# COMPARING A WAY TO CALCULATE THE HEAT LOSS COEFFICIENT OF SOLAR FLAT PLATE COLLECTOR

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**ABSTRACT**

The need for a simple solution to derive the total heat loss coefficient, $U_L$ , is unquestioned as this reduces time to compute the performance of investigated system, especially in atmosphere when practicality is highly needed. This paper describes a simulation and comparison of several ways to obtained $U_L$ The assumptions used and the method are described briefly. The analysis of the result shows that the derived equation (10) applied for solar box cooker type HS is the simplest. The long field test has proved its simplicity and people can understand it easily in practice. This numerical experiment is provided for the readers to validate this simple equation as it can be a tool for the scientist who needs to transfer their knowledge to a wider education level in the context to popularize the application of renewable energy.

**ABSTRAK**

Kebutuhan akan penyelesaian sederhana dalam menghitung kehilangan panas total, $U_L$ , adalah nyata karena akan mengurangi waktu perhitungan dalam menentukan unjuk kerja sistem, terutama pada lingkungan dimana aspek praktis amat diperlukan. Makalah ini menguraikan simulasi dan perbandingan dari beberapa cara menghitung $U_L$. Asumsi dan metoda yang digunakan diuraikan secara ringkas. Analisa hasil perhitungan menunjukkan persamaan (10) yang dirumuskan dengan menganalisa banyak data hasil penelitian oven matahari tipe HS dilapangan adalah yang tersingkat. Pengujian lapangan yang panjang membuktikan bahwa persamaan ini sederhana dalam praktek dan mudah dimengerti masyarakat. Percobaan simulasi angka diberikan agar pembaca dapat mengujinya dan mengunakannya karena persamaan tersebut bisa menjadi alat untuk mempermudah para ilmuwan dalam misi alih teknologi dan alih pengetahuan pada masyarakat dengan tingkat pendidikan yang berbeda-beda dalam kerangka mempopulerkan penerapan enegi terbarukan.

## 1. PREVIOUS WORKS TO CALCULATE $U_L$.

An effort to derive $U_L$ was firstly exerted by Hottel and Woertz (1942), then remodified by Klein (1975) as cited in Channiwala and Doshi (1989) to be:

$$U_L = \left[ \frac{N}{\frac{C'}{T_{p,m}} \left( \frac{T_{p,m} - T_a}{N + f} \right) 0.33} + \frac{1}{h_{wind}} \right]^{-1} + \frac{\sigma (T_{p,m} + T_a)^2 (T_{p,m} + T_a)}{\left( \frac{1}{\varepsilon_p + 0.05N(1-\varepsilon_p)} \right) + \left( \frac{2N + f - 1}{\varepsilon_g} \right) - N} \quad (1)$$

where: $C' = 365.9\,(1 - 0.00883\beta + 0.0001298\,\beta^2)$ where $\beta$ is the tilt angle of the collector (degree); $\sigma$ is Stefan Boltman constant (= $5.6697\ 10^{-8}$ Watt/m$^2$K$^4$); N is the number of glass covers; $T_a$ is ambient temperature (C); $T_{p,m}$ is mean temperature of the absorber plate (C); $\varepsilon_g$ is emittance of glass; $\varepsilon_p$ is emittance of plate; $f = (1 - 0.04\,h_{wind} + 0.0005\,h_{wind}^{\ 2})(1 + 0.091N)$ and $h_{wind}$ = wind heat transfer coefficient (W/m$^2$C)
Watmuff *et al.* (1977) gibes $h_{wind} = 2.8 + 3.0\,\nu$ for the collector area less then 0.5 m$^2$, where $\nu$ is the wind velocity (m/sec). They got $h_{wind}$ = 16 W/m$^2$C at the world average wind speed of 5 m/second and at temperature of 25 $^o$C. It is not valid for other plate lengths.

Four years later, Klein (1979) developed an empirical equation for $U_L$ as:

$$U_L = \left[ \frac{N}{\frac{C'}{T_{p,m}}\left(\frac{T_{p,m} - T_a}{N + f}\right)^e} + \frac{1}{h_{wind}} \right]^{-1} + \frac{\sigma\,(T_{p,m} + T_a)(T_{p,m}^2 + T_a^2)}{(\varepsilon_p + 0.00591\,N\,h_{wind})^{-1} + \frac{2N + f - 1 + 0.133\,\varepsilon_p}{\varepsilon_g} - N} \tag{2}$$

where $C' = 520\,(1 - 0.000051\beta^2)$ for $0 < \beta < 70^o$. For $70^o < \beta < 90^o$ use $\beta = 70^o$
$f = (1 + 0.089\,h_{wind} - 0.1166\,h_{wind}\,\varepsilon_p)(1 + 0.07866\,N)$ and $e = 0.43\,(1 - 100/T_{p,m})$.

