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An Experimental Analysis of Solar Air Heater with Staggered Plate Aluminium Absorber Plate with Selective Coating

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Abstract
This study experimentally investigates the performance characteristics of Solar Air Heater (SAH) with staggered type absorber plate construction with black chrome selective coating with varying mass flow rates and angle of incidence. The optimum efficiency of the collector was found to be 76.1% at 27 degrees angle of incidence with flow rate of 0.0645 kg/s and 50.12 % at 27 degrees angle of incidence with flow rate of 0.0344 kg/s. The collector was compared with SAH of the published literature and good agreements have been found justifying the design of the collector.

Keywords
Solar Air Heater – Absorber Plate – Collector Efficiency

1. Introduction

In simplest form, a flat plate solar air heater consists of one or more sheets of glass or transparent material situated above an absorbing plate with the ambient air flowing either above or under the absorbing surface so it acts as a black body to absorb heat [1]. Being simple in design and maintenance, corrosion and leakage problems are less severe in SAH compared with the liquid heater solar systems while the main drawback of SAHs is that the heat-transfer coefficient between the absorber plate and the air stream is low, which results in a lower thermal efficiency of the heater [2]. However, different modifications are suggested and applied to improve the heat-transfer coefficient between the absorber plate and air [3, 4, 5].

Benli [6] studied an experimental performance and exergy analysis of five types of air heating solar collectors: corrugated trapeze, reverse corrugated, reverse trapeze and a base flat-plate collector and concluded that increasing the mass flow rates caused 1.5 to 4 fold increase in efficiency in each collector as well as the outlet temperature of air significantly changed with the geometry of the absorber. Bekele et al [7] studied the solar air heater with surface mounted obstacles and concluded that solar air heater with delta shaped obstacles mounted on the absorber plate gives better performance than the other heat transfer enhancement techniques. Ho, et al., [1] theoretically investigated the collector efficiency of upward-type double pass flat plate solar air heaters with fins attached and external recycle was investigated theoretically and concluded that efficiency increases as mass flow rate, number of fins attached and incident solar radiation increases.

Ozgen et al., [2] experimentally investigated the thermal performance of a double-flow solar air heater having aluminium cans and three types; can with zigzag, can with parallel order and one without cans ware tested and that the highest efficiency was obtained for type I collector (zigzag type cans) at 0.05 kg/s. Saxena, et al., [8] designed a solar air heater to produce good exhaust temperature for long hours and a mixture of desert and granular carbon in the ratio of 4:6 was used as thermal storage inside SAH along with halogen lights of 300 W at the inlet and outlet ducts. The thermal efficiencies of the novel SAH was found from 18.04 % to 20.78 % of natural convection and 52.21 %-80.05 % with forced convection. Nowzari, et al., [9] studied the best configuration for a solar air heater by design and analysis of experiment and concluded that double-pass solar collector with a quarter- perforated cover with 3-cm hole-to-hole spacing and mass flow rate of 0.032 kg/s yielded best results. Similarly two analytical models were developed by [10] that described the thermal behaviour of solar air heaters of double-parallel flow and double counter flow. They developed the algebraic expressions for the efficiency factor, and overall heat loss coefficient UL were deduced, as well as the air temperature distribution along the collectors. Also an extensive thermodynamic review of solar air heaters has been provided by Saxena, et al., [11] studied various elements of solar air heater such as: an absorber tray, the ducts, glazing, insulation, extended surfaces as well as tilt angles and found that these elements has significant effect on the thermal performance of the system.

This paper presents the experimental analysis of new staggered type Solar Air Heater with selective coated aluminum absorber plate. An experimental setup is constructed and tested in Sun Works Nepal Pvt. Ltd., Kathmandu, Nepal. The efficiency is determined from the experimental measurements and compared with efficiencies of other collectors with different absorber plate design reported in literature.

