Estimating Air Flow and Drying Rate Due to Natural Convection in Solar Rice Dryers

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ABSTRACT

A simple method is described to calculate the air flow through the grain bed in a solar dryer in which heated air rises by natural convection. The estimation of air velocity in the proposed method is based on the thickness of grain bed, the height of the hot air column and the temperature difference between the hot and ambient air. It is shown that the direct calculation of air flow through the rice bed can be made conveniently using a graphical solution of the related equations. The application of estimated air flow is discussed in designing the solar rice dryers based upon the simulated drying rate results.

INTRODUCTION

Simple solar dryers in which heated air rises by natural convection through the grain have been proposed for use in the rural areas to dry rough rice in small batches of ½ to 1 ton (Wieneke, 1977; Exell and Kornsakoo, 1978; Exell, 1980; Phongsupasamit, 1981; Boonthumjinda, 1981). These dryers can be constructed at a low cost with locally obtainable materials and used effectively even during the wet season in tropical climates. However, extensive field testing and more technical data on the construction, operation and economic aspects of the solar drying systems using natural convection of warm air are needed to harness their full potential and to popularize them.

Exell (1980) has presented the design procedure for a simple solar rice dryer which is essentially based on a back calculation approach aimed at knowing the total volume of air needed for drying and then fixing the grain bed depth accordingly. In addition, simple heat balance used by Exell for drying calculation purposes assumes the final conditions of the air in an arbitrary manner. Therefore, it is necessary first to estimate realistically the drying taking place in a grain bed due to convective flow of air, and then to compute the temperature and relative humidity of exit air. However, Exell (1980) clearly illustrated the importance of estimating the convective air flow through the grain bed due to the temperature difference existing between the inside and outside of the dryer. This paper presents a simple procedure to calculate the air flow across the grain bed in a solar rice dryer. The estimated air flow rate can then be used, along with other information, to determine the moisture removal rate, or the extent of drying over a given period of time.

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DEVELOPMENT OF WORKING EQUATIONS

Assumptions

In the present analysis, it is necessary to make a few simple assumptions based on the typical design configuration of a solar dryer shown in Fig. 1. These assumptions are:

(i) The air temperature at all points inside the solar dryer and thus the air density is uniform.

(ii) There is no leakage of air from the sides of the dryer and the warm air leaves only from the outlet of the chimney.

(iii) The drying of grain takes place in convective mode as a result of air flow through the grain.

(iv) The resistance to air flow through the dryer components, such as the heater, drying chamber and chimney, is negligible in comparison with the resistance of the grain bed.

The first two assumptions imply that the air flow is solely due to the chimney effect. The third assumption excludes the extra drying taking place at the top layer of the grain exposed to