Channiwala and Doshi (1989) derived the heat loss coefficient of a solar box cooker as:

$$U_L = \left[ \frac{2.8}{\frac{1}{\varepsilon_p} + \frac{1}{N^{0.025}\varepsilon_g} - 1} + 0.825(x_m)^{0.21} + a\nu^b - 0.5(N^{0.95} - 1) \right](T_{p,m} - T_a)^{0.2} \tag{3}$$

where:
$a = \{0.6 - 0.05\,(N-1)\}$; $b = \{1.1 - 0.10\,(N - 1)\}$ and $\nu$ = the wind velocity (m/second).
$\chi_m$ is the distance between the bottom of tray and the bottom of glass layer (70 mm).
Their cooker overall dimension is 48x48x16 cm, the absorber area is 1600 cm$^2$. They used one until four glass layers of 3.8 mm thick with a spacing between layers of 2.5 cm. Glass wool of 60 mm thick is used at the sides and of 65 mm thick placed underneath for insulator. They used an iron coil to get $T_{p,m}$ from 50$^o$C until 180$^o$C and used a blower to get wind speeds from 0- 3.33 m/sec. At $(T_{p,m} - T_a)$ = 130 C, the cooker having three glass layers has $U_L$ = 6.7 Watt/m$^2$C at the wind velocity of 2 m/sec and at no wind $U_L$ = 4.6 Watt/m$^2$C**.** $U_L$ of the cooker having 3-glass layers is smaller than that having 2-glass layers.

## 2. DERIVING THE TOTAL HEAT LOSS COEFFICIENT OF SOLAR BOX COOKER TYPE HS.

Based on theory of thermal network, Duffie and Beckman (1980:201-211, 209) calculate $U_L$ of one until three glass covers spaced 25 mm apart. It applies $T_a$ = -20 C, 10 C and 40 C, $h_{wind}$ = 20 Watt/m$^2$C; $\varepsilon_p$= 0.95; $\beta$ =45$^o$ and various $T_{p,m}$. For three glass covers at $T_a$ = 40C and $T_{p,m}$ = 200C they got $U_L$ = 4.375 Watt/m$^2$C. It can be used for other plate spacing greater than 15 mm with little error. Klein (1979) calculation fits this result for $T_{p,m}$ between ambient until 200$^o$C to within ± 0.3 W/m$^2$C.
The thermal network of solar box cooker type HS is given in **Fig. 1.** The heat flows is assumed as one-dimensional. The absorber plate is made of thin aluminium painted black, which shaping the oven chamber as "cut-pyramid upside down" and an ordinary glass pane is placed at the upper surface. This chamber should be isolated, therefore the gap between the oven chamber and the outer box is filled with cotton *to form a thick heat encapsulation at the side and underneath.* Dietz (1954) showed that a glass with 0.10% $Fe_2O_3$ has $\boldsymbol{\tau}$ about 0.8–0.89 for visible light (0.4 – 0.8 μm) and is fluctuating about 0.69-0.8 until the wavelength of 2.55 μm. This glass becomes substantially opaque for wavelength in the range of 2.75 – 3.5 μm. If $Fe_2O_3$ content is high, the glass will absorb in the infrared of the solar spectrum.
Suharta *et al*. (1999) utilize this fact finding to design their solar box cooker. They use triple glazing cover to create an upper heater to get a homogenous temperature in the oven chamber and to reduce condensation when the cooker is used for cooking. A little water vapor is needed to maintain the plywood not too dry to avoid splitting.

Suharta *et al.* (2000a) found that the heat conduction losses are small compare to total heat loss. Plante (1983) also states that the radiation loss is only one fifth of the convection losses at 10 mph wind speeds.
The total heat loss factor to the upper side can be written in term of heat resistance, as:

$$U_L = \frac{1}{R_{oven} + R_{bottomair\,gap} + R_{upperair\,gap} + R_{wind}} = \frac{1}{R} \tag{4}$$

