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Evaluating the optimum load range for box-type solar cookers

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ABSTRACT

This paper introduces a new concept of Optimum Load Range (OLR) for solar cookers. OLR gives the load values for which cooker preferably shows good thermal as well as good cooking performance; it may be considered a crucial parameter for solar cookers. This OLR concept is based on the dependence of rate of rise of load temperature on different heat transfer processes between load and cooker interior. This concept illustrates solar cooking in two simple steps. The total time required to complete these steps puts an essential constraint for cooking of any load amount. The maximum value of load (upper limit of OLR) till which cooker shows satisfactory cooking may be determined from this constraint. This constraint requires determination of two OLR parameters which are $t_{\text{step I}}$ and $t_{\text{step II}}$. The load for which cooker remain almost 30% efficient, may be referred as lower limit (minimum value) of OLR. For the verification of OLR, experimental studies have been conducted with a solar cooker named SFSC. The OLR parameters along with different thermal performance parameters (TPPs) (second figure of merit (F_2), utilization efficiency (η_u) etc.) suggested by different researches for solar cookers in water load condition have been computed from the measured thermal profiles of different loads (0.8–3.0 kg). From the curve analysis of different TPPs with load, the existence of upper limit of OLR is observed. The values of rate of rise of load temperature at water temperatures 80, 85 and 90 °C for different loads also confirm the same. The OLR of SFSC is found to be 1.2–1.6 kg.

1. Introduction

Fast depletion of conventional energy resources, increasing environmental degradation and growing radiation threats of nuclear fuel have generated renewed interest of scientists in solar energy research. Solar thermal technologies have a special relevance for countries which have scarcity of conventional fuel resources but have good solar potential i.e. radiation about 4.5–6 kWh/m^2/day with average 280 clear days. Among various solar thermal appliances, solar cookers are of utmost importance as these directly affect mass population. The current cooking practices are unhealthy and will be unavailable to the future generation [1,2]. Solar cooking may pave a path for sustainable development for nations having high solar potential. For the design development as well as for the optimization of different components of solar cookers, various experimental and theoretical studies have been conducted by many authors [3–7]. Besides, the design development of solar cookers, different authors have also defined and used several parameters to test the performance of solar cookers [6,8–18]. Most of the defined parameters are determined with water load. Mullick et al. [10], El-Sebaii and Ibrahim [15] and Kumar [16] have studied different characteristic parameters which are also called as thermal performance parameters (TPPs) (second figure of merit (F_2), utilization efficiency (η_u), specific boiling time (t_s) and characteristic boiling time (t_c)). Several studies have been done to determine TPPs with variation in water loads but assessment of optimum load for good performance of a solar cooker has not been addressed so far.

In the present study a concept of optimum load range (OLR) for solar cookers is introduced. This is based on the dependence of rate of rise of load temperature (R_T) on different heat transfer processes between the load and the cooker interior. Different heat transfer processes for different amount of loads and their impact on cooking have been explained in detail. Solar cooking is a two steps process as per the phenomenological concept of OLR discussed in this paper. The time required to complete these steps have been referred as $t_{\text{step I}}$ and $t_{\text{step II}}$, respectively. The total time required to complete these steps puts an essential constraint for cooking of any load amount. The maximum value of load (upper limit of OLR) till which cooker shows satisfactory cooking may be determined from this

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Nomenclature

A_p	aperture area of the cooker (m^2)
F_1	first figure of merit (K m^2/W)
F_2	second figure of merit
I_s	intensity of total solar radiation on horizontal surface (W/m^2)
$\overline{I_s}$	average solar radiation (W/m^2)
I_s^*	reference solar radiation (W/m^2)
M	mass of load (kg)
$(MC)_w$	thermal capacity of water (J/K)
q_{al}	available rate of heat (power) at the lid of vessel (W)
q_{aL}	available rate of heat to the load (W)
q_{ap}	available rate of heat at absorber plate (W)
$q_{c,a\text{-}L}$	rate of heat transfer from air to load through convection (W)
$q_{c,s\text{-}a}$	rate of heat loss from cylindrical side of vessel to air through convection (W)
$q_{d,p\text{-}b}$	rate of heat transfer from absorber plate to bottom of vessel through conduction (W)
$q_{d,b\text{-}L}$	rate of heat transfer from bottom of vessel to load through conduction (W)
q_{lL}	overall rate of heat loss from the load (W)
$q_{r,l\text{-}L}$	rate of heat transfer from lid to load through radiation (W)
$q_{r,s}$	rate of heat loss from cylindrical side of vessel through radiation (W)
q_{uL}	rate of useful heat transfer to the load
R_T	rate of rise of load temperature (°C/min)
R_T^*	reference rate of rise of load temperature (°C/min)
T_a	ambient temperature (°C)
$\overline{T_a}$	average ambient temperature (°C)
T_w	water load temperature (°C)
Δt	time interval (min)
t_c	characteristic boiling time (min m^2/kg)
t_s	specific boiling time (min m^2/kg)
$t_{step\ I}$	time required to complete step I (min)
$t_{step\ II}$	time required to complete step II (min)
η_u	utilization efficiency
δ_{air}	air gap between lid and load (mm)

constraint. The load for which cooker remain almost 30% efficient, can be referred as lower limit (minimum value) of OLR.

