A NOVEL IMAGING LIGHT FUNNEL AND ITS COLLECTING HEAT EXPERIMENTS

by

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This paper presents a novel imaging light funnel. Its structure and operation principle are introduced, and its ray path is analyzed by computational simulation. The relationship between the light concentrating of the light funnel and the incident angle is investigated. The results show that the changes of focal spot size, shape, energy distribution, and center of focal spot are affected by incident angle. In addition to theoretical analysis, several imaging light funnels are constructed, and experiments for single funnel and multiple funnels with series heating system are carried out. Two experiments results and heat collection efficiency of system are obtained. Experiment results show that the heating temperature of this system can reach 335 °C and the heat collection efficiency could reach 40%. When the multiple funnels with series heat the water, the temperature can reach 150 °C.

Key words: *solar concentrator, ray analysis, multiple funnels with series, collecting heat experiments*

Introduction

Light funnel concentrator is of great advantage with high light concentration and low-cost connection. As a result, it has wide applications. The 3-D compound parabolic concentrator (CPC) is a typical light funnel concentrator, which has efficiency and large hot spot [1-6]. Wirz *et al.* [7] used Monte-Carlo ray tracing to model 3-D heat transfer in a parabolic trough solar concentrator system, and obtained an innovation of the heat transfer model used spectral optical data for the absorber tube with selective coating and glass envelop. Sharaf [8] proposed a V-shape light funnel concentrator, and used it to achieve high temperature heat collection. Saffa and Abdulkarim [9] presented the working principle and thermal performance of a new V-trough solar concentrator, which does not require high precision tracking device and reflective material. In addition, outdoor and indoor experimental tests were carried out using the new V-trough solar concentrator. The results show that the collector system can have thermal efficiency up to 38% at 100 °C operating temperature. Togrul *et al.* [10] also made some research on conical solar concentrators. Nazmi and Tapas [11] constructed a 3-D crossed compound parabolic concentrator (CPCC). A 3-D ray trace code has been developed using MATLAB to investigate the theoretical efficiency and the optical flux distribution on

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the acceptor. A series of experimental measurements were taken on. The experimental results confirm that the code can be used to study different concentration rates of the CPCC. A new conical concentrator used to provide heat energy for a solar air heater was constructed by Inci and Dursun [12]. Maximum efficiency was obtained by using aluminum wire mesh and the efficiency of the system can be obtained 84%. The 3-D CPC and V-shape funnel concentrator are not able to focus light to one point, as a result, its concentrating ratio is relatively low, which in general is under 15. In order to improve flux density, some researchers came up with secondary concentrator design [13]. But this design will make the size of the device become larger, which is material consuming and not good for installation.

In order to enhance the advantages of light funnel concentrator, and overcome its drawbacks and reduce its light tracking precision requirement. This paper puts forward a new design of CPC (light funnel), its main property is that this funnel has real focus. The light focus is at the outside of outlet of the unit, which could guarantee no obstruct subject in the funnel and, as a result, is good for connection and energy conservation leading to get high temperature solar energy. This funnel actualizes reflection style consequent light focus to Sun light, and all of its support frame and energy receiver are at the outside of the funnel, which makes installation and control easier [14, 15].

Outdoor experiments show that this light funnel could collect solar energy effectively. Combined with particular heat receiver, this new solar energy collecting system could concentrate the low density solar power to over 300 °C heat energy which provides a new efficient way for using medium temperature solar energy.

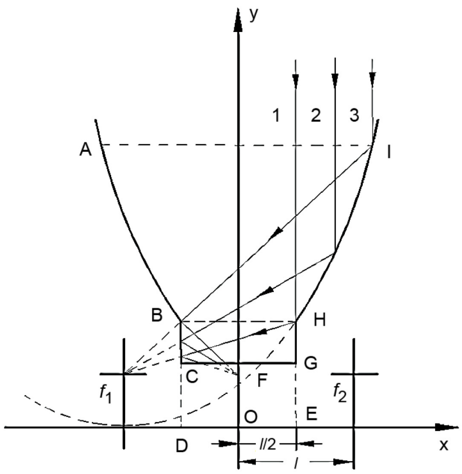

Figure 1. The cutaway view and light focus principle of the concentrator

Structure and operation principle of the novel imaging light funnel

Design of the imaging light funnel

Figure 1 shows the cutaway view and light transmitting of the concentrator which is consisted by two parabolic line, AB and IH, and two straight line segments, BC and HG. When these combined segments rotate round the y-axis, a 3-D concentrator is obtained. The two straight lines consist of the cylinder in the bottom [13]. The two parabolic segments belong, respectively, to two parabolic lines and their symmetry axis is parallel to each other. Their focus is at f_1 and f_2, respectively. By the mirror reflection, the two foci overlap at the point F. Point F is defined as the focus of the system. It is at the outside of the funnel bottom. For normal incidence of the parallel light rays, *i. e.* when the rays parallel to y axis cast on the parabolic line IH, the parabolic surface will reflect the beam to focus f_1, however, with the mirror of the straight line, the rays will be reflected to the overlapped focus F. It is the same as rays from the left part of the parabolic surface.

