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Convection Heat Loss Characterization for Solar Concentrators

Mahesh M. Rathore[1], Dr. Ravi M. Warkhedkar[2]

[1]Research Scholar, Dept of Mech. Engg. Govt. Engineering College Aurangabad, India,
[2]Department of Mechanical Engineering, Govt. College of Engineering, Karad, India,
Corresponding author: mmrathore@gmail.com

Abstract . New protocol for evaluation of thermal performance of solar cooking system is being proposed herewith. There are a few standards reported in the literature for testing and evaluation of thermal performance of solar concentrators based on sensible heating of working fluid. The earlier standard measures only the cooking efficiency and cooking capacity. Apart from thermal efficiency of solar cookers, there is an urgent need to look into other important parameters of the cooker such as its stagnation temperature, cooking capacity, cost per watts delivered, weight of the cooker, ease of handling and aesthetics. The characterization of a concentrator at its operating temperature settles appropriate size and type of concentrator for any thermal application. The proposal will also serve as standard testing procedure since it can easily be understood by layman who wishes to use one.

Keywords: Solar Cooker Tests, Cooker Efficiency, cooking power, Standardization in Tests and Reporting.

Nomenclature

A_p = aperture area of dish concentrator, m^2
A_a = area of absorber surface, m^2
C = concentration ratio ,
C_p = specific heat, J/kg.K
F_R = heat removal factor,
h = convective heat transfer coefficient, $W/m^2.K$
h_{fg} = enthalpy of vaporization of water, J/kg
h_{sup} = enthalpy of superheated steam, J/kg
I_{bn} = normal intensity of radiation, W/m^2
$\dot{i}_{av}$ = reference solar intensity, W/m^2
k_f= thermal conductivity of air, W/m.K
m_w = mass of water, kg
m_s = mass of steam, kg
Q_{cond} = conductive heat loss rate, W
Q_{conv}= convection heat loss rate, W
Q_L = heat loss rate from receiver, W
Q_r = concentrated heat rate on receiver, W
Q_s = energy incident rate on dish, W
Q_u = useful energy rate, W
Q_{un} = normalized useful energy rate, W
Q_{rad} = radiative heat loss rate, W
Q_{rad} = radiative heat loss rate, W
Q_{sup} = heat of superheated steam, W
T = surface absolute temperature, K
T_∞ = overall heat loss coefficient, K
T_{sat} = saturation temperature, K
T_{sup} = temperature of superheated steam, K
T_1 = initial temperature of water, K
U_L = overall heat loss coefficient, $W/m^2.L$
x = dryness fraction of steam.

Greek symbols

η_c = efficiency of concentrator
η_o= optical efficiency of concentrator
η_n = normalized efficiency of concentrator
η_r = efficiency of receiver
α = absorptivity of absorber surface,
ρ = reflectivity of surface
ε = emissivity of surface
σ = Stefan Boltzmann Constant,
□ = difference in quantity,
φ = tilt angle of receiver, radian

I. INTRODUCTION

A large number of solar cookers have been developed in many countries. These cookers are broadly classified as indirect focusing type or solar ovens (1, 2), direct focusing type [3, 4], indirect or box-type [4 - 6], and advanced solar cookers [10,11]. The box solar cookers/ovens are designed for low temperature cooking applications and solar concentrators for medium and high temperature applications. Different test standards are developed and followed worldwide for testing of the 'Solar Cookers'. The test standards normally deliver technical information like thermal efficiency; cooking power, heating/cooling rates etc. under standard or normalized conditions. This information may be useful only for the test centers.

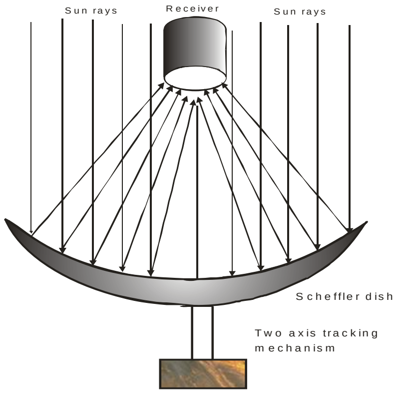


Fig.1 Principle of point focus concentration

In case of concentrating solar cookers, the pot is exposed to atmosphere without a greenhouse as shown in Fig.1. The operating conditions are very much dissimilar than considered during testing of solar ovens. The solar concentration ratio of about 75 gives an operating temperature of 400°C [11]. The receiver of many concentrators have stagnation temperatures above 600^{o}C, Schefflers @ 700^{o}C, Arun @ 1300^{o}C, PRINCE-250 @ 1000^{o}C etc. Almost all solar concentrators operate on mainly latent heating principle that is completely different from sensible heating behavior. Further, the receiver of these concentrators has significant radiation losses in addition to convective losses. The radiation heat losses are proportional to fourth power of temperature. For this reason the loss characterization in case of concentrating solar cookers can't be treated as linear.

