

## **OPTIMISATION OF SOLAR AIR HEATING COLLECTORS USED FOR CROP DRYING**

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### **ABSTRACT**

This paper describes theoretical analyses applied to the optimum design of two types of solar crop dryers. One uses a flat plate solar collector and the other a multilayered one. The design specification was to reduce moisture content of 90kg of shelled maize from 20% to 13% moisture content, wet basis, in one day. The dryer with a flat plate collector achieved only a third of the target drying rate. The design using a multilayered collector achieved higher temperatures but grain drying duration was not substantially reduced. Using the theoretical analysis and experience with the two experimental dryers, a suitable prototype solar crop dryer was designed and constructed. For simplicity, the eventual design adopted had a flat plate collector.

### **INTRODUCTION**

Traditionally, many cereal crops, vegetables and fruits are dried by thinly spreading them on prepared ground in open sunlight. Generally, there are large losses of product due to dispersal by wind and destruction by rodents, birds and domestic animals. Moreover, the traditional drying method is not easy to control and overheating can occur, making insect penetration easier and hence high storage losses. Rewetting and overdrying in variable weather conditions can also cause some losses and reduction of the quality of the product.

In the case of maize, it has been reported (Moody 1980) that losses increase with time when maize is left in the field after maturing. Losses of up to 22% after two months, increasing to 50% after three months have been reported in the humid tropics. In order to reduce such losses, maize must be harvested as soon as it matures and then dried.

In recent years, attempts have been made to reduce post-harvest losses and also improve the quality of the product by using small scale solar drying devices. For example, a solar air heater can be designed to supply warm air to the product placed in a safely locked cabinet.

This paper describes theoretical analyses of the optimal specification for flat plate and multilayer solar collectors. Two prototype dryers were designed with the expectation of drying 90kg of shelled maize from 20% to 13% moisture content, wet basis, within one day.

The paper outlines the further optimisation of these crop dryers and the final prototype constructed for use by farmers in Kimalewa, Bungoma, and Homa Bay. The choice of prototype design was governed both by performance characteristics and the need to produce a design that is simple for farmers to construct.

### **ANALYSIS OF THE COLLECTORS**

A very large, and hence expensive, collector would be capable of drying a small quantity of grain in a very short time. The aim of optimisation is to reduce this

ratio of collector size to quantity of grain by increasing the efficiency and hence decreasing the necessary size of the collector.

### Flat plate collector

In order to optimise the collector design, it is necessary to understand the processes of heat and mass transfer inside the collector. The analysis of these processes is complicated due to the constantly changing environmental conditions. However, if some simplifying assumptions are made, as discussed by Othieno (1983), heat balance equations can be formulated and solved analytically. These equations for a simple flat plate collector (Figure 1) are given below:

For the transparent cover:

$$h_{go}(T_g - T_o) + h_{ga}(T_g - T_a) + \sigma \epsilon_g (T_g^4 - T_s^4) + \sigma \epsilon_g (T_g^4 - T_p^4) = \tilde{d}_g G \quad (1)$$

Sum of power lost by convection to ambient and air stream	+	sum of power lost by radiation to sky and collector plate	=	solar power gained by the transparent cover
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For air stream through the collector:

$$h_{ga}(T_a - T_g) + h_{pa}(T_a - T_p) = \rho d_a c_p \frac{\Delta T_a}{\Delta X} \quad (2)$$

For the bottom absorber plate:

$$\sigma \epsilon_e (T_p^4 - T_g^4) + h_{pa}(T_p - T_a) + k_e (T_p - T_o) = \rho_g (\theta) \alpha_p G \quad (3)$$

The temperatures of the transparent cover ( $T_g$ ), the air stream ( $T_a$ ) and the black absorber plate ( $T_p$ ) vary in the direction of air flow. Therefore the above equations can only be valid for a small section of the collector of length  $\Delta X$  where the temperatures can be assumed to be uniform.

The solutions of these equations for an optimised flat plate collector are shown in Figure 2. Theoretically the highest air temperatures would be achieved when the collector depth,  $d$ , is close to zero. However, in practice if the collector depth is too small, the air significantly cools down when it reaches the crop bin because of the available large volume for expansion. Furthermore, as the collector depth is reduced, the air flow pattern changes thereby causing a drop of air temperature. This means that there is a minimum collector depth below which overall heat loss increases so fast that efficiency drops. It has been suggested (Macedo and Altamani 1978; Grainger *et al.* 1981; Grainger 1982) that this depth should be about 5 cm.

