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DESIGN AND MEASURED PERFORMANCE OF A SOLAR CHIMNEY FOR NATURAL–CIRCULATION SOLAR–ENERGY DRYERS

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ABSTRACT

The design and construction of a solar chimney which was undertaken as part of a study on natural–circulation solar–energy dryers is reported. The experimental solar chimney consists of a $5.3m$ high and $1.64m$ diameter cylindrical polyethylene-clad vertical chamber, supported structurally by steel framework and draped internally with a selectively–absorbing surface. The performance of the chimney which was monitored extensively with and without the selective surface in place (to study the effectiveness of this design option) is also reported.

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INTRODUCTION

The low prevalent air flow rates within natural-circulation solar-energy drying systems are the major handicap to achieving efficient performance of such systems. This results in very poor air circulation and thus in most cases excessive temperatures within the drying chamber. Proper design of solar chimneys which enhance the bouyant flow of air is thus critical to the overall design of such dryers. For most practically-realised natural-circulation solar-energy dryers, very little attention has been paid to the efficient design of chimneys. For these dryers, final product qualities are poor, sometimes below that obtainable from open air drying.

In a solar chimney, the boyancy force required to generate the air flow through the chimney is directly proportional to the difference between the mean air density within the chimney and the ambient air density, represented usually as [1, 2, 3]:

$$\Delta P_b = gH(\rho_a - \bar{\rho}_{ch}) \tag{1}$$

The air densities are related to air temperatures and humidity ratios according to the following [3].

$$\rho = \rho_o \left[\frac{1}{(1 + T/273)}\right](1 + h) \tag{2}$$

If the air inside the chimney has the same temperature and humidity conditions and thus the same density as the ambient air, and there is no wind to produce Bernoulli effect, then there would be no flow through the chimney. If however, the mean chimney temperature is greater than the air temperature such that $\rho_a > \bar{\rho}_{ch}$, there is a pressure head which encourages upward air flow. Solar chimneys should be designed usually such that pressure losses are small compared to the differential bouyancy head in the chimney. Generally, pressure drops in natural flow systems due to duct wall friction are negligible [2], thus the main emphasis on solar chimney designs should be to minimise the rate at which the air temperature cools relative to the ambient. In most cases, the air leaving the crop mass is moist and close to ambient temperature [2, 4, 5]. Sometimes it may be close to the drying chamber wet bulb temperature if saturated and thus it may be at a temperature lower than ambient. In these circumstances, the contribution of bouyancy force would be negligible, unless the air is heated subsequently above the stacked-crop (i.e. within the chimney). It has been suggested [4, 5] that the incorporation of a chimney above the crop stack in natural circulation dryers will thus have little effect on the dryer performance unless the solar heating of the air within the chimney is significant. It was noted that since chimneys are vertical usually, heating of solar chimneys will be negligible except for dryers located far from the equator. As a result it was assumed that bouyancy forces occur effectively only in the collector and drying chamber (i.e. if the chamber is glazed). However, we observe that even for dryers located near the equator, vertical chimneys receive diffuse solar radiation and for these tropical locations, the received diffuse components of solar radiation are fairly high. For such conditions, solar chimneys can be designed efficiently such that mean chimney temperatures remain well above ambient air temperatures.

PREVIOUS SOLAR DRYER CHIMNEY DESIGNS

Various types of solar dryer chimney designs have been reported. In some cases the chimneys are constructed from opaque metal materials with no insulation [6], with the result that little additional solar heating takes place within the chimney and heat losses from the chimney walls are high. These result in little or no temperature difference between the chimney air and ambient air (and thus no density gradient). Bouyancy-induced forces are thus very low resulting in stagnation within the chimney (or even reverse flow). Some dryers have very short chimneys ($< 0.1m$) above the drying chamber [7], resulting in very low pressure head. It has been suggested [2] that the rate of heat losses within the chimney should be considered in determining the optimum height of the chimney so as not to exceed the height at which the chimney air cools to same temperature as ambient. We observe that if the chimney is designed properly as to keep the air temperature within it consistently higher than ambient throughout the height of the chimney, cooling within the chimney would thus not be the critical factor in determining the appropriate chimney height. The design of a solar chimney similar to and operating on same principles as a flat-plate solar air-heating collector has been reported [8, 9], (See figure 1). The solar chimney consisted simply of a well insulated vertical, shallow and high flat-plate air-heating collector. The solar collector-chimney should be orientated appropriately to maximize solar radiation absorption. This design should maintain mean chimney temperatures above ambient temperature.

