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THERMAL TEST PROCEDURE FOR BOX-TYPE SOLAR COOKERS†

S. C. MULLICK,‡ T. C. KANDPAL and A. K. SAXENA
Centre for Energy Studies, Indian Institute of Technology: Delhi, New Delhi 110016, India

Abstract—Some guidelines are provided for thermal evaluation of box-type solar cookers. Suitable thermal tests have been proposed and appropriate parameters identified, which pertain to the solar cooker and are relatively independent of the climatic variables as well as the products cooked. These parameters have been combined into two figures of merit.

1. INTRODUCTION

Box-type solar cookers are suitable mainly for the boiling type of cooking. The cooking temperature in this case is close to 100°C. A large fraction of the mass of most food products is due to water, and more water may be added in the boiling type of cooking. As a result, sensible heating up to the cooking temperature requires almost 4.2 kJ/kg °C[1].

Löf[1] has described the principles of cooking. He has pointed out that the quantities of heat required for physical and chemical changes involved in cooking are small compared to the sensible heat of increasing food temperature and energy required for meeting heat losses that normally occur in cooking. Thus, once the contents of the vessel have been sensibly heated up to the cooking temperature (100°C), the speed of cooking is practically independent of heat rate as long as thermal losses are supplied. Differences in the time required to cook equal quantities of food in cookers of various heat supply capabilities are due mainly to different sensible heating up periods.

The complete thermal analysis of the cooker is complex due to the 3-dimensional transient heat transfers involved. However, the standardization procedure should be reasonably simple in order to make implementation easy. The procedures followed at present consist of determination of either (1) cooking times of different food products, or of (2) the time required for sensible heating of a known quantity of water up to the boiling point. The second method is a better approach since it does not involve uncertainties due to variations in the quality of ingredients used and the judgement of the observer as to when exactly the food is completely cooked. However, the time for sensible heating depends on the climatic variables—solar radiation and ambient temperature. To permit evaluation of solar cookers and comparisons between cookers we require cooker parameters that are more or less independent of the climatic variables. Such parameters have been identified in the present work and a procedure for obtaining these is outlined.

The first test proposed is a stagnation test without load and an important parameter (the first figure of merit—the ratio of optical efficiency to heat loss factor) is obtained. The second test involves sensible heating of a full load of water in containers and from this is obtained the second figure of merit, which is more or less independent of the climatic variables, and which takes into account the heat exchange efficiency factor (F'). Proof of concept experiments have been carried out on a box-type cooker with double glazing (Fig. 1).

2. PRELIMINARY CONSIDERATIONS

In case of flat plate collectors, to find the heat loss factor U_L experimentally water is circulated through the tubes at different temperatures and observations are recorded in steady state. In a solar cooker, there is no control over the temperature and the operation is transient. A quasi-steady state is achieved when the stagnation temperature is attained. The energy balance for the horizontally placed empty solar cooker at stagnation is

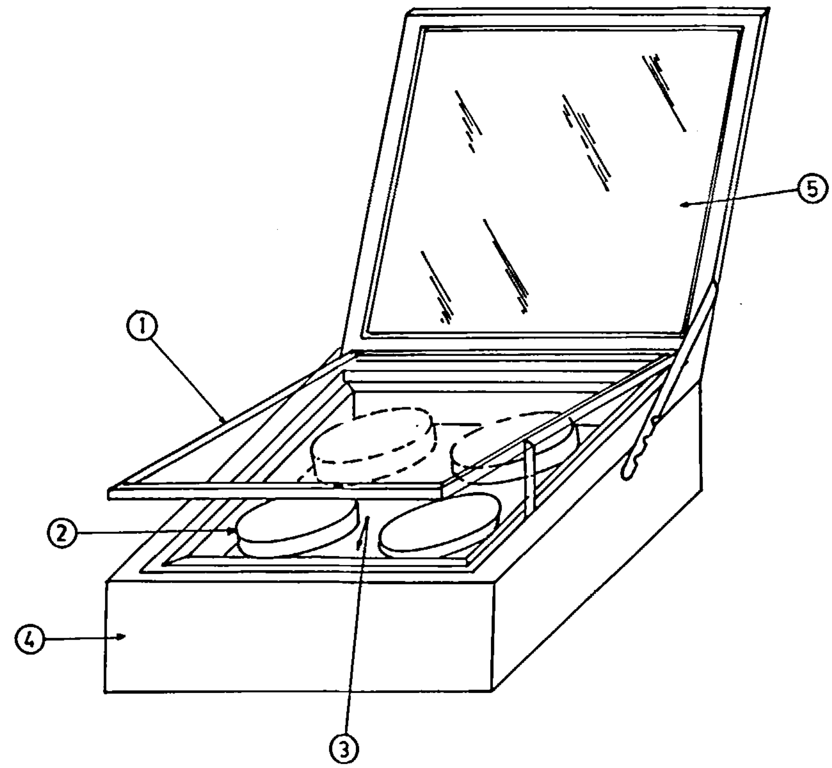
$$\eta_0 H_s = U_L(T_{ps} - T_{as}), \qquad (1)$$

