Thermal analysis of paraboloid dish type solar cooker

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Abstract. This study presents thermal performance analysis of paraboloid dish type solar cooker under steady and unsteady state conditions. The performance is analyzed under two conditions: firstly steady state operation of cooker subjected to radiation and convection losses from vertical cylindrical surface & top cover of the cooker and secondly unsteady state operation of cooker associated with mass transfer from cooker to the surrounding when heat is supplied at a constant rate to the cooker after saturation pressure is reached. Under steady state condition, predicted value of average thermal efficiency of cooker is 54%, first and second figures of merit are respectively 1.7 and 3.4, time taken to raise the temperature to 95°C is 24 minutes and time for boiling is 26 minutes. The difference in predicted and experimental results can be attributed to unaccounted losses from the cooker surface and operational error. In the second case, energy leaves the cooker with steam at a rate of 0.91 kW, accompanied by heat losses by convection and radiation from the outer surface of the cooker.

1. Introduction

The world energy demand has a dynamic property which is expected to rise by more than 25% in next 20 years [1]. Asia is catching up with North America and Europe in maximum energy consumption with India and China majorly contributing to increase in energy demand in Asia. On the sector wise division of energy consumption, industrial sector accounts for more than 50% of the World's energy consumption followed by transport sector and building sector.

Energy usage is very different in rural and urban households. An energy usage survey conducted for rural India revealed the fact that rural energy requirement is around 510 kcal(2.13MJ) per capita daily [2]. Rural India energy usage is dedicated mostly for lighting and cooking. Firewood, dung cake, agriculture residues, kerosene are used as fuel for cooking which accounts for thermal energy consumption of rural India [3]. These cooking techniques and practices are inefficient and harmful for health contributing to high levels of indoor air pollution. Burning biomass and firewood produces carbon dioxide and green house gases and usage of forest wood for meeting energy demand of rural population leads to deforestation. Renewable sources of energy addresses these problems and are found to be a clean and secure source of energy. Solar cookers have been used since very long time to partly meet the energy requirement for cooking because of inherent simplicity in construction, operation and reliability.