Introduction text goes here. An example reference is here

2. Methodology

The Solar Air Heater is (2 m x 1 m x 82 mm) made of staggered type absorber plate with black chrome selective coating. The collector frame is designed with Anodized Aluminium Profile and the glazing utilized is 4mm thick Low Iron, Toughened, and Patterned Glass. High density thermocole Styrofoam insulation of thickness 17.5 mm is used as insulation. The outlet was made with a cutout below the absorber at near end of the collector. Two mercury thermometers were positioned at inlet and outlet of the collector to measure the inlet and outlet temperatures. The least count of inlet thermometer was 0.5 deg centigrade and that of outlet thermometer was 1 deg centigrade . The ambient temperature was measured with the digital thermometer placed around the proximity of the collector. The total solar radiation incident on the surface was measured with Hand Pyranometer 98 HP form SolData. The outlet velocity of air from the

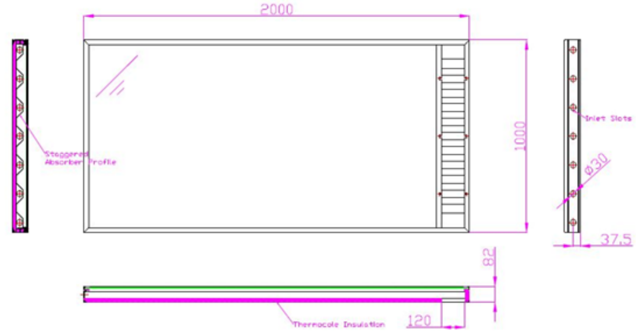

Figure 1: Construction of Staggered type Solar Air Heater

blower was measured with . The fan placed at the outlet of the collector was used to create the forced convection. Two types of fan (SAN ACE 172 and Sunon DP200A) was used to create different flow situation. The pressure drop was measured by U-Tube Manometer. All tests were conducted from 10 AM to 5 PM.

2.1 Basic Equations for Flat Plate Collectors

The basic parameter to consider is the collector thermal efficiency. This is defined as the ratio of the useful energy delivered to the energy incident on the collector aperture.In steady state the useful energy output of a collector of area A_c is the difference between the absorbed solar radiation and the thermal loss [12, 13]

$$Q_u = A_c[S - U_L(T_{pm} - T_a)] \tag{1}$$

The problem with this equation is that the mean absorber plate temperature is difficult to calculate or measure since it is a function of the collector design, the incident solar radiation, and the entering fluid conditions If conditions are constant over a time period, the efficiency is given by

$$\eta = \frac{Q_u}{I_t A_c} \tag{2}$$

2.1.1 Collector Efficiency Factor

Collector Efficiency Factor (F') represents the ratio of the actual useful energy gain to the useful gain that would result if the collector absorbing surface had been at the local fluid temperature. F' is the ratio between, $F' = \frac{U_O}{U_L}$ The collector efficiency factor is essentially a constant for any collector design and fluid flow rate.

2.1.2 Collector Heat Removal Factor and Flow rate

It is convenient to define a quantity that relates the actual useful energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is called the collector heat removal factor F_R. In equation form it is

$$F_R = \frac{\dot{m}C_p(T_{fo} - T_{fi})}{A_c[S - U_L(T_{fi} - T_a)]} \tag{3}$$

The collector heat removal factor can be expressed as

$$F_R = \frac{\dot{m}C_P}{A_c U_L}\left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m}C_P}\right)\right] \tag{4}$$

To present above equation graphically, it is convenient to define the collector flow factor F'' as a ratio of F_R to F'. Thus,

$$F'' = \frac{F_R}{F'} = \frac{\dot{m}C_P}{A_c U_L F'} = \frac{\dot{m}C_P}{A_c U_L}\left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m}C_P}\right)\right] \tag{5}$$

The quantity F_R is equivalent to the effectiveness of a conventional heat exchanger, which is defined as the ratio of the actual heat transfer to the maximum possible heat transfer. The maximum possible useful energy gain (heat transfer) in a solar collector occurs when the whole collector is at the inlet fluid temperature; heat losses to the surroundings are then at a minimum. The collector heat removal factor times this maximum possible useful energy gain is equal to the actual useful energy gain

$$Q_u = A_c F_R[S - U_L(T_i - T_a)] \tag{6}$$

With it, the useful energy gain is calculated as a function of the inlet fluid temperature. This is a convenient representation when analyzing solar energy systems, since the inlet fluid temperature is usually known. As the mass flow rate through the collector increases, the temperature rise through the collector decreases. This causes lower losses since the average collector temperature is lower and there is a corresponding increase in the useful energy gain. This increase is reflected by an increase in the collector heat removal factor F_R as the mass flow rate increases.