where η_0 is the optical efficiency, T_{ps} is the plate stagnation temperature, H_s and T_{as} are, respectively, the insolation on a horizontal surface and the ambient temperature at the time stagnation temperature is reached.

A high optical efficiency and a low heat loss factor are desirable. The ratio of optical efficiency to heat loss factor can serve as one figure of merit for thermal performance. (The cooling curve has not been used. See Appendix I.) The first figure of merit, F_1, is defined as

$$F_1 = \frac{T_{ps} - T_{as}}{H_s} \qquad (2)$$

† Preliminary concepts of this work were presented at the National Solar Energy Convention (1984) of Indian Section of ISES.
‡ Member, ISES.



1. Double glass lid, aperture 58·9 x 58·5 cm
2. Aluminium cooking pots (17·5cm dia, 6·9 cm deep), each containing 250 ml water during full load test
3. Inner tray formed out of aluminium sheet ('the plate'), 50 x 50 cm at bottom, 15 cm deep
4. Outer box of teakwood (69 x 69 x 28cm) with glasswool insulation
5. Booster mirror, 59 x 59 cm

Fig. 1. The box-type solar cooker.

and can be obtained from the simple stagnation test without load. An approximation made in the above analysis is that the heat loss factor is assumed constant.

A lower permissible limit of the value of F_1 may be specified to ensure a minimum level of thermal performance. For example, if it is stipulated that F_1 should equal or exceed 0.12, in a region where solar radiation and ambient temperature are H_s = 800 W/m^2 and T_{as} = 15°C, respectively, we would have

$$\frac{T_{ps} - T_{as}}{H_s} \geq 0.12$$

or

$$T_{ps} \geq 111°\text{C}.$$

That is, the plate temperature would equal or exceed 111°C. By specifying a suitable minimum value of F_1 (probably between 0.12 and 0.16), depending on the climate of the country, it may be ensured that the stagnation temperature is sufficiently high so that the boiling type of cooking is possible.

The second test proposed consists of heating water sensibly in containers up to 100°C. As explained earlier maximum energy is required during the preheating period. This period should be as small as possible so that cooking time is minimized. The second figure of merit is therefore obtained from this sensible heating test. The proposed figure of merit is based on the following analysis.

Analyzing over an infinitesimal time interval during the sensible heating of water, the time taken,

$d\tau$, for a water temperature rise dT_w is

$$d\tau = \frac{(MC)'_w \, dT_w}{\mathring{Q}_u} = \frac{(MC)'_w \, dT_w}{AF'[\eta_0 H - U_L(T_w - T_a)]}, \quad (3)$$

where $\mathring{Q}_u$ is the rate of useful heat gain by water, A is the aperture area, H the insolation on a horizontal surface, and F' is the heat exchange efficiency factor. $(MC)_w$ is the product of mass of water taken and its specific heat capacity. $(MC)'_w$ includes also the heat capacity of the utensils and a certain portion of the cooker interiors.