PERFORMANCE EVALUATION THEORY OF THE SOLAR CHIMNEY

The pressure difference due to the bouyant pressure head is given by [4, 10, 11],

$$\Delta P_b = gH(\rho_a - \bar{\rho}_{ch}) = \beta g H \rho (T_{ch} - T_a) \tag{3}$$

Over the temperature range $25°C - 90°C$ (within which natural-circulation solar-energy dryers would operate), the density of dry air is related to the temperature by the following empirical expression [11],

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

Combining equations 3 and 4

$$\Delta P_b = 0.00308 g H (T_{ch} - T_a) \tag{5}$$

Within the chimney, pressure drops are due mainly to wall friction. Assuming turbulent flow (with a friction coefficient of 0.03) [12], the pressure drop due to friction loss can be given as [13, 14],

$$\Delta P_b = 0.03\bar{\rho}\left(\frac{v^2}{2}\frac{H}{D}\right) \tag{6}$$

$\bar{\rho}$ is the average density of the fluid through the cylindrical duct (corresponding to the mean chimney air density for the case of the solar chimney).

Combining equations 5 and 6,

$$0.03\bar{\rho}\frac{v^2}{2D} = 0.00308 g \Delta T_{ch} \tag{7}$$

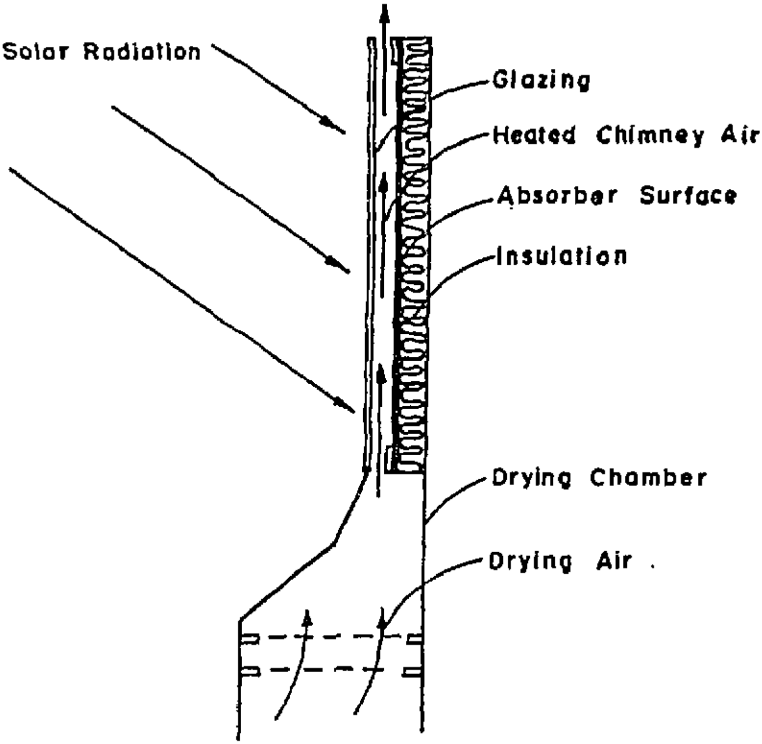

Fig. 1 : Schematic Illustration of an Air-heating Flat-plate Solar-energy Collector Type Chimney

where

$\Delta T_{ch} = T_{ch} - T_a$

Thus,

$$v = 0.453 \left[\frac{Dg}{\bar{\rho}} \Delta T_{ch} \right]^{1/2} \tag{8}$$

We can write

$$v = f(\Delta T_{ch})^{1/2} \tag{9}$$

It should be noted that the above expression is derived without taking into account the additional bouyancy arising from the increased humidity of the air stream. To include this would require assumptions to be made concerning the amount of moisture added to the air stream. Such assumption would reduce the generality of the analysis. The effect of neglecting the moisture gain to the air stream is to give a different value for "f" in equation (9), the functional relationship between v and ΔT_{ch} remains unchanged.