2.1.3 Collector Tests

The basic method of measuring collector performance is to expose the operating collector to solar radiation and measure the fluid inlet and outlet temperatures and the fluid flow rate. The useful gain is then

$$Q_u = \dot{m}C_p(T_o - T_i) \tag{7}$$

From above analytical analysis, the thermal performance of a collector operating under steady conditions can be written in terms of the incident radiation:

$$Q_u = A_c F_R[G_t \tau\alpha - U_L(T_i - T_a)] \tag{8}$$

The above two equations can be used to define an instantaneous efficiency

$$\eta_i = \frac{Q_u}{A_c G_t} = F_R(\tau\alpha) - \frac{F_R U_L(T_i - T_a)}{G_t} = \frac{\dot{m}C_p(T_o - T_i)}{A_c G_t} \tag{9}$$

The outdoor tests are done in the midday hours on clear days when the beam radiation is high and usually with the beam radiation nearly normal to the collector.

3. Results and Discussion

The test was carried out on 6th, 7th and 8th of September at constant mass flow rate of 0.0645 kg/s. The incidence angle was changed as 37°, 27°and 17°respectively on the 6th , 7th and 8th of September. Then the flow rate was reduced to 0.0344 kg/s with respective incidence angle of 37°and 27°on 9th and 10th of September 2015. Figure 2 shows the variation of ambient temperature,

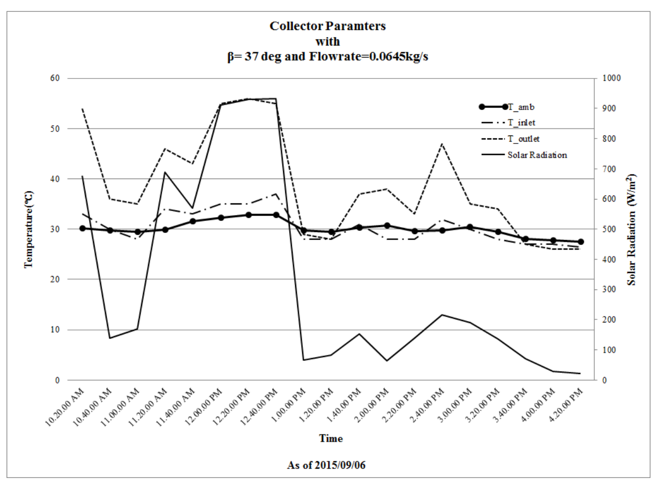

Figure 2: Collector Performance as of September 6, 2015

inlet temperature, outlet temperature and solar radiation in each 20 min interval at constant mass flow rate of 0.0645 kg/s and at incidence angle of 37 °. The highest daily solar radiation obtained is 932 W/m^2, during which ambient, inlet and outlet temperature were also recorded highest as 32.9 °C, 37 °Cand 66 °Crespectively. The solar radiation decreased drastically from 1:00:00 pm due to increasing cloud cover with the solar radiation as low as 22 W/m^2. The pressure drop measured on the collector was 4 mm of WC.

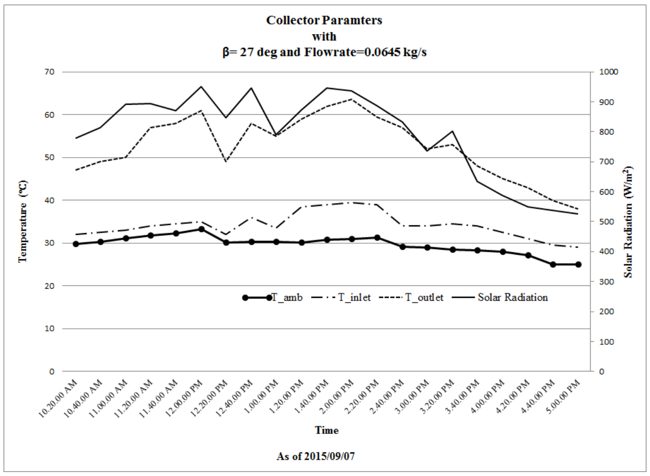

Figure 3: Collector Performance as of September 7, 2015

Figure 3 shows the variation of ambient temperature, inlet temperature, outlet temperature and solar radiation in each 20 min interval at constant mass flow rate of 0.0645 kg/s and at incidence angle of 27 °. The highest daily solar radiation obtained is 946 W/m^2 during which ambient temperature was recorded highest as 33.4°C. The maximum inlet and outlet temperature occurred as 39 °Cand 63.5 °Cwhen there were uniform high solar radiation of above 900 W/m^2 around 12:00:00 to 1:00:00 pm.The solar radiation gradually decreased after that but maintained a value minimum of 525 W/m^2 due to good sunshine in the experiment day. The pressure drop measured on the collector was 3 mm of WC.