The parabolic equations of the left and right part are shown, respectively:

$$y = \frac{1}{2p}(x+l)^2 \quad \text{and} \quad y = \frac{1}{2p}(x-l)^2, \quad (p>0) \tag{1}$$

The maximum effective inlet diameter is:

$$\varphi = \mathrm{AI} = 2x_I = 2l\left[\frac{5}{4} - \frac{p^2}{l^2} + \sqrt{\left(\frac{9}{4} - \frac{p^2}{l^2}\right)^2 + \frac{p^2}{l^2}}\right] \tag{2}$$

The vertical height of the parabolic line is:

$$H = y_\mathrm{A} - y_\mathrm{B} = \frac{1}{2p}\left[\frac{9l}{4} - \frac{p^2}{l} + \sqrt{\left(\frac{9l}{4} - \frac{p^2}{l}\right)^2 + p^2}\right]^2 - \frac{9l^2}{8p} \tag{3}$$

The minimum effective height of cylinder BC is:

$$h = y_\mathrm{B} - y_\mathrm{C} = \frac{3l^2}{4p} - \frac{p}{3} \tag{4}$$

In the eqs. (1)-(4), p is a focus parameter of the parabolic line, l is the inlet width of the concentrator, and also mentioned describe the geometry and optical parameters of the concentrator in integrity. These equations are the basic descriptions in mathematic for making the funnel. These equations will be used, and according to them, a 3-D concentrating system is made. By ray tracing, the optical property of the model will be analyzed, and the size, shape, position, energy distribution of the light focus and their relationship with different type is obtained.

Modeling and ray tracing analyze of the imaging light funnel

The size of focal spot and energy distribution

A 3-D model of the funnel was obtained in commercial software UG, which is shown in fig. 2. Its geometry and optical parameters of the funnel are shown in fig. 1 ($l = p = 0.23$ m was taken).

The inlet diameter and outlet diameter of device are 1.4 m and 0.35 m, respectively. The height of the compound parabolic part is 1.1 m, and the height of the cylinder BC is 0.2 m. The model is exported in IGES digital format, which could be imported to LightTools to analyze ray tracing.

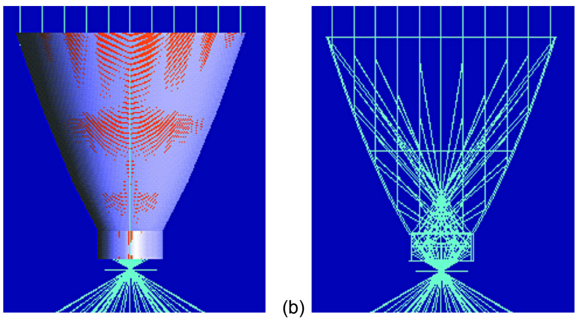
(a) (b)

Figure 2. Diagram of concentrator; (a) solid view (b) transparent view *(for color image see journal web-site)*

The model is imported into LightTools software. Here, the inner surface of the funnel is defined as aluminum, the reflectivity of the mirror walls is supposed as 100%. The light transmitting inside the concentrator is shown in fig. 2. The light beam is defined as 11 × 11 parallel beam, fig. 2(b) is the transparent format from which the light tracing inside the system could be seen.

In theory, this system will get an ideal result only when the incident light is parallel. If no geometric error in the system, the parallel incident light will focus on a point. However, in reality, geometric error is inevitable. The Sun light is also with a 0.53° incident angle. As a result, the focus will not be a point, while it will be a spot instead, called focal spot. Cast the Sun light in vertical to the inlet surface, the light distribution at the focus point is shown in fig. 3. The maximum diameter of the focal spot is 36.20 mm (here the effective numbers of light are 10094). The factor leading to the focal spot is mainly due to the geometrical error and the unparallel of the incident Sun light. In practical, the real focal spot should be larger than that is shown in fig. 3 for here the geometrical error is not considered.