EXPERIMENTAL OBSERVATION

The experimental solar chimney consists of a 5.3m high and 1.64m diameter cylindrical polyethylene-clad vertical chamber, supported structurally by steel framework and draped internally with a selectively-absorbing surface. A schematic illustration of the features of this design is shown in figure 2. The resultant "greenhouse effect" is expected to keep chimney temperatures above ambient temperatures consistently.

Experimental tests were undertaken with and without the selective surface in place to study the effectiveness of the design options. A selective surface was used rather than simply a black-painted surface as the former's radiative properties were known precisely. It is not envisaged that selective surfaces would be employed in practice. The accurate monitoring of the air velocities both within the drying chamber and the chimney in the experimental unit was difficult. However, as can be seen from equation (9), the chimney air temperature elevation above ambient ΔT_{ch}, can be used as an "index" for evaluating the performance of the solar chimney.

RESULTS AND DISCUSSION

A typical diurnal variation of the mean chimney air temperature against the ambient temperature is illustrated in figure 3. It can be observed that the chimney air temperatures were significantly above the ambient. This is representative of the pattern for all the tests undertaken. Typical values of peak chimney air temperatures were between $38°C - 45°C$ compared with peak ambient temperatures of $31°C - 38°C$. Corresponding peak chimney temperature elevations ΔT_{ch} ranged between $6°C - 15°C$ above ambient during fairly high insolation periods. Velocities calculated from these range of ΔT_{ch} values based on equation (8) would give errornously very high values due to the assumption that the solar chimney is independent of the drying chamber, hence the assumption that pressure drops are mainly due to wall friction within the chimney. Moreso, these values of ΔT_{ch} are peak