Figure 4 shows the variation of ambient temperature, inlet temperature, outlet temperature and solar radiation in each 20 min interval at constant mass flow rate of 0.0645 kg/s and at incidence angle of 17 °. The highest daily solar radiation obtained is 972 W/m^2, during which ambient temperature was recorded as 30.2 °C. The maximum ambient, inlet and outlet temperature occurred as 34.3 °C, 40 °Cand 59 °Cwhen there were

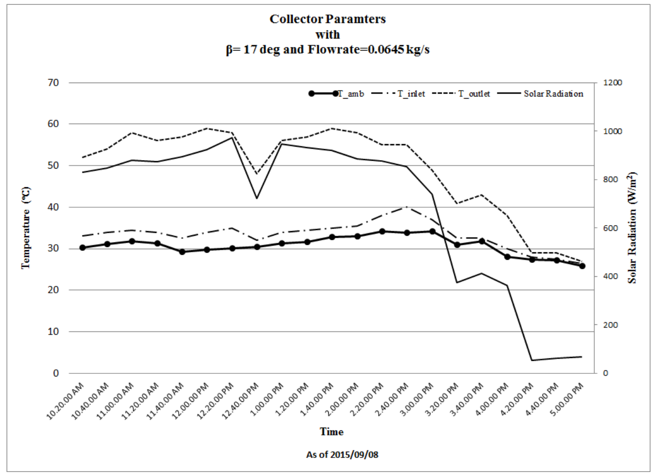

Figure 4: Collector Performance as of September 8, 2015

uniform high solar radiation of above 800 W/m^2 around 12:00:00 to 1:00:00 pm. The solar radiation gradually decreased and then significantly after 3:00:00 pm due to cloud cover during experiment day. The pressure drop measured on the collector was 2.5 mm of WC.

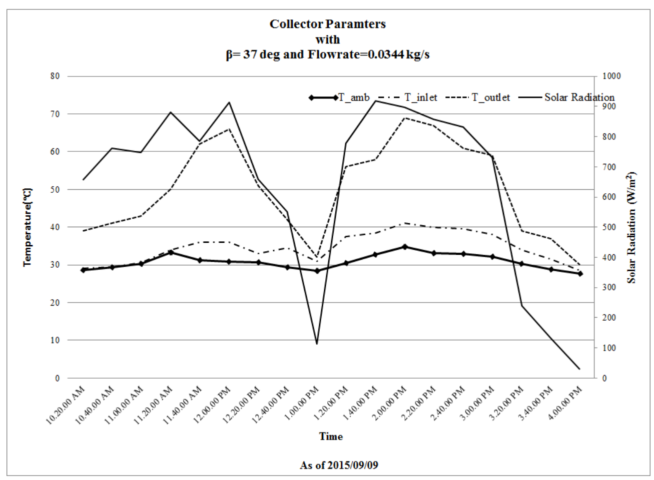

Figure 5: Collector Performance as of September 9, 2015

Figure 5 shows the variation of ambient temperature, inlet temperature, outlet temperature and solar radiation at constant and reduced mass flow rate of 0.0343 kg/s and at incidence angle of 37 degrees. The highest daily solar radiation obtained is 919 W/m^2, around the periphery of which ambient temperature was recorded as 34.9°C. and maximum outlet temperature reaching 69°C. The maximum inlet temperature recorded was 41°Caround 2 pm. The solar radiation showed drastic drop during

1:00 pm due to complete cloud cover thereby reducing all the measured temperatures to the minimum. The pressure drop measured on the collector was 6 mm of WC which is significant due to reduced flow rate and reduced turbulence in the ducts.