In this work, it was confirmed that a depth of 5 cm does not allow adequate air flowrate through the grain. Thus the collector depth should be more than 5 cm if a reasonable amount of grain is to be dried within the desired period.

Collector efficiency is low due to the high heat losses caused by high cover and absorber plate temperatures. It was therefore necessary to:

- (i) reduce the heat losses
- (ii) improve heat transfer process to the air stream
- (iii) increase the volume flowrate of air

These requirements led to the development of a multilayer solar collector.

### Multilayer collector

A multilayer collector has two or more air ducts. The air streams can be completely isolated or joined by perforations in the partitioning absorber plates. Many types of multilayer collectors have been studied (Othieno 1983). This paper reports studies, on one design with perforations in the parallel partitioning absorber plates as shown in Figure 3. Due to the additional absorber plates, the multilayer collector must be deeper than the simple flat plate collector. The perforated layer increases the heat transfer area in contact with the air stream and hence improves the heat transfer process. Consequently, the temperatures of the absorbing surface including that of the transparent cover are low compared to those of a simple flat plate collector. This significantly reduced heat losses from the collector as shown in Figure 4. This is a graphical representation of the solutions to the mathematical model developed by Othieno (1983) for an optimised multilayer collector.

Optimising a multilayer collector is more complex. The number of perforated absorber plates, and hence the overall depth of the collector, depends on the energy transmittance of the perforations. This transmittance is referred to here as the void factor,  $F_v$ , to distinguish it from that of the transparent cover. The void factor of the perforations was measured using two similarly calibrated pyranometers. One measured the direct unobstrated solar radiation while the other measured the radiation under the perforated absorber. At normal incidence, this measurement was checked by calculating the ratio of the area of the holes to the total area of the absorber plate.

The optimum gap,  $\delta$ , between adjacent perforated absorbers and the void factor, depend on the effective diameter of each perforation while the optimum number of perforated absorbers depends on the void factor. After several experiments, it was established that the optimum number of perforated absorbers could be estimated using the expression:

$$F_v^n = 0.1 - F_v \quad (4)$$

The best distance between the layers,  $\delta$ , is  $3D$  (5)

Where  $D$  is the effective diameter of a single perforation. Having determined  $n$  and  $\delta$ , the collector depth,  $d$ , can be found from the expression:

$$d = \delta / (n + 1) \quad (6)$$

The width of the collector is determined by the total amount of energy required to dry the grain within the desired drying duration. The collector length, on the

other hand, is determined by the velocity of the air passing through it and the maximum air temperature required for the drying process. This length can be estimated experimentally or obtained from the solutions of the mathematical model.

### GENERAL DESIGN CONSIDERATIONS

In order to design a useful dryer, all the relevant environmental conditions and the drying requirements of the wet product must be known. In this work an optimised dryer was specifically designed to dry maize, but the method can be used to design dryers for any other products. The information needed includes:

- i. environmental data (insolation, wind speed, ambient air temperature, humidity).
- ii. the initial and final moisture contents and the quantity of grain to be dried.
- iii. the required drying time (duration) and any other limitations, for example, the safe maximum drying air temperature for the particular product.

The drying rate of any product is generally limited by the diffusion process of water from inside the material to the surface. At the surface, the drying process is defined by the properties of moist air. The relationships of these properties can be obtained from psychrometric charts for the particular location.

If the drying process was not limited by diffusion processes, the total energy required for drying a given quantity of grain could be estimated by using the basic energy balance equation:

$$m_{wa} \lambda_v = m_a c_a (T_{ai} - T_{ae}) \quad (7)$$

The mass of water,  $m_{wa}$ , can be estimated from the initial and final moisture contents,  $M_i$  and  $M_f$  respectively:

$$m_{wa} = m_w \frac{M_i - M_f}{100 - M_f} \quad (8)$$

The drying duration in days and the width of the collector are related by the expression:

$$t_d = m_w \frac{M_i - M_f}{100 - M_f} \lambda_v (WL \bar{\eta}_c \bar{\eta}_d E) \quad (9)$$

The numerator is the energy required to evaporate a mass of water,  $m_{wa}$  so as to reduce the moisture content of the grain from the initial moisture content,  $M_i$ , to the desired final moisture content,  $M_f$ , wet basis. The denominator represents the energy required per day to evaporate the water. The daily average efficiency,  $\bar{\eta}_d$ , should take into account the required energy to remove water from inside the grain to the surface.

