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WIND INDUCED HEAT LOSS COEFFICIENT IN OUTDOOR THERMAL PERFORMANCE TESTING OF SOLAR BOX COOKERS

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Abstract

Solar thermal collectors being used outdoors are naturally exposed to the outside wind and this has an effect on the heat losses from the collector. This is equally important for simulation and indoor collector testing. For designing and thermal performance evaluation of solar thermal collecting systems the wind induced heat loss coefficient (also called wind heat transfer coefficient) is a major concern. Different correlations, available in the literature, give different values of wind heat transfer coefficient at the same wind velocity. To avoid the use of these correlations for estimating the wind heat transfer coefficient, of a solar box cooker or flat plate solar collector, the glass cover temperature is needed. The measurement of glass cover temperature, of these solar thermal devices, is not so
easy in outdoor conditions as the thermocouple junction is directly exposed to solar radiation.

In the present work a method is developed and proposed to estimate the wind heat transfer coefficient from the outer surface of the glass cover of a solar box cooker in outdoor testing. An unglazed heated plate, of same size of cooker aperture, is used to estimate the wind heat transfer coefficient. The unglazed heated plate can be placed near the cooker or collector for the measurement of wind heat transfer coefficient, exactly in the same conditions. Some outdoor experiments have been performed on double glazed solar box cooker and unglazed heated plate placed side by side in the same outdoor conditions. Under similar wind conditions the values of wind heat transfer coefficient from the solar box cooker and unglazed plate are within 5% rms error.

Keywords: Solar Box Cooker, Thermal Performance Testing, Outdoor Experiments, Wind Heat Transfer Coefficient, Unglazed Heated Plate

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1. Introduction

Solar box cookers/flat plate solar collectors being used outdoors are naturally exposed to the outside wind and this has an effect on the heat loss factor. In order to design a solar thermal collecting system or to evaluate the thermal performance of the system under different operating conditions, the overall heat loss factor must be known. The overall heat loss factor, U_L, is the sum of top heat loss factor (U_t) and bottom and sides heat loss factors (U_b and U_s). In a well-insulated collector (solar box cooker or flat plate collector) the bottom and side losses are small. The top heat loss factor is a function of the basics variables: plate temperature (T_p), ambient temperature (T_a), plate emittance (ε_p), air spacing (L), collector tilt (β) and wind heat transfer coefficient (h_w).
Estimation of the wind heat transfer coefficient, of a solar box cooker, requires glass cover temperature. Measurement of glass cover temperature in outdoor conditions is very difficult as the thermocouple junction is directly exposed to solar radiation. An additional amount of solar radiation may be absorbed at the junction which will have an extra effect of heating of the thermocouple tip other than the temperature of glass. The other way of estimation of the wind heat transfer coefficient from the outer glass cover is by using existing correlations which are based on the wind velocity to which the system is subjected.

Presently the wind heat transfer coefficient, from outer glass cover of a solar box cooker or flat plate collector, is determined using the following correlations,

i. Mc Adam's Correlation (1954),

$$h_w = 5.7 + 3.8\ V \quad \text{----------- (1)}$$

ii. Watmuff's Correlation (1977)

$$h_w = 2.8 + 3.0\ V \quad \text{----------- (2)}$$

iii Test et al. Correlation (1980)

$$h_w = (8.55\pm0.86) + (2.56\pm0.32)\ V \quad \text{----------- (3)}$$

iv. Subodh et al. Correlation (1997)

$$h_w = 10.03 + 4.687\ V \quad \text{----------- (4)}$$

These Correlations are based on wind tunnel tests of isolated plates. But wind flow over a solar box cooker (or flat plate collector) is not always well represented by wind tunnel flow. In actual outdoor conditions the collector will sometimes be exposed directly to the wind and other times will be in the wake region. Moreover there is considerable difference in the values of h_w obtained from different correlations (equations -1 to 4 above) at the same wind velocity. Although a small approximation in the wind heat transfer coefficient will not cause too much error, but arbitrary selection of a correlation will cause substantial error in the thermal analysis. Values of the wind heat transfer coefficient were calculated using these four correlations as given above for wind velocity range 1-5 m/s. The wind heat transfer coefficient was plotted against the wind velocity as shown in the following Figure 1.