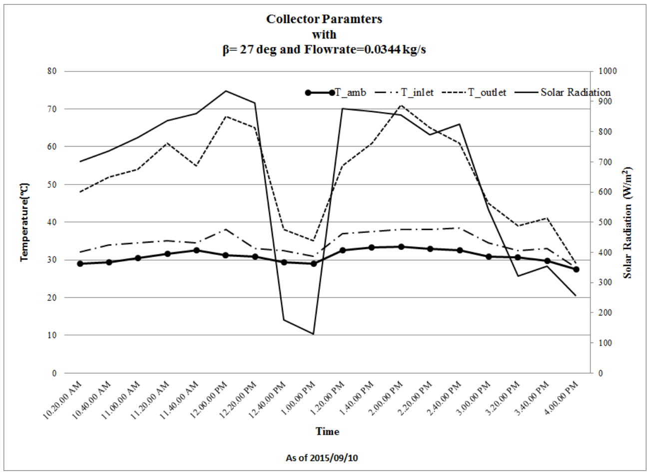

Figure 6: Collector Performance as of September 10, 2015

Figure 6 depicts the measured ambient, inlet and outlet temperatures alongside the corresponding solar radiation. Besides rapid decrease in solar radiation during 1:00 pm for brief period of time, the day had good amount of solar radiation with maximum radiation reaching up to 935 W/m^2 at noon. The outlet temperature reached maximum around 2:00 pm with constant radiation of greater than 750 W/m^2 around 1:20 to 2:00 pm with values reaching upto 71°C. Similarly the corresponding ambient and outlet temperatures were maximum at that period. The pressure drop measured on the collector was 5 mm of WC Figure 7 shows the temperature Difference between outlet and inlet temperatures on the different experiment days. The maximum and significant temperature difference were recorded during 10th September and 9th September; during days in which experiment were conducted with reduced flow rate of 0.0344 kg/s than that compared to other days in which the experiment was conducted at flow rate of 0.0645 kg/s. Figure 8 shows the efficiency for different angle of incidence in the collector by least-square fitting of the experimental data. The efficiency of test data can be summarized as For mass flow rate of $\dot{m} = 0.0645$ kg/s,

