VOL. 9, NO. 10, OCTOBER 2014 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

www.arpnjournals.com

COMPARATIVE EVALUATION OF THE TOP HEAT LOSS COEFFICIENT OF A TRIPLE GLAZING TRAPEZOIDAL SOLAR COOKER

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ABSTRACT

A solar cooker requires absorber temperatures that are definitely higher than 100°C. A proper estimate of the heat losses is important to evaluate the solar collector efficiency. The heat losses from the bottom and the lateral sides of the collector are easily estimated from the knowledge of the thermal insulating materials. As for the heat losses from the top, they represent a more important fraction of the energy balance. Hence, a proper estimate of the top loss coefficient U_L is relevant. In the present paper, some experimental data are used to evaluate U_L. This evaluation is performed by using the electrical analogy, but also by means of some empirical correlations. The values of U_L are plotted against time. The evaluations of U_L with the absorber temperature are also plotted. Some statistical parameters such as MBE and RMSE are calculated. The study shows that U_L is overestimated by the empirical correlations. In addition, for the triple glazing solar cooker studied here, the comparative study showed a better agreement between the top loss coefficient obtained from the electrical analogy and the prediction by the Malhotra *et al.,* correlation.

Keywords: solar cooker, triple glazing, top heat loss coefficient, RMSE error, MBE error.

1. INTRODUCTION

In Côte d'Ivoire, the solar energy potential is important. The daily total radiation varies from 3 to 5 Kwh/m², depending on the regions [1]. This makes the solar energy thermal conversion a feasible solution to the problem of energy in rural communities. One of the most significant potential applications of solar energy is solar cooking.

As a matter of fact, in many developing countries, about 72% of the total energy consumption is provided by firewood and charcoal. So, a wide so spread of solar cookers may be a solution of this lack of energy source.

The calculation of the performance of a solar cooker requires the knowledge of the energy losses. The bottom and lateral losses are easy to estimate. As for the top heat losses through the cover glass, they represent a more important fraction of the energy losses and are more difficult to estimate. J.M. Chasseriaux [2] indicated that the top energy loss may be reduced by using several glasses. In the literature, several correlations are used to estimate the top heat loss coefficient U_L of a collector. The most commonly used is the empirical relation proposed by Klein [3]. S.C. Mullick *et al*., [4] evaluated the top heat loss coefficient of double- glazed box-type solar cooker. By comparing the analytical and experimental results, they found that the root mean square error (RMSE) is positive and is 2.6 %. Hence, the coefficient calculated by using the Klein correlation overestimates the losses. A. Benkhelifa [5] compared the top heat losses obtained from three relations: the Klein correlation, the Agarwal and Larsen relation and the relation proposed by Malhotra *et al*. He concluded that the top heat loss coefficient decreases with increase in distance between the absorber and the inner glass. He also concluded that the Malhotra *et al.,* correlation is better if compared with the two other relations. Y.U. Abdullah and N. Akhtar [6] experimented a single glazing flat plate solar collector and compared five correlations of the top heat loss coefficients, namely the Klein correlation, the Agarwal and Larsen relation, the Malhotra *et al*., correlation, the Mullick and Samdarshi correlation and the Akhtar and Mullick correlation. For this single glazed collector, they concluded that the Akhtar and Mullick correlation gives a better prediction of the top heat loss coefficient.

The objective of the present study is to estimate the top heat loss coefficient of a triple glazing solar cooker, comparing the electrical analogy method to the results found by using some empirical correlations.

2. PRESENTATION OF THE SYSTEM STUDIED

The system studied is a box type solar cooker shown on Figure-1. It is a wooden trapezoidal box. The thickness of the plywood is 0.015 m. The cooker is fitted with a triple glazing transparent cover. It is also fitted with four external reflectors. The two eastern and western reflectors are adjustable, with three allowable tilt angles, depending on the height of the sun. As for the two reflectors that are oriented southward and northward, they have a fixed tilt angle. An aluminium sheet covers the inside of the cooker. The bottom and lateral thermal insulation is made of polystyrene which lies between two wooden frames. A plaster slab, inserted under the absorber, is used as thermal insulation. The absorber is stainless steel painted in black tie increase its absorption capacity. The lateral faces are inclined as shown on Figure-1.

