# PERFORMANCE COMPARISON OF A NEW-TYPE ROUGH SOLAR CONCENTRATOR THERMAL SYSTEM IN DIFFERENT INSTALLATIONS

by

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*This paper puts forward a new-type trough solar concentrator with a compound surface, which is comprised of two upper paraboloids, lower planar mirrors, and one base paraboloid. This structure forms a co-focus where a solar receiver is installed. The performance of the new-type trough solar concentrator combined with a cylinder receiver and a flat plate receiver, respectively, was tested. For comparison, the reflector of the concentrator was made of a polished aluminum sheet and a mirror glass, respectively. The experimental results show that the prototype concentrator systems may have an average efficiency around 40% for the hot water temperature up to 80 °C and the ambient temperature below 0 °C in winter. To test and verify the performance of the system in higher temperature range, a scaled-down new concentrator of the same structure was made and tested in the outdoor. It was found from the results that the designed new-type trough concentrator can produce 220 °C solar heat. It indicates that the proposed design may be promising for solar thermal application at a medium temperature of 80 °C-150 °C.*

Key words: *new-type trough solar concentrator, ray tracing analysis, compound surface, outdoor testing, performance comparison*

## Introduction

In the recent years, many innovative trough solar concentrators have been designed for medium temperature applications. For example, Tripanagnostopoulos *et al.* [1] presented a new double curve surface compound parabolic concentrator (CPC) and gave an analysis for it being combined with a flat bifacial absorber. Oommen and Jayaraman [2] established a solar collector with multiple troughs to obtain the medium temperature heat. Tang *et al*. [3] analyzed the optical performance of the east-west orientated static CPC for application in China. Zauner *et al*. [4] introduced some methods to develop the medium temperature collector with CPC. Bakos *et al*. [5] studied the thermal performance of a trough collector using an asymmetric CPC reflector. On the other hand, many researches about the receivers used with trough parabolic concentrators have been also reported. Bakos *et al.* [5] introduced a heat-pipe absorber and gave the optimiza-

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tion analysis of the whole system. Kumar and Reddy [6] presented a porous disc receiver and used it in a solar parabolic trough system. Padilla *et al.* [7] analyzed the heat transfer of a new circular tube receiver and calculated the function distribution of heat loss. Singh and Eames [8] summarized the natural convective heat transfer correlations in rectangular cross-section cavities and discussed their potential applications in the CPC solar collector. Li *et al.* [9] compared two novel intermediate temperature compound parabolic solar collectors with the U-shape evacuated tubular absorber. All above efforts have given the contribution to the progress of trough compound parabolic solar concentrator systems. However, continuous innovation is still required.

Another disadvantage of the traditional trough parabolic concentrator is that it needs a high accuracy Sun tracking system and is unable to collect the diffuse skylight [10]. This has caused the problems of high cost and unsuitability for the regions with high diffuse component in solar radiation. Contrarily, the non-imaging CPC has different features of no need for Sun tracking and having a solar receiver installed on its base, but its concentration ratio is relatively low [11]. Abdul-Jabbar and Al-Mutawalli [12] analyzed the effect of two-axis Sun tracking on the performance of CPC and indicated the concentration rate of the CPC is about 10 and collection temperature less than 150 °C. Thus, it is only suitable to middle or low temperature application fields.

To balance the individual advantages of conventional trough parabolic solar concentrators and non-imaging CPC, a novel compound curved surface solar concentrator has been proposed by the authors. The novel design of this concentrator is that its surface is composed of multiple curved surfaces, and this allows the solar receiver to be synchronously heated by upper and lower surfaces. It is helpful to improve the efficiency of the receiver. The detailed design consideration and optimization of geometrical parameters of the new type trough concentrator have been reported previously [13]. This study will present design, construction, performance testing, and comparison of the two 4 m long prototype new-type trough solar concentrators using aluminum and glass mirror, respectively. A further ray tracing analysis will also be given to compare flat and cylindrical receivers used in the concentrators.