Horace de Saussure, a Swiss scientist is known as the first person to make a solar collector in 1767 which was later used to cook food [4]. Box type cooker is a very old technology which is robust in manufacturing and application. The performance of the cooker depends on several factors like radiation received, environmental conditions and materials used. Thermal performance of solar box
type cooker is tested following two tests: stagnation temperature test and load test [5]. First figure of merit is derived from stagnation temperature test which is defined as the ratio of optical efficiency to heat loss factor. From the designer’s perspective, high optical efficiency and a low heat loss coefficient is desirable. Second figure of merit is derived from load test which reflects the heat transfer capacity of the cooker. The figures of merits are affected by increase in load and number of cooking vessels [6]. Thermal performance analysis of box type solar cooker in different climatic conditions following these tests had been a topic of interest for many researchers [7, 8]. A solar box type cooker made of recyclable material (cardboard) was made and tested in the month of January when the days are cloudy till 11am and solar radiation varied between 350-1050 W/m², ambient temperature varied between 26°C to 30°C and average wind speed was1.26 m/s [9]. It was observed that thermal efficiency increased from 50% to 70% from 11 am – 3pm whereas the efficiency was less than 50% during morning time when it was cloudy. In past, researchers have also made modification in the design of box type solar cooker to improve its heat transfer characteristics. Energy and exergy analysis of a box type solar cooker with finned absorber surface was conducted and its performance was compared with conventional cooker [10]. The finned type cooker showed better heat transfer characteristics than conventional cooker. Aliyu et al.[11] developed a double exposure solar cooker to increase incident solar radiation on the absorber surface and compared its performance with conventional box type solar cooker. It was observed that oven air temperature and absorber plate temperature for double glazed cooker were significantly larger than that of conventional cooker. Also cooking time also reduced significantly with the new design. A truncated pyramidal shaped solar cooker was fabricated and tested by a group of researchers from Nigeria following BIS Test procedure [12]. The first and second figure of merit were obtained as 0.12 and 0.410 respectively which meets the prescribed limit set by BIS for these parameters. The pyramidal shaped absorber enclosure enhanced the heat trapping capacity of the cooker. Cuce et al. [13] conducted a comprehensive review of solar cooking technology covering the historic overview of the technology, detailing various types of solar cookers and design parameters affecting performance of cooker. Thermodynamic analysis of solar cooker with and without thermal storage was discussed along with economic feasibility, environmental impact and prospect of these systems. Thermal performance analysis of five different solar cookers was conducted at Central Arid Zone Research Institute, Jodhpur, India by a group of researchers [14]. Of these five cookers, two were of reflector type, two hot box type and one uses flat plate collector. A comparative study of these cookers showed that thermal efficiency of hot box type solar cooker was highest among all and has greater potential to meet future energy demand for cooking. It is customary in concentrating type cookers to position cooking pot without cover (bare surface) at the focal point. This adversely affects the performance of cooker and cooking time is susceptible to the wind speed due to increased losses from the bare surface [14]. Experiments were conducted in Delhi having Fresnel and paraboloidal reflector of 1.2 m diameter and found that if speed of wind goes beyond 10 km/h, maximum temperature cannot exceed 80°C whereas if wind speed is reduced to 3 km/h, water in the pot reaches its boiling point within half an hour. Solar cooker performance in various climatic zones has been studied by researchers. A Jordanian study revealed the performance of two cookers one with black base and another having internal reflecting mirrors and tracking mechanism [15]. It was observed that overall efficiency for cookers with tracking mechanism ranged between 25.3% to 53%. The need of standard test procedure to test the performance of solar cookers was envisioned by researchers. As a result three testing standards for evaluating performance of solar cooksers viz. American Society of Agricultural Engineering (ASAE) Standard S580, The standard developed by the European Committee on Solar Cooking Research (ECSCR) and the Bureau of Indian Standards [16] came into place to evaluate the performance of solar cooker. BIS provide testing standards based on thermal test procedures for box-type solar cookers.

Box type solar cookers are non tracking, fixed type of cookers. This limitation of box type solar cooker made researchers work day and night to provide solution to increase the incident solar radiation on absorber surface so as to increase thermal performance of solar cooker. Consequently
focus shifted from box type solar cooker technology to concentrated solar cooking systems. There are two basic type of concentrating solar cooking technology: parabolic trough type and paraboloid dish type solar cooker. Trough type solar cooker consists of parabolic concentrator with a receiver tube placed along the focal line. The concentrator concentrates the solar radiation on receiver which is converted to thermal energy inside the receiver tube filled with heat transfer fluid. A parabolic trough cooker was designed for facilitating indoor cooking [17]. The cooking stove was placed inside which received the energy for cooking from hot soya bean oil which was heated in the receiver tube of solar parabolic trough collector placed outdoor. Temperature of heat transfer fluid at the cooking stove was found to be 119°C and thermal efficiency of the system was reported as 6%. Various versions of these concentrators have been manufactured and implemented in many countries. Continuing to the development of solar cookers Khalifa et al[18] designed, simulated and tested an oven type solar cooker that received heat from the bottom and side of the cooking pot. Researchers from Tunisia designed, fabricated and tested a dish type solar cooker to determine best cooking period for their climatic condition [19]. Lof [20] studied thermal performance of six different models of solar cooker and also designed concentrating solar cooker. He worked on principles of cooking and explained that during sensible heating, requirement of energy is maximum and after attaining its boiling temperature the heat requirement is quite small. He elucidated that once the food reached its cooking temperature, cooking speed becomes independent of rate of energy input provided that thermal losses are compensated. A fixed focus Fresnel lens solar cooker integrated with building was proposed and tested by Wang et al., [21]. A cavity receiver with bottom reflective cone was used as a fixed receiver to increase system optical efficiency. Researchers had been studying the performance of paraboloidal dish type solar cooker over years to determine various parameters that affect its performance [22, 23, 24]. Mbodji et al. [25] conducted dynamical thermodynamic modelling of parabolic solar cooking system with heat storage and studied heat transfer mechanism between different parts of the system. Heat losses from unglazed cooking pot, its cover and air contained in the pot under different weather conditions shows the dominance of convective heat losses from these components [26]. Transient state heat transfer analysis from different components of the cooker had been studied by Dasin et al.[27] using linear regression analysis. A biaxial manual tracking paraboloidal solar cooker was designed, fabricated and tested by Suple et al.[28] and was found useful in cooking variety of food materials. A cylindrical solar cooker with two axes tracking system was designed and fabricated to track the sun automatically [29]. The two axes tracking enhanced heat transfer properties in the cooking vessel. Kumar et al.[30] studied solar parabolic cooker with integrated PCM based thermal storage. During daytime heat is stored in the thermal storage and also being used for cooking food in the cooking pot. During no sun condition, cooking pot is placed inside an insulated box and heat is supplied to the pot from thermal storage for cooking. Continuing the developments in solar cookers, Hermelinda S. C. [31] proposed a system using 3 absorber pots and estimated cooking power, figure of merits and thermal performance. Thakkar et al. [32] studied thermal performance of a parabolic dish solar cooker using thermic fluid for heat transfer in the receiver. They studied the effect of design criteria, solar insolation and operation parameters on performance of solar cooker. Kimambo, [33] reviewed solar concentrating cookers, test procedures and studied thermal performance of the system in Tanzanian perspective and provided detailed recommendations for the usage, operations, climatic condition under which the system will work efficiently.