The thermal loss ($Q_L$) to the upper side per unit area is written as:

$$Q_L = U_L\,(T_{ov} - T_a) \tag{5}$$

$Q_L$ in term of convection and radiation heat transfer coefficient between the plate and the bottom glass is written as:

$$Q_L = Q_{Lp\text{-}bg} = [h_{CV\,p\text{-}bg} + h_{R\,p\text{-}bg}]\,(T_{ov} - T_{bg}) = (T_{ov} - T_{bg}) / \mathbf{R_{oven}}$$

$$= \left[\frac{N_u\,k}{L} + \frac{\sigma\,(T_{ov}^2 + T_{bg}^2)\,(T_{ov} + T_{bg})}{\frac{1-\varepsilon_{bg}}{\varepsilon_{bg}} + \frac{1}{F_{bg-p}} + \frac{(1-\varepsilon_p)A_{bg}}{\varepsilon_p\,A_p}}\right](T_{ov} - T_{bg}) \tag{6}$$

Let us imagine that the absorber plate shaping the oven chamber is flat. This "flat absorber" area ($A_p$) will be bigger than the glazing area ($A_{bg}$). This leads to a dominant heat loss to the upper side. The sensor to record the oven temperature ($T_{ov}$) is located at the center of the oven chamber, therefore the distance between the plate and the bottom glass is assumed half of the chamber height. $T_{ov}$ replaces ($T_{p,m}$).
If the absorber is equal to the bottom glazing area, the view factor ($F_{bg\text{-}p}$) is unity.

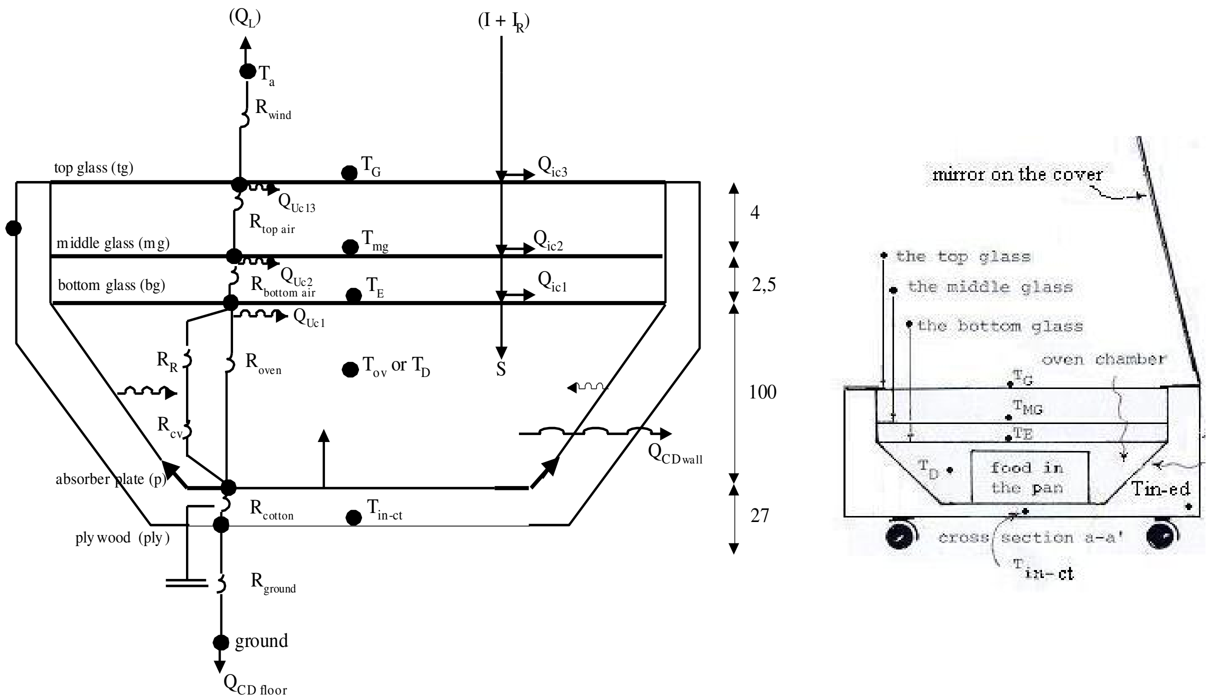


**Fig. 1 The thermal network of solar box cooker type HS.**
Black ball is the points where the thermometer sensors are placed.
$T_D = T_{ov}$ is the temperature sensor inside the oven chamber
$T_E = T_{bg}$ is the temperature on the bottom glass
$T_{mg} = T_{MG}$ is the temperature on the middle glass
$T_G$ is the temperature on the aperture.

The thermal losses from the aperture per unit area is written as:

$$Q_L = Q_{Laperture\text{-}ambient} = [\, h_{wind} + h_{R\ tg\text{-}Ta} \,] (T_{tg} - T_a) = (T_{tg} - T_a) / R_{wind}$$

$$= [(h_{wind}) + \varepsilon_{glass}\, \sigma \frac{(T_{tg}^2 + T_{sky}^2)(T_{tg} + T_{sky})(T_{tg} - T_{sky})}{(T_{tg} - T_a)}] (T_{tg} - T_a) \qquad (7)$$

where: $T_{tg}$ is the temperature on the top glass.
$T_{sky}$ is the sky temperature, see Duffie & Beckman (1980: 203).