Replacing the ratio η_0/U_L by the factor F_1, eqn (3) can be written as

$$d\tau = \frac{(MC)'_w \, dT_w}{AF'\eta_0\left[H - \frac{1}{F_1}(T_w - T_a)\right]}. \quad (4)$$

Assuming that insolation H and ambient or surrounding air temperature T_a are constant (as would strictly be the case if experiments were performed with the help of a solar simulator in an air-conditioned laboratory), eqn (4) can be integrated over the time interval τ, during which water temperature rises from T_{w1} to T_{w2}:

$$\tau = \frac{-F_1(MC)'_w}{AF'\eta_0} \ln\left[\frac{H - \frac{1}{F_1}(T_{w2} - T_a)}{H - \frac{1}{F_1}(T_{w1} - T_a)}\right]. \quad (5)$$

As seen from eqn (5), the value of τ is a function of the climatic conditions—solar radiation and ambient temperature—during the time of test and it does not have a unique value for the cooker under test. It would be preferable to obtain the value of the cooker parameter $F'\eta_0$. Rewriting eqn (5),

$$F'\eta_0 = \frac{F_1(MC)'_w}{A\tau} \ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)}\right]. \quad (6)$$

However, $F'\eta_0$ cannot be computed since $(MC)'_w$ is not known. An approximate calculation shows that the heat capacity of utensils is small compared to that of their contents. The heat capacity of the cooker interiors to be considered is difficult to specify. The problem is circumvented by introducing an additional parameter for the cooker—the heat capacity ratio, $C_R = (MC)_w/(MC)'_w$. Equation (6) can now be rewritten as

$$F'\eta_0 C_R = \frac{F_1(MC)_w}{A\tau} \ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)}\right] = F_2. \quad (7)$$

The cooker parameter $F'\eta_0 C_R$ can be calculated from eqn (7) since $(MC)_w$, the heat capacity of water in the containers, is known. This parameter serves as the second figure of merit, F_2.

Suitable vessels should be supplied by the manufacturer along with the cooker, and are to be considered a part of the cooker being tested, since the thermal conductivity of the vessel material as well as the wall thickness influence heat transfer to the contents of the vessel. Moreover, tests should be carried out with a "full load" as specified (or claimed) by the manufacturer, so that the heat capacity ratio C_R has a more or less unique value. The factor F_2 as calculated from eqn (7) can be expected to pertain to the cooker. It is seen from eqn (7) that the important factor "τ" (the measured time for sensible heating of water between two known temperatures) has not been ignored. It has been normalized suitably with respect to the climatic variables so that the factors finally reported are relatively independent of the climatic variables.

An alternate computational procedure for F_2: It may be noted that solar radiation and ambient air temperature have been assumed constant to fecilitate integration of eqn (4). Outdoor tests would be performed as close to the solar noon as possible. (In case of flat plate collector testing, ASHRAE[2] recommends testing within ± 2 hours from solar noon. One of the authors[3] has limited the time for optical efficiency tests of concentrating collectors to within ± 1 hour from solar noon.) However, there would be some variation in insolation and ambient temperature, so that exact integration of eqn (4) is not possible. Average values of insolation and ambient temperature may be employed. When insolation varies excessively and/or when higher accuracy is desired, integration may be carried out by summation of finite differences. The following scheme may be followed: Summing up eqn (4) over small, equal temperature intervals (ΔT_w) we have

$$\sum \Delta\tau = \frac{(MC)_w \, \Delta T_w}{AF'\eta_0 C_R} \sum_{T_{w1}}^{T_{w2}} \left[\frac{1}{\overline{H} - \frac{1}{F_1}(\overline{T}_w - T_a)}\right], \quad (8)$$

where $\overline{T}_w$ is the average water temperature over an interval. Insolation may be assumed constant and equal to the average value ($\overline{H}$) over the time interval. Rewriting eqn (8):

$$F_2 = C_R F' \eta_0$$

$$= \frac{(MC)_w}{A\tau} \Delta T_w \sum_{T_{w1}}^{T_{w2}} \left[\frac{1}{\bar{H} - \frac{1}{F_1}(\bar{T}_w - T_a)} \right]. \quad (9)$$

The temperature interval ΔT_w can be gradually reduced until the computed values of F_2 attain the desired degree of convergence.