For the experimental verification of OLR, on-field studies have been conducted with a solar cooker named SFSC. In this study thermal profiles of SFSC under different water load conditions (0.8, 1.2, 1.6, 2.0, 2.2, 2.6 and 3.0 kg) have been measured. The OLR parameters ($t_{step\ I}$ and $t_{step\ II}$) along with different TPPs have been computed from the measured thermal profiles of different loads. The values of reference rate of rise of load temperature (R_T*, defined in paper) at water temperatures 80, 85 and 90 °C for different loads also confirm the same. The OLR of SFSC is found to be 1.2 to 1.6 kg.

2. Different load dependent parameters

To analyze the performance of a solar cooker with water load a number of parameters have been suggested and discussed by many authors [6,8–18]. This section includes only those parameters which are determined in the present study.

2.1. Second figure of merit (F_2)

In a solar cooker the time required for sensible heating of a known quantity of water up to the boiling point depends on the climatic variables such as solar radiation and ambient temperature. For the good thermal performance of a solar cooker it is equally important that there is a good heat transfer to the contents of the vessel and the heat capacity of the cooker interiors is small. The second figure of merit (F_2) is a parameter which is independent from the climatic variables and plays a roll of controlling factor in the sensible heating of the load. It permits evaluation of a solar cooker and provides comparison between different solar cookers.

To determine this parameter the sensible heat test is carried out with water load and without reflector as per procedure recommended by Bureau of Indian Standards (BIS) [9,11,12]. This experiment should be done within ±1:30 h of the solar noon with the intensity of radiation above or equal to 600 W/m^2. The amount of full water loads for this test should be calculated according to 8.0 kg water/m^2 and the load should be equally distributed among all pots. From the experimental sensible heating curve (such as in Figs. 2 and 3) the second figure of merit (F_2) is computed using the following relation:

$$F_2 = \frac{F_1 (MC)_w}{A_p \Delta t} \ln \left[\frac{1 - \frac{1}{F_1}\left(\frac{T_{w1} - \overline{T}_a}{\overline{I}_s}\right)}{1 - \frac{1}{F_1}\left(\frac{T_{w2} - \overline{T}_a}{\overline{I}_s}\right)} \right] \quad (1)$$

where A_p is the aperture area of the cooker, $(MC)_w$ is the thermal capacity of water; Δt is the time, during which water temperature rises from T_{W1} to T_{W2}. $\overline{I}_s$ is the average solar radiation (W/m^2) and $\overline{T}_a$ is the average ambient temperature for the time period Δt. F_1 (K m^2/W) is the first figure of merit; this is determined from the stagnation test under no load condition [9–12] using following relation:

$$F_1 = \frac{(T_{ps} - T_{as})}{I_s} \quad (2)$$

where T_{ps}, T_{as}, I_s are the absorber plate temperature, ambient temperature and the insolation on the horizontal surface at the time when plate temperature stagnated.

The value of F_2 has been reported in a number of Refs. [9,12,15–21], for example in the previous paper of authors [20], the value of F_2 is reported 0.466 for 1.2 kg mass of water equally distributed in two pots for the developed system (for which $A_p = 0.167$ m^2, $F_1 = 0.116$ °C m^2/W, $\overline{I}_s = 830$ W/m^2, $\overline{T}_a = 34.6$ °C, $T_{w1} = 61.9$ °C, $T_{w2} = 94.5$ °C).

2.2. Overall utilizable efficiency (η_u), specific boiling time (t_s) and characteristic boiling time (t_c)

Overall utilizable efficiency η_u, specific boiling time t_s (min m^2/kg) and characteristic boiling time t_c (min m^2/kg) as discussed by Khalifa et al. [8] and, Olwi and Khalifa [11] for the box type solar cookers, are calculated by using following relations:

$$\eta_u = \frac{(MC)_w (T_w - T_a)}{\overline{I}_s A_p \Delta t} \quad (3)$$

$$t_s = \frac{\Delta t A_p}{M} \quad (4)$$