The objective of this paper is to conduct thermal analysis of a paraboloid dish type solar cooker under two conditions: firstly steady state operation of cooker subjected to radiation and convection losses from vertical cylindrical surface & top cover of the cooker and secondly unsteady state operation of cooker associated with mass transfer from cooker to the surrounding when heat is supplied at a constant rate to the cooker after saturation pressure is reached.
2. Thermodynamic study under steady state condition

The analysis is carried out for a dish type solar cooker having aperture area \( A_a \), receiver area \( A_p \) and concentration ratio \( C \) as shown in figure 1. Solar energy absorbed by the cooker is the sum of incident beam radiation absorbed by the cooker after reflection and incident beam radiation which falls directly on cooker surface and absorbed by the cooker.

![Dish Type solar cooker](image)

**Figure 1:** Dish Type solar cooker

Under steady state condition, energy absorbed by the cooker is partly transferred to the water inside the cooking vessel and rest is lost to the ambient by convection and radiation. An energy balance of absorber yields the following equation under steady state condition

\[
Q_u = A_a S - Q_L
\]  

(1)

The losses from cooker under steady state condition is due to convection and radiation from the cooker surface to the ambient and is given by

\[
Q_L = Q_{L,C} + Q_{L,R}
\]

(2)

Where

\[
Q_{L,C} = A_p h_c(T_s - T_a)
\]

\[
Q_{L,R} = A_p h_r(T_s - T_{sky})
\]

The convective heat loss is from vertical cylindrical wall and from top of the cooker. Thus, convective heat transfer coefficient \( h_c = h_{c,wall} + h_{c, top} \).

The \( h_{c,wall} \) can be obtained using any of the following two Nusselt number correlations [35] which applies to both laminar and turbulent flow for \( \frac{L/D}{Gr_L^{1/4}} < 0.025 \)

\[
Nu_m = 0.825 + \frac{0.387 Ra_L^{1/6}}{[1 + (0.492/Pr)^{9/16}]^{1/27}} \text{ for } 10^{-1} < Ra_L < 10^{12}
\]

(3a)

Or for laminar flow which holds for all values of Prandtl number

\[
Nu_m = 0.68 + \frac{0.67 Ra_L^{1/4}}{[1 + (0.492/Pr)^{9/16}]^{1/476}} \text{ for } 10^{-1} < Ra_L < 10^9
\]