If it were possible to balance this equation, the task of designing a dryer would be very simple and straight forward. But  $\eta_d$  and  $\tau_c$  are not known before the dryer is designed. However,  $\eta_d$  can be calculated from the estimated values of the temperatures of air entering and leaving the grain stack if grain depth, moisture content and drying time are known. Brooker et al (1974) suggested a drying equation which relates all these parameters:

$$\theta = \frac{2^Y}{2^Y + 2^d - 1} \quad (10)$$

Where  $\theta$  is the dimensionless air temperature,  $y$  is the time unit and  $d$  is the grain depth factor. For moisture ration, MR, the relationship is:

$$MR = \frac{2^d}{2^d + 2^Y - 1} \quad (11)$$

The grain depth factor and the actual grain depth,  $d_g$ , are related by the expression:

$$d = \frac{d_g (M_{dl} - M_{d,eg}) d \lambda_{vg}}{36000 m_a c_a t_n (T_{ai} - T_{a,eg})} \quad (12)$$

Where  $t_n$  is the period of half response for the crop at different initial moisture contents and for air temperatures. The equilibrium moisture content,  $M_{d,eg}$  and equilibrium temperature,  $T_{a,eg}$  at various relative humidities can be obtained from data given by Brooker et al (1974) for various cereals.

Since the temperature of air reaching the grain from the collector is known from the collector optimisation process, it is possible to select a suitable temperature for the air leaving the grain so that a suitable grain depth can be calculated from the drying Equation (12). Hence daily average drying efficiency,  $\eta_d$ , can also be calculated. Obviously, knowing the grain depth and the quantity of grain to be dried will make it possible to determine the crop bin area. For convenience, the collector width should be equal to the side of the bin to which the collector is connected.

For a natural convection dryer, it is necessary to know the buoyancy-induced flow and the pressure head created above the atmospheric pressure. The buoyancy-induced pressure which initiates the motion of air through the dryer is:

$$P_{ha1} = (\rho_o - \rho_{ai}) g H_1 \quad (13)$$

As air flows through the dryer, its pressure decreases due to wall friction and bends in the system. For an indirect crop dryer, the largest pressure drop occurs inside the grain stack. The magnitude of this pressure drop can be estimated from the expression:

$$P_{g1} = K (u_g)^2 d_g \quad (14)$$

Where  $K (u_g)$  is the pressure drop per unit depth of grain and is air velocity dependent such that any available pressure head above the surrounding atmospheric pressure will cause air-flow through the grain.

### Chimney height

Airflow through the dryer can be enhanced by the presence of a chimney, carefully designed for the purpose. Chimney design must consider the balance between forces which produce the flow against those which retard the flow. A chimney would be useful if it creates the Bernoulli effect to suck air into the dryer or if the air inside the chimney is warmer than the air outside so that there is an upward pressure drop in the chimney. In the latter situation, the rate at which air in the chimney cools down to ambient temperature determines the maximum height of the chimney. For example, if the air cools down to ambient air temperature within 1m height, then the chimney height should not be more than 1m. For a rectangular chimney, this maximum chimney height can be determined from the expression:

$$Q = U_c S_c H_c \frac{[(T_{ai} - T_{ae}) - T_o]}{2} \quad (15)$$

However, in natural circulation dryers, the air leaving the grain stack is generally moist and almost as cold as ambient air, and so the presence of a chimney may not have any effect ( $T_{ai} \approx T_{ae}$ ). In this case there is no need to have a chimney. This has been experimentally confirmed and therefore the dryers have been built without a chimney (see Figure 1).

### Design checks (steps)

The design of the whole dryer is complex. The procedure recommended here enables the designer to check the scale and likely operation when a specific crop is to be dried. It has been used when designing a number of crop dryers. The following are the steps to be taken:

1. Determine solar radiation at the location, maximum safe temperature for the crop, initial and final moisture content of the crop, and the desired drying duration of a known quantity of crop.
2. Estimate air mass flowrate through the crop stack and the width of the solar air heater and then calculate the required crop depth using Equations 10, 11 and 12.
3. Since the quantity of the crop is known and the crop depth has been determined, the cross-sectional area of the crop bin can now be determined.
4. Determine the average drying efficiency using Equation 10.
5. Obtain collector depth from the model analysis as outlined above, calculate air velocity through the collector and determine the collector length required to heat air to the maximum safe temperature for the crop.

