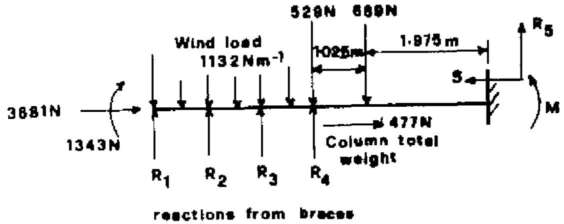

FIGURE 3 A Simplified Loading Diagram for the Main Column.

Each of the reactions R_1 to R_5 is assummed to support the load within its tributary area. The remaining unknown forces and moment are determined using equilibrium conditions. The maximum bending moment is found to be $1705.3Nm$ at $2.47m$ from the top of column. The compressive force, including column weight up to that point = $3877N$.
Condition to be satisfied by stresses in the column is given by,

$$F_c/S_c + F_b/(S_b - JF_c) \leq 1.0 \tag{17}$$

where F_c, F_b and J are compression and bending stresses and compression deflection factor respectively, S_c and S_b are allowed compression and bending stresses, respectively.
For a $100 \times 150mm$ cross-section,

$F_c = 3877/0.015 = 2.59 \times 10^5 Nm^{-2}$
$F_b = Md/2K = 1706.4 \times 0.15/2 \times 2.813 \times 10^{-5} = 4.55 \times 10^6 Nm^{-2}$

where M, d and K are bending moment, depth of cross-section and area moment of inertia respectively.

Unbraced length of column = $3m$.
Corrected slenderness ratio L_c/d for compression = $1.2 \times 3/0.15 = 24$.

$$S_c = f_c \times 0.3E/(L_c/d)^2 \text{ [5]} \tag{18}$$

E = Young's modulus = $13.5 \times 10^9 Nm^{-2}$ for mahogany
f_c = condition of use factor for compression, taken as 0.7 for a moist environment
$\Rightarrow S_c = 4.9 \times 10^6 Nm^{-2}$
$J = 1.0$ [5]
Corrected slenderness ratio (L_b/d) for bending = $1.375 \times 3/0.15 = 27.5$.
$S_b = f_b \times 0.4E/(L_b/d)^2$ [5] (for design against buckling)
f_b = condition of use factor for bending in moist environment, taken as 0.86.
$\Rightarrow S_b = 6.14 \times 10^6 Nm^{-2}$

By substitution, equation (17) is seen to give $0.83 < 1$. Thus the chosen joist size of $100 \times 150mm$ is acceptable.

DESIGN OF AUXILLIARY HEATER

The auxilliary heating system which is still under construction comprises an incenerator which burns rice husks, a waste product in the farm, to deliver the desired heat via a network of heat exchangers located below each tray. The floor and rack tray heat exchangers on each side of the gangway have seperate hot gas supply and cool gas discharge lines. The supply lines tee-off from a common line (one for each side of the gangway), that eventually exhaust the gas at a level just beneath the roof of the chimney. The auxilliary heater is designed to provide heat twice the drying capacity of the solar dryer ($\approx 16.58kw$). Thus with the auxilliary heater, the drying time is reduced (by half) to 12 hours per batch. The fuel (i.e rice husk) consumption rate of the incenerator is $41.2kg/hr$ (i.e. $494.4kg/batch$ of 12 hours). Details of the design calculations, construction and measured performance of this auxilliary heating system would be reported elsewhere.

RESULTS OF PRELIMINARY TEST RUN OF THE SOLAR DRYER

A preliminary test run of the solar dryer was undertaken with the dryer only partially loaded. Selected trays at the ends and middle of both the floor and rack compartments on either side of the central gangway were loaded with freshly harvested rice. The summary of the results are given below.

Initial moisture content (of the fresh rice)	= $23.5\%db$
Final moisture content (of dry rice)	= $12.8\%db$
Drying time	= 14 sunshine hours
Ambient temperature (day time)	= $28 - 32°C$
Ambient relative humidity (day time)	= $66 - 79\%$
Average drying chamber temperature	= $42°C$
Maximum drying chamber temperature recorded	= $48°C$
Average drying chamber relative humidity	= 55%

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