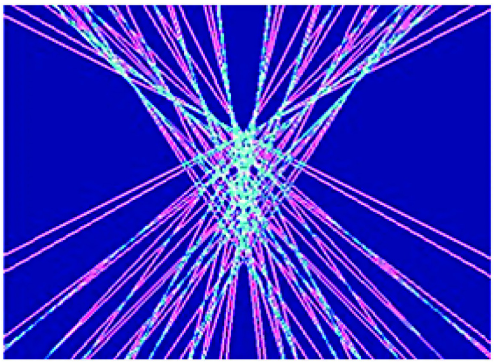

Figure 3. Light distribution around the focus

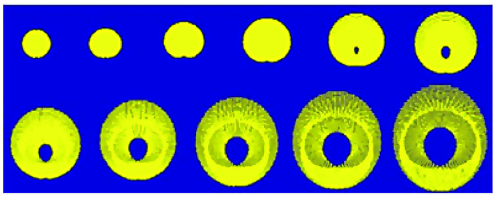

Figure 4. The change of focal spot with error angle (from left to right and from top to bottom, the error angle is: 0°, 0.2°, 0.4°, 0.6°, 0.8°, 1.0°, 1.2°, 1.4°, 1.6°, 1.8°, and 2.0°, respectively)
(for color image see journal web-site)

The change of focal spot with tracking error

In practice, the system could not track the solar precisely. Therefore, the incident Sun light could not parallel to the funnel's symmetrical axis exactly. In order to realize the differences of focal spot when the Sun light is not parallel to the symmetry axis, a simulation is undertaken. Here, the incident angle is defined as 0.53°, which is similar to Sun light. The number of Sun light is 100 × 100. Then using these parameters, the relationship between the size and light distribution of focus and the incident angle could be achieved. As usual, the tracking precision about 2° could be satisfied easily. Therefore, the arrange of incident angle is 0°-2°. The change of size and shape of focal spot under different incident angle is shown in fig. 4. The maximum diameter of focal plot and the distance between the spot center and the original focus under different incident angle is given in tab. 1.

Table 1. The change of position and size of focal spot with error angle

Error angle, [°]	0	0.2	0.4	0.6	0.8	1.0	1.2	1.4	1.6	1.8	2.0
Size of focal spot, [mm]	19.2	21.8	27.2	32.5	37.9	42.9	48.9	55.3	61.6	68.0	74.2
Offset of center focal spot, [mm]	0	3.9	6.1	7.6	8.9	10.0	11.1	12.2	13.3	14.5	15.5

From the previous simulation result, some points could be obtained: when the incident angle is 0°, the shape of spot is roundness, and its light distribution is symmetry. The light density of the unit is strongest at the center, and become weak at the edge. In the spot, there is no light cavity. When the incident light is not parallel to the system axis, the focal spot will become larger as the incident angle goes larger. When the incident angle reaches 2°, the maximum size of spot will be 3.9 times larger than the ones when the incident angle is 0°.

As the size of spot becomes large, its shape also changed. It is not roundness any more. Instead light cavity occurs and light is uneven distribution, which means the energy is also uneven distribution. The geometrical center of the spot is also deflecting from the originate center increasingly when the incident angle becomes larger and larger.

Results simulated provide basis for the design of light funnel. For consideration of heat preservation, the inlet opening of system should be as small as possible. But for consideration of energy receive, which is discussed previously, when tracking system is not very accuracy, deflection of focus will occur. So the inlet opening should be as large as possible.

Experiment of single funnel indirect heating type solar concentrating system

Structure of single imaging light funnel

According to geometric parameters discussed previously, an experiment used light funnel was carried out. Its light inlet opening diameter is 1.4 m, height of the compound parabolic part is 1.3 m, the diameter of cylinder mirror is 0.35 m, and its height is 0.17 m. The reflectivity of cylinder mirror is 85%, the others are defined as aluminum film with a 75-80% reflectivity. The structure material is glass fiber reinforced plastics.

A solar heating device used the experimental funnel is established as shown in fig. 5. Figure 6 shows its real device photo. The experiment device is made up by three main parts: the novel imaging light funnel, cavity receiver device, and solar tracking system.

