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Heat Loss Charecterization of Cylindrical Plain Receiver of Scheffler Concentrator

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Abstract— Author has developed a protocolfor evaluation of thermal performance of solar steam generating system, using concentrating solar collector is being proposed herewith. He has conducted experiment investigation on plain cylindrical receiver employed at focal point of on 16 m^2Scheffler concentrator, generating steam at 10-15 bar (gauge) pressure. At the same time, energy and exergy analysis are used to predict the thermal performance and heat loss pattern. The effects of wind velocity on convection heat loss have also been investigated. The effects of operational parameter such as pressure and mass flow rate of steam, wind velocity and structural parameters such as receiver geometry and its inclination are investigated.

Index Terms—Concentrators, testing, quality of steam, concentration ratio, collector efficiency, heat loss pattern, standardization of tests.

1 Introduction

THE solar concentrators can be classified as line focus concentrators and point focus concentrators. The concentrating systems include a reflecting surface (collector), a receiver and a tracking mechanism. The reflecting surface may be constructed with the help of low iron glass mirror pieces or specially treated metallic surface like anodized aluminium sheet. The solar-radiation incident on the collector surface is reflected towards the receiver located at the focal point/line. The reflected solar radiation is concentrated on the smaller area (receiver) at the focus thus increasing energy flux. The working fluid in the receiver absorbs this concentrated energy thus subjected to sensible as well as latent heating. The increased energy flux makes the solarenergy meaningful for thermal applications and power generation.

Point focus concentrating solar system reflects concentrated heat flux at a single point using single or multiple reflectors. It attains higher stagnation temperature at the receiver, thus point focus solar concentrating cookers are gaining popularity because of their capability to deliver operations like frying, roasting, stewing steaming and baking along with boiling. Also they offer faster cooking speed competing with conventional cooking appliances. The characterization of a concentrator at its operating temperature settles appropriatesize and type of concentratorforanythermalapplication.

2 REVIEW of Existing Test Standards for Solar Concentrators

In case of solar concentrating collectors, the receiver is exposed to atmosphere without a greenhouse as shown in Fig.1. The operating conditions are very much dissimilar than those for solar ovens. The solar concentration ratio of about 75 gives an operating temperature of 400°C [7]. The receiver of many concentrators have stagnation temperatures above 600°C, Schefflers @ 700°C, Arun @ 1300°C, PRINCE-250 @ 1000°C etc. Almost all solar concentrators operate onmainlylatent heating principle that is entirely 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 the absolute temperature of receiver. For this reason the heat loss characterization for concentrating solar collectors are complex in nature.

American Society for Testing of Materials (ASTM) has published a Standard Test Method for Determining Thermal Performance of Tracking Concentrating Solar Collectors [1]. This test standard appears more universal and appropriate for different designs of line and point concentrators. Further, this standard is suitable for outdoor conditions and is valid only; if there will no phase change of working fluid. This test standard can only be used for sensible heating regimes and steam generation will not fall under purview of this standard.

Kundapur and Sudhir [2], Mullick S.C. *et al*. [3] have also proposed new world standard for testing solar cookers which has consideration of nine parameters including ergonomics, cooking test, user interaction and cost.

Shaw [4] worked extensively to analyze the development of a comparative framework for evaluating the performance of solar cookers and compared test standards proposed by various researchers. He reported that no test standard protocol satisfies all the criteria that a user expects and thus, the proposed one more standard that accounts for technical parameters like efficiency along with other parameters like reproducibility, understandability and objectivity.

Pillai*et al.*[6] have also used above procedure for evaluation performance of a Scheffler concentrator of 16 m² and got realistic results. Sardeshpande*et al.* [7] have developed a procedure to observe the performance of a 25 m² solar concentrator. Their results appeared to be reasonable, consistent and satisfactory. These both the trials were conducted with latent heat exchange only; not with sensible heat exchange.

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3 Heat Loss Pattern

Authors conducted rigorous experimentation on 16 m^2Scheffler collector used for direct steam generation. He found that the performance of concentrating collector is very sensitive to design parameters and operating conditions. The task of development a test protocol for standardization and certification is challenging. All these developments indicate that there is a urgent need of improvement in test standards for solar concentrating collectors.

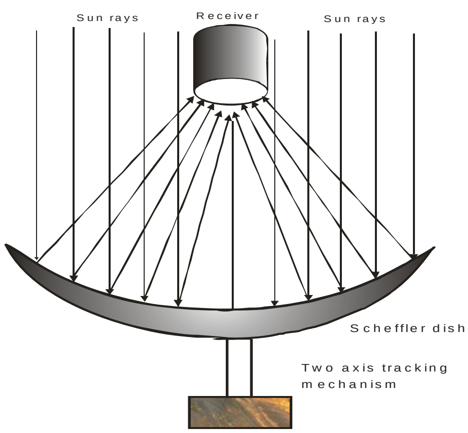

Fig.1 Principle of point focus concentration

4 New Proposal for Test Protocol

Proposed test standard deviates from conservative philosophy of recording heat gain in sensible heat regimes only. Instead author proposed a test protocol with the latent heat interaction as in most of practical situations. Prime reasons for this change of approach are discussed herewith.