3. PROPOSED TESTING AND EVALUATION PROCEDURES

3.1 *The first figure of merit, F_1 (from the no load test)*

The first figure of merit is obtained by keeping the solar cooker without vessels in the sunshine in the morning on a clear day. The cooker plate temperature, the ambient temperature and the total insolation on a horizontal surface are recorded at regular intervals of time. The observations are continued after solar noon. The stagnation temperature is ascertained from these observations (Fig. 2) and the first figure of merit is found from eqn (2).

The above test can also be performed indoors with the help of a solar simulator. However, outdoor test may be preferred. One of the reasons for this preference is that the optical efficiency is best determined in natural sunlight.

3.2 *The second figure of merit (from the full load test)*

The first figure of merit ensures that the glass covers have a good optical transmission and the cooker has a low overall heat loss factor. However, for good performance it is equally important that there is a good heat transfer to the contents of the vessel and the heat capacity of cooker interiors is small. This implies that the system to be considered should consist of the cooker and the vessels together and tested with a "full load". The heat exchange efficiency factor F', which indicates the effectiveness of the heat transfer from the plate or the vessel top to the contents of the vessel (water in the present case), cannot be measured by tests similar to those for a flat plate collector since there is no arrangement for liquid flow or for obtaining a steady-state withdrawal of energy from the cooker. Therefore, a novel factor is proposed for this purpose.

The tests for the second figure of merit consist of operating the solar cooker with a full load of vessels with contents (equivalent amounts of distilled water in the present case). The cooker is kept in the sunshine in the forenoon (or under a solar simulator) and the water temperature is allowed to rise gradually until it reaches the boiling point, soon after the solar noon. Such a plot of temperature is shown in Fig. 3. The value of F_2 can be evaluated from this plot using eqn (7) by specifying the water temperature limits, T_{w1} and T_{w2}.

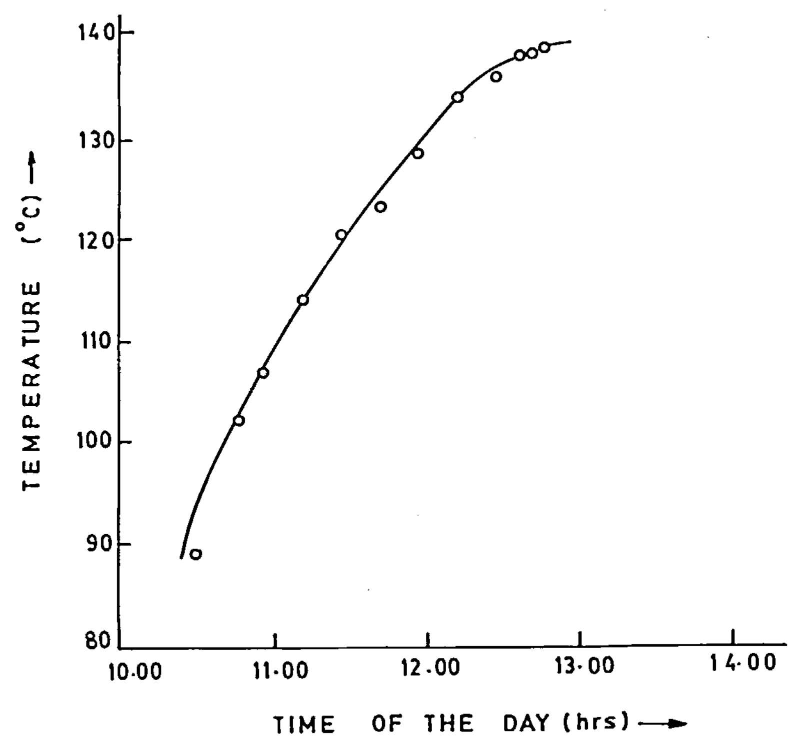


Fig. 2. Variation of plate temperature with time of the day (cooker without load).

The upper limit of the water temperature, T_{w2}, for the time period analyzed could have been taken as 100°C, the boiling temperature. However, this has a drawback. Since the rate of variation of water temperature approaches zero as the water temperature approaches 100°C, there is a great uncertainty in deciding the termination point of the time interval τ (see Fig. 3). Therefore, the upper limit of sensible heating (T_{w2}) should be fixed in the temperature range 90°–95°C, and this value should be used consistently.