 ISSN 1819-6608

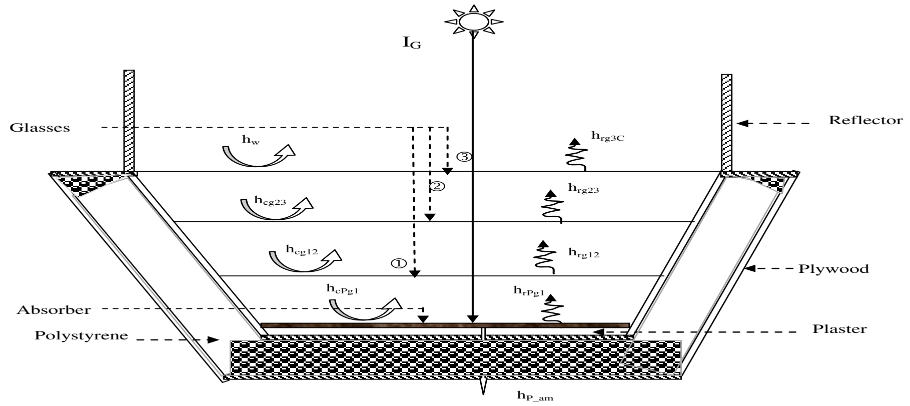

Figure-1. Cut of the trapezoidal solar cooker.

3. EXPERIMENTAL STUDY

The convective and radiative coefficients which depend on temperature are calculated using experimental data. Several tests were carried out. The day chosen for this study is April 5th 2008 because of its high solar activity. The data measured were:

- The absorber temperature (T_P), the three glasses temperatures (T_{g1}, T_{g2}, T_{g3}), the ambient temperature (T_a), the internal and external side walls temperatures;
- Solar irradiance.

The temperatures were measured by platinum resistance thermometers, while solar irradiance was measured with an Eppley type pyranometer PSP 43527-F3. The interval time between two consecutive measurements was five minutes.

4. RESULTS AND DISCUSSIONS

The heat transfer coefficients are obtained from the equations of the functional surfaces.

4.1. Heat equations

4.1.1. Energy loss equations

The energy lost by convection and radiation per unit area between the absorber and the first glass is written as:

$$Q_{pg1} = (h_{cPg1} + h_{rPg1})(T_P - T_{g1}) \quad (1)$$

Between the i and j glasses convective and radiative energy loss is written as:

$$Q_{gij} = (h_{cgij} + h_{rgij})(T_{gi} - T_{gj}) \quad (2)$$

Between the outer glass and the ambient air the convective energy loss is:

$$Q_{cg3a} = h_w(T_{g3} - T_a) \quad (3)$$

Between the outer glass and the sky the radiative energy loss is:

$$Q_{rg3C} = h_{rg3C}(T_{g3} - T_C) \quad (4)$$

4.1.2. Expressions of top heat loss coefficient

The top heat loss coefficient U_L can be expressed by using the electric analogy method. This method uses the thermal resistance network shown on Figure-2.

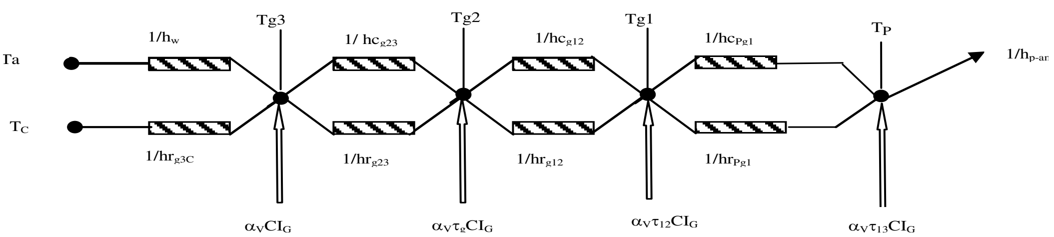

Figure-2. Network diagram of the electrical analogy of the triple glazing trapezoidal cooker.

$$\frac{1}{U_L} = \left(\frac{1}{h_{cPg1}+h_{rPg1}}\right) + \left(\frac{1}{h_{cg12}+h_{rg12}}\right) + \left(\frac{1}{h_{cg23}+h_{rg23}}\right) + \left(\frac{1}{h_w+h_{rg3C}}\right) \quad (5)$$

The thermal resistances depend of exchange coefficients between the functional surfaces considered.