## Design principle of the new-type trough concentrator

Figure 1 shows the cross-sectional view of the new-type trough concentrator, the outline of which consists of three parabolic curve sections AG, BH, and CED, and two line segments AC and BD. The cross-sectional curve of the concentrator is symmetric about the $y$- axis. The $F_1$, $F_2$, and $F_3$ are the focuses of three parabolic curves. The $F_2$ and $F_3$ are symmetric about the line AC, and $F_1$ and $F_3$ are symmetric about the line BD. Therefore, the incident rays that are parallel to the symmetric axis are reflected by AG or BH, and then by AC or BD to the focus $F_3$ instead of $F_1$ and $F_2$. If the incident rays strike on the base parabolic curve CED, it will be reflected directly to $F_3$. So, $F_3$ may be considered as the focus of the whole compound concentrator. The detailed mathematical description of the new-type concentrator can be found in [13].

## Choice of receiver and tracking precision requirement

The geometrical parameters of the new-type trough concentrator are given out (referred to fig. 1):

- the focal length of the upper parabolic curves AG and BH is: $p_1 = 230$ mm,
- the focal length of the base parabolic curve CED is: $p_2 = 80$ mm,
- according to [13], the horizontal distance between A and B was: $x_B - x_A = l = p_1 = 230$ mm,
- the horizontal distance between G and H was: $x_H - x_G = 700$ mm, and
- points C and D were on the $x$- axis, *i. e.*, $x_C - x_D = 0$.

From these parameters, the positions of points A, B, G, and H were determined, hence the heights of curves or lines were given: $y_G - y_A = 615.3$ mm, $y_A - y_C = 182.4$ mm, and $y_C - y_E = 95.8$ mm.

A flat receiver of 80 mm wide and a cylindrical receiver of 50 mm diameter, respectively, were chosen in the experiments.

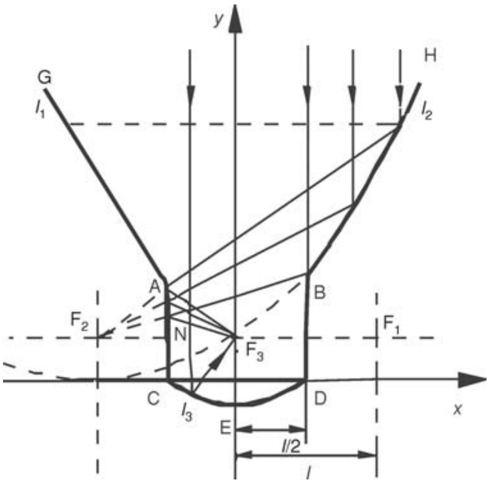

**Figure 1. Working principle of the new-type trough concentrator**

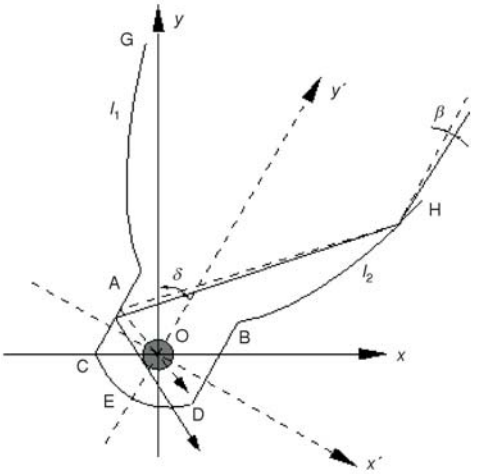

**Figure 2. Tracking error angle of the concentrator and tilt angle of the receiver**

As reported in the [14], ray tracing simulation was initially conducted with the incoming rays parallel to the symmetrical axis of the trough concentrator. Figure 2 illustrates the tracking error angle $\beta$, from the symmetrical axis and the tilt angle $\delta$, of the flat receiver, which is the angle between the receivers's normal to the symmetrical axis of the concentrator. The simulation results indicate that the tracking precision requirement is $\beta \leq 2°$ for 80 mm wide flat receiver when the receiver's surface is normal to the entrance plane of the concentrator and $\beta \leq 1.6°$ for a cylindrical receiver with 50 mm diameter. However, for the flat receiver, if the tilt angle $\delta$ of the flat receiver (flat plane in x-axis, Sun light in y'-axis) is not 90°, the tracking precision requirement will be more than 2°.