(3b)

The convective heat transfer coefficient from the top \( h_{c, top} \) is calculated using following relation [35]:

\[
Nu_m = c (Gr, Pr)^n
\]

(3c)

where \( c = 0.54 \) and \( n = 0.25 \)

The Grashof and Rayleigh numbers respectively are defined as:

\[
Gr_L = \frac{g \beta (T_w - T_a) L^3}{\nu^2}
\]

(4)

\[
Ra_L = Gr_L Pr
\]

(5)
The radiative heat transfer coefficient $h_r$ can be obtained using the following equation:

$$ h_r = \sigma \varepsilon \left( T_s^4 + T_{sky}^4 \right) \left( T_s + T_{sky} \right) $$

(6)

Therefore, the overall heat transfer coefficient $U_L$ can be expressed as:

$$ U_L = h_c + h_r $$

(7)

The useful energy gain can be expressed in terms of cooker efficiency factor $F'$ as:

$$ Q_u = A_a F' \left[ S - \frac{U_L}{c} (T_w - T_a) \right] $$

(8)

2.1. Stagnation temperature test

The figure of merit $F_1$ is determined using stagnation temperature test (without load) as described by Mullick et al [5]. Let $T_{pz}$ be stagnation temperature of the cooker and $I_{bz}$ & $T_{az}$ be incident beam radiation and ambient temperature respectively at the time when stagnation temperature is reached. Thus, the first figure of merit $F_1$ is obtained as:

$$ F_1 = \frac{c (\tau a)_b \rho r r^2}{u_L} = \frac{c \eta_0}{u_L} = \frac{r_{pz} - T_{az}}{I_{bz}} $$

(9)

where $\eta_0$ is the optical efficiency of the cooker and is given by

$$ \eta_0 = (\tau a)_b \left[ \rho y + \frac{1}{C} \right] $$

(10)

2.2. Sensible heating test

The tests for the second figure of merit consist of operating the solar cooker with a full load of vessels with contents. The cooker is kept in sunshine in forenoon and water temperature is allowed to rise gradually until it reaches the boiling point.

Thermal analysis is conducted to find the time required to raise temperature of a given mass ‘M’ of a substance from $T_{w1}$ to $T_{w2}$. Let $dt$ be the time required for a known thermal capacity of water $(MC)_w$ to increase its temperature by $dT_w$. Then

$$ Q_u = (MC)_w \frac{dT_w}{dt} $$

(11)

Integrating equation (11) for time interval [0, t] during which mean solar radiation is $\bar{S}$ and average ambient temperature is $T_{a}^{'}$, and water temperature rises from $T_{w1}$ to $T_{w2}$; we get:

$$ t = \frac{(MC)_w C}{A_a F' U_L} \ln \left[ \frac{1 - \frac{U_L (T_{w1} - T_a)}{cS}}{1 - \frac{U_L (T_{w2} - T_a)}{cS}} \right] $$

(12)

The value of $F'U_L$ is obtained from equation (12) as follows:

$$ F'U_L = \frac{(MC)_w C}{A_a t} \ln \left[ \frac{1 - \frac{U_L (T_{w1} - T_a)}{cS}}{1 - \frac{U_L (T_{w2} - T_a)}{cS}} \right] $$

(13)

The product $F'U_L$ cannot be used as a parameter to measure the performance of cooker since it is desirable to have larger value of efficiency factor $F'$ and small overall heat loss $U_L$. Thus, $F'U_L$ will give misleading values. Thus, second figure of merit $F_2$ is defined as $F_2 = F_1 (F' U_L)$ and hence from equation (13) we get

$$ F_2 = \frac{F_1 (MC)_w C}{A_a t} \ln \left[ \frac{1 - \frac{(T_{w1} - T_a)}{F_1 I_b}}{1 - \frac{(T_{w2} - T_a)}{F_1 I_b}} \right] $$

(14)