The selection of the initial temperature of water for the sensible heating period, T_{w1}, can be made in two alternative ways. One alternative is to take T_{w1} equal to T_a, the ambient temperature. This would simplify eqn (7) to

$$F'\eta_0 C_R = \frac{-F_1(MC)_w}{A\tau} \times \ln\left[1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)\right]. \quad (10)$$

However, this procedure may not be the preferred one since the value of the heat loss factor in F_1 is that measured at stagnation. The second alternative is to take T_{w1} at some value (say, midway) between the ambient and the boiling point. In this case the

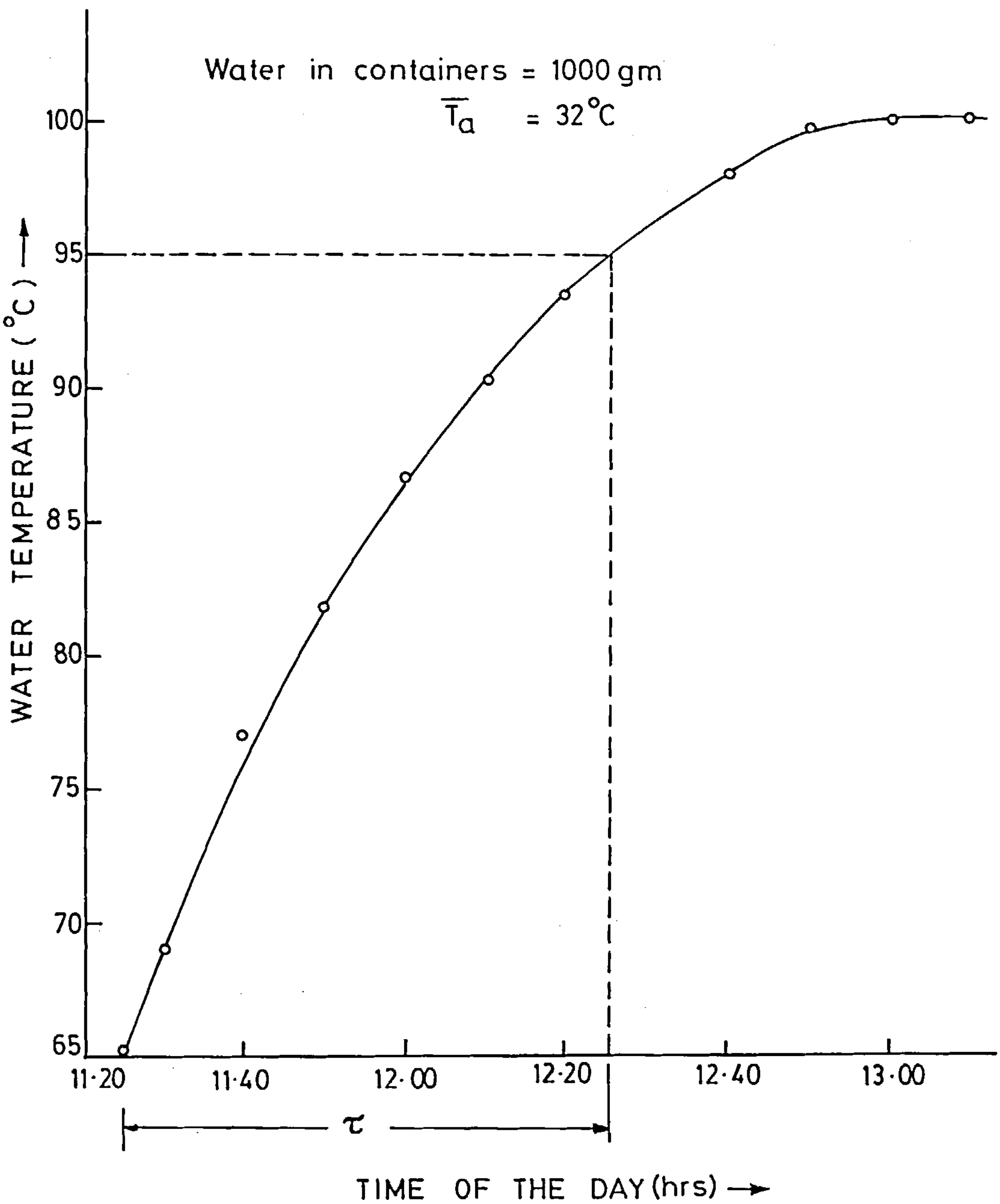


Fig. 3. Variation of temperature of water in the vessels with time of the day (with load).

range of temperature for analysis is reduced and the assumption of a constant heat loss factor is a closer approximation to the actual situation. This alternative has therefore been used in the present work.