Calculations were made by considering the following simplifying hypotheses:

- The surface is gray (all emission and absorption properties are independent of the wavelength),
- The surface is specular diffuse or diffuse,
- The incident energy on the surface is uniform.

The radiative heat transfer coefficient h_{rij} between i and j surfaces of the collector is written as [7]:

$$h_{rij} = \frac{\sigma(T_i+T_j)(T_i^2+T_j^2)}{\frac{1-\varepsilon_i}{\varepsilon_i}+\frac{1}{F_{ij}}+\frac{1-\varepsilon_j}{\varepsilon_j}\cdot\frac{S_i}{S_j}} \quad (6)$$

In equation (6), ε_i is the emissivity of surface i, F_{ij} is the radiative shape factor between S_i and S_j surface. F_{ij} is obtained using graph or formular [7].

The exchange coefficient by radiation between the glass 3 and the sky is written as:

$$h_{rg3C} = \varepsilon_g\sigma(T_{g3}^2 + T_C^2)(T_{g3} + T_C) \quad (7)$$

Where the temperature of the sky is given by Swinbank relation [7]:

$$T_C = 0{,}0552T_a^{1,5} \quad (8)$$

Between the absorber and the inner glass or between two consecutive glasses there is a natural convective heat tranfer.

The exchange coefficient that characterizes this natural convective depends on the Nusselt number and is written:

$$h_C = \frac{\overline{N_u}}{L}k \quad (9)$$

In this relation, L is the characteristic length (m), while k is the conductivity of the fluid (air), (W/m. K).

The mean Nusselt number $\overline{N_u}$ can be estimated from Buchberg *et al.*, correlation [5, 6, 8] or from the Hollands *et al.*, [5, 8, 9, 10] correlation. This correlation is expressed as:

$$\overline{N}_u = 1.0 + \left[1.44\left(1.0 - {}^{1708}/_{R_a}\right)\right]^* + \left[(R_a/5830)^{1/3} - 1\right]^* \quad (10)$$

where R_a refers to the Rayleigh number for the characteristic length L (distance between two horizontal planes); the superscript * means that the term in brackets has to be taken equal is zero if negative.

Above the outer glass, there is a forced convective transfer.

Its exchange coefficient is given by the correlation of Mc Adams [7]:

$$h_w = 5{,}7 + 3{,}8V \quad (11)$$

where V is the wind speed, m / s.

Several approximate methods are available in the literature to express the top heat loss coefficient. Some of them are given by the following empirical correlations.

- **Correlation of Klein**

$$U_L = \left[\frac{N}{\left(\frac{C}{T_P}\right)\left(\frac{T_P-T_a}{N+f}\right)^e} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_P^2+T_a^2)(T_P+T_a)}{\left(\frac{1}{\varepsilon_P+0.0059Nh_w}\right)+\left(\frac{2N+f-1+0.133\varepsilon_P}{\varepsilon_g}\right)-N} \quad (12)$$

where

σ = Constant of Stefan (W/m². K);
T_P = Temperature of absorber (K);
Ta = Temperature of ambient air (K);
ϵ_P = Emissivity of absorber, (dimensionless);
ϵ_g = Emissivity of glass, (dimensionless);
N = Number of glasses;
C=520 [1 – 0.000051ϕ²];
$\boldsymbol{e = 0,43\left(1 - \frac{100}{T_P}\right)}$
ϕ = Tilt angle of the collector relative to the horizontal.
f = $(1 – 0.04\ h_w + 0.005\ h_w)\ (1 + 0.091N)$

- **Correlation of Agarwal and Larson**

$$U_L = \left[\frac{N}{\left(\frac{C}{T_P}\right)\left(\frac{T_P-T_a}{N+f}\right)^{0.33}} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma(T_P^2+T_a^2)(T_P+T_a)}{\left(\frac{1}{\varepsilon_P+0.0059Nh_w}\right)+\left(\frac{2N+f-1}{\varepsilon_g}\right)-N} \quad (13)$$

where:
C = 250 [1 - 0.0044 (ϕ - 90)]
f = $(1 – 0.04\ h_w + 0.005\ h_w^2)\ (1 + 0.091N)$
Correlation of Malhotra *et al*,

$$U_L = \left[\frac{N}{\left(\frac{C}{T_P}\right)\frac{\left(\left(T_P - T_a\right)L^3\cos\phi / (N+f)\right)^{0,252}}{L}} + \frac{1}{h_w}\right]^{-1} + \frac{\sigma\left(T_P^2 + T_a^2\right)\left(T_P + T_a\right)}{\left(\frac{1}{\varepsilon_P + 0.0425N(1-\varepsilon_P)}\right) + \left(\frac{2N+f-1}{\varepsilon_g}\right) - N} \quad (14)$$

where

C = 204.429

$f = (9/h_w - 30/h_w^2)(1 + 0.091\ N)(Ta/316.9)$

These correlations are valid for a tilt angle $0 \le \phi < 70°$. For $70° \le \phi \le 90°$, $\phi = 70°$ is used.