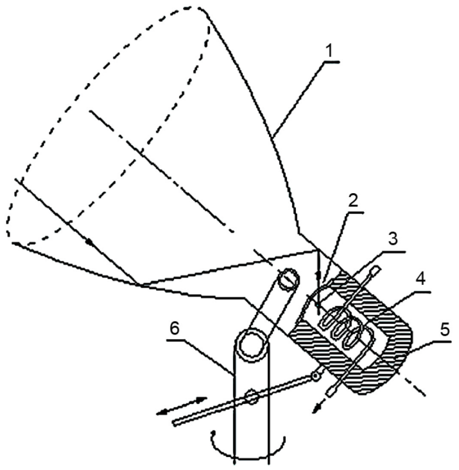

Figure 5. Schematic drawing of the funnel collector with indirection heating;
1 – concentrator, 2 – import window, 3 – focus, 4 – coil tube, 5 – heat insulation, 6 – tracer

Figure 6. Photo of the unit with single funnel

In this experiment, cavity receiver is used to absorb solar energy. The focus of the funnel is on the receiver's light inlet. The diameter of receiver's lumen is 0.25 m, its height is 0.36 m, the thickness of its insulating layer is 0.05 m, and its diameter of light inlet window is 0.17 m. The window is enveloped by heat resisting glass. In the receiver, the diameter of inside receiving tube is 16 mm, its thickness is 0.5 mm and its length is 15 m, which equals to heats receive surface of 0.75 m^2. Its outside shell is made by 1 mm thickness steel plate.

The change of temperature of the system without load

To obtain the maximum value of temperature on the receiver, an experiment without load was undertaken. In the times of experiment, no water or liquid flows in the receiver pipe. But at the bottom of receiver, an energy storage material was installed. It is solid-solid transition material and its transition temperature is 186 °C. It was installed in two boxes and total weight is 1.5 kg. The environment temperature was 6-8 °C. During the experiment, solar irradiance variation with the local time is shown in fig. 7. The temperature variation in the energy collecting cavity with the time is shown in fig. 8. Here, the temperature detecting point was placed at the bottom and top of the collecting cavity. The temperature signature was obtained by thermocouple.

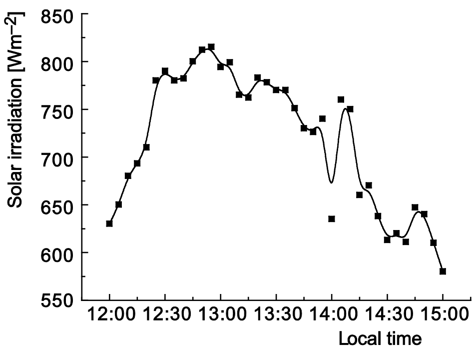

Figure 7. Solar irradiance variation with the local time

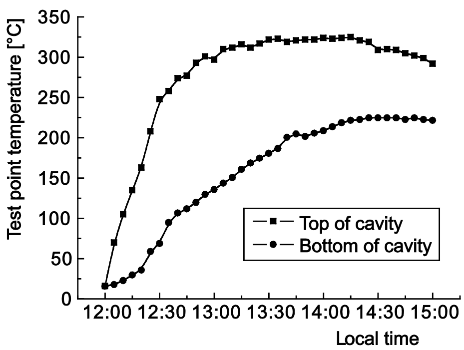

Figure 8. The temperature variation in the energy collecting cavity with the time

Experiment results show that, when the solar irradiance is about 600-800 W/m^2 in winter, the highest temperature obtained of the unit could reach 335 °C. Even at the bottom of cavity, its temperature will reach 230 °C, which showed an obvious advantage in obtaining high temperature heat. As the focus is at the light inlet, temperature at the top of heat receiver pipe increases to 300 °C rapidly in just one hour, which shows a good energy absorbing property.

Heat-collecting efficiency of the funnel

In order to test the heat-collecting efficiency of the funnel in winter, water was regarded as load medium, improved temperature was measured, and the input energy value was gotten indirectly. This energy is from the Sun light reflected by parabolic mirror and cylinder mirror. So the energy that increases the water temperature is the energy absorbed by the system. Then the efficiency of the funnel is written:

$$\eta = \frac{m\, c_p (T_\mathrm{o} - T_\mathrm{i})}{AIt} \tag{5}$$

where t is the running time of the system, A [m^2] – the area that receive the Sun light, I [Wm^{-2}] – the average solar irradiance during the running time, m – the water flow rate, c_p [kJ^{-1}kg^{-1}°C] – the specific heat capacity of water, T_i and T_o [°C] are the water temperature at the inlet and outlet of receiver pipe, respectively.