**Figure 3. Two prototype concentrators (a) made by reflecting aluminum sheet, (b) made by glass of coating reflection film**

## Construction and testing of two prototype new-type trough concentrators

### *Two prototypes*

Based on the optical analysis [14], the prototype new-type trough concentrators were designed and constructed. Figure 3 shows two prototypes with the same geometry but different reflective surface materials. The prototype on fig. 3(a) was made of a polished aluminum sheet with a reflectance of 92% while the prototype one fig. 3(b) was made of a curved mirror glass with a reflectance of 75~80% (non-standard production). Two prototypes had the same geometry and their aperture was 0.7 m wide and 4.0 m long, giving the aperture area of 2.8 m$^2$.

### *The structure of the receivers*

Two different types of glass evacuated-tube solar receivers were adopted in the experiment. They were a concentric pipe solar receiver and a finned plate solar receiver. The first one was used together with the aluminum concentrator prototype and the second one was used for the mirror glass concentrator prototype. The structures and dimensions of two solar receivers are shown in figs. 4 and 5.

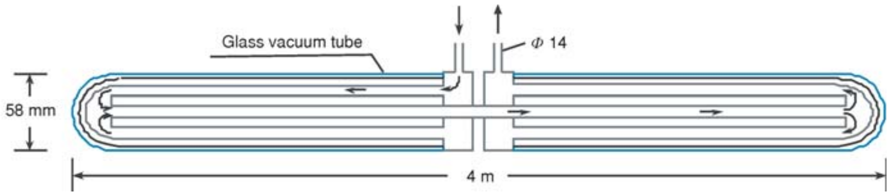

**Figure 4. Glass evacuated-tube concentric pipe solar receiver**

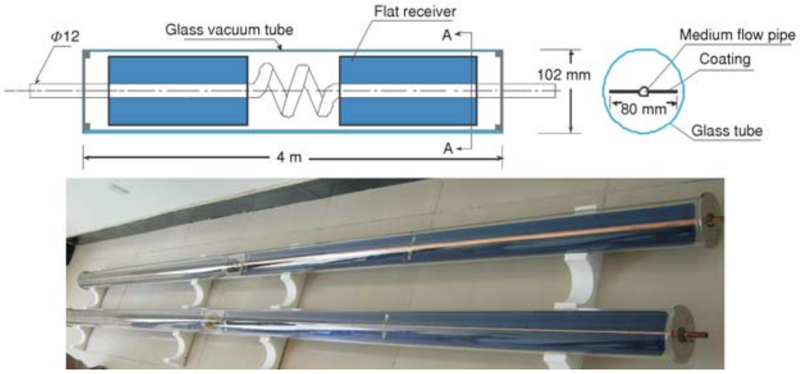

**Figure 5. The design and photo of the evacuated-tube flat plate solar receiver**

### *Configuration of the experimental system*

In order to test the performance of the new-type trough concentrator, an experimental system was built as shown in fig. 6. The experimental system mainly consists of a new type trough solar concentrator, a glass evacuated-tube solar receiver, a water tank with a submerged coil heat exchanger, and a circulating pump. Heat conductive oil was used as the working fluid to transport the solar heat. The flow rate of the working fluid was testes to be 4.3 litre per minute.

When the system runs, the sunlight will be focused by the trough concentrator onto the receiver, which converts the solar radiation into heat and transfers it to the heat conductive oil. Driven by the circulating pump, the oil flows through the coil heat exchanger inside the water tank and release heat in the water at the same time. When the water is heated to a stated temperature, the temperature-control valves will open to discharge the hot water through the tope valve of the water tank, meanwhile the cold water is fed by way of the bottom valve.

According to fig. 6, the energy balance function of the system can be written:

$$Q_u = Q_s - Q_{loss} = IA\eta_0 - U_L A_L (T_L - T_a)$$

where $Q_u$ is the obtained heat in water tank, $Q_s$ – the receiving heat by concentrating system, and $Q_{loss}$ – the lost heat from the whole system. At the same time, $I$ is the average solar irradiation on the aperture of the concentrator, $\eta_0$ – the optical efficiency of the concentrator, $A$ – the aperture area of the concentrator, $U_L$ – the total heat loss coefficient of the system, $A_L$ – the total heat loss area. The $T_L$ and $T_a$ are the average loss heat temperature and ambient temperature, respectively. Based on the obtaining heat by water tank, $Q_u$ can be written:

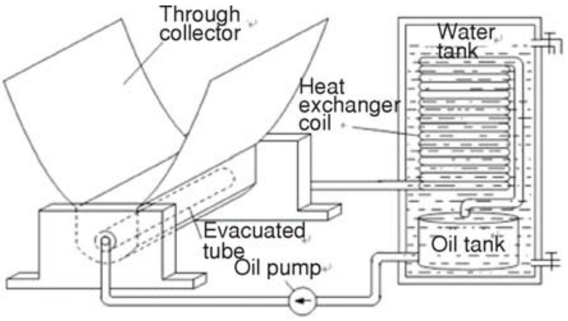

**Figure 6. Schematic of the experimental system for testing the new type trough solar concentrator**

$$Q_u = mC_p \frac{\Delta T}{\Delta t}$$

Therefore, the thermal efficiency of the system in different operation temperature can be calculated:

$$\eta = \frac{C_p m \Delta T}{IA\Delta t}$$

where $C_p$ is the specific heat capacity of water, $m$ – the mass of water, and $\Delta T$ – the temperature rise of water in time.

### *Measuring instruments*

In the experiment, the solar irradiance was recorded automatically by TRM-2 solar test meter with precision of ± 5%. The temperatures at different measuring points were recorded by the calibrated K-type thermocouples and the signals were input to a temperature recording instrument (TT-12). A single-axis Sun tracking system with a tracking accuracy of about 1.5° was used to fit into the tilt angle of the concentrator. Figure 7 shows the controller and the sensor assembly which includes a set of symmetrical photosensitive resistors. When the symmetrical plane of the concentrator deviates from the Sun, the sensor will give a signal to the controller, and then calculate the movement of the servo motor required to adjust the concentrator to the optimum position.

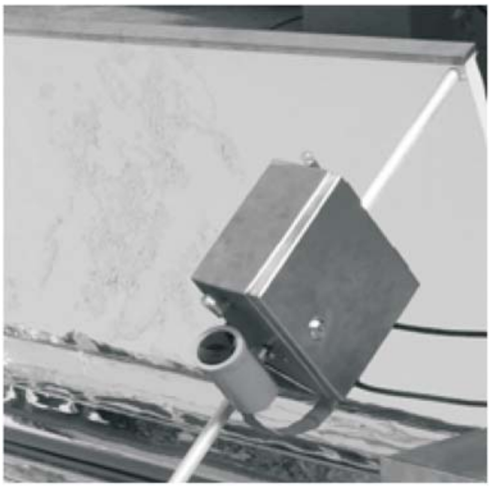

**Figure 7. The Sun tracker**

## Experimental results and analysis

### *Testing testing of the 1st prototype concentrator system*

#### *Solar concentrator orientated at north-south and use of a cylindrical receiver*

In this situation, part of the experimental results was introduced in the study [15]. The glass evacuated-tube concentric pipe solar receiver shown in fig. 4 was used in combination with the 1st prototype concentrator made of a polished aluminum sheet. The length of a single concentric pipe was 1.88 m and two pipes were butt jointed to form a total length of 3.8 m. The mass of water in the storage tank was 55 kg and it was expected that the water could be heated up to above 100 °C. The prototype trough solar concentrator was placed at the north-south orientation.

The water temperature variations were recorded in the experiment to calculate the system efficiency and then find the relationship between the efficiency and water temperature for performance comparison. Given that the prototype concentrator was only 4 m long and the sunlight is oblique in the morning and evening, there would be some significant edge effects, which should be considered when calculating the efficiency of the system.

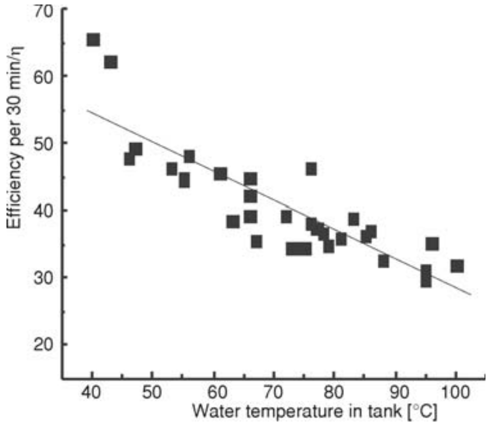

**Figure 8. Variation of the transient efficiency of system with the water temperature**

The relation between the efficiency and water temperature is shown in fig. 8, where $\Delta t$ is 30 minute.