6. Calculate the efficiency and width of the collector. Use Equation 9 to calculate the width. If the calculated width is not numerically close to the estimated width, take the calculated width and repeat the procedure from step 5. If the calculated width is within 80% of the estimated width, take the estimated width and calculate air velocity through the grain.
7. Compare the buoyancy-induced pressure and the pressure drop across the crop stack. If pressure drop across the crop is higher than the buoyancy-induced pressure, take a new smaller value of air velocity through the crop, obtain a new air mass flowrate through the crop and repeat the procedure from step 2. If pressure drop through the grain is much lower than buoyancy-induced pressure, take a new larger value of air velocity through the grain, obtain a new air mass flowrate and repeat the procedure from step 2. If buoyancy-induced pressure is slightly higher than pressure drop through the crop then the obtained dimensions of the dryers are well matched and the dryers can now be constructed.

Two dryers were constructed on the basis of theoretical analyses outlined above. In each case the specification was to dry 90kg of shelled maize from 20% to 13% of wet weight in one day. In practice, the dryer with a flat plate collectors only achieved a third the expected drying rate. The second dryer with a multilayered solar collector achieved higher temperatures but the grain drying duration was not significantly reduced.

The results of theoretical analyses and experiences gained with the two experimental dryers were used to further optimise the designs and to design a suitable prototype solar crop dryer. Prototypes were constructed and installed for use by farmers in Kimalewa, Bungona and Homa Bay.

### **CONSTRUCTION OF THE DRYERS**

The solar collector (air heater), crop bin and two trays were all separate units which could be easily removed for repair or replacement. The solar collectors were made of aluminium sheets painted with several coats of matt-black paint. In one case the collector plate was insulated at the back with a sheet of plywood. In general the back and sides of the collector plate should be insulated with 5 to 10 cm thick good insulating material (eg diatomite). The collectors were then covered with two sheets of transparent ultra-violet resistant polythene, leaving an air gap of about 5 cm between the cover and the collector plate. This size of air gap had been previously found to be the optimum for this type of air heater. For this air gap, the heater should be about 1m long so as to heat air to about 60°C when the insolation is about 1000W m<sup>-2</sup>. According to the Kenya Bureau of Standards, grain dried for human consumption should not be heated above 60°C during drying. However, since the grain temperature is generally lower than the drying air temperature, it is safe to use air temperatures up to about 70°C. Thus the collector length would generally be longer than 1 m but less than 3m.

The air heaters were each coupled to a crop bin which could take up to 90 kg of shelled wet maize. Thus, the crop bin had to have a volume of about 0.15 m<sup>3</sup> with a thin layer (less than 15 cm) of grain to allow unidirectional natural flow of warm air through the grain. Having determined the width of the solar collector that would provide enough energy for the required drying duration, it was simple to make the crop bin width the same as that of the collector. Grain depth of about 10 cm was found to produce a pressure drop of about the same value as the pressure difference created by the hot air in the heater.

Like the air heater, the crop bin should generally be properly insulated to minimise excessive loss of heat from the dryer. The dryers constructed in this work were however not insulated since the construction of insulation chambers would make the dryers too complicated for an unskilled person to construct.

Earlier, during the experimental stage, observations showed that the temperature of air inside the grain stack and the actual temperature of the grain were higher at the bottom of the stack than at the top. Thus the bottom layer of the grain dries much faster than the top layer. For this reason two trays were constructed to facilitate the removal of the bottom layer as soon as maize had dried down to the required moisture content. The top tray would then be moved to the bottom position with fresh wet maize placed at the top. This arrangement has made it possible to dry more maize per day than was originally considered in the design.

The air heater, facing South at Kimalewa and Bungoma and North at Homa Bay was inclined at an angle of about  $20^{\circ}$  to the horizontal. These collector orientations had been determined as the best for the latitudes and time of the year.

The sun's rays pass through the transparent cover and are absorbed by the black plate which becomes hot and heats the air above it. Since the air heater is inclined to the horizontal, the hot air, being less dense than the surrounding air, rises along the air heater and so air flow through the system is established. The temperature of the air leaving the collector depends on the length of the collector; the longer the collector the hotter will be the air at the collector exit. However, the air temperature is not a linear function of length since the heat losses increase as the temperature increases.