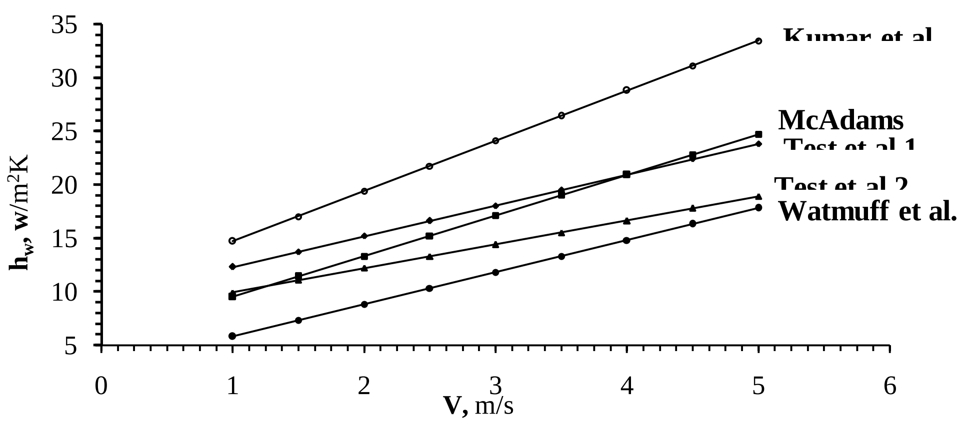

Figure 1: h_w at Various Wind Velocities from different Correlations

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Therefore these correlations are not correctly applicable for determining the h_w for thermal modeling of solar box cookers. There is a need of measurement of wind heat transfer coefficient in the same outdoor conditions in which the solar box cooker being tested. An unglazed heated plate of almost of same size of cooker aperture was used to measure the wind heat transfer coefficient. The unglazed plate is well insulated at the bottom and sides to compel most of the heat to flow through upward. The plate is painted dull black at the upper side. The unglazed heated plate can be placed near the solar box cooker for the measurement of wind heat transfer coefficient.

In the present work a method is proposed and developed to estimate the wind heat transfer coefficient in the analysis of outdoor testing of solar box cookers. In outdoor testing of solar box cookers (and also flat plate solar collectors), the wind heat transfer coefficient from the outer glass cover can be approximated by the wind heat transfer coefficient from an unglazed heated plate of the same size as the aperture of the solar box cooker. The unglazed heated plate can be placed near the cooker or collector for the measurement of the wind heat transfer coefficient exactly in the same conditions. Outdoor experiments were performed on a large size experimental double glazed solar box cooker and an unglazed heated plate, which are placed side by side in the same outdoor conditions. Under same wind conditions the values of wind heat transfer coefficient from the solar box cooker and that of unglazed plate are within 5% rms error.

2. Experimental Set-ups

2.1 Experimental Solar Box Cooker

The experimental solar box cooker consists of an aluminum tray of 870 x 870 mm in size and 2 mm thickness coated with dull black paint. Bottom and sides of the cooker were well insulated by using the sufficient quantity of glass wool. The thicknesses of insulation at the bottom and sides are 150 mm and 80 mm respectively to reduce back losses. The air spacing between plate and inner glass is 98 mm. The ratio of aperture area (950 mm X 950 mm) to the plate-glass air spacing (98 mm) is large, therefore the side losses are small.

Experimental solar box cooker, as discussed above, is made up of wooden board with the following specifications

Size of Box	= 1.185 m X 1.175 m X 0.28 m.
Aperture Area	= 0.95 m X 0.95 = 0.9025 m^2
Size of Tray	= 0.87 m X 0.87 m (bottom)
Tray Taperness	= 144^o with the horizontal
Tray Material	= 24 Gauge Aluminum Sheet.
Glazing:	Double Glazed, 4 mm Ordinary Glasses

Air Spacing between glasses = 12 mm.
Air Spacing between Plate and Glazing = 98 mm.