To ensure consistency the magnitudes of T_{w1} and T_{w2} should be fixed by the standardizing agency. The central portion of eqn (7) provides a value which is close to $F'\eta_0 C_R$. This value can be expected to permit comparative evaluation with much greater consistency than "the time required for boiling water".

The second figure of merit checks whether F' is high, i.e. whether there is a good heat transfer to the contents in the vessel, and whether C_R is high, i.e. effective heat capacity of cooker interiors and vessels is small.

3.3 *Empirical time constant for sensible heating period*

In addition to finding the cooker's figures of merit, F_1 and F_2, a time constant (τ_0) can also be found from the following equation obtained from eqn (7):

$$\tau_0 = \frac{F_1 (MC)_w}{F_2 A} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_{a0}}{H_0}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_{a0}}{H_0}\right)} \right] \frac{1}{3600}, \tag{11}$$

where T_{a0} and H_0 are some arbitrary standard climatic conditions. The time constant obtained from eqn (11) has the units of time (in hours) and is a measure of the sensible heating time or preheating time for the cooker with full load under some standard conditions. This factor is necessarily empirical since preheating time varies according to the climate. Its importance is that it provides a combined single measure to the lay user of solar cookers who may otherwise find it difficult to compare cookers with different sets of values of F_1 and F_2. For example, if T_{a0} = 15°C and H_0 = 650 W/m², and for sensible heating from $T_{w1} = T_{a0}$ to T_{w2} = 100°C, we have

$$\tau_0 = \frac{-F_1 (MC)_w}{F_2 A} \ln \left[1 - \frac{0.654}{F_1} \right] \frac{1}{3600}.$$

It may be noted that the standard climatic conditions for this purpose should be specified very carefully by the national standardizing agency since the sensible heating time is very sensitive to climatic conditions.

4. EXPERIMENTAL RESULTS

Experiments have been carried out on a box-type cooker (Fig. 1) of double-walled construction with the outer wall made of teak wood and the inner wall of a thin aluminium sheet with glass wool insulation in between. It has a window of about a 60 cm × 60 cm aperture with double glazing at the top. The cooker can be adjusted towards the sun with the help of castor wheels provided under the cooker box. Calibrated copper-constantan thermocouples with a potentiometer have been used for temperature measurements. A horizontal Kipp and Zonen pyranometer has been employed for recording insolation.

(i) *No load test:* Observations of a no load test carried out in summer leading to stagnation are shown in Fig. 2. The first figure of merit,

$$F_1 = \frac{T_{ps} - T_{as}}{H_s} = \frac{139 - 32}{918} = 0.12.$$

Values of F_1 measured in summer and winter indicate an agreement of better than 5%.

(ii) *Full load test:* The observations of a full load test are shown in Fig. 3. Analyzing over the temperature interval from T_{w1} = 65°C to T_{w2} = 95°C, the time interval of sensible heating τ is 3660 seconds. Mass of distilled water in the four containers is 1.000 kg. With ambient temperature of 32°C and average insolation on horizontal surface 805 W/m², the value of the second figure of merit obtained from eqn (7) is F_2 = 0.254.

Calculations were also carried out using eqn (9), with temperature intervals of 6°C, and repeated for intervals of 3°C and 2°C to check convergence. It was found that intervals of 6 degrees are sufficiently small for the present calculation. However, to be on the conservative side, intervals of 2 degrees were employed in the present work.