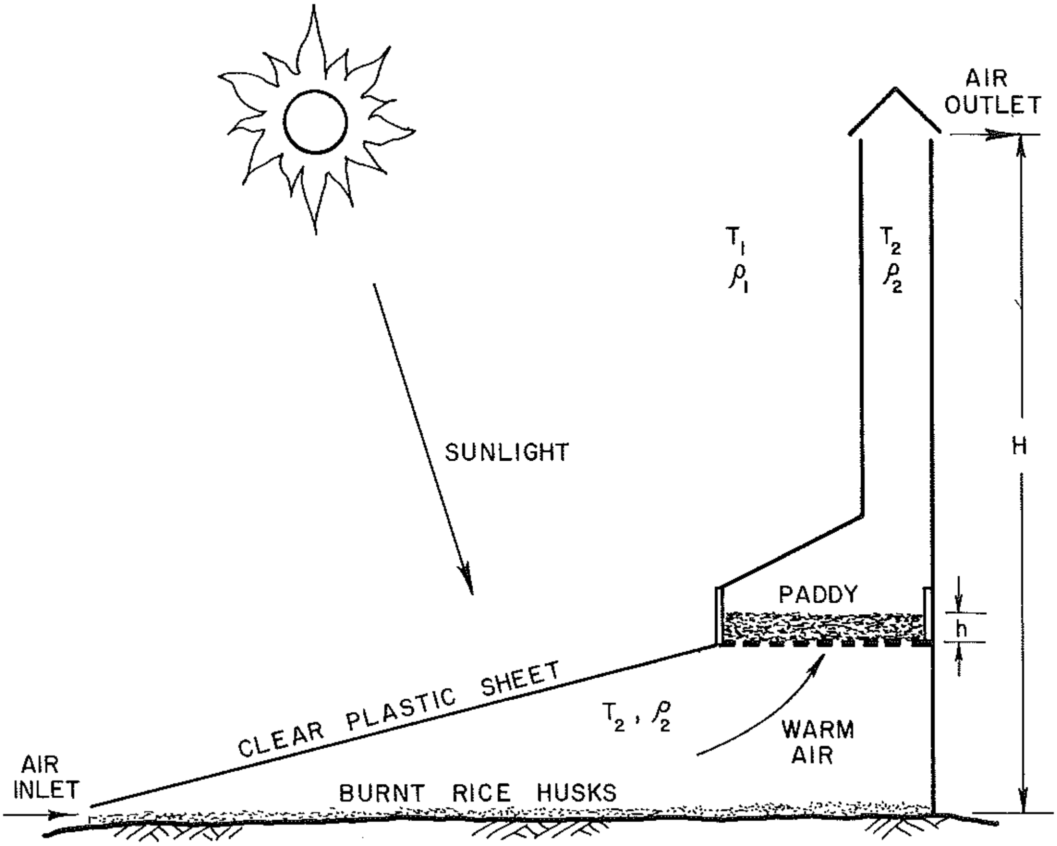

Fig. 1 Cross-section of a solar rice dryer adapted from Exell (1980).

direct sun radiation through the clear plastic sheet. The resistance to air flow in the dryer itself is considered negligible in the last assumption.

Resistance to Air Flow

The resistance to air flow data for grains are conveniently expressed in the following form:

$$Q = a\,(\Delta P/h)^b \tag{1}$$

where Q = air flow rate based on the unit cross-sectional area of grain column, m^3/s per m^2
ΔP = pressure drop across the grain bed, Pa
h = grain bed thickness, m
a, b = empirically determined constants.

The experimental values of constants a and b for low air flow conditions arising from natural convection in rice beds were reported by Gunasekaran (1981) to be 0.0008 and 0.87, with the S.I. units specified above, respectively. Therefore, equation (1) reduces to

$$Q = 0.0008\ (\Delta P/h)^{0.87} \tag{2}$$

Since the air flow rate is expressed on the basis of unit cross-sectional area, it directly gives the nominal air velocity in m/s across the grain bed.

Air Density-Temperature Relationship

The air density-temperature relationship is given in the Handbook of Chemistry and Physics, edited by Weast (1969) as follows:

$$\rho = 1.2929\,(273.13/\theta)\ (B - 0.3783e)/760 \tag{3}$$

where ρ = air density, kg/m^3
θ = absolute temperature, K
B = barometric pressure, mm of water
e = vapor pressure of moisture in air, mm of water

Assuming initial air conditions of 25°C and 75% relative humidity, the air densities were computed using equation (3) corresponding to various temperatures in the range of 25-90°C. A plot of air density versus temperature revealed that the air density could be linearly related to the temperature with a coefficient of determination of 0.998. Therefore, equation (3) could be approximated by a simpler relationship of form

$$\rho = 1.11363 - 0.00308\,T \tag{4}$$

where T = air temperature, °C

Pressure Difference Across the Bed

In a solar dryer, the pressure difference across the grain bed will be solely due to the density difference between the hot air inside the dryer and the ambient air. Therefore,

$$\Delta P = (\rho_1 - \rho_2)\ g H \tag{5}$$

where ρ_1, ρ_2 = air densities at temperatures T_1 and T_2, respectively, kg/m^3 (Note: $T_2 > T_1$)
g = acceleration due to gravity, 9.81 m/s^2
H = height of hot air column, m

The densities of air appearing in equation (5) can be determined corresponding to the ambient air and hot air temperatures respectively, and substituted in equation (5) to give

$$\Delta P = 0.00308 \; \Delta T \; gH \qquad (6)$$

where $\Delta T = T_2 - T_1$

Working Equation for Air Flow Calculation

The cross-section of a solar rice dryer as given by Exell (1980) is reproduced in Fig. 1 with minor alterations. In general, the air flow due to natural convection through the grain bed will depend upon the following factors:

(i) grain type
(ii) grain bed thickness, h
(iii) pressure drop across the grain bed, ΔP
(iv) density difference between the hot and cold air, $\Delta\rho$
(v) height of hot air column, H

Thus, it should be possible to have a relationship for a particular grain as follows:

$$Q = f(h, \; \Delta P, \; \Delta\rho, \; H) \qquad (7)$$

Equation (7) will then enable one to calculate the total volume of air passing through the grain bed during a given time.