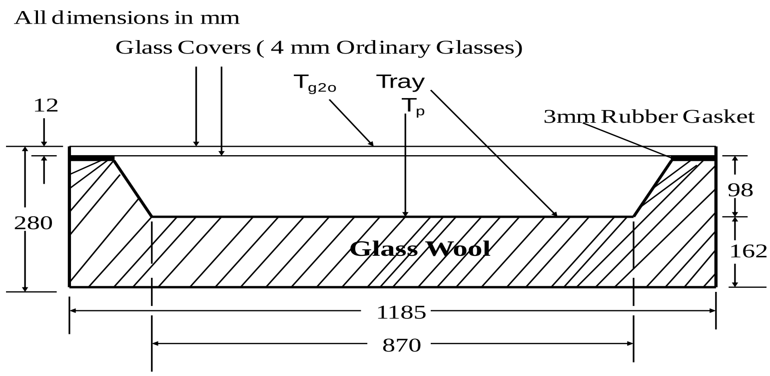

Figure 2: Experimental Solar Box Cooker

Calibrated chromel-alumel thermocouples (type K) were attached to the tray and glass cover for temperatures measurement. For the measurement of the plate temperature, the thermocouple was fixed at the centre of the plate with the help of adhesive and a thin aluminum foil which was then painted dull black. A thermocouple was attached at the central portion of the upper glass for the measurement of the outer glass temperature.

2.2 Unglazed Heated Plate

2 mm thick aluminum sheet of size 950 x 950 mm (same as aperture area of cooker) is painted dull black and fixed over an insulated pad comprises a 50 mm glass wool layer and 50 mm thermocole layer as shown in the following Figure 3. For the measurement of the plate temperature, the thermocouple was fixed at the centre of the plate with the help of adhesive and a thin aluminum foil which was then painted dull black. For the measurement of temperatures across the glass wool layer (T_1 and T_2), two thermocouples were fixed at the central portion of the plate from underside.

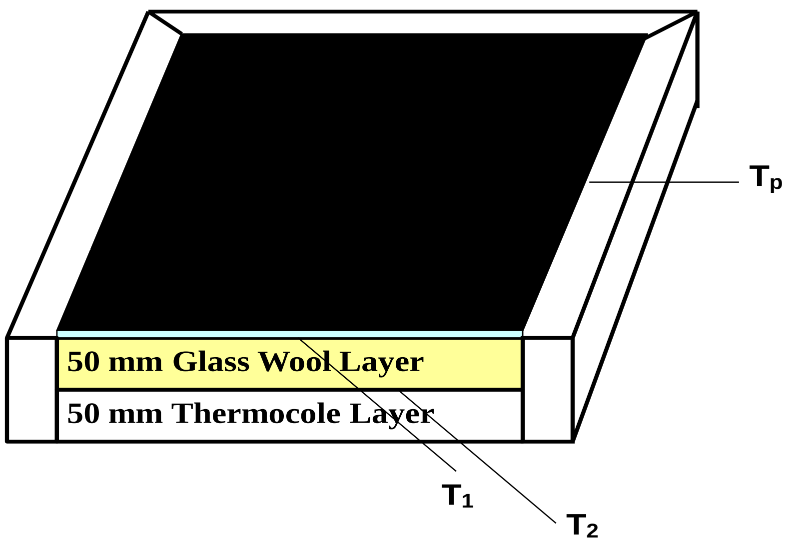

Figure 3: Outdoor Unglazed Heated Plate

3. Experimentations

Outdoor experiments were conducted during the months of March to May when the sky is clear and sufficient solar radiations are available. During this period (March to May) the outdoor wind conditions are also stable. The solar box cooker and unglazed plate were placed side by side on the rooftop of building with other measuring instruments as shown in the following Figure 4. A 3-cup anemometer using chopper type sensor was used for the measurement of wind velocity. The temperature of the outer surface of the outer glass cover was measured very carefully. A very small cavity is formed in the glass surface to accommodate the tip of the thermocouple. A small piece of a thin shiny aluminum foil was placed at the thermocouple junction to protect it from direct absorption of the solar radiation, which may increase the temperature of the thermocouple junction, above the actual temperature of the glass cover. The experiment was started at about 10:00 A.M. and the cooker as well as unglazed plate attained the steady state condition at about solar noon.