If $Q_L$ between the node (see **Fig 1)** is assumed the same, it means no thermal energy is absorbed by the upper covers, but this is not true. It is difficult to distinguish the multiple reflection of solar irradiation and thermal radiation that influence $T_{bg}$, $T_{mg}$, $T_{tg}$ from which the convection and radiation heat transfer coefficients are calculated to get $R_{bottom\ air\ gap}$ and $R_{upper\ air\ gap}$ .It is an iterative process and time consuming. Target of this research work is to design a cheap solar box cooker and a simpler method to rate the performance is needed.

## 3. DERIVE THE HEAT LOSS COEFFICIENT BASED SOLELY ON THE OVEN TEMPERATURE.

Mullick *et al.* (1987) proposed a guideline to evaluate their solar box cooker, as:

$$F_1 = \eta_o / U_L = \{(T_p - T_a)/ I \}_{stagnation\ condition}$$

where I is the incoming solar radiation (insolation) on horizontal surface. $\eta_o = \tau\alpha$.
Their cooker would have $F_1 = 0.12$ at assumed stagnation condition at which I = 800 Watt/m$^2$, $T_a$ = 15 C and $T_p$ = 111 C. They predicted a possible range of $F_1$ is between 0.12 – 0.16.
Duffie and Beckman (1980:189, 246) define $(\tau\alpha)$ as the ratio of the absorbed solar radiation by the system (S) to the insolation, as: $S = (\tau\alpha)$ I. In a sunny day, the contribution of the diffuse and ground reflected radiation are low so that the used of transmittance–absorbtance of the beam value, $(\tau\alpha)_b$, is a reasonable assumption.
In a way to reach the plate, part of solar irradiation absorbed by the glazing cover. Of the radiation passing through the cover is striking the absorber plate, part of it is then reflected back to the cover. Part of this reflected radiation is absorbed in the glass cover and the rest is reflected back to the plate. This multiple reflection is assumed to be diffuse and continues so that the energy ultimately absorbed by the glazing cover. If the energy absorbed by the glass is taken into account, an effective transmittance–absorbtance is used.
Duffie and Beckman (1980: 229-3; 248; 251-8) made assumption that for a single cover of normal glass in a non selective collector, if the covers absorb about 4% of the insolation then $(\tau\alpha)_e = 1.01(\tau\alpha)$. For a double covers, $(\tau\alpha)_e = 1.02\ (\tau\alpha)$. This parameter is independent for incident angle less than 40$^o$ or 50$^o$.

Continuing these ideas, Suharta *et al*. (1999) defined a model to evaluate the performance of their solar box cooker based solely on the oven temperature recorded to simplify the mathematics as the oven temperature has covered the nature and surrounding environment effect. Since 1995, they tested revamping designs of solar cooker through technology transfer training in which 5-40 units were made simultaneously. Participants of various education levels are able to point the best cooker by comparing the development of the oven temperature profiles, see Suharta *et al.* (2002).

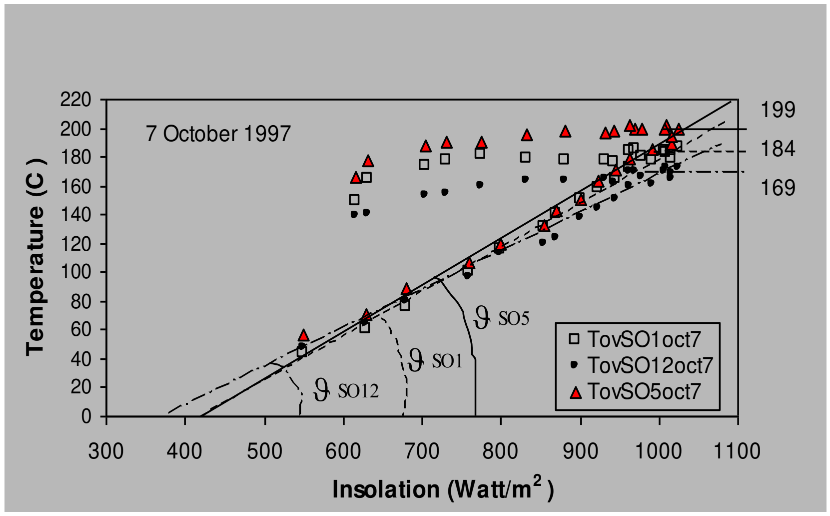


**Fig. 2 The oven temperature of 3 solar box cooker type HS7033**

A higher peak of $T_{ov}$ profile indicates a better cooker, which also proves cook faster. The peak of $T_{ov}$ profile recorded in a clear sunny day ripples about constant. They draws $T_{ov}$ versus insolation as shown in **Fig. 2,** then they defined three states, those are:

- before steady state for data in the morning. This morning data is shaping a linear trend, which is then named as a heat collection rate (HCR) that predicts how good this solar box cooker will perform if it is operated in a better insolation.
- quasi steady state data, that are gathering at the hook point. This temperature level is named as "Quasi Steady State Average (QSSAV) Level" that dictates the $\vartheta$ angle of the HCR trendline. It is the peak temperature level. The duration of QSSAV level is called as a stagnation period.
- after steady state for data in the afternoon, which is shaping a polynomial curve.

Suharta *et al.* (2000b) derived the solar energy absorbed by the cooker per unit aperture area, as:

$$S = (\tau\alpha)_{av} (I + I_R) = I (\tau\alpha)_{av} (1 + \rho_m . f_R . b) \quad (8)$$

where $I_R$ is the reflected insolation by the mirror reflector, $\rho_m$ is the reflectance of the mirror, $f_R$ is the design factor and **b** is the surrounding factor.
For the solar box cooker without reflector, b = 0. They use $(\tau\alpha)_e = 1.01\ (\tau\alpha)$ to characterize the optical properties of their solar box cooker, then renamed it to be $(\tau\alpha)_{av}$

Energy Balance. "The rate at which thermal energy enters a control volume minus the rate at which thermal energy leaves the control volume must equal the rate of increase of energy stored within the control volume". There must be a balance between all energy rates. This first law of thermodynamics or the law of conservation of energy on a rate basis must be

satisfied at every instant of time (t). For solar box cooker, the control volume is the box cooker and the *rate* of increase of energy stored within the solar box cooker is $Q_u$. This energy rate is measured in joules per second or Watt.
At an instant time (t):

$$Q_u = S - O_L = A_o \,[\, I\,(\tau\alpha)_{av}\,(1+\rho_m.f_R.b) - (U_L)_{av}\,(T_{ov}-T_a)] \qquad (9)$$

The peak of $T_{ov}$ ripples about constant for a significant period. This means $S = Q_L$ . At noon, the solar incident angle (θ) is zero, this causes a lesser ground and beam reflection hit the mirror, therefore the surrounding factor (b) is assumed equal to zero. By taking the average values of $T_{ov}$ , $T_a$ and I during the stagnation period we get a single value of $U_L$, which then named as $(U_L)_{av}$ . This condition leads to equation below:

$$\frac{(\tau\alpha)_{av}}{(U_L)_{av}} = \left(\frac{\bar{T}ov_{SS} - \bar{T}a_{SS}}{\bar{I}_{SS}}\right) \qquad (10)$$

The parameter at the right side is named as a quasi steady state constant ($C_{QSS}$ ).
Over a time interval (Δt), the amount of thermal energy that enters the box cooker minus the amount of thermal energy that leaves the box cooker must equal to the increase in the amount of energy stored in the box cooker. It is measured in joules. As the insolation fluctuates, an approximate integration technique is carried out to summing up S, $Q_L$ and $Q_u$ over small and equal time intervals. Trapezoid rule is used to fit the mode of recorded data, see Suharta *et al.* (2000a) for the calculation result.
Suharta *et al.*(2000 and 2002) have calculated $(\tau\alpha/U_L)_{av}$ of their solar box cookers. They got $(\tau\alpha/U_L)_{av}$ = 0.1694 for solar box cooker type HS 7033. It has QSSAV level at 199 C at the stagnation period of 11:45-13:30. $(U_L)_{av}$=3.6969 Watt/m$^2$C at $(\tau\alpha)_{av}$=0.623. For a smaller cooker HS 5521, at assummed QSSAV level of 186 C in the period of 13:00-13:15, they got $(\tau\alpha/U_L)_{av}$ = 0.1694. $(U_L)_{av}$=3.8397 Watt/m$^2$C at $(\tau\alpha)_{av}$=0.63.