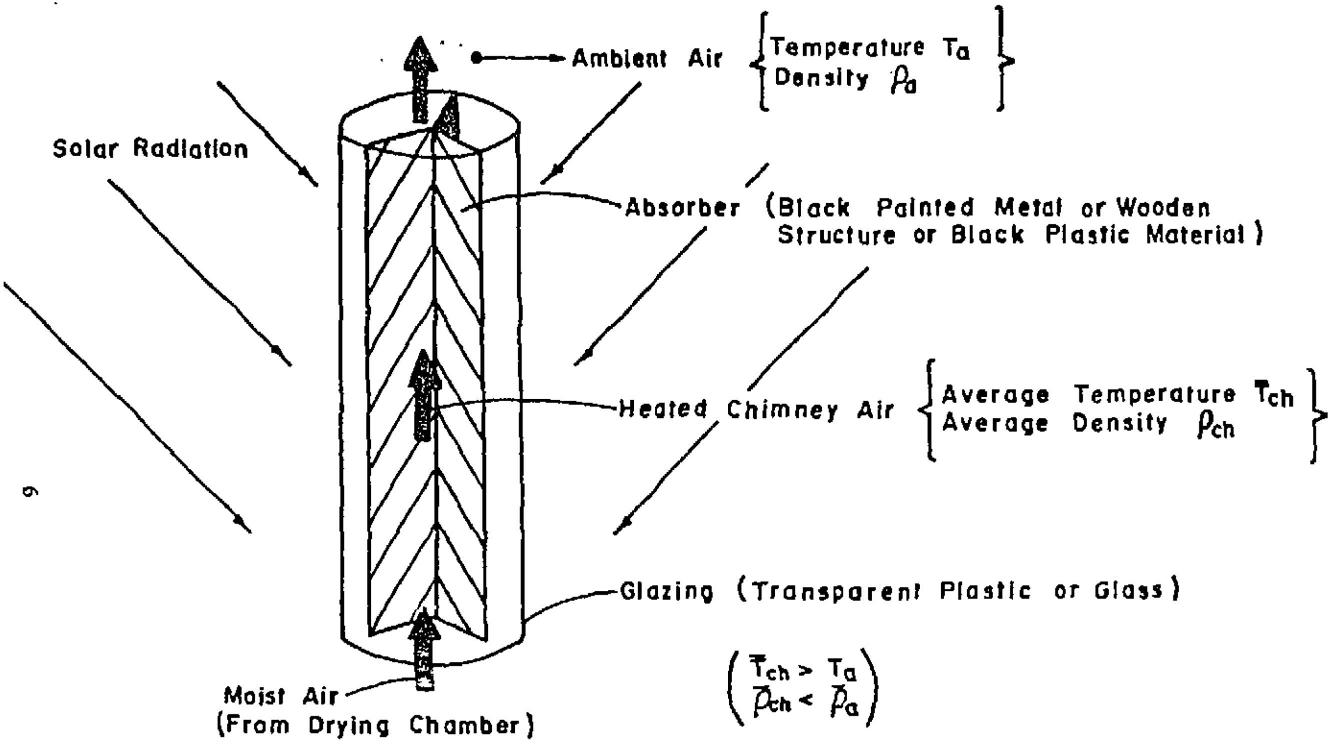

Fig.2 : Schematic Diagram of the Proposed Solar Chimney (Greenhouse Type Solar Chimney)

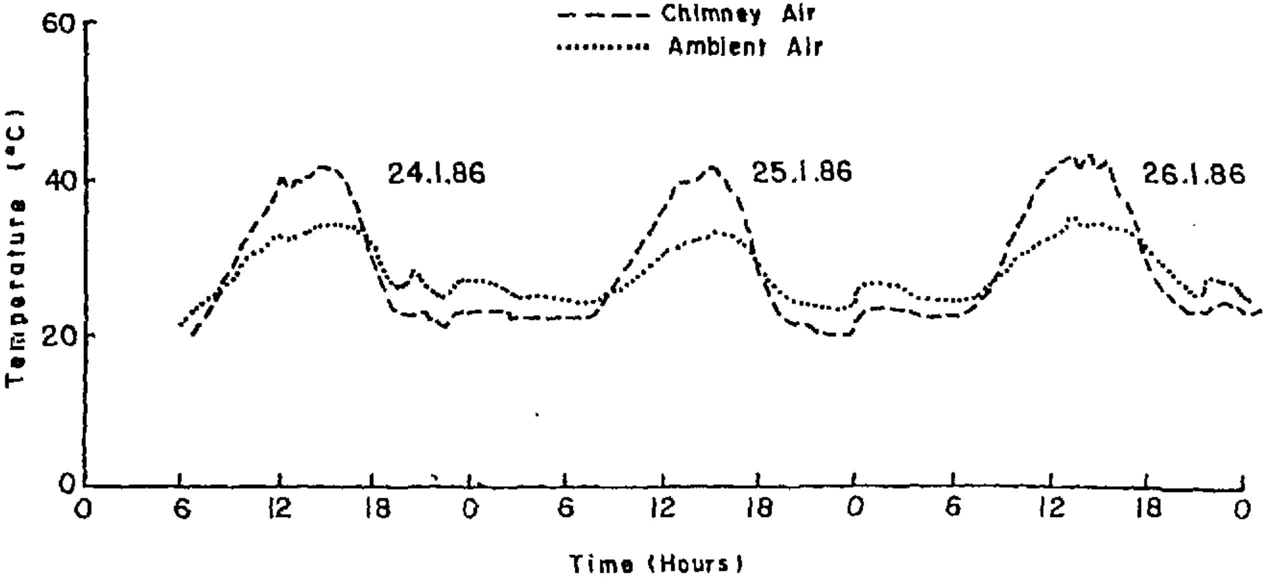

Fig. 3. : Diurnal Variations of Chimney Air and Ambient Air Temperature

values and would result in peak air velocity values if applied on equation (8). In reality, pressure drops associated with crop resistance to air flow, frictional losses on the walls of the chamber and structural members which impede air flow would account for a more reduced air velocity. The result do, however illustrate the desired effectiveness of the solar chimney.