Figure 4: Experimental arrangement for outdoor experiments

During testing, the following quantities were measured using data loggers with an interval of five minutes until the steady state was reached;

1. Plate temperature (T_{pc}) at the centre of absorber plate (tray) of the cooker.
2. Outer surface temperature (T_{2go}) of the outer glass cover of the cooker.
3. Plate temperature (T_{pu}) at the center of the unglazed plate.
4. Temperatures (T_1 and T_2) across the glass wool layer of unglazed plate.
5. Ambient temperature (T_a) using thermocouple whose junction is placed in shade and exposed to free air stream.
6. Solar radiation (I) on the horizontal surface using pyranometer.
7. Wind velocity (V) using a 3-cup anemometer

A series of experiments were performed on number of days during the period as specified above. Some observations, of those days have chosen for analysis, when the wind conditions were most stable. The observations of steady state are arranged and tabulated in the increasing value of wind velocity irrespective of their sequence of experiment as shown in the following Table 1.

Table 1. Experimental Data for Outdoor Experiments

V	**Solar Box Cooker**		**Unglazed Plate**				
	T_{pc}	**T_{g2o}**	**T_{pu}**	**T_1**	**T_2**	**T_a**	**I**
m/s	^oC	^oC	^oC	^oC	^oC	^oC	W/m^2
0.1	141.0	65.4	78.6	76.7	46.0	27.6	818.0
0.2	144.8	72.0	81.1	81.3	50.2	32.0	830.0
0.3	141.4	64.4	77.2	75.0	45.3	27.8	844.0
0.4	138.3	65.0	78.4	77.4	46.5	31.5	833.5
0.6	136.5	63.7	72.7	73.5	44.2	25.8	853.0
0.8	152.0	74.2	83.0	82.5	57.5	38.0	885.0
1.5	147.0	73.0	74.0	73.3	51.0	40.0	820.0
2.1	149.0	71.2	71.2	67.3	47.4	39.1	868.6

3. Analysis

From the experimental data of solar box cooker (T_{pc}, T_{2go}, T_a and I) in the above Table 1, for each set of observations at the steady state, the heat balance at the cooker (equations 1.1 to 1.6, Appendix-I) gives the value of wind heat transfer coefficient from the outer glass cover of the solar box cooker. An average value of optical efficiency (η_o) of a double glazed solar box cooker as 0.69 (Duffie, J.A., Beckman, W.A., 1991) was taken in the calculation.

Similarly from the experimental data of unglazed heated plate (T_{pu}, T_1, T_2, T_a and I) in the Table 1, for each set of observations at the steady state, the heat balance at the plate (equations 2.1 to 2.6, Appendix-II) gives the value of wind heat transfer coefficient from the unglazed plate.

The values of the wind heat transfer coefficient obtained from the unglazed plate and that of outer glass cover of solar box cooker were plotted against wind velocity as shown in following Figure 5. The deviation of the values of the wind heat transfer obtained from solar box cooker to that of unglazed heated plate was studied. The root mean square deviation is 0.39 w/m^{2}K as shown in the following Table 2.

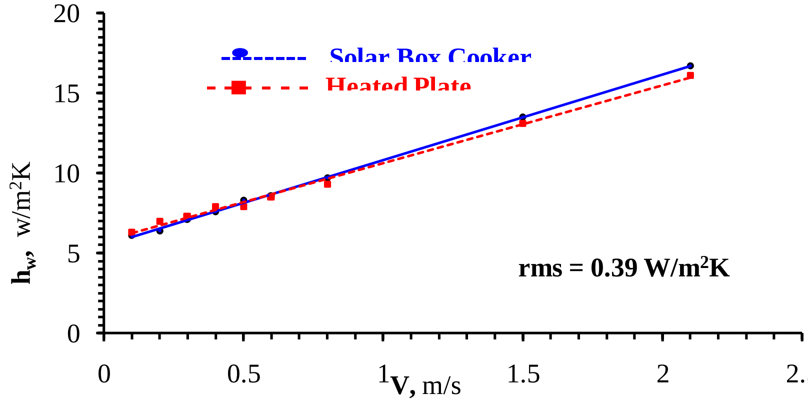

Figure 5. Comparison of h_w from glass cover of solar box cooker and unglazed plate