However, it should be realized that the air density varies linearly with temperature (eq. 4). Also the pressure drop across the grain bed is a function of temperature difference (ΔT) and the height of hot air column (H) as shown by equation (6). Therefore, equation (6) can now be substituted directly into equation (2) to yield the working relationship

$$\begin{aligned} Q &= 0.0008\,(0.00308\, g\, H\, \Delta T/h)^{0.87} \\ \text{or} \quad Q &= 3.81 \times 10^{-5} \;\; (\Delta T.H/h)^{0.87} \end{aligned} \qquad (8)$$

For a given solar dryer, equation (8) can be used to estimate the volume flow rate of the air. Alternately, a solar dryer could be designed if conditions of minimum air flow rate are established first to accomplish drying in a given period. A graphical solution of equation (8) is presented in Fig. 2 to further simplify its use for design calculation purposes. An illustrated example follows in the next section.

Illustrated Example

Ambient air at a temperature of 30°C and with a relative humidity of 75% is heated to 45°C in a solar dryer (shown in Fig. 1). Estimate the air flow rate across the rice bed having a thickness of (a) 10 cm and (b) 20 cm. Assume that the warm air leaves the chimney outlet 4 m above the ground level.

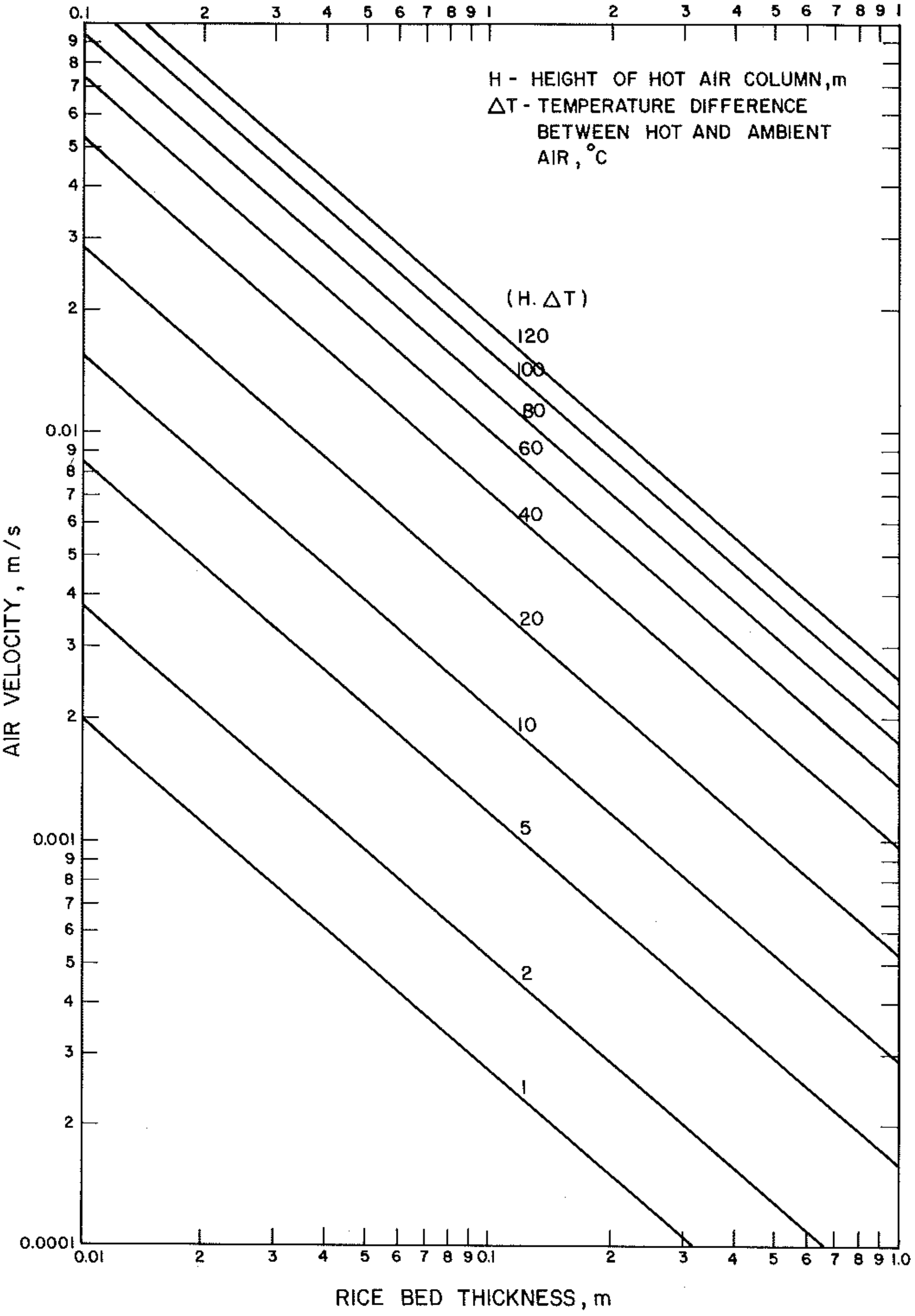

Fig. 2 Graphical solution for computing air flow rate through the grain bed in a solar rice dryer.

Solution: It is given that

$$\Delta T = (45 - 30)^\circ\mathrm{C} = 15^\circ\mathrm{C}$$
$$h = 0.10\ \mathrm{m}$$
$$H = 4.0\ \mathrm{m}$$

The line corresponding to $(H.\Delta T)$ value of 60 is located first in Fig. 2. The air flow rate or the air velocity corresponding to a rice bed thickness of 10 cm is directly found to be 1 cm/s. If the grain depth is doubled, and assuming other conditions to be unchanged, the air velocity will be reduced to 0.55 cm/s.

Application in Dryer Design

A basic procedure for designing a grain dryer operating on the convection principle will require a knowledge of the moisture removal rate from the grain and the associated changes in the air temperature and relative humidity. Since during the drying process the conditions of the air and the grain continuously change, care must be exercised in selecting a proper procedure for estimating the extent of drying at various time intervals.