A comparison between instataneous values of the mean chimney temperature elevation-above ambient temperature ΔT_{ch}, recorded for two representative tests, one without the selective surface in place (test 1) and the other with the selective surface in place (test 2) over the insolation period during the tests is shown in figure (4). It can be observed clearly that over the range of insolation encountered, test 2 shows a higher ΔT_{ch} values than test 1. This result illustrates clearly the improved performance of the solar chimney due to the presence of the selective surface. In practice, the use of a selective surface in the chimney would certainly not be justifiable economically, moreso as the material was very brittle and highly susceptible to damage. They were in actuality damaged within few months of installation and replacement from local sources were difficult. The result however illustrates the effectiveness of the principle of the "greenhouse" solar chimney employed in this study and the need for a solar radiation absorbing surface within the chimney. The use of black painted wood or metal poles (which would serve equally as structural support) or black plastic materials are recommended.

The variation of the temperature of the vertically draped selective surface within the chimney with the diffuse component of insolation shows a strong linear correlation (see figure 5) with a correlation coefficient R, of 0.92. The corresponding variation of the selective surface temperature with global insolation (see figure 6) shows that at high values of global insolation ($> 700Wm^{-2}$), the selective surface temperature tends to an assymptotic value. Such high global insolation values are associated with low diffuse ratio (i.e. high direct components of insolation). The results seem to suggest that the chimney receives mainly diffuse radiation. However, it should be noted that high absolute values of the diffuse component of insolation are generally due to high global insolation levels, thus an increase in the selective surface temperature may be due to an overall increase in global radiation. Generally, the results indicate that the solar chimney does collect substantial insolation (either global or mainly diffuse), which would enhance solar heating of the chimney.

The variation of the selective surface temperature along the height of the chimney (figure 7) shows an increase of the selective surface temperature with height. This maintains the temperature of the air column all through the chimney consistently above ambient. As noted earlier, it has been suggested [2] that the rate at which the air within the chimney cools down to ambient temperature should determine the optimum height. This recommendation, however, was for opaque systems constructed from wooden or metal structures where convective, conductive and re-radiative heat losses are comparatively high and negligible solar heating ensues subsequently of the air column within the chimney. For the "greenhouse" solar chimney design, figure 7 implies appreciable heating of the air column all through the entire chimney height, thus cooling along the chimney height would not be a limiting factor in determining the critical height.