The second figure of merit is a measure of cooker efficiency factor. It tells about the rate of heat transfer to the food in cooker and heat content of the cooker. The figure of merits $F_1$ and $F_2$ derived are independent of climatic conditions and depends on cooker’s design parameters.
2.3 Boiling time

The empirical time constant \( t_0 \) is a measure of sensible heating time for the cooker with full load under standard test conditions for a given location and is derived from the following relation:

\[
t_0 = \frac{F_1 (MC_w C)}{F_2 A_a} \ln \left[ \frac{1 - \left( \frac{T_{w1} - T_{a0}}{1} \right)}{1 - \left( \frac{T_{w2} - T_{a0}}{F_1 t_{bo}} \right)} \right] \times \frac{1}{3600}
\]  

(15)

where \( T_{a0} \) and \( I_{bo} \) are some arbitrary standard climatic conditions. Thus, the time for sensible heating from ambient temperature up to 100°C is obtained as:

\[
t_{boil} = \frac{F_1 (MC_w C)}{F_2 A_a} \ln \left[ 1 - \left( \frac{(100-T_{a0})}{F_1 t_{bo}} \right) \right]
\]  

(16)

2.4 Thermal efficiency

Thermal efficiency of the cooker is defined as the ratio of useful energy output from the cooker to energy input in the form of solar radiation.

\[
\eta = \frac{Q_u}{A_a I_b}
\]  

(17)

Substituting for \( Q_u \) from equation (8) we get

\[
\eta = F' \eta_0 - \frac{F U_L}{C} \times \frac{(T_w - T_a)}{t_b}
\]  

(18)

3. Thermal analysis under unsteady state condition

Thermal analysis of solar dish type cooker under unsteady state condition is studied when heat is supplied at a constant rate for \( \Delta t \) time after the operating pressure is reached. During the process, mass within the system boundaries does not remain constant. Solar radiation from the concentrator is concentrated at the receiver which supplies heat at constant rate at any instant of time to the pressure cooker through bottom of the cooker. Also the cooker receives solar radiation directly which is absorbed by the cooker surface and is transferred to the fluid inside. The properties of steam leaving the control volume are assumed to remain constant during the entire cooking period. It is also assumed that kinetic and potential energies of the streams are negligible. The cooker is stationary and thus it’s kinetic and potential energy changes are zero. The pressure and thus the temperature in the cooker remain constant. Steam leaves as saturated vapour at the cooker operating pressure. There is no boundary, electrical or shaft work interactions involved.

Writing the microscopic energies of flowing and non flowing fluids by enthalpy \( h \) and internal energy \( u \) respectively, the mass and energy balance for this uniform flow system can be expressed as:

**Mass balance:**

\[
(m_1 - m_2)_{CV} = m_e
\]  

(19)

**Energy Balance:** At any instant of time the cooker receives solar radiation in two ways: i) directly from the sun and ii) solar radiation reflected by the concentrator on the receiver surface. Energy flowing out of cooker is in the form of steam at saturated pressure and convection & radiation losses from surface of cooker to the ambient. Thus, energy balance for the cooker is expressed as

\[
Q_{ln} - Q_{L,c} - Q_{L,r} - m_e h_e = (m_2 u_2 - m_1 u_1)_{CV}
\]  

(20)

Therefore, the total loss from the cooker under unsteady state condition is given by

\[
Q_L = Q_{L,c} + Q_{L,r} + m_e h_e
\]  

(21)
4. Results and discussion

The performance analysis was conducted for a concentrating cooker of aperture area 1.54 m$^2$ made of anodized aluminium film having 85% reflectivity. The cooking pot is made of aluminium which is painted black with dull black paint having outer surface area 0.212 m$^2$. The thermal capacity of the pot is 920 J/kg$^\circ$C. The concentrator is so adjusted that it focuses the solar radiation on the receiver of area 0.037 m$^2$ on which the cooking pot is placed. Experimental data has been taken from the research work done by Gavisiddesh et al. (2011) for the sensible heating test. A mass of 0.5 kg of water has been heated from normal temperature to reach 95$^\circ$C. The temperature of water, ambient temperature and solar radiation has been recorded at an interval of 5 minutes and corresponding thermal efficiency of the cooker is computed and tabulated below in Table 1.