4.1.3. Statistical evaluation of results

The fitting of the empirical correlations to the electrical analogy method was investigated by using some statistical tests such as the relative mean bias error (MBE) and the relative root mean square error (RMSE) given by equations (15) and (16) [11].

$$\mathrm{MBE} = \frac{1}{n}\sum_1^n e_i \quad (15)$$

$$\mathrm{RMSE} = \left[\frac{1}{n}\sum_1^n e_i^2\right]^{1/2} \quad (16)$$

where

$$e_i = (x_{corr} - x_{mes}) \times 100 / x_{corr}$$

x_{corr} = value of x from the empirical correlation,

x_{mes} = value of x from the electrical analogy.

If MBE >0, that means that the correlation used overestimates the top heat loss coefficient small values of MBE and RMSE indicate a good fitting of the correlation used to the electrical analogy method.

5. RESULTS

The data were processed by using a code written under Matlab R2007b of the top heat loss coefficient calculations. The system has been exposed to the sun from 6:00 hours until 10:00 hours (local time). This enables the system to activate its thermal capacity. Measurements of temperature and irradiance were carried out between 10:00 a.m. to 2:00 p.m. local time.

The solar irradiance curve is represented in Figure-3. The curve shows, from 10:30 to 11:00, disturbances on irradiance owed to cloudiness.

On the Figure-4, the variation curves of absorber, glasses 1, 2 and 3, and ambient temperatures reproduce the shape of irradiance. However, the cloudy periods are less perceptible.

The maximum temperatures observed are:

- 153.5 °C at 12:50 for the absorber,
- 133.76 °C at 12:20 for the glass 1,
- 100.34 °C at 12:05 for the glass 2,
- 67.19 °C at 12:00 for the glass 3,

Figure-5 shows the evolution curves of top heat loss coefficient with time. In this Figure, we find that all curves from correlations are above that obtained from the electrical analogy. The same remarks are observed in the Figure-6 representing the evolution curves of the top heat loss coefficient as a function of the absorber temperature.

Hence, the correlations used overestimate the top heat lost coefficient of the solar cooker studied. Statistical calculations were performed. The following values of MBE were found: 0.40% for the correlation of Klein, 0.31% for the correlation of Agarwal and Larson and 0.22% when the correlation of Malhotra *et al*., is used.

It can be seen that the MBE values are positive.

In Table-1, are reported the values of the different top heat loss coefficients together with the instantaneous RMSE values.

It is observed that the Malhotra *et al*., correlation gives the smallest values of RMSE. Therefore this correlation fits better our system. This result is consistent with the one obtained by A. Benkhelifa [5] who also found that the correlation of Malhotra *et al*., is better if compared to the Klein relation and also to the Agarwal and Larson correlation.

Table-1. Comparative results of top heat loss coefficient and RMSE values.