## 5. RESULT AND CONCLUDING REMARKS.

Equation (1) need 11 parameters: 3 are a function {C'= f(β); f = f($h_{wind}$); $h_{wind}$ = f(ν)}; 6 inputs (σ, N, $\varepsilon_g$, $\varepsilon_p$, ν, β) while $T_{p,m}$ and $T_a$ are the inputs taken from the recorded temperature profile of the tested cookers type HS. Equation (2) needs 12 parameters. Equation (3) needs 8 parameters. Equation (4) is the most complicated way to get $U_L$ . Equation (10) need 5 inputs: τ , α while I, $T_a$ and $T_{ov}$ are the inputs taken from the average data recorded during the stagnation period. Instead of using temperature input from ambient until 210 C with step 10 for example, this numerical experiment applies the recorded $T_{ov}$ and $T_a$ profiles to simulate $T_{p,m}$ and $T_a$ in order to find out the relation between the design factor ($f_R$) and the calculated $U_L$.from various equations.

Result. The insolations when the solar box cookers HS7033, HS5521 and HS5921 were tested are shown in **Fig. 3a.** The recorded $T_{ov}$ profiles, which have a different QSSAV level and a different stag period, are shown in **Fig. 3b**. QSSAV level can be decided upon a brief evaluation on $T_{ov}$ profile. The improvement in the design factor ($f_R$) has improved QSSAV level of the revamping solar box cookers. The insolation on 7 October 1997 drops after the noon so that the peak of $T_{ov}$ profile can not be obtained, while HS5521 was closed between 13:15 and 13:45 to transport it to schools for promotion. In these reason, QSSAV level for HS5521 is assumed 186 C at the stag period 13:00 -13:15, while QSSAV level for HS5921 it is assumed 179 C at the stag period 12:00-12:15. The real stag period of HS7033 is 11:45-13:30 at QSSAV level =199 C.

The equations derived by Klein (1975; 1979) and Chaniwala and Doshi (1989) give a significant change in $U_L$ for various glazing number, see **Fig. 4a.** This calculation applies recorded $T_{ov}$ and $T_a$ of solar box cooker type HS7033 tested at Kerato on 7 October 1997. Based on our design experiences, this high $T_{ov}$ used in this numerical experiment will never be attained in the solar box cooker type HS having 1 or 2 glazing covers. $U_L$ almost the same for various plate and glass emittance, see **Fig. 4b**. Wind speed gives a little effect on the collector according Klein's equations (1975; 1979), see **Fig. 4c**. Chaniwalla and Doshi' equation (1989) show that various thickness of the box cooker effect $U_L$ significantly, see **Fig. 4d.** These numerical experiment results were considered for designing a cheap but a better solar cooker type HS.

$U_L$ calculated using equation (1), (2), (3) and (10) and applies $T_{ov}$ and $T_a$ recorded on 7 October 1997 as input is shown in **Fig. 5a**.
Equation (1) gives $U_L$ in the range 6.9 to 7.3 Watt/$m^2$C.
Equation (2) gives $U_L$ in the range 1.875 to 2 Watt/$m^2$C.
Equation (3) gives $U_L$ in the range 14.8 to 15.5 Watt/$m^2$C. At stagnation period, $U_L$ reach a highest value.
Equation (10) gives $(U_L)_{av}$ = 3.6969 Watt/$m^2$C.

Duffie and Beckman (1980: 209) calculation gives $U_L$ = 4.375 Watt/$m^2$C for three glass covers spaced 25 mm apart, at $h_{wind}$ = 20 Watt/$m^2$C; $\varepsilon_p$= 0.95; $\beta = 45^o$, $T_a$ = 40 C and $T_{p,m}$ = 200 C.

Klein's equation (1979) produces a constant $U_L$ value over all temperature input.
$U_L$ calculated using Klein's equation (1979) and applies $T_{ov}$ and $T_a$ at QSSAV levels of three cookers HS7033, HS5521 and HS5921 is shown in **Fig. 5b.** These $U_L$ values show a linear trend.

If we do not know about the design factor ($f_R$), which effect the QSSAV level achievement, it is difficult to recognize this effect through the numerical experiment as temperature input could be from ambient until 210C with whatever step as prefered with a blank meaning on design factor effect. Based on these facts, it is reasonable to use $(U_L)_{av}$ at QSSAV level to characterize the solar box cooker. It can be calculated in a shorter time. It is the highest value, so, the exaggeration of performance can be avoided.

Concluding remarks.

- This comparison work shows that the way in getting $(U_L)_{av}$ using the equation (10) has proved effective in saving time to compute, so the performance of the revamping design can be investigated easily make the effect of design factor on the $T_{ov}$ achievement can be recognized faster.
- The design factor $(f_R)$ is an important parameter design to produce a higher peak of the $T_{ov}$ profile.
- If direct measurement of $T_{ov}$, I and $T_a$ are available, it is convenient to calculate $(U_L)_{av}$, then $Q_L$, $Q_u$ and $\eta$.
- This simple way to rate the performance of the solar box cooker type HS can be explained easily to a wider education level of audience in the context to popularize the application of renewable energy.