| Time (min) | $T_w$ $^\circ$C | $T_a$ $^\circ$C | $I_b$ | $\eta$ |
|-----------------|----------------|-----------------|------|-------|
| 0               | 38.7           | 38.7            | 650.56 | 0.07  |
| 5               | 48.8           | 37.3            | 653.98 | 0.06  |
| 10              | 57             | 38.1            | 657.35 | 0.07  |
| 15              | 66.6           | 38.2            | 660.67 | 0.07  |
| 20              | 72.8           | 38.2            | 663.95 | 0.04  |
| 25              | 81.5           | 39.1            | 667.18 | 0.06  |
| 30              | 89             | 39.3            | 670.37 | 0.05  |
| 35              | 92.1           | 39.4            | 673.5  | 0.02  |
| 40              | 95.1           | 39.4            | 676.59 | 0.02  |
| **Average**     | **38.63**      | **38.63**       | **663.79** |       |

It is observed that thermal efficiency of the cooker is low whereas predicted thermal efficiency of the cooker is 54%. This implies that energy losses from the cooker are very large and are not accounted in the thermal analysis of the system. Also maybe climatic conditions were also not favourable for the operation of the system. A graph of thermal efficiency vs. ($T_w - T_a$)/$I_b$ is plotted which shows linear variation and is shown in figure 2. From the plot we obtain the following:

$F'\eta_0 =$ intercept of the straight line on vertical axis = 0.0828
$F'U_1/C =$ slope of the straight line = 0.6288.

For the given dish type cooker with optical efficiency $\eta_o = 0.72$ and concentration ratio $C = 41.6$, we obtain $F' = 0.11$ and $F'U_1 = 26.2$ W/m$^2$K.

4.1 Predicted and Experimental Time for Cooking

From equation (12) we calculate the time taken to raise temperature of water from $T_{w1} = 38.7^\circ$C to $T_{w2} = 95.1^\circ$C as $t = 24$ minutes whereas the corresponding time obtained experimentally was 40 minutes as tabulated in Table 1.

The difference in time between the predicted and actual cooking time maybe attributed to the fact that while doing thermal analysis of the cooker under steady state condition we do not consider heat loss due to evaporation and losses due to irreversibilities occurring in the system. It may also be accounted for
operational errors like defocusing, heat loss while measuring temperature of water etc. These may account for additional heat losses from the cooker consequently resulting in increase in cooking time.

4.2 First & Second Figure of Merit and Boiling Temperature
The first and second figures of merit are calculated using equation (9) and equation (14) respectively and we obtain $F_1 = 1.7$ and $F_2 = 3.4$.
The boiling time has been plotted for different values of the function $(100 - T_a)/I_b$ and is referred as the characteristic curve for cooker and is shown in figure 3. It is observed that boiling time is significantly affected by climatic variables. It increases with increase in value of the function $(100 - T_a)/I_b$ and takes an infinite value for $(100 - T_a)/I_b > 0.13$. This shows that cooker will not be able to cook if solar radiation is very low.

4.3 Energy loss from cooker in steady state condition
The convective heat loss from the cooker is due to convection losses from vertical wall and top of the cooker. The convective heat transfer coefficient $h_c = h_{c,\text{wall}} + h_{c,\text{top}}$ is calculated using equations (3a and 3c) and is obtained as $h_c = 6.6 \text{ W/m}^2\text{K}$. The radiative heat transfer coefficient $h_r$ is calculated using equation (6) and is obtained as $h_r = 6.7 \text{ W/m}^2\text{K}$. Therefore, overall heat transfer coefficient of the cooker is obtained as $U_L = 13.3 \text{ W/m}^2\text{K}$ and the total energy loss from cooker is $177.7\text{W}$.