In this experiment, $m = 8.07 \cdot 10^{-3}$ kg/s, $A = 1.5$ m^2, $c_\mathrm{p} = 4.18$ kJ/kg°C, $T_\mathrm{i} = 12.8$ °C. The curves of solar irradiance and water temperature at the outlet of pipe during the running time are given in figs. 9 and 10. From fig. 10, we can get the results at weak solar irradiance environment. In fig. 9, the experiment parameters are: $t = 2850$ seconds, $I = 636.4$ W/m^2. Average water temperature at the outlet is 25 °C, the environment temperature is 2-8 °C. Then the efficiency of the system based on the experiment in fig. 9 would be 43.1%. Under the weak solar irradiance environment and a 5 °C environment temperature, the efficiency of the system in fig. 10 is 39.3%.

From figs. 9 and 10, it could be concluded that the temperature of outlet water is closely related with solar irradiance. And the variation tendency of the temperature and solar irradiance is the same. When the solar irradiance is stronger, the temperature of output water will be higher. From figs. 9 and 10, it could also be concluded that when the solar irradiance is stronger, the total efficiency of concentrator will also be higher. Hence, this system would have a better performance at good Sun light weather like in summer.

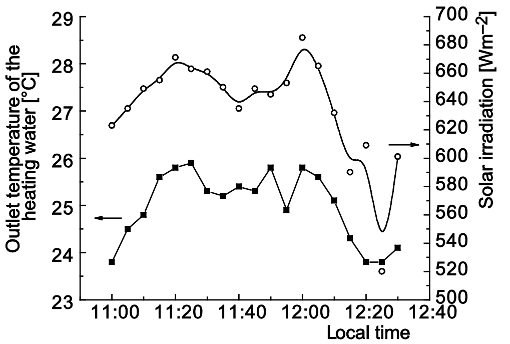

Figure 9. The heating water temperature and solar irradiance variation with the local time in winter

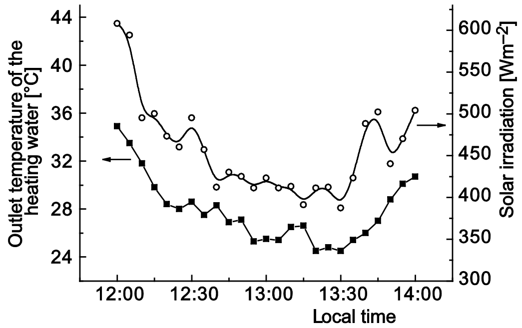

Figure 10. The heating water temperature and solar irradiance variation with the local time under weak Sun light condition

Experiment of multiple funnels with series direct heating type solar concentrating system

Structure and operation principle of solar concentrating system

The Sun light directly cast on the tube receiver to heat the black transfer heat oil. The oil is then used to heat the water in the steam generator to produce high temperature and high pressure steam. The schematic diagram is shown in fig. 11, and its photo is shown in fig. 12. The cross section of single funnel is shown in fig. 13. The geometric parameters of the light concentrator part are the same as the system previously discussed. But the size of the receiver is changed. The diameter of receiver's lumen is 0.20 m, its height is 0.15 m, and as a result, the volume of receiver is 4.7 L. The thickness of insulating layer is 0.06 m, the diameter of transparent window is 0.15 m, and the window is enveloped by heat resisting glass with two layers. The shell of receiver is made of stainless steel with 1.5 mm thickness. The power of the pump that strive the heat transfer oil is 120 W.

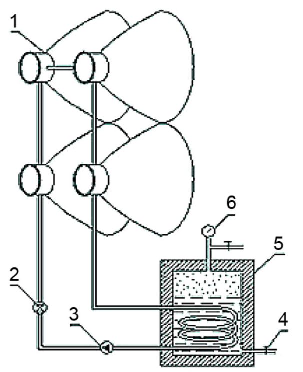

Figure 11. The schematic drawing of the multiple funnels direction heating system; *1 - funnel heat collector, 2 - valve, 3 - pump, 4 – import water valve, 5 - thermal storage tank, 6 - pressure meter*

Its operation principle can be shown: every funnel of the four are connected with cavity receiver (1). Then in the receiver, it is filled with the black heat transfer oil. The oil is heated by the concentrated light. Then the heated oil is driven by pump (3), through valve (2) to water tank

Figure 12. Photo of the unit with four funnels

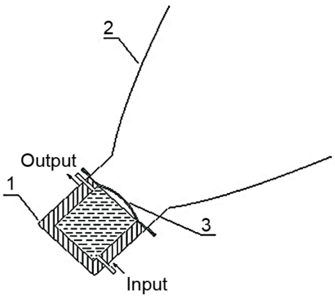

Figure 13. The section of the direction heating funnel; *1 - storage oil tank, 2 - concentrator, 3 – import window*

(5) to heat the water inside the tank. The cold water is input through valve (4), and heated water is output through the valve in the top. Pressure meter (6) measures the pressure of the system.