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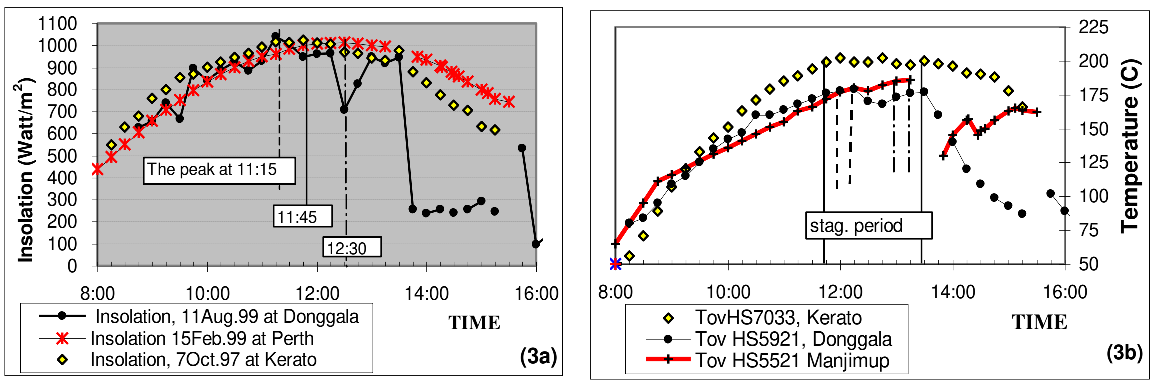



**Fig. 3a** The insolation data when the solar box cookers type HS7033; HS5521 and HS5921 are tested. The peak of insolation on 11 Aug 1999 at 11:15; on 7 Oct 1997 at 11:45 and on 15 Feb. 1999 at 12:30.
**Fig. 3b** The oven temperature profiles of HS7033, HS5521 and HS5921. The stag. period of HS7033 is 11:45-13:30 at QSSAV level =199 C; of HS5521 is 13:00-13:15 at QSSAV level =186 C and of HS5921 is 12:00-12:15 at QSSAV level = 179 C.

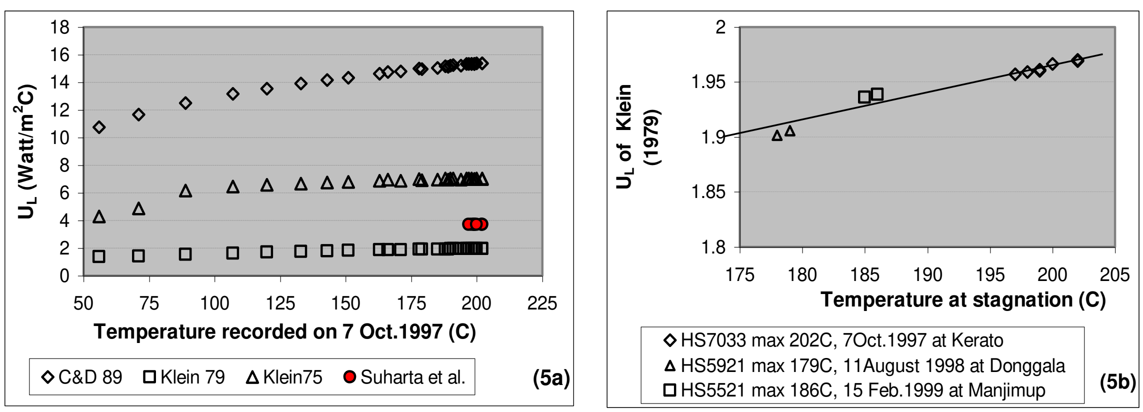
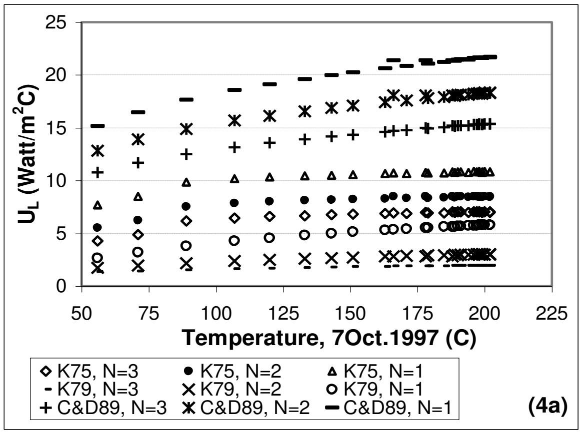
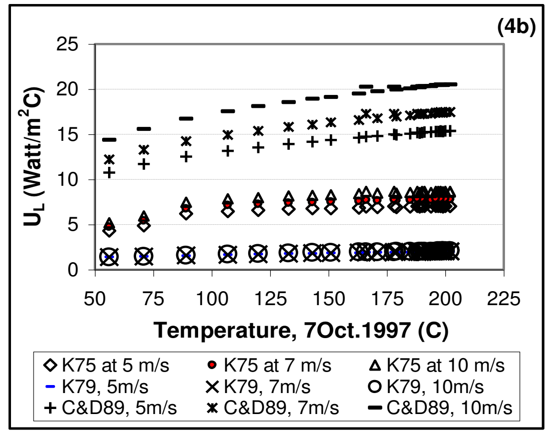
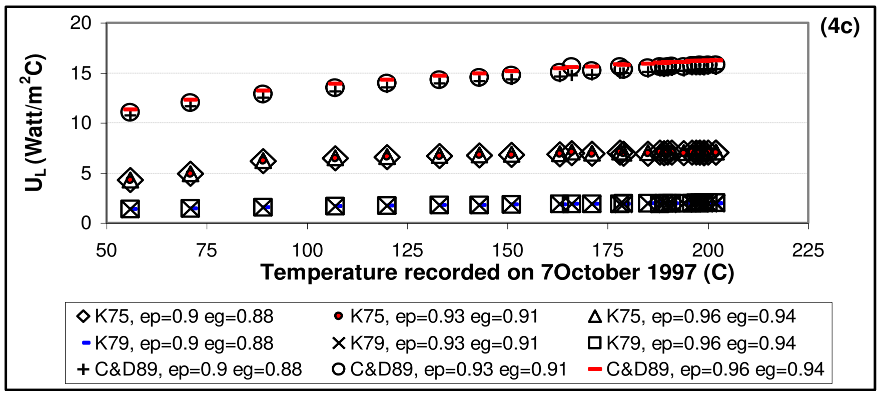