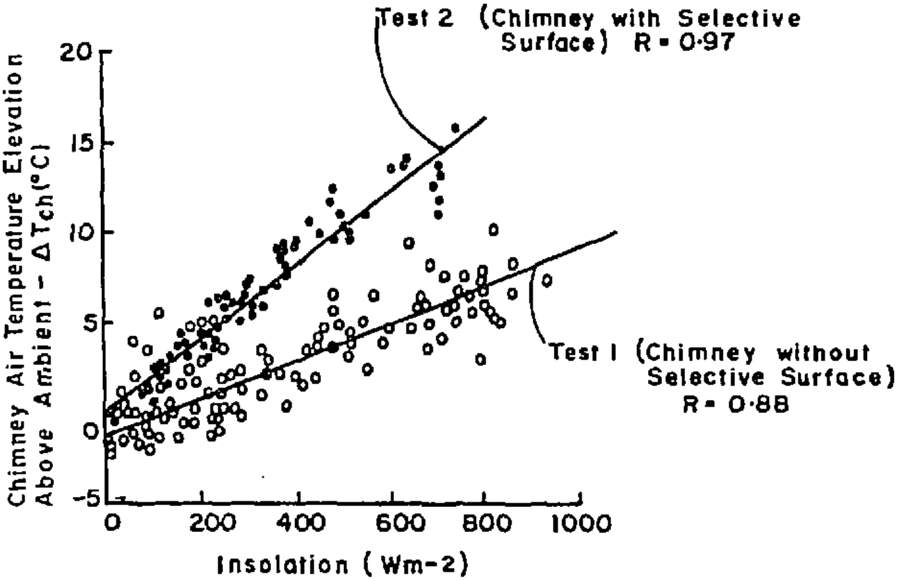

Fig.4: Variation of Chimney Air Temperature Elevation Above Ambient (ΔT_{ch}) with Insolation for Chimney without Selective Surface (Test I) and Chimney with Selective Surface (Test 2) R = Correlation Co-efficient

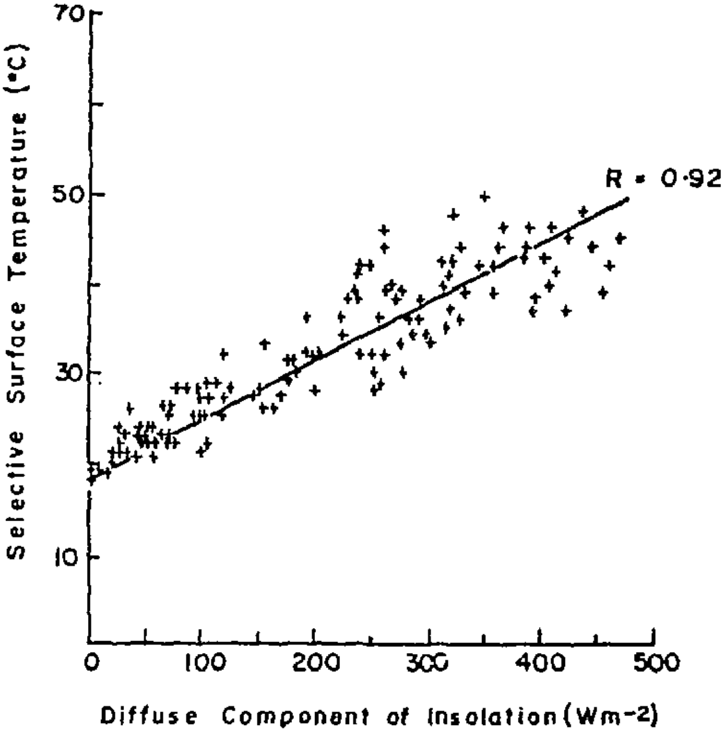

Fig.5: Variation of Chimney Selective Surface Temperature with Diffuse Component of Insolation