Table 2. Deviation of h_w of unglazed plate from that of solar box cooker

V m/s	**h_w** w/m^{2}K		**Δh_w**	**$(\Delta h_w)^2$**
	Solar Box Cooker	Unglazed Heated Plate		
0.1	6.1	6.3	-0.20	0.040
0.2	6.4	7.0	-0.60	0.360
0.3	7.1	7.3	-0.20	0.040
0.4	7.6	7.9	-0.30	0.090
0.5	8.3	7.9	0.40	0.160
0.6	8.6	8.5	0.10	0.010
0.8	9.7	9.3	0.40	0.160
1.5	13.5	13.1	0.40	0.160
2.1	16.7	16.1	0.60	0.360

rms deviation = 0.39 W/m^{2}K

rms error = 4.2%

The validity of using the wind heat transfer coefficient of unglazed plate for the thermal performance analysis of solar box cookers was also varified. For this purpose another set of data of experiments (which were not included in Table 1) was selected as shown in the following Table 3. Heat balancing at the stagnation of the cooker was done using the following eqns. (5)-(8) for the various plate temperatures, ambient temperatures and wind conditions.

At the stagnation;
The heat input to the cooker per unit time per unit area

$$\dot{Q}''_{in} = \eta_o I \qquad \text{---------------- (5)}$$

The overall heat loss factor of the cooker

$$U_L = U_t + U_{bs} \qquad \text{-------------- (6)}$$

Total heat loss from the cooker per unit time per unit area

$$\dot{Q}''_{loss} = U_L (T_{pc} - T_a) \qquad \text{---------------- (7)}$$

$$\text{Error} = \frac{\left(\dot{Q}''_{in} - \dot{Q}''_{loss}\right)}{\dot{Q}''_{loss}} \times 100 \qquad \text{---------------- (8)}$$

Top heat loss factor U_t of the cooker was calculated using the equations 3.1-3.7 in the appendix-III. Bottom and sides heat loss factor (U_{bs}= 0.85 W/m^{2}K) of the cooker was calculated considering the conduction across the wooden board at bottom and sides. For the plate temperature from 125 –165 ^{o}C and ambient 24 – 45^o, heat balancing was made for the solar box cooker using the h_w obtained from the corresponding data of unglazed plate of same experiments. At the stagnation, the difference between the input heat to the cooker and heat loss from the cooker was calculated and compared. A good agreement was found. The error (difference) was found to be within 4%.

Table 3. Heat balance at stagnation of the solar box cooker

T_p ^{o}C	T_a ^{o}C	I ^{o}C	h_w W/m^{2}K	$Q_{in}^{//}$ W/m^2	$Q_{loss}^{//}$ W/m^2	Error %
161.5	41.8	943.0	9.0	674.9	692.5	-2.6
150.0	39.2	878.5	11.5	629.4	638.5	-1.4
146.0	42.5	820.0	10.2	587.9	582.5	0.9
139.0	43.0	708.0	8.6	506.1	518.7	-2.5
128.5	24.5	767.1	8.3	540.9	534.2	1.2
125.4	26.1	745.8	8.5	527.0	507.9	3.6