It can be seen from fig. 8 that before the water temperature reached 60 °C, the thermal efficiency of system maintained at 45% or more. At 80 °C, the efficiency dropped to about 35%. When the temperature of water got to be about 90 °C, the efficiency still maintained at about 30%. Therefore, at high operating temperature, the designed concentrator system is more competitive than the conventional glass evacuated-tube solar collectors and flat solar collectors.

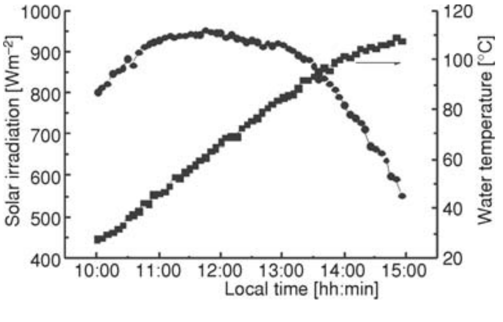

**Figure 9. Variation of solar irradiation and water temperature at local time (west-east orientated, cylinder receiver)**

#### *Solar concentrator orientated at east-west and use of a cylindrical receiver*

The prototype system was also tested with the concentrator oriented at the east-west direction. One experiment was done in December with the initial water temperature of 27.7 °C and the ambient temperature in the range of –2 °C ~ 0 °C. The system started to run from 10:00 hours. The solar irradiation intensity was above 800 W/m$^2$ from the start of the experiment to 13:50 h. The water temperature reached 100 °C at 13:50 h, 109 °C at 14:50 h, and then increased slowly, as shown in fig. 9. The average efficiency of system was calculated to be $\eta_{27.7\sim100} = 46.7\%$ for the temperature range of 27.7 to 100 °C and $\eta_{70\text{-}100} = 46.2\%$ for the temperature range between 70 to 100 °C. It is apparent that the average efficiency of system did not decrease significantly with the rise of temperature for the east-west oriented prototype. Compared with the results in fig. 8, this may indicate that the east-west oriented installation of the concentrator would lead a higher efficiency than the north-south orientation for the high latitude locations such as in Beijing.

### *Solar concentrator orientated at east-west and use of a flat receiver*

The concentrator was still placed in east-west direction with a flat receiver and then the previous experiment was repeated. The receiver is the one shown in fig. 5 with the evacuated-tube flat receiver. The fluid flows in the evacuated-tube from its one end and goes out from the other end. The initial temperature of the water in the tank was 24.3 °C, the environmental temperature was 7 °C ~ 15 °C. System operated from 9:30 h, the water temperature reached 70 °C at 12:10 h, and the water temperature reached 110 °C at 15:30 h.

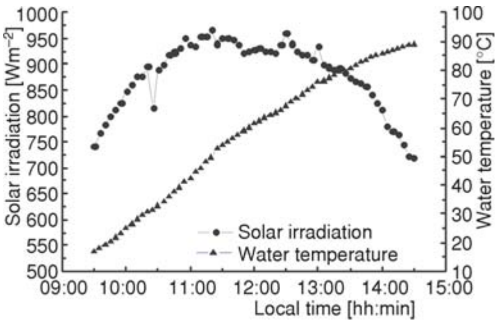

**Figure 10. Variation of solar irradiation and water temperature at local time (west-east orientated, flat receiver)**

The experimental results in fig. 10 show that the system has good thermal conversion efficiency. From the beginning of the experiment to 13:00 h, the solar radiation intensity is more than 800 W/m$^2$. During this stage, the temperature curve rises smoothly. The efficiency of the system is 48.3% prior to 70 °C, and the daily efficiency is 43%.