$$\eta_{17deg.} = 0.8908 - \frac{38.56(T_i - T_a)}{G_t} \tag{10}$$

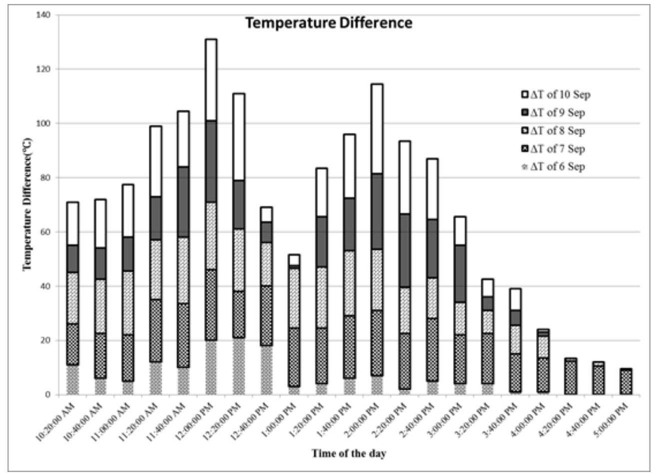

Figure 7: Temperature Difference Between Outlet and Inlet Temperatures

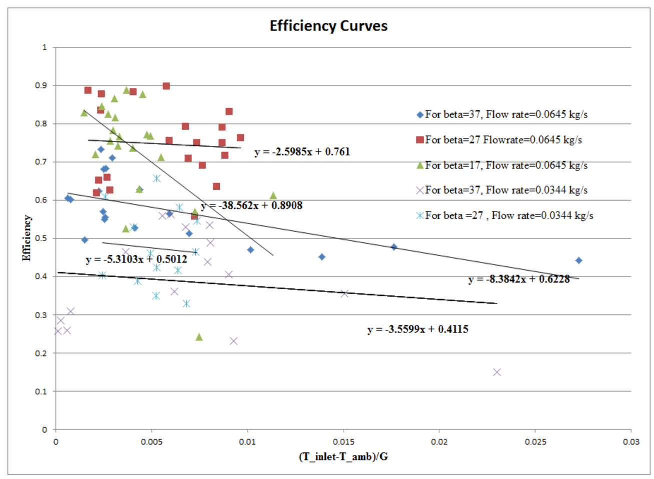

Figure 8: Efficiency Curves for Different angle of incidence

$$\eta_{27deg.} = 0.761 - \frac{2.5985(T_i - T_a)}{G_t} \tag{11}$$

$$\eta_{37deg.} = 0.6228 - \frac{8.3842(T_i - T_a)}{G_t} \tag{12}$$

From Figure 8 even though the highest efficiency intercept is obtained for the 17 degree inclination angle, the slope of the equation is steep so effective for instantaneous efficiency but not promising for more energy collection. The efficiency intercept at the 27 degrees angle of incidence is 0.761 and slope is also very less steep so making in a good alternative for using in different ranges of inlet temperature without significant drop in the efficiency. Also the intercept at the 37 degrees incidence angle is low and also more slope than that of 17 degree equation so overall efficiency of the system is lowered.With significant slope for the 17 degree inclination angle being too pronounced in decreasing the efficiency, further tests at reduced flowrate was avoided.

For mass flow rate of $\dot{m} = 0.0343$ kg/s,

$$\eta_{27deg.} = 0.5012 - \frac{5.3103(T_i - T_a)}{G_t} \tag{13}$$

$$\eta_{37deg.} = 0.4115 - \frac{3.5599(T_i - T_a)}{G_t} \tag{14}$$

The efficiency is more when the flow rate in the collector is high due to higher turbulence created in the collector than at the reduced flow rate. The optimum operating point for the collector at 0.0645 kg/s is at 27 degree angle of incidence with maximum efficiency of 76.1 % and at 0.0344 kg/s is at 27 degree angle of incidence with maximum efficiency of 50.12 %.

In order to make the comparison for the thermal performance of staggered type, black chrome coated aluminum absorber plate, following configurations of SAHs reported in literature were selected.Hernandez et. al, [10] analytically studied the thermal behaviour of solar air heaters of double-parallel flow and double-pass counter flow at the flow rate of 0.04 kg/s. Ozgen et al., [2] experimentally investigated the thermal performance of a double-flow solar air heater having aluminum cans for mass flow rates of 0.03 kg/s and 0.05 kg/s.

Figure 9 depicts the good agreement of efficiency of the staggered plate absorber plate Solar Air heater with reported literature. The greater efficiency at the greater flow rate of 0.0645 kg/s is obvious due to increase turbulence in the collectors.

4. Conclusions

Following the experimental study, efficiency of Solar Air heater with staggered type absorber plate with black chrome selective coating was conducted. The optimal operating conditions for both the flow rate occurred at 27 degree angle of incidence. The maximum efficiency occurred at greater flow rate of 0.0645 kg/s with minimal pressure drop while the efficiency decreased with

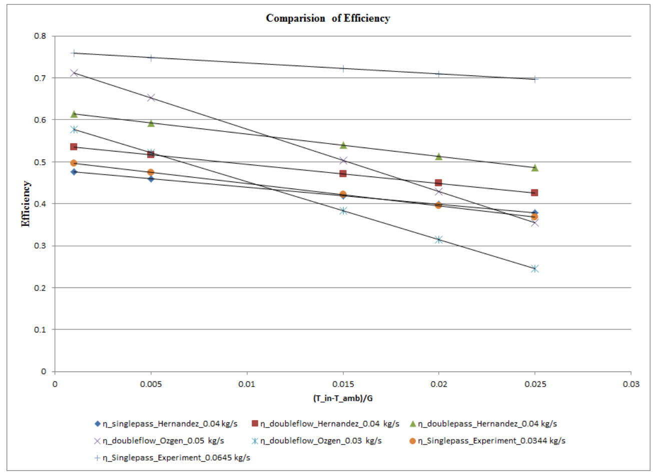

Figure 9: Comparision of thermal efficiency of the experimented collector with the reported ones

the reduction in flow rate to 0.0344 kg/s with increase in pressure drop. The efficiency plots also shows good agreement with that of the published literature. So with the known efficiency parameters of the collector its suitable end use application can be ascertained more easily and reliably.

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