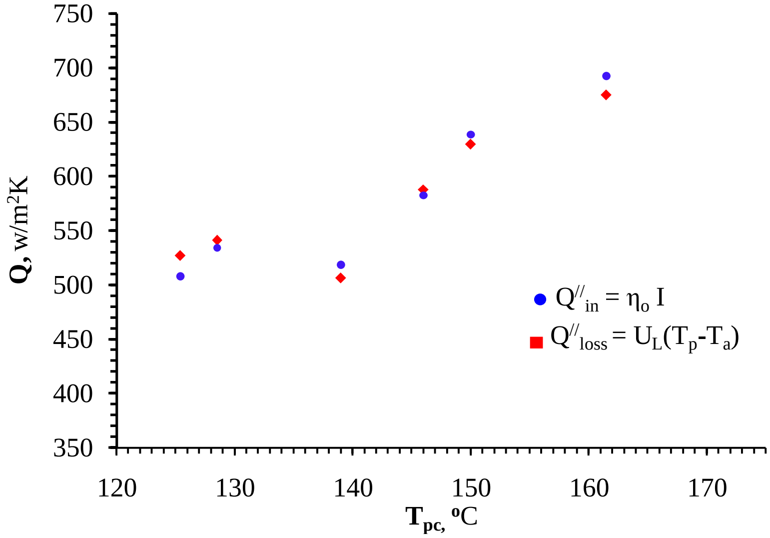

Figure 6. Heat balance for solar box cooker using h_w of unglazed plate

4. Results and Discussion

At the same outdoor wind conditions, the values of wind heat transfer coefficient from the outer glass cover of the solar box cooker were found to be very close to the values obtained from an unglazed plate of the same size. The values of wind heat transfer coefficient from an unglazed plate at any wind velocity have a very small deviation from the values obtained from the cooker at the same wind velocity. It is shown in Table 2, the rms deviation between these two values of h_w is 0.39 w/m^2 K.

The validity of estimating h_w from the unglazed plate for cooker (or collector) was also established by applying the heat balance at stagnation of the cooker using h_w of the unglazed plate. A very good agreement was found between heat input to the cooker and heat loss (calculated using h_w of the unglazed plate) from the cooker. As shown in Figure 6 and Table 3 above, a difference within 4% was encountered.

5. Conclusion

From the above analysis and discussion it can be concluded that in outdoor testing and thermal analysis of a solar box cooker (or flat plate collector) the wind heat transfer coefficient from its outer glass cover can be approximated by the wind heat transfer coefficient from an unglazed plate of the same size. The use of this proposed method for the estimation of h_w eliminates the need of measurement of glass temperature (which is difficult in outdoor) or the use of velocity based correlations, which creates a substantial amount of uncertainty. The adoption of proposed method, for estimating the h_w in outdoor conditions will minimize the uncertainties due to h_w in the thermal analyses of solar box cookers or flat plate collectors.

Symbols and Abbreviations

h_{rgsky} = Radiative heat transfer coefficient of glass cover with sky temperature (w/m^{2}K).
h_{rpsky} = Radiative heat transfer coefficient of unglazed plate with sky temperature (w/m^{2}K).
h_w = Wind heat transfer coefficient (w/m^{2}K).
I = Solar radiation at stagnation.
K_g = Thermal conductivity of glass (w/mK).
K_{gw} = Thermal conductivity of glass wool (w/mK).
$\dot{Q}''_{ab}$ = Heat absorbed by the unglazed plate per unit area per unit time (w/m^2)

$\dot{Q}''_b$ = Bottom heat loss per unit area per unit time (w/m^2)
$\dot{Q}''_{in}$ = Heat input to the cooker per unit area per unit time (w/m^2)
$\dot{Q}''_t$ = Top heat loss per unit area per unit time (w/m^2)
T_{pc} = Absorber plate temperature of cooker (^oC)
T_{pu} = Absorber plate temperature of unglazed plate (^oC).
T_a = Ambient temperature (^oC).
T_{sky} = Sky temperature (Swinbank relation) = $0.055*(T_a)^{1.5}$
T_{g1} = Mean temperature of inner glass cover ($^o C$).
T_{g2} = Mean temperature of outer glass cover ($^o C$).
T_{2go} = Outer surface temperature of outer glass cover (^{o} C).
U_{bs}= Bottom and sides heat loss factor (w/m^2K).
U_{ga} = Heat transfer coefficient between glass cover and ambient (w/m^2K).
U_{pa} = Heat transfer coefficient between unglazed plate and ambient (w/m^2K).
V = Wind velocity (m/s).

Greek Symbols

α_p = Absorptance of the unglazed plate
η_o =Optical efficiency of the cooker
δ_g = Thickness of the glass cover (m)

δ_{gw}=Thickness of the glass wool in the unglazed plate (m)
ε_g = Emittance of Glass surface
ε_p = Emittance of unglazed plate
σ =Stefan's-Boltzman constant (w/m^2K^4)

Subscripts

a = atmosphere
p = absorber plate
g = glass cover
i = inner
o = outer

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Appendix-I

Determination of h_w from the Outer Glass Cover of Solar Box Cooker

At steady state of solar box cooker;