There are three commonly used deep-bed grain drying models, reported in the literature, which resolve the final grain and air conditions as follows:

1. models based on the basic laws of heat and mass transfer, usually leading to complicated systems of partial differential equations (Bakker-Arkema et al., 1966, 1967, 1968),
2. models employing a semi-theoretical approach in the form of an empirical thin layer drying equation (Thompson et al., 1968; Islam and Jindal, 1981), and
3. models employing grossly simplified assumptions and requiring no formal drying equation (Bloom and Shove, 1971; Thompson, 1972; Jindal and Agarwalla, 1979; Pordesimo, 1981).

The applicability of the first two approaches is well documented for selected grains. It has been suggested that the third approach is the most effective when the moisture transfer from the grain to the air is slow. The underlying assumptions of the third approach consist of the following:

(i) the grain and air attain temperature equilibrium during each drying time interval of usually one hour or more,

(ii) the rate of moisture transfer is controlled by the available heat, depending upon the temperature difference between the grain and the air,

(iii) the final equilibrium temperature will fall between the range of the initial grain and air temperature,

(iv) the drying process is adiabatic, such that the algebraic sum of heat changed by air, and heat changed by grain and by latent heat equals zero, and

(v) all processes are reversible without hysteresis.

In the solution scheme of this so-called near-equilibrium drying simulation model, three conditions are specified in terms of a heat balance equation, a mass balance equation between the air and the grain, and the equivalence between the equilibrium relative humidity of the grain and the relative humidity of the air. The solution of these equations is obtained to determine the final values of the temperature and absolute humidity of the air, and of the grain moisture content.