Four complete sets of observations were recorded on four days, one in each season. Calculations were made using both the integral form, eqn (7), and the summation of finite differences, eqn (9), in order to estimate the error caused by assuming insolation constant and equal to the average value during the entire time period considered for integration. There was an excellent agreement (closer than 1%) between the two methods on each one of these days, in spite of insolation fluctuations of as much as 50 to 100 W/m² (peak to valley) due to slight haziness on two of the days. Hence, results computed by eqn (7) should be acceptable for most purposes. The error due to this mathematical approximation is expected to be less than the error that would result from the use of different pyranometers for measurement of insolation.

5. COOKER PERFORMANCE CHARACTERISTICS

It is also of interest to predict, at least approximately, the sensible heating period of the cooker under any given climatic conditions (H and T_a) knowing its figures of merit (F_1 and F_2). Rewriting

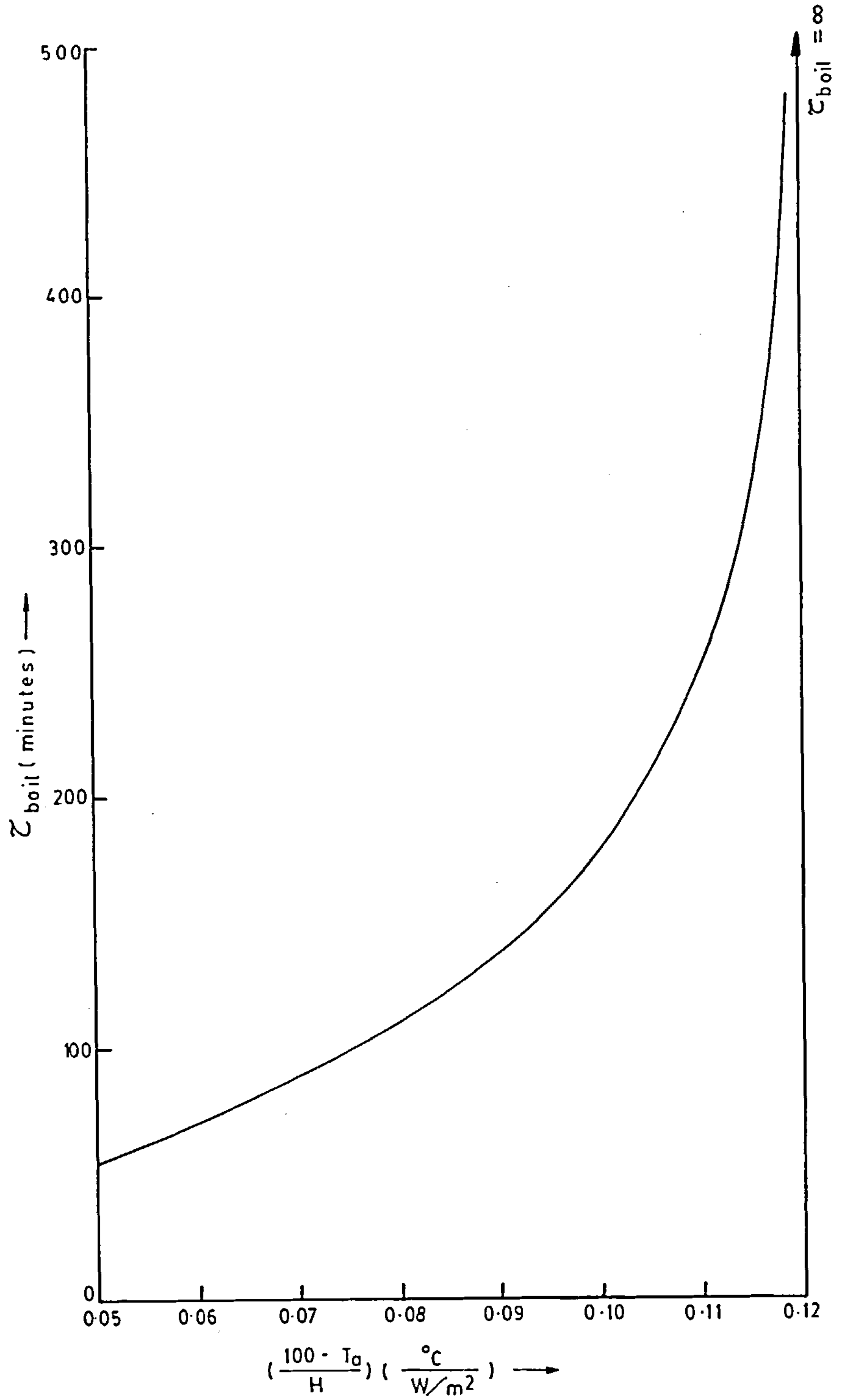


Fig. 4. Characteristic curve of a solar cooker.