II. PROPOSAL FOR TEST PROTOCOL

a. Principle of operation

The proposed method is based on steam generation at constant temperature and hence is very close to practical situations. The heat energy supplied to working fluid is used to change the phase of water at constant temperature and pressure. The operating pressure of working fluid regulates boiling temperature. The enthalpy of vaporization of water can be obtained from steam tables at operating pressure. The product of dryness fraction of steam and enthalpy of vaporization is the amount of heat supplied for phase change of one kilogram of water.

b. Test Setup

The proposed experimental setup consists of a 16 sqm. parabolide Scheffler Reflector dish fitted with low iron glass mirror as shown in Fig. 2. A mild steel structure supports the reflector dish and sun tracking system. The tracking system swivels the reflector throughout the day to ensure maximizes solar radiation on to the reflector. A steam generating receiver is installed at the focus of reflector dish to receive the concentrated solar heat flux, which in turn transferred to water present in the receiver. The receiver is equipped with pressure relief valve, an air vent and moisture separator. A steam/water tank supplies water to receiver and stores generated steam. The operating pressure can be set with the help of relief valve. If pressure of generated steam exceeds the operating pressure, some quantity of steam escapes to bring the steam pressure. The air vent removes the air and dissolved gases during initial heating of water. A moisture separator is mounted between receiver and pressure relief valve to avoid moisture droplets carry over with steam.

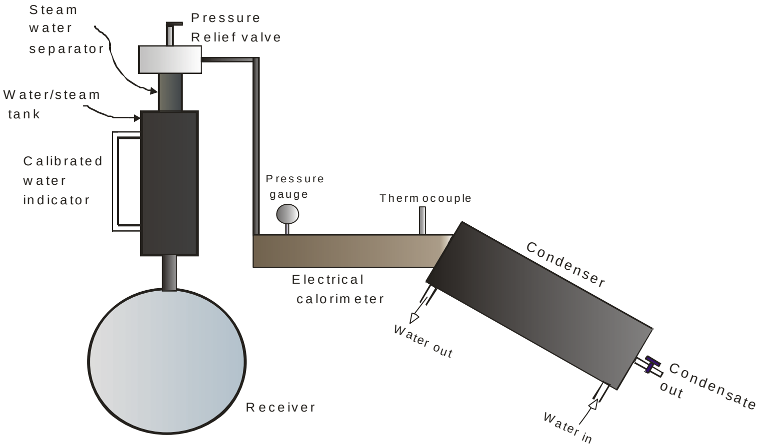


Fig.2. Proposed setup for evaluation of thermal performance of direct steam generating solar concentrators

The instrumentation includes pressure and temperature measurement of steam, ambient temperature, solar radiation intensity measurement, wind velocity, infrared thermometer and water level indicator and water quantity measurement arrangement etc.

III ANALYSIS

The energy balance on Scheffler concentrator and receiver is shown graphically in Fig. 3.

Energy incident on Scheffler dish

$$Q_s = \frac{A_a \times I_{bn}}{1000} \times 3600 \quad \text{(kJ/h)} \qquad (1)$$

Where I_{bn} is average of beam normal radiation over one hour test period.

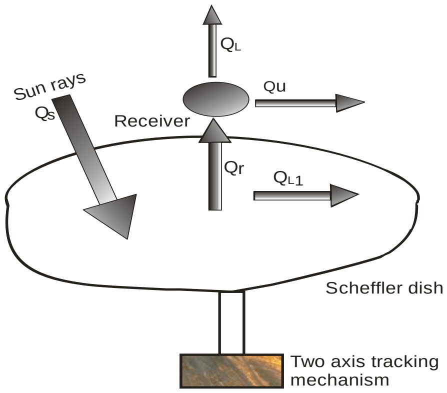


Fig.3 Energy balance on concentrator receiver system

Under steady state condition, the useful energy delivered by solar collector is equal to energy absorbed by working fluid.