The grain bed is assumed to consist of a series of thin layers positioned normal to the direction of the air flow. Drying calculations must be made for each successive layer, starting from the bottom layer to the top layer of the grain bed for each drying time interval of usually one hour. Thus, the average final conditions of the grain and the exhaust air in each layer of the grain can be computed when subjected to a known volume of air over a known drying period. The detailed procedure is outlined by Jindal and Agarwalla (1979).

Fig. 3 shows two estimated drying curves for rough rice based on a near-equilibrium drying simulation approach (Jindal and Agarwalla, 1979) under the two sets of conditions given in the preceding illustrated example. The drying curves in Fig. 3 clearly indicate that doubling the grain depth from 10 cm to 20 cm will approximately result in a four-fold increase in the drying time to reach a given moisture content. Therefore, the design procedure even for a simple solar dryer should consist of two parts. The first part should enable the calculation of the air flow for a given dryer configuration as presented in this paper. The second part should then involve the estimation of the drying rate under the conditions established in part one.

It is generally reported that the air flow rate does not influence the drying rate in mechanical dryers having an abundant supply of heated air. However, low air flow rates such as encountered in simple convective solar dryers will perhaps have a dominant effect on the moisture removal rate. Therefore, the thickness of the grain bed and the initial moisture will are the important factors in the design of solar dryers operating on the principle of natural convection. In addition, a realistic design approach will include the diffusion of moisture from the top layer of the grain bed due to direct solar radiation and the resistance to the air flow of the empty dryer.

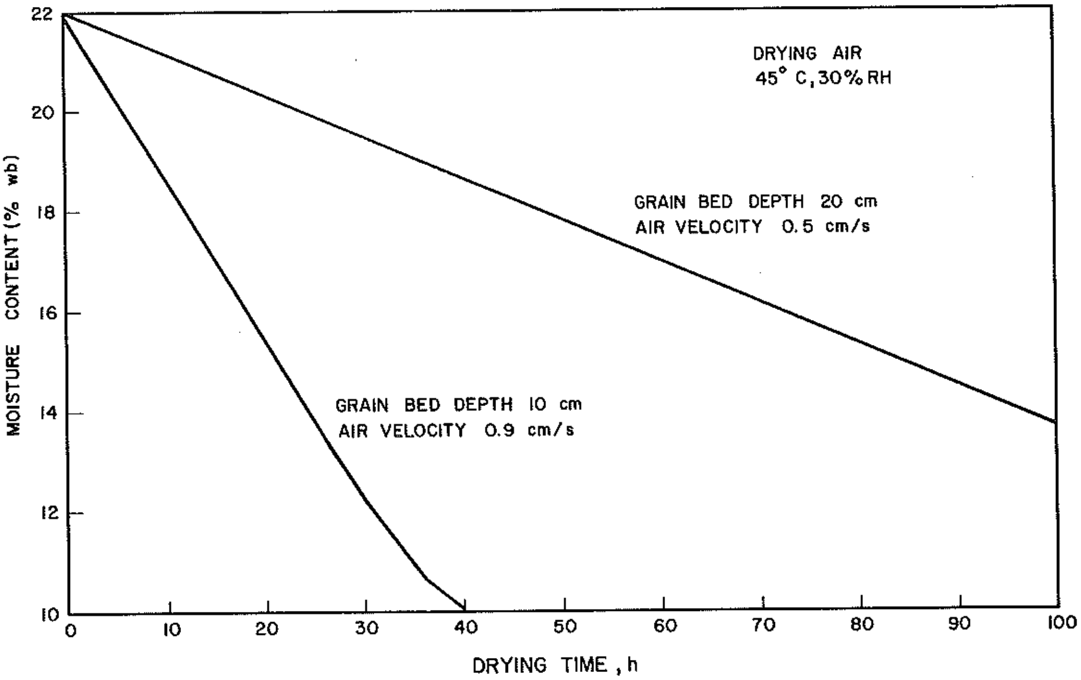

Fig. 3 Estimated drying curves for paddy in a solar dryer based on convective flow of air.

SUMMARY

A simple graphical solution has been presented to compute the air flow rate through the grain bed in solar rice dryers similar to those developed at the Asian Institute of Technology. The proposed solution could be adapted to other products to be dried in solar dryers provided the information on resistance to the air flow for those products is available. It is shown that air flow calculations can be directly used in designing solar dryers.

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