eqn (7),

$$\tau = \frac{-F_1}{F_2}\frac{(MC)_w}{A}\ln\left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w2} - T_a}{H}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w1} - T_a}{H}\right)}\right]. \tag{12}$$

The time for sensible heating from ambient temperature up to 100°C, τ_{boil}, is therefore

$$\tau_{boil} = \frac{-F_1}{F_2}\frac{(MC)_w}{A} \times \ln\left[1 - \frac{1}{F_1}\left(\frac{100 - T_a}{H}\right)\right]. \tag{13}$$

This time is a function of $(100 - T_a)/H$ and thus the plot of τ_{boil} versus $(100 - T_a)/H$ could be referred to as the characteristic curve of the cooker. Such a curve for the cooker tested is shown in Fig. 4.

6. DISCUSSIONS

(i) The assumption of constant solar radiation and ambient air temperature does not seem to constrain the use of eqn (7) for calculation of factor F_2 from outdoor full load tests, as indicated by experiments. Average values of solar radiation and ambient temperature suffice for most purposes. Computations using finite differences may be employed when insolation varies excessively and/or when higher accuracy is desired.

(ii) It would be better to evaluate the booster mirror size and quality independent of the cooker box since the booster is exterior to the box and the manufacturers generally do not provide any mirror tilting schedules. One possible standardization procedure is given in Appendix II.

7. CONCLUSIONS

A procedure for testing the box-type solar cookers and obtaining two figures of merit for their evaluation has been described.

(i) The first figure of merit, F_1, is found from eqn (2) and the second figure of merit, F_2, from eqn (7) in a consistent manner. These figures are relatively independent of the climatic variables and pertain to the cooker. A high value of F_1 indicates good optical efficiency and low heat loss factor. A high value of F_2 indicates good heat exchange efficiency factor F', good optical efficiency η_0, and low heat capacity of the cooker interiors and vessels compared to a full load of water.

(ii) The plot of τ_{boil} versus $(100 - T_a)/H$ can serve as the characteristic curve of the cooker. It is noted that the boiling time is a very strong function of the climatic variables (Fig. 4).

(iii) A time factor τ_0 can be evaluated from eqn (11) and it is a measure in standard heating hours of the combined effect of the two figures of merit, F_1 and F_2, in a given standard climate.

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APPENDIX I

Some heat transfer studies on the box-type solar cooker have been reported in [4]. General experimental work has included plotting of the cooling curve—cutting off insolation by shading the cooker. The time constant obtained from the cooling curve represents the ratio of heat capacity of the cooker interiors to the heat loss factor. One of the problems with the use of this time constant for evaluation of the solar cooker is that it is desired that the heat capacity of cooker interiors should be small (to reduce the time for sensible heating) and the heat loss factor should also be small. Therefore the ratio of these quantities does not serve as a figure of merit.

APPENDIX II

Owing to the lower values of solar radiation on a horizontal surface in winter, especially at places of higher latitudes, the required plate temperature or stagnation temperature may not be achieved unless suitable measures such as employment of a booster mirror are taken. In Delhi (latitude $\simeq 29°$), the radiation on a horizontal surface in peak winter is reduced by a factor of approximately cosine 45° during bright sunshine hours. From simple geometrical optics it can be concluded that a booster mirror of at least the same size as the aperture of the cooker (A) and solar reflectance greater than 0.5 must be provided to make up the lower horizontal insolation resulting from the lower cosine factor. Smaller mirror length may be used if its reflectance is higher. In fact, the product of the mirror area and its reflectance should be maintained above a value of $A/2$. An appropriate size of the booster mirror may have to be insisted upon depending on the latitude of the place where the cooker is to be used. This will have to be specified in the detailed standards.