Actual mass of water evaporated during test period, $m_s = m\tilde{}_1\ m_2$

The total heat energy of steam coming out electrical calorimeter

$$Q_{sup} = \frac{m_s \times h_{\sup}}{3600} \quad \text{(kJ/h)} \qquad (2)$$

Electrical work input, $Q_{\text{electrical}} = \frac{W_{electrical} \times 3600}{1000}$ (kJ/h) (3)

Useful heat energy gain rate at receiver during test period can be obtained as

$$Q_u = Q_{sup} - Q_{\text{electrical}} \quad \text{(kJ/h)}$$

The quality of steam can be obtained as

$$x = \frac{3600}{m_s h_{fg}} \times \left(Q_u - \frac{m_w C_{pw} (T_{sat} - T_1)}{3600} \right) \quad \text{(kJ/h)} \qquad (4)$$

Where x is dryness fraction of steam and h_{fg} is latent heat for water at operating pressure, in kJ/kg.

The thermal efficiency of collector system is defined as ratio of useful energy on the receiver to the energy incident on the concentrator

Collector efficiency, $\eta_c = \frac{\text{Heat gain rate at receiver}}{\text{Heat incident rate on collector}} = \frac{Q_u}{Q_s}$ (5)

Further, useful energy can also be expressed as difference of energy falling onto receiver, Q_r, and heat losses from the receiver, Q_L.

$$Q_L = Q_r - Q_u \qquad (6)$$

The concentrated solar energy reaching on the receiver Q_r depends on the optical efficiency η_o of collector, which may be defined as

$$\eta_o = \frac{\text{Energy delivery rate on receiver}}{\text{Energy incident rate on concentrator's a perture}} = \frac{Q_r}{Q_s} \qquad (7)$$

The optical efficiency depends optical characteristic of material and geometry used for collector. It also accounts cosine loss, shading loss, reflection loss, transmission and absorption losses and energy spillage. Optical efficiency of most of collectors falls in range of 0.70 to 0.85 [13]. Further, the system efficiency can be defined as

$$\eta_{\text{system}} = \frac{\text{Useful energy gain rate by receiver}}{\text{Energy incident rate on receiver}} = \frac{Q_u}{Q_r} \qquad (8)$$

Combining eqs (3) - (6), the collector efficiency can be interpreted as

$$\eta_c = \frac{Q_u}{Q_s} = \frac{Q_r}{Q_s} \times \frac{Q_u}{Q_r} = \eta_o \times \eta_r = \eta_o \left(1 - \frac{Q_L}{Q_r} \right) = \eta_o \left(1 - \frac{Q_L}{\eta_o Q_s} \right) = \eta_o - \frac{Q_L}{Q_s} \qquad (9)$$

It is evident from eqn.(9), the thermal efficiency of collector is function of optical efficiency and total heat loss rate from the receiver.

The total heat loss rate Q_L from the receiver is sum of conductive, convective and radiative heat losses from the receiver surface. Mathematically;

$$Q_L = Q_{cond} + Q_{conv} + Q_{rad} \tag{10}$$

The outer surface of the receiver is covered with thick glass wool insulation to minimize the conductive heat loss and it is insignificant compare to convective and radiative losses [17]. Therefore, authors consider outer receiver wall adiabatic ($Q_{cond} = 0$) in this study.

The convection heat losses from receiver are most complicated phenomenon. It includes free and forced convections and contributes major portion of heat losses. The characteristic of convection heat losses is investigated by many researchers [14-17] and developed various laboratory models for estimation of natural convection heat losses. Paitoonsurikarn *et. al.*[18] developed a angle dependent correlation for estimation of convection heat loss from receiver that is

$$Nu_L = 0.106 Gr_L^{1.3} \left(\frac{T_w}{T_\infty}\right)^{0.18} \left(\frac{40256 A_r}{A_w}\right)^{s} h(\varphi) \tag{11}$$

Where $Gr_L = \frac{g\beta(T_w - T_\infty)L^3}{\nu^2}$, Grashof number and $s = 0.56 – 1.01(A_r/A_w)^{0.5}$

and an angle dependent function $h(\varphi) = 1.1677 - 1.0762 \sin(\varphi^{0.8324})$

In our experimental arrangement, the plain/cavity cylindrical receivers are mounted vertical, thus characteristic length is considered diameter of receiver. All properties of air are taken at film temperature; i.e average of receiver's surface temperature and ambient temperature.