- The sensible heat gain is recorded in transient state. Temperature is not constant. Its measurement is problematic and leads to error proneness. The magnitude of temperature depends on the location and position of thermocouple in the receiver. The convective current inside the fluid causes time delay in actual heat gain and reported temperature rise.
- In case of latent heat transaction, the minimum instrumentation is required: measurement of solar radiation, ambient temperature, operating pressure and weight lost of working fluid. The weight of water lost by evaporation can be measured very precisely. The total heat supplied can be obtained by adding sensible heat to latent heat. These parameters are more judicious to estimate the thermal performance as well as heat loss characterization of the system.

Authors have tried to provide a new test setup as shown in Fig. 2, which can take care of all limitations as well as to serve a very reliable method for testing, performance prediction, monitoring and verifications programs. Further, it is recommended that the experimentation for evaluation of thermal performance must be carried out when sky is clear and solar radiation intensity I_{bn} is above 550 W/m^2 and average wind speed during test duration should be less than 3 m/sec.

4.1 Principle of operation

The proposed method is based on steam generation at constant pressure and hence is very close to practical situations. The heat energy supplied to working fluid is used to change the phase of water. The operating pressure of working fluid regulates boiling temperature. 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.

4.2 Test Setup

The proposed experimental setup consists of a 16 m^2parabolideScheffler Reflector dish fitted with low iron glass mirror. The system has geometric concentration ratio of 81, but its optical concentration ratio varies from 58 to 75 with seasonal variations. 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 point 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.

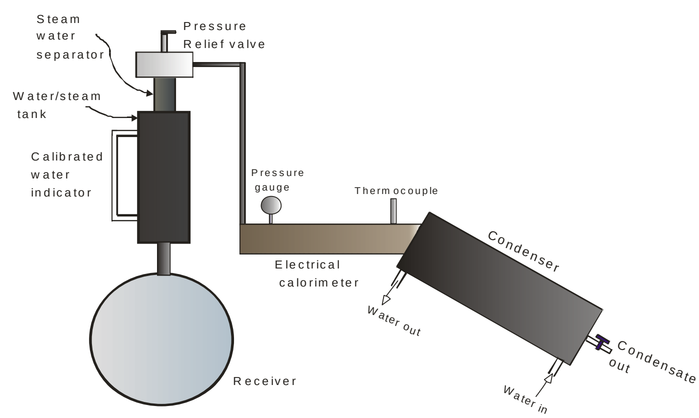

Fig.2. Proposed setup for evaluation of thermal performance of direct steam generating solar concentrators

The operating pressure can be set with the help of pressure relief valve. If pressure of generated steam exceeds the operating pressure, some quantity of steam escapes to bring the steam pressure down. 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.

The instrumentation includes pressure and temperature sensors, solar radiation intensity measurement, anemometer, infrared thermometer, water level indicator and water quantity measurement arrangement etc.

5 CALCULATIONS

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

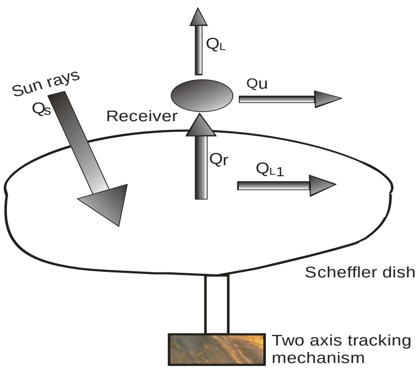

Fig.3 Energy balance on concentrator receiver system

Energy incident on Scheffler dish

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

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

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,

$$m_s = m_1 - m_2$$

The total heat energy of steam coming out electrical calorimeter

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

Electrical work input,

$$Q_{elect} = \frac{W_{elect} \times 3600}{1000} \text{ (kJ/h)} \quad (3)$$

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

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

The quality of steam can be obtained as

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

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,

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

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

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

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

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

The optical efficiency depends on 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

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

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

$$\eta_c = \frac{Q_u}{Q_s} = \frac{Q_r}{Q_s} \times \frac{Q_u}{Q_r} = \eta_o \times \eta_r$$

or $$\eta_c = \eta_o \left(1 - \frac{Q_L}{Q_r} \right) = \eta_o \left(1 - \frac{Q_L}{\eta_o Q_s} \right) = \eta_o - \frac{Q_L}{Q_s} \quad (9)$$