### **COST OF THE DRYER**

Apart from the transparent collector cover and the support legs, all other exposed parts of the dryer were made out of expensive metal sheets (eg galvanised iron sheets). This was intentionally done to ensure the long life of the dryers. The dryers are therefore expensive at approximately shs. 3000 (K£ 150).

An example of energy calculations showed that the energy required to dry 90kg of maize from 20% to 12.5% moisture content wet basis is about 24 MJ. This is equivalent to 0.52 kg of liquid oil (Calorific value = 10,400 calories per gram). Thus with a burning efficiency of 50% and drying efficiency of about 80%, about 1.3 kg of oil fuel would be required and this would cost in 1985 in Kenya £0.75 sterling. The cost of the dryer can therefore be recovered from oil savings in about 2 to 3 years if the dryer is used for at least 6 months each year (90 kg of maize dried every 3 days). With minor repairs, the dryer would normally last at least 6 years. This is a realistic economic advantage which indicates that this type of dryer will have a vital role to play in the rural development of farming techniques.

### **CONCLUSION**

One of the aims of this work was to simplify the design of an efficient solar crop dryer so that unskilled farmers can construct efficient dryers. But, dryer design remains a complex task which can only be accomplished by technically qualified people. It is therefore necessary to train the farmers to design and construct dryers while a simpler design approach is being sought.

The acceptance analysis of the crop dryers which have been built is still in progress. However, it is hoped that the farmers will accept them on the basis of the following advantages:

1. reduced crop losses.
2. safety from insects, rodents, domestic animals and theft.
3. controllable drying.
4. high quality product especially when climatic conditions make traditional drying method difficult to achieve without severe losses.
5. reduced amount of labour compared with traditional drying systems.
6. reduced land area than normally required for traditional sun drying.

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### **NOMENCLATURE**

- Cp = specific heat of air at constant pressure ( $J K_g^{-1} K^{-1}$ )
- G = solar radiation ( $W m^{-2}$ )
- H = vertical height (m)

$h$	=	corrective heat transfer coefficient ( $W m^{-2} K^{-1}$ )
$K$	=	thermal conductivity ( $W m^{-2} K^{-1}$ )
$m$	=	mass (kg)
$\dot{m}$	=	mass flowrate ( $kg s^{-1}$ )
$M$	=	per cent moisture content wet basis
$n$	=	number of perforated absorbing layers
$p$	=	pressure ( $N m^{-2}$ )
$Q$	=	heat flux ( $W m^{-2}$ )
$T$	=	temperature (K)
$U$	=	heat loss coefficient ( $W m^{-2} K^{-1}$ )
$u$	=	velocity ( $m s^{-1}$ )
$x$	=	distance along the collector (m)
$\alpha$	=	absorptivity of a surface
$\epsilon$	=	emmissivity of a surface
$\delta$	=	Stefan - Boltzmann constant = $5.67 \times 10^{-8} Wm^{-2} K^{-4}$
$\tau$	=	transmissivity of a material
$\theta$	=	angle of incidence (deg.)
$\rho$	=	density ( $kg m^{-3}$ )
$\eta$	=	efficiency
$S$	=	area per unit length

Subscripts:

$a$	=	air
$c$	=	collector/chimney
$d$	=	drying
$e$	=	exit/effective
$f$	=	final
$g$	=	transparent cover/grain

i	=	initial/inlet
l	=	layer
o	=	ambient
p	=	plate
s	=	sky/surrounding
w	=	wet grain
wa	=	water