Rate of heat input to the cooker per unit area

$$\dot{Q}''_{in} = \eta_o I \qquad \text{--------- (1.1)}$$

Rate of bottom and sides heat loss per unit area

$$\dot{Q}''_b = U_{bs}(T_{pc} - T_a) \qquad \text{--------- (1.2)}$$

Top heat loss per unit time per unit area

$$\dot{Q}''_t = \dot{Q}''_{in} - \dot{Q}''_b \qquad \text{---------- (1.3)}$$

Heat transfer coefficient between outer glass surface and the ambient

$$U_{ga} = \frac{\dot{Q}''_t}{(T_{g2o} - T_a)} \qquad \text{---------- (1.4)}$$

Radioactive heat transfer coefficient between outer glass surface and ambient (sky)

$$h_{rgsky} = \frac{\varepsilon_g \sigma\{(T_{2go})^4 - (T_{sky})^4\}}{(T_{2go} - T_a)} \qquad \text{-------- (1.5)}$$

Wind Heat Transfer Coefficient from the outer glass surface of the Cooker

$$h_w = U_{ga} - h_{rgsky} \qquad \text{---------- (1.6)}$$

Appendix-II

Determination of h_w from the Unglazed Plate

At steady state of unglazed plate;

Rate of heat absorbed by the plate per unit area

$$\dot{Q}''_{ab} = \alpha_p \cdot I \qquad \text{----------- (2.1)}$$

Rate of bottom heat loss per unit area

$$\dot{Q}''_b = \frac{K_{gw}(T_1 - T_2)}{\delta_{gw}} \qquad \text{---------- (2.2)}$$

Top heat loss per unit area per unit time

$$\dot{Q}''_t = \dot{Q}''_{ab} - \dot{Q}''_b \qquad \text{----------- (2.3)}$$

Heat transfer coefficient from the unglazed plate to the ambient

$$U_{pa} = \frac{\dot{Q}''_t}{(T_{pu} - T_a)}$$

----------- (2.4)

Radiative heat transfer coefficient of unglazed heated plate to the sky

$$h_{rpsky} = \frac{\varepsilon_p \sigma\{(T_{pu})^4 - (T_{sky})^4\}}{(T_{pu} - T_a)} \qquad \text{----------- (2.5)}$$

Wind heat transfer coefficient from the unglazed plate

$$h_w = U_{pa} - h_{rpsky} \qquad \text{----------- (2.6)}$$

Appendix-III

The mean temperatures of glass covers (T_{g1}, and T_{g2}) and top heat loss factor (U_t) of a doubled glazed solar box cooker are calculated [5] as follows;

Mean temperature of the outer glass cover

$$T_{g_2} = T_a + \left[\left(0.652 + 0.00267 T_{pc}\right) / \left(h_w\right)^{0.5637}\right]\left(T_{pc} - T_a\right) \qquad \text{--------- (3.1)}$$

Mean temperature of the inner glass cover

$$T_{g_1} = 0.568 T_{pc} + 0.432 T_{g_2} \qquad \text{-------- (3.2)}$$

Heat transfer coefficient between plate (tray) and inner glass cover is given as;

$$U_{p_1} = 15.4\left(T_p - T\right)^{0.285} / \left(T_{mp_1}\right)^{0.34} + 0.802\sigma\left(T_p^2 + T_1^2\right)\left(T_p + T_1\right) \qquad \text{--------- (3.3)}$$

Heat transfer coefficient between inner and outer glass covers is given as;

$$U_{12} = 2.454\left[1 + 1.44\left\{1 - 15.6/\left(T_1 - T_2\right)\right\}\right] + 0.786\left(T_1^2 + T_2^2\right)\left(T_1 + T_2\right) \qquad \text{------ (3.4)}$$

Heat transfer coefficient between outer glass cover and ambient is given as;

$$U_{2a} = h_w + 0.88\sigma\left(T_2^2 + T_a^2\right)\left(T_2 + T_a\right) \qquad \text{------- (3.5)}$$

Top heat loss factor (U_t) of the cooker is calculated as

$$\frac{1}{U_t} = \frac{1}{U_{p_1}} + \frac{1}{U_{12}} + A_r \frac{1}{U_{2a}} + \left(L_{g_1} + L_{g_2}\right)/K_g \qquad \text{-------- (3.6)}$$

Overall heat loss factor of the cooker

$$U_L = U_t + U_b \qquad \text{-------- (3.7)}$$