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

5.1 Calculation of Heat Losses

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

$$Q_L = Q_{cond} + Q_{conv} + Q_{rad} \quad (10)$$

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 [7-14] and developed various laboratory models for estimation of natural convection heat losses. Paitoonsurikarn*et. al*.[15] developed an angle dependent correlation for estimation of convection heat loss from receiver that is

$$Nu_L = 0.106 Gr_L^{1.3} \left(\frac{T_w}{T_\infty} \right)^{0.18} \left(\frac{4.256 A_{ap}}{A_r} \right)^{s} h(\varphi) \quad (11)$$

Where $Gr_L = \dfrac{g\beta(T_w - T_\infty)L^3}{\nu^2}$, Grashof number

$$s = 0.56 - 1.01 \times \left(\frac{A_{ap}}{A_r}\right)^{0.5}$$

andan 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 the 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

$$h = \frac{Nu\,k_f}{L} \qquad (12)$$

and convective heat loss from receiver

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

The radiation heat loss from the receiver can be obtained as

$$Q_{rad} = A_r\,\varepsilon\,\sigma\left(T_w^4 - T_\infty^4\right) \qquad (14)$$

5 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.

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

	Tw=150°C			Tw=200°C			Tw=250°C		
ϕ (°)	Q1 (W)	Q2 (W)	Error %	Q1 (W)	Q2 (W)	Error %	Q1 (W)	Q2 (W)	Error %
0	144.1	125	15.2	175.9	155.8	12.9	208.2	165.2	26.2
15	101.4	86.2	17.6	123.7	100	23.7	146.4	126.5	15.7
30	70.9	62.6	13.2	86.6	70.8	22.3	102.5	92.6	10.7
45	47.2	41.2	14.6	57.6	48.6	18.5	68.2	56.8	20.1
60	29.6	30	-1.3	36.2	38.2	-5.2	42.8	48.6	-11.9
75	18	19.8	9.1	22.0	25.4	13.4	26.0	30.8	-15.6
90	12.2	12	-1.7	14.8	15.2	-2.6	17.6	23.0	-23.5

Q_1 = calculated value and Q_2 = experimental measured value

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° receiver tilt and then it decreases.

Matlab 7.0 is used to analyse the data with different possible polynomial curve fitting. Derived equation with polynomial curve fitting

$Q_{conv} = 47.86 \times V^{0.285} \times \theta^{0.0772} \times T^{0.632}$ with R^2 value of 88.2%