Time	TP (K)	UL analogy (W/m²K)	UL Klein (W/m²K)	UL Agarwal (W/m²K)	UL Malhotra (W/m²K)	RMSE for Klein correlation (%)	RMSE for Agarwal correlation (%)	RMSE for Malhotra correlation (%)
10:00	369,06	2,07	2,67	2,52	2,39	3,15	2,95	1,88
10:05	369,91	2,10	2,68	2,53	2,40	3,07	2,42	1,80
10:10	374,75	2,14	2,73	2,58	2,45	3,05	2,40	1,77
10:15	375,53	2,15	2,74	2,59	2,46	3,05	2,40	1,77
10:20	376,56	2,16	2,75	2,60	2,47	3,04	2,39	1,76
10:25	377,34	2,17	2,76	2,61	2,48	3,04	2,39	1,76
10:30	378,11	2,17	2,77	2,62	2,48	3,05	2,40	1,78
10:35	381,99	2,21	2,81	2,65	2,52	2,99	2,34	1,71
10:40	384,06	2,23	2,83	2,68	2,54	3,03	2,39	1,78
10:45	386,91	2,25	2,86	2,71	2,57	3,05	2,41	1,78
10:50	386,65	2,24	2,86	2,70	2,56	3,03	2,38	1,75
10:55	385,36	2,24	2,85	2,69	2,55	2,99	2,34	1,71
11:00	387,42	2,27	2,87	2,71	2,57	2,92	2,27	1,64
11:05	389,23	2,29	2,88	2,73	2,59	2,92	2,26	1,63
11:10	391,82	2,32	2,92	2,76	2,62	2,89	2,25	1,61
11:15	394,92	2,35	2,95	2,79	2,65	2,85	2,21	1,57
11:20	396,47	2,38	2,97	2,81	2,65	2,80	2,15	1,12
11:25	397,77	2,38	2,98	2,82	2,67	2,82	2,17	1,53
11:30	402,42	2,41	3,03	2,86	2,72	2,88	2,24	1,61
11:35	402,94	2,43	3,03	2,87	2,73	2,82	2,19	1,55
11:40	405,53	2,45	3,06	2,90	2,76	2,83	2,19	1,56
11:45	406,56	2,46	3,07	2,91	2,76	2,83	2,19	1,57
11:50	409,66	2,49	3,11	2,94	2,80	2,83	2,20	1,57
11:55	411,73	2,51	3,14	2,96	2,81	2,79	2,15	1,53
12:00	412,51	2,54	3,14	2,97	2,83	2,68	2,05	1,42
12:05	414,83	2,57	3,16	3,00	2,85	2,66	2,02	1,39
12:10	417,16	2,58	3,19	3,02	2,87	2,69	2,06	1,44
12:15	420,01	2,60	3,22	3,05	2,90	2,72	2,09	1,47
12:20	423,11	2,62	3,25	3,09	2,94	2,75	2,13	1,52
12:25	421,3	2,62	3,23	3,07	2,92	2,70	2,07	1,45
12:30	423,11	2,63	3,25	3,09	2,94	2,71	2,09	1,48
12:35	424,68	2,64	3,27	3,10	2,95	2,74	2,11	1,50
12:40	424,4	2,63	3,26	3,10	2,95	2,74	2,12	1,51
12:45	425,95	2,65	3,28	3,11	2,96	2,73	2,11	1,50
12:50	426,47	2,65	3,29	3,12	2,97	2,74	2,13	1,52
12:55	425,7	2,65	3,28	3,11	2,96	2,72	2,10	1,49
13:00	425,44	2,65	3,28	3,11	2,96	2,71	2,09	1,48
13:05	425,18	2,65	3,28	3,11	2,96	2,72	2,10	1,49
13:10	424,92	2,65	3,27	3,11	2,96	2,72	2,10	1,49
13:15	424,66	2,64	3,27	3,10	2,95	2,72	2,10	1,49
13:20	424,14	2,64	3,26	3,10	2,95	2,71	2,09	1,48
13:25	423,63	2,64	3,26	3,09	2,94	2,69	2,07	1,45
13:30	423,37	2,64	3,25	3,09	2,94	2,69	2,06	1,45
13:35	423,11	2,63	3,25	3,09	2,94	2,70	2,07	1,46
13:40	422,33	2,63	3,24	3,07	2,92	2,68	2,05	1,43
13:45	421,56	2,62	3,24	3,07	2,92	2,69	2,06	1,44
13:50	421,3	2,62	3,23	3,06	2,91	2,68	2,02	1,43
13:55	420,78	2,61	3,23	3,06	2,91	2,68	2,05	1,43
14:00	420,52	2,61	3,22	3,05	2,90	2,67	2,03	1,41
		Mean RMSE values				2,82	2,20	1,56

Furthermore, the evolution of the top heat loss U_L with oven ambient temperature T_{AF} was investigated. The values of U_L estimated from the electrical analogy were plotted versus T_{AF}. The following equations were found:

- for the linear correlation, with $R^2 = 0.992$

$$U_L = 0.012 * T_{AF} + 1 \quad (17)$$

- for the polynomial correlation, with $R^2 = 0.992$

$$U_L = 2.8\,10^{-5} * T_{AF}^2 + 0.0055 * T_{AF} + 1.4 \quad (18)$$

Figure-7 shows the curves obtained.