**Fig. 5a** $U_L$ calculated using equation (1), (2), (3) and (10) and apply $T_{ov}$ recorded on 7 October 1997. $U_L$ shows a maximum value at stagnation period.
$U_L$ calculated using Klein's equation (1979) produce almost a constant value over all temperature input.
**Fig. 5b.** $U_L$ values calculated using Klein's equation (1979) and apply $T_{ov}$ at QSSAV level of three cookers (HS7033, HS5521 and HS5921) show a linear trend.



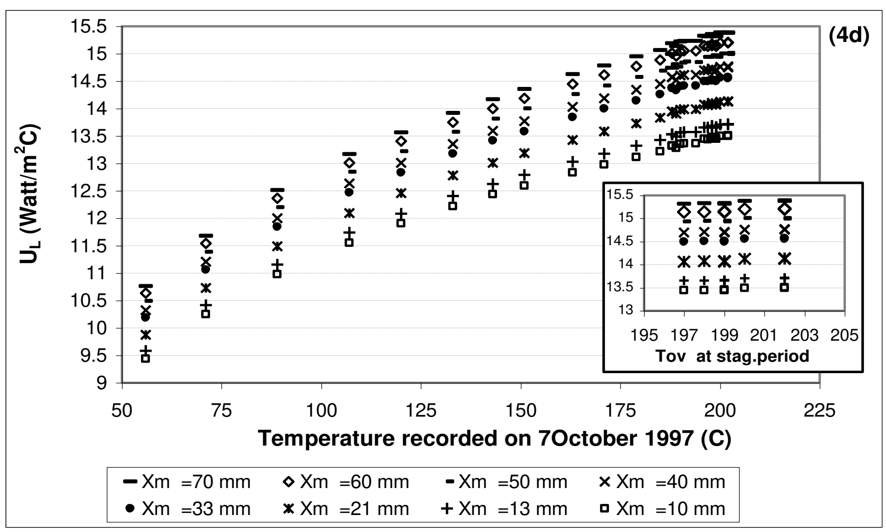




**Fig. 4a** Klein's (1975;1979) and Chaniwala and Doshi's (1989) equations give a different $U_L$ for different number of glass covers (N).

**Fig. 4b** Various wind speed gives a little effect on $U_L$ according Klein's equations (1975; 1979).

**Fig. 4c** They all shows that $U_L$ almost the same for various plate and glass emittance.

**Fig. 4d** Chaniwalla and Doshi shows that various thickness of box cooker effects $U_L$ significantly.