Figure 2: Graph showing the variation of thermal efficiency of cooker as a function of $(T_w - T_a)/I_b$.

Figure 3: Characteristic curve of the cooker
4.4 Energy loss due to mass transfer

When heat is transferred to the cooker after saturation pressure is attained for 20 minutes, steam leaves the cooker at saturation pressure. Saturation conditions exist in the cooker at all times. The amount of liquid that evaporated in 20 minutes is computed to be equal to 0.405 kg with a mass flow rate of $m = 3.38 \times 10^{-4}$ kg/s. The kinetic and potential energies of the exiting steam is negligible compared to enthalpy $h_e = 2706.3 \text{ kJ/kg}$ of the steam and hence are disregarded. Therefore, rate at which energy is leaving the cooker with steam is equal to product of mass flow rate and total energy of the steam per unit mass.

$$E_{mass} = m h_e = (3.38 \times 10^{-4} \text{ kg/s}) \times 2706.3 = 0.91 kW$$

5. Conclusions

Thermal analysis of dish type solar cooker is conducted to identify heat transfer processes in the system. Heat losses from the cooker surface are majorly due to convection and radiation under steady state condition. The figures of merits $F_1$ and $F_2$ are good indicators for the performance of solar cooker. A high value of $F_1$ indicates high optical efficiency and low overall thermal loss factor. A high value of $F_2$ indicates high heat transfer efficiency factor, high optical efficiency and low heat capacity of the cooking pot for full load of water. The impact of climatic conditions on performance of solar cooker can be studied from the analysis of boiling time. The characteristic curve for the cooker suggests range of the parameter $(100 - T_a)/I_b$ beyond which water will not boil in a finite time i.e., suggests environmental condition under which cooker cannot cook. In contrast to steady state operation, heat loss due to mass transfer is also accounted for while calculating energy losses from the system. Energy of the exiting steam is represented in terms of its enthalpy.

6. Nomenclature

| Symbol | Description |
|--------|-------------|
| $\alpha$ | Absorptivity of receiver |
| $\tau$ | Transmissivity of cover |
| $(\tau \alpha)_b$ | Absorptivity- transmissivity product for beam radiation |
| $\rho$ | Reflectivity of paraboloid dish collector |
| $\gamma$ | Intercept factor |
| $\varepsilon$ | Emissivity |
| $\sigma$ | Stefan Boltzmann constant, W/m²K⁴ |
| $A_a$ | Aperture area, m² |
| $A_p$ | Receiver area, m² |
| $C$ | Concentration ratio |
| $D$ | Diameter of cooker |
| $F_1$ | First figure of merit |
| $F_2$ | Second figure of merit |
| $F'_c$ | Collector efficiency factor |
| $Gr_L$ | Grashof number |
| $h_c$ | Convective heat transfer coefficient, W/m²K |
| $h_e$ | Enthalpy of fluid at exit, kJ/kg |
| $h_r$ | Radiative heat transfer coefficient, W/m²K |
| $I_b$ | Incident beam solar radiation, W/m² |
| $L$ | Height of cooker |
| $m$ | Mass, kg |

| Symbol | Description |
|--------|-------------|
| $(MC)_w$ | Heat capacity of water, J/°C |
| $Ntu_m$ | Mean Nusselt number |
| $S$ | Solar beam radiation per unit aperture area absorbed by the cooker, W/m² |
| $Ra_L$ | Rayleigh number |
| $T_{w1}$ | Initial water temperature, °C |
| $T_{w2}$ | Final water temperature, °C |
| $T_a$ | Average ambient temperature |
| $t$ | Time, s |
| $Q_u$ | Rate of useful heat gain, W/m²K |
| $Q_l$ | Losses from the absorber, W/m²K |
| $U_1$ | Overall heat loss coefficient, W/m²K |

Suffix

| Suffix | Description |
|--------|-------------|
| 1 | initial |
| 2 | final |
| e | exit |
| c | Convection |
| r | Radiation |
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