Then the values of U_L estimated from the correlation of Malhotra *et al.*, were used to get the evolution of U_L with T_{AF}. The following equations were found:

- for the linear correlation, with $R^2 = 0.987$

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

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$$U_L = 0.011 * T_{AF} + 1.3 \qquad (19)$$

- for the polynomial correlation, with $R^2 = 0.989$

$$U_L = 4.9\ 10^{-5} * T_{AF}^2 + 0.00035 * T_{AF} + 1.9 \qquad (20)$$

The curves are shown on Figure-8.

A better fitting of the polynomial correlation to the data is observed.

This result agrees with that of the study carried out on a oven fitted with two glasses [12].

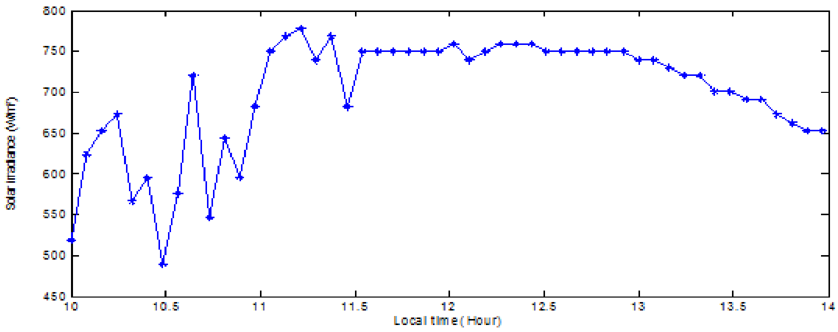

Figure-3. Variation of irradiance with time.

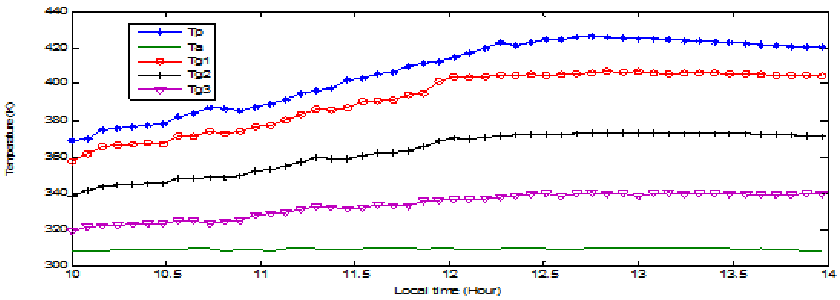

Figure-4. Absorber, ambient, glasses 1, 2 and 3 temperature versus time.

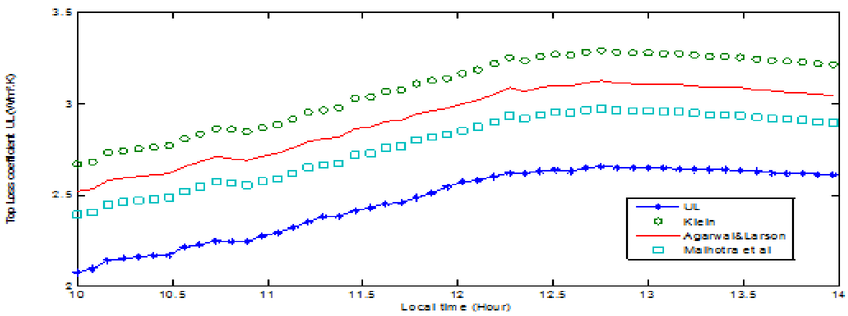

Figure-5. Variation of top heat loss coefficient U_L with time.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences

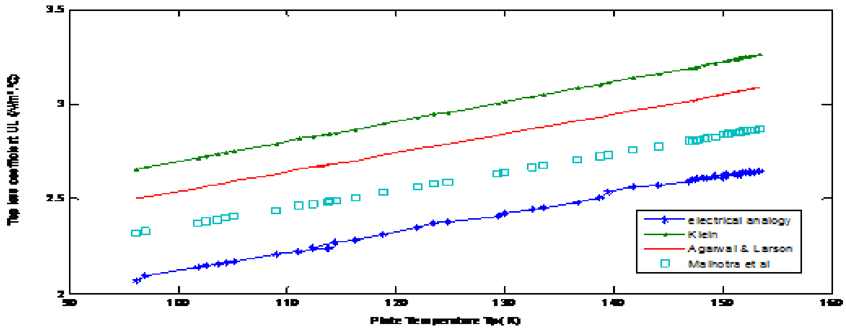

Figure-6. Variation of top heat loss coefficient U_L with absorber temperature Tp.