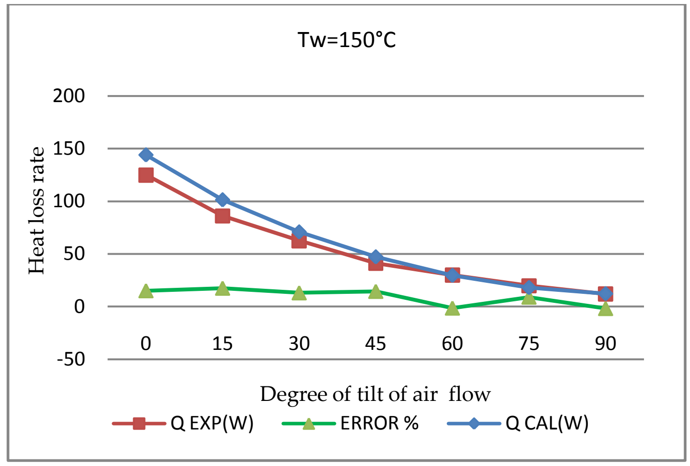

Fig. 4 Convection heat loss pattern with wind direction at 150°C

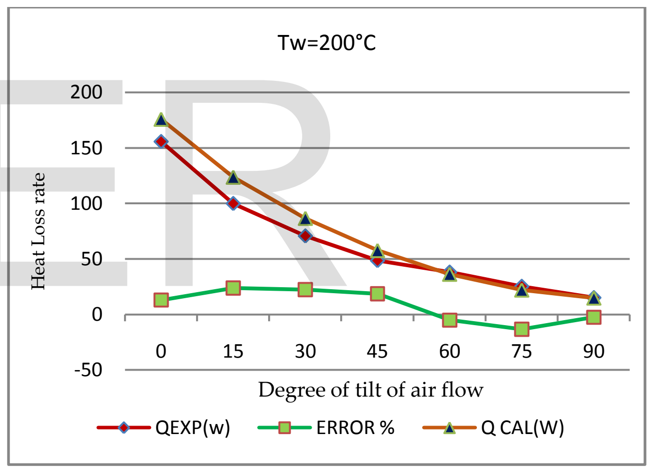

Fig. 5 Convection heat loss pattern with wind direction at 200°C

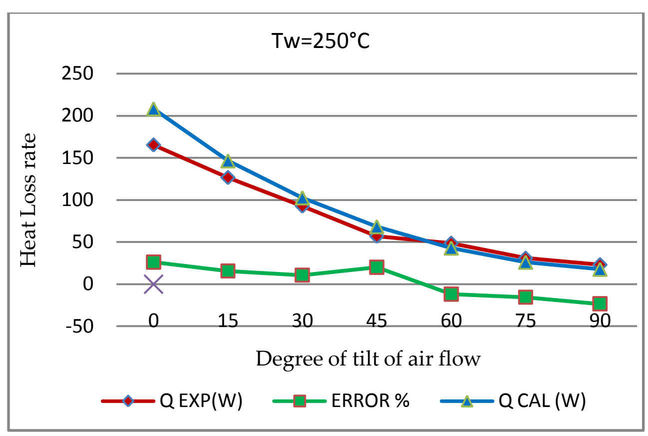

Fig. 6 Convection heat loss pattern with wind direction at 250°C

6 Conclusions

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 organizations. The technical data 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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Nomenclature

A_{ap} = aperture area of dish concentrator, m²
A_r = area of reciever surface, m²
C = concentration ratio ,
C_p= specific heat, J/kg.K
h = convective heat transfer coefficient, W/m².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/m²
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_{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
x = dryness fraction of steam.

Greek symbols

η_c = efficiency of concentrator
η_o= optical 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,
Δ = difference in quantity,
φ = tilt angle of receiver, radian

References

[1]. ASTM International "Standard Test Method for Determining Thermal Performance of Tracking Concentrating Solar Collectors" Designation: E 905 – 87, Reapproved 2007, PP. 1-14, 2007.

[2]. Kundapur Ashok , Sudhir C V, "Proposal for New World Standard for Testing Solar Cookers" PP 1-5, 2009.

[3]. Mullick S.C., Kandpal T.C. and Subodh Kumar, "Thermal Test Procedure for a Paraboloid Concentrator Solar Cooker", Solar Energy Volume 46, Issue 3, 1991, PP. 139-144.

[4]. Shaw Shawn "Development of a Comparative Framework for Evaluating the Performance of Solar Cooking Devices" A Thesis submitted at Rensselaer Polytechnic Institute, USA, (http://www.solarcooker.org/ Evaluating- Solar-Cookers.doc). Report PP 1-63, 2006.

[5]. PillaiIndu R., Chandak Ajay G., Sardeshpande Vishal and Somani Sunil K., "Methodology for Performance Evaluation of Fixed Focus Moving Solar Concentrators" World Renewable Energy Congress XI, 25-30 September 2010, Abu Dhabi, UAE, PP 1-6.

[6]. Sardeshpande Vishal R, Ajay G. Chandak, Indu R. Pillai, "Procedure for Thermal Performance Evaluation of Steam Generating Point-Focus Solar Concentrators", Solar Energy, Volume 85, Issue 7, July 2011, Pages 1390-1398

[7]. Chandak Ajay, "Apparatus for Testing Solar Concentrators' Patent application no 2377/MUM/2009. Filed with Controller of Patents, Mumbai.

[8]. Subodh Kumar, T. C. Kandpal and S. C. Mullick, "Heat losses from a paraboloid concentrator solar cooker: Experimental investigations on effect of reflector orientation", Renewable Energy, 3(8),871-876, 1993.

[9]. Subodh Kumar, Kandpal T.C., Mullick S. C. (1994), "Effect of Wind on the Thermal Performance of a Paraboloid Concentrator Solar Cookers", Renewable Energy, Vol.4 No.3, 1994, PP. 333-337.

[10]. Ravi Kumar K, Reddy K. S.,"Thermal analysis of solar parabolic trough with porous disc receiver",Appl Energy 2009, 86(9):1804–12.

[11]. Reddy KS, Kumar NS.,"Combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish", Int. J. ThermSci 2008;47(12):1647–57.

[12]. Yong Shuai, Xin-Lin Xia, He-Ping Tan, "Radiation performance of dish solar concentrator/cavity receiver systems", Solar Energy 82 (2008) 13–21.

[13]. K.S. Reddy, N. Sendhil Kumar, "Combined laminar natural convection and surface radiation heat transfer in a modified cavity receiver of solar parabolic dish", International Journal of Thermal Sciences 47 (2008) 1647–1657.

[14]. Leibfried U. Ortjohann J., "Convective heat loss from upward and downward facing cavity receivers: measurements and calculations". ASME J. Sol Energy Engineering.; vol 117: pp 75–84., 1995.

[15]. Paitoonsurikarn S, Taumoefolau T, LovegroveK.,"Estimation of convection loss from paraboloidal dish cavity receivers". In: Proceedings of 42nd conference of the Australia and New Zealand solar energy society (ANZSES), Perth, Australia; 2004.