Experiment of heating water

The tank is filled with 100 kg water, and the temperature of water was measured by thermocouple. In the water tank, besides the water, there is still some empty volume for generating high temperature and high pressure steam. The pressure of steam was measured by pressure meter.

The experiment was conducted in May 5th and May 15th. The solar irradiance of those two days is shown in fig. 14. Temperature variations at different time of the two days are shown in fig. 15. From fig. 14, it could be concluded that the solar irradiance of May 15th is a bit higher than that of May 5th. Figure 14 shows that the temperature increase steadily, and at the temperature point of 100 °C, the increase goes slowly at this point where some part of water transferred from water to steam and absorbed some part of the solar energy. The temperature curves also show that the water temperature of May 15th is a bit higher than that of May 5th, in accordance with the weather.

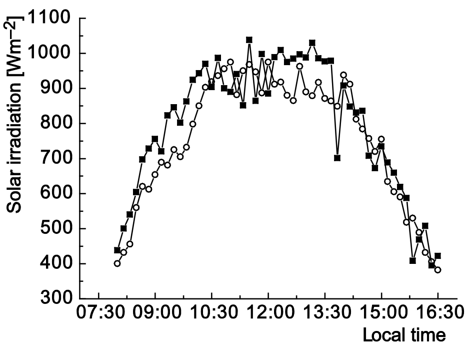

Figure 14. Solar irradiance variation with the local time

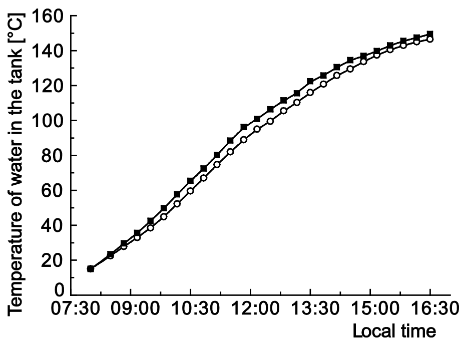

Figure 15. The temperature variation in the water local time tank with the

Heat collection efficiency of solar concentrating system

The average efficiency of 20 minutes' variation is shown in fig. 16. From fig. 16, it could be learnt when the temperature of water is under 100 °C, the efficiency is about 45%, which is relatively high. When the temperature is over 100 °C after 12:00 p. m., the efficiency goes down obviously. There are two main reasons, one is the heat dissipation goes up when the temperature is high. Another is due to phase transition for it will absorb some energy not considered in calculation which lowers the calculated efficiency.

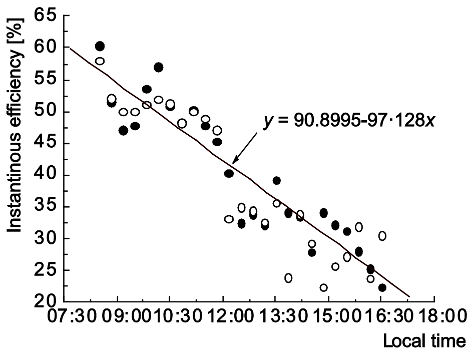

Figure 16. Instantaneous efficiency in 20 minutes' variety with local time

Conclusions

In this paper, a novel light imaging funnel concentrator was designed, and its structure and operation principles were introduced. The most advantage of this system is that its focus is at the outside of the funnel which makes the connection of receiver and funnel easy and reduce energy dissipation.

By building a 3-D model, the ray transmitting in the system was analyzed. The result shows that the size of focal spot increases with the increase of incident angle of the Sun light. When the incident angle is 2°, the maximum diameter of spot is 74.2 mm.

Using the novel funnel, a new single solar energy heating system was established and experiments with load and without load were undertaken. The experiments results show that the highest temperature of the receiver with no load could reach 335 °C. And the efficiency with load could reach about 43%. It is an idea high temperature solar energy concentrator.

Based on the new single solar energy heating system, a multiple series concentrating and heating system was designed and built. In addition, experiments of the system were also undertaken. Results show under good sunshine, the temperature in the water tank could be heated to 150 °C, thus, it is able to provide steam to user directly, which is an idea solar energy system for solar energy heat system and sea water desalination.

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