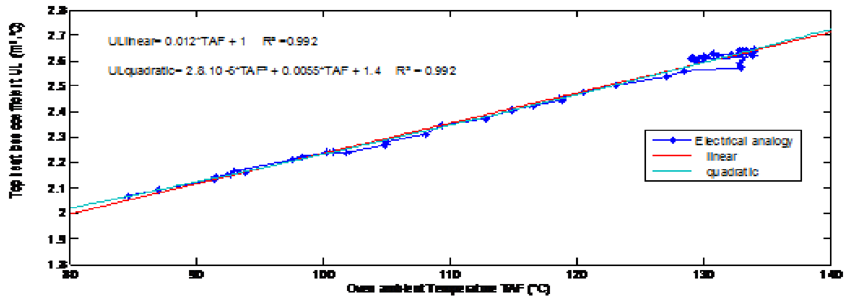

Figure-7. Variation of top heat loss coefficient U_L with oven ambient temperature T_{AF} (Electrical analogy).

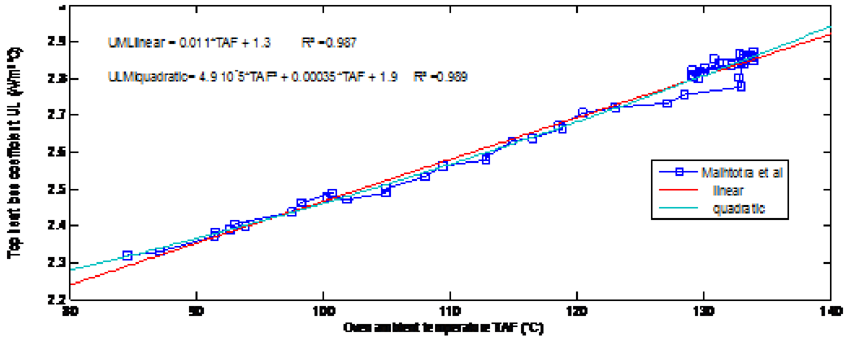

Figure-8. Variation of top heat loss coefficient U_L with oven ambient temperature T_{AF} (Malhotra *et al*).

CONCLUSIONS

Empirical correlations and the electrical analogy method were used to estimate the top heat loss coefficient of the triple glazed trapezoidal solar cooker. A better agreement was found between the top loss coefficient obtained from the electrical analogy and the prediction by the Malhotra *et al*., correlation.

In addition, the values of the top heat loss coefficient arising from the work of S.C. Mullick *et al*., [4] with a double glazed system are greater than those of our triple glazed cooker. A simulation of the cooker will be done to confirm this result.

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Nomenclature

D	: Distance absorber and glass 1	m
h_c	: Exchange coefficient by convection between two parallel plates	W/m².°C
h_{cPg1}	: Exchange coefficient by convection between absorber and glass 1	W/m².°C
h_{rPg1}	: Exchange coefficient by radiation between absorber and glass 1	W/m².°C
h_{rij}	: Exchange coefficient by radiation between the glass i and glass j	W/m².°C
h_{p_am}	: Exchange coefficient by conduction outwards	W/m².°C
h_{rg3C}	: Exchange coefficient by radiation between the glass 3 and the sky	W/m².°C
h_w	: Exchange coefficient by convection between the glass 3 and the ambient	
I_G	: Instantaneous irradiance	W/m²
L	: Characteristic length between two horizontal plates surface	m
T_a	: Temperature of the ambient	K
T_P	: Temperature of the absorber	K
T_C	: Temperature of the sky	K
T_{g3}	: Temperature of glass 3	K
T_{g2}	: Temperature of glass 2	K
T_{g1}	: Temperature of glass 1	K
V	: Speed of wind	m/s
Greek letters		
ε_g	: Emissivity of the glass	
ε_P	: Emissivity of the absorber	
τ_g	: Transmittivity of the glass	
$\tau_{1,2}$	: Transmittivity of two glasses	
$\tau_{1,3}$	: Transmittivity of three glasses.	