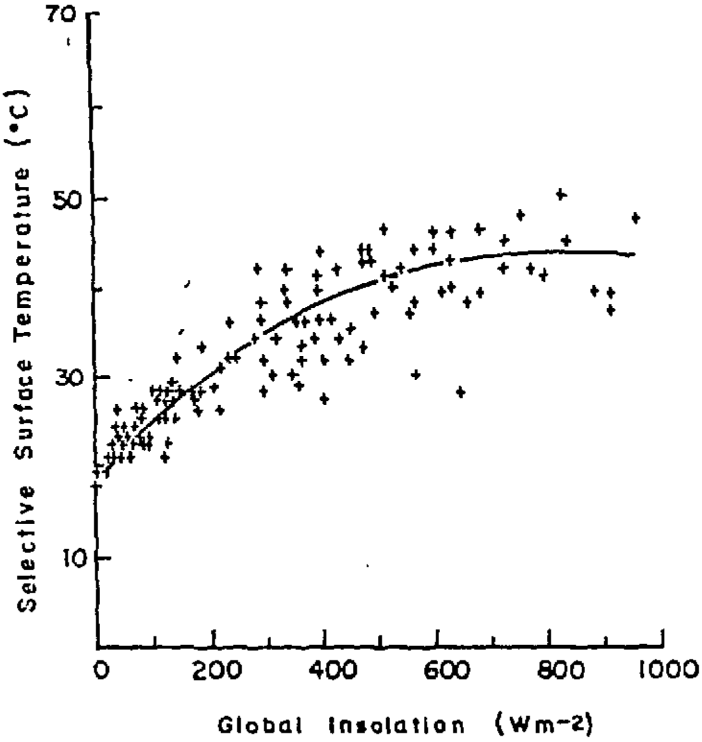

Fig.6: Variation of Chimney Selective Surface Temperature with Global Insolation

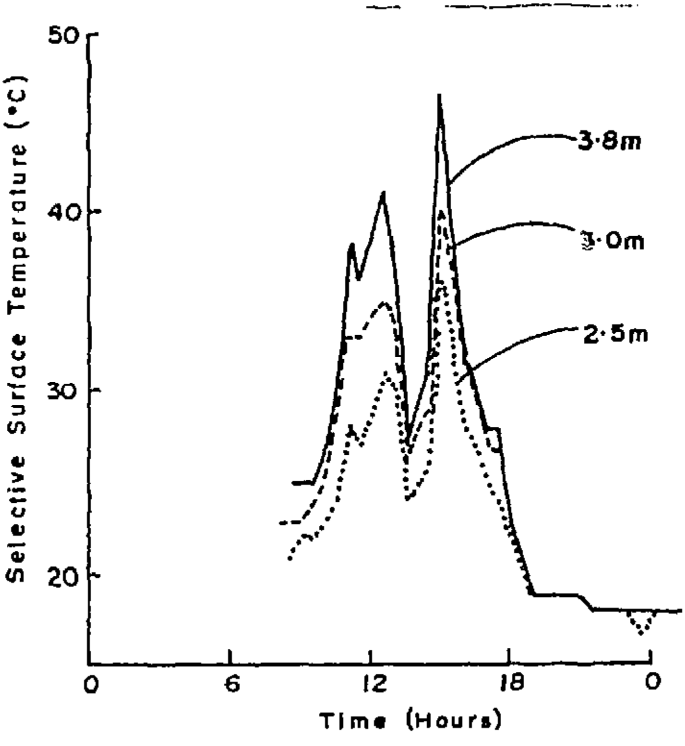

Fig.7: Comparison of Chimney Selective Surface Temperature at Different Heights (Above the Dryer Floor)

The optimum height for a transparent solar chimney would tend to be determined by:

- pressure drops due to friction losses within the chimney and the drying chamber,
- crop resistance to air flow and structures within the chamber and chimney which would impede air flow and
- the desired drying rate for the particular conditions encountered.

CONCLUSION

The results obtained from the experimental solar chimney have illustrated that solar chimneys if designed properly can maintain chimney air temperatures consistently above the ambient temperature which would enhance the desired bouyancy induced air flow through the chimney. The desired performance was achieved with the solar "greenhouse" chimney studied. Better performance was obtained with a solar radiation absorbing surface within the chimney.

NOMENCLATURE

D	Duct diameter (i.e. chimney diameter) (m)
g	Acceleration due to gravity (ms^{-2})
H	Chimney height (m)
h	Humidity ratio
ΔP_b	Pressure drop due to bouyancy (Nm^{-2})
T	Air temperature (K)
T_a	Ambient air temperature (K)
T_{ch}	Mean chimney air temperature (k)
ΔT_{ch}	Mean chimney temperature elevation above ambient temperature (K)
β	Bulk coefficient of expansion of air (K^{-1})
ρ	Air density (kgm^{-3})
$\bar{\rho}$	Mean air density (kgm^{-3})
ρ_a	Ambient air density (kgm^{-3})
ρ_{ch}	Mean chimney air density (kgm^{-3})
ρ_o	Air density at T = 273K (=1.293 kgm^{-3})

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