FIGURE 1: Solar crop dryer

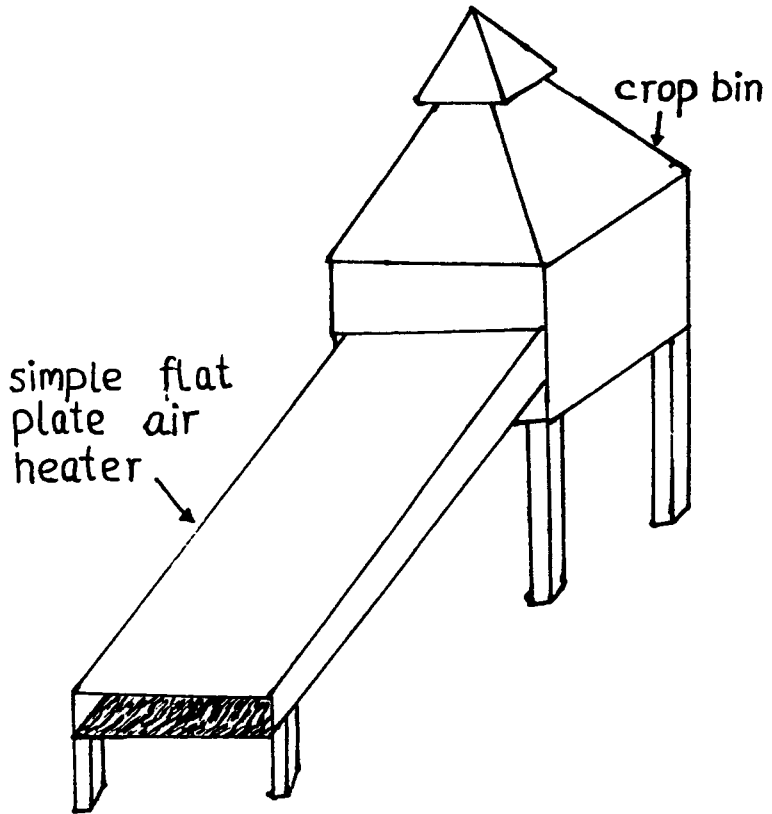
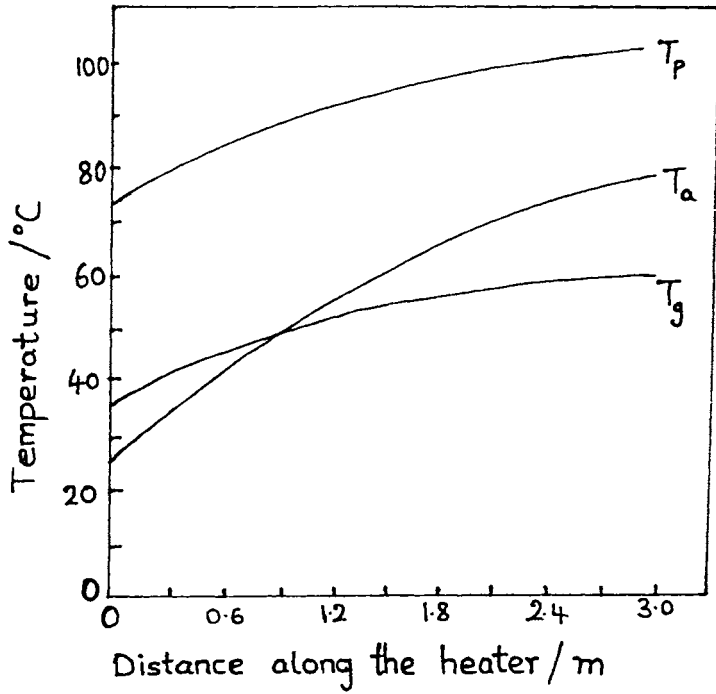


FIGURE 2: Model solution for a flat plate collector



**FIGURE 3: Multilayer solar air heater with perforated absorbing layers**

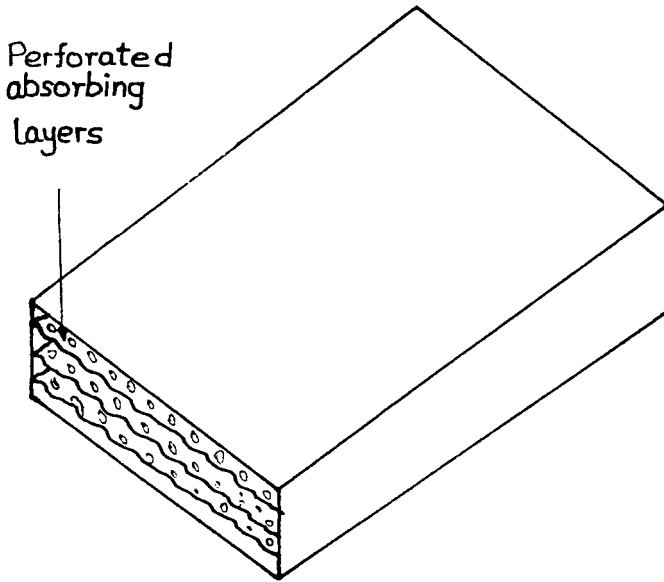


FIGURE 4: Model solution for multilayer solar air heater with two perforated absorbing layers