The convective heat transfer coefficient can be obtained as

$$h = \frac{Nu\, k_f}{L} \tag{12}$$

and convective heat loss from receiver

$$Q_{conv} = h\, A_r\, (T_w - T_\infty) \tag{13}$$

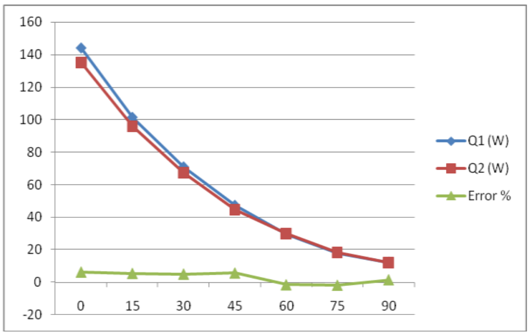
The radiation heat loss from the receiver can be obtained as

$$Q_{rad} = A_r \varepsilon \sigma\ T_w^4 - T_\infty^4 \tag{14}$$

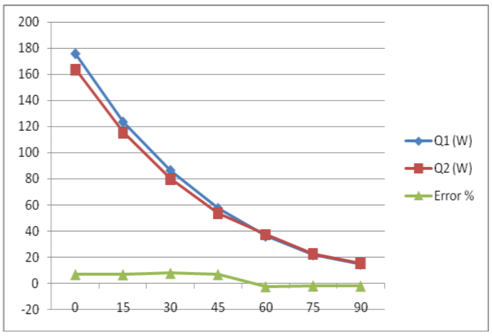
Table.1 Comparison convection heat loss between calculated and experimental values

Φ (°)	Tw=150°C			Tw=200°C				Tw=250°C		
	Q1 (W)	Q2 (W)	Error %	Q1 (W)	Q2 (W)	Error %		Q1 (W)	Q2 (W)	Error %
0	144.1	135	6.32	175.9	163.8	6.88		208.2	188.2	9.61
15	101.4	95.82	5.50	123.7	115.3	6.79		146.4	135.5	7.44
30	70.9	67.26	5.13	86.6	80.8	6.69		102.5	94.6	7.70
45	47.2	44.5	5.72	57.6	53.6	6.94		68.2	65.8	3.52
60	29.6	30	-1.35	36.2	37.1	-2.49		42.8	43.8	-2.34
75	18	18.3	-1.67	22	22.4	-1.82		26	26.5	-1.92
90	12.2	12	1.64	14.8	15.1	-2.03		17.9	18.2	-1.68

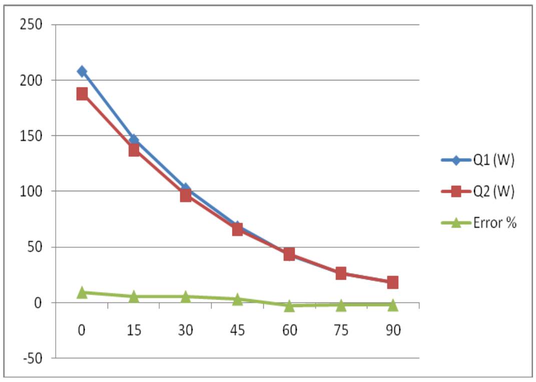
Q1 = calculated value and Q2 = experimental measured value, φ= receiver tilt angle



Convection heat loss pattern with wind direction at 150 °C



Convection heat loss pattern with wind direction at 200 °C



Convection heat loss pattern with wind direction at 250 °C

RESULT AND DISCUSSION

The heat losses from the receiver at different operating temperature is determined from eqn.(6). The conduction heat losses are considered negligible and radiation heat loss from plain cylindrical receiver is calculated from eqn.(14). The remaining heat loss is assumed convection heat loss, which is presented in table 1. The heat transfer coefficient is obtained by using empirical relation eqn. (11) and is used to obtain calculated values of convection heat losses.

Further, it is evident that the experimental and empirical values of convection losses closely agree, but as operating temperature increases, the error in estimation becomes widen from 0-30 degree receiver tilt and then it decreases.

CONCLUSIONS

Thermal performance test provides important technical parameters which can be used for certification of the solar concentrating cookers. The convection heat and radiation losses from receiver reduce efficiency of system significantly. These losses must be estimated carefully. Only a few researchers have attempted to estimate the convection heat losses through cylindrical cavity receiver and some have developed mathematical models in windy atmosphere. Further, at high operating temperature, the radiation heat losses are also considerable, even at higher temperature, the radiation heat loss is dominated over convection heat transfer. A rigorous work is required to develop a mathematical model for estimation of radiation losses.

Proposed test standard provides useful information to be reported to all stakeholders. Thermal performance test, are to be performed by the 'Test Centers'.

The solar concentrators have huge potential for conventional fuel saving opportunity and cooking capability, thus interest to prospective beneficiary organisations. The technical date generated from the test will be useful for policy makers like GACC (Global Alliance for Clean Cookstoves), UNDP (United Nations Development Programs) and for governments especially in Asia and Africa. Data generated can be used for generation as well as validation of projects for CDM and similar carbon trading mechanisms.

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