## ***Testing of the 2$^{nd}$ prototype concentrator system***

### *Solar concentrator orientated at east-west and use of a flat receiver*

The finned plate solar receiver shown in fig. 5 was used together with the 2$^{nd}$ prototype concentrator made of a mirror glass. The prototype concentrator was oriented at the east-west direction and the flat receiver was installed with its normal perpendicular to the sunlight rays at 11:00 h. The testing day was with the ambient temperature at about –10 °C. The mass of water in the storage tank was 55 kg, and the mass of thermal oil in the transfer pipeline was 13 kg. Variation of solar irradiance and water temperature with local time are shown in fig. 11. The total quantity of solar irradiation on the day was 17.74 MJ/m$^2$. The water temperature increased linearly from 16 °C to 75 °C and then slowly increased until 110 °C.

### *Solar concentrator orientated at east-west and use of a cylinder receiver*

The concentrator was remained at the same orientation, but with the flat receiver being replaced with a cylindrical one. The system was then tested at the same conditions as in the previous section. The ambient temperature was –7 °C ~ –10 °C on the test day. The recorded solar irradiance values and water temperatures in the tank are shown in fig. 12. The results show that the water temperature increased about linearly from 16 °C to 75 °C, and then increased slowly due to decreased solar irradiation. Finally, the temperature reached about 95 °C. Comparison

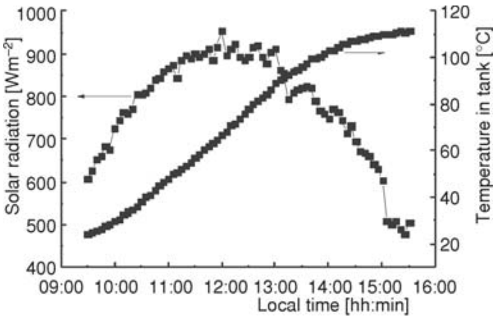

**Figure 11. Variation of solar irradiation and water temperature at local time (west-east orientated, flat receiver)**

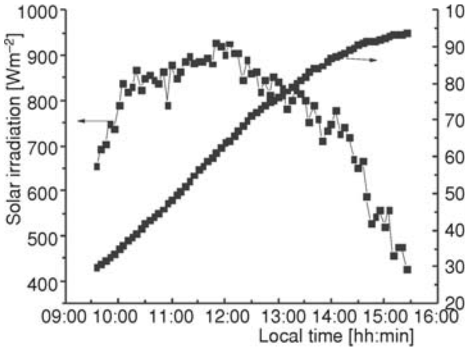

**Figure 12. Variation of solar irradiation and water temperature at local time**

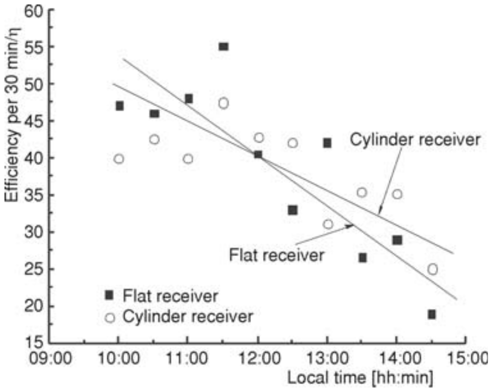

**Figure 13. Variation of the solar collection efficiency at local time**

figs. 11 and 12, it can be found that fig. 11 obtained higher temperature in the tank. That is to say the flat receiver seems better than the cylinder receiver. The reason may be the width of the flat receiver is bigger then the diameter of the cylinder receiver so that the flat receiver can receive more solar light during the midday.

Figure 13 shows the instantaneous solar collection efficiency for a 30 minutes interval. It can be found that the test points are a bit discrete. The reason is that the time interval to calculate the efficiency is too short. The previous interval may store some energy to next one. Also, it can be found, at the initial stage of the experiment, the efficiency was about 45%. During this period, it can be found that to use the flat receiver is better than to use cylinder receiver. After 13:40 h, because of the high water temperature, the low ambient temperature and the insufficient insulation of the water tank, heat dissipation rate increased, the efficiency went down. During this period, to use the cylinder receiver is better than to use flat receiver. The straight lines in the figure are the fitting lines about the experimental points.

The daily average thermal efficiency of the system on typical day was calculated to be $\eta$ = 35.9%. With the temperature rising from the initial 16.9 °C to 60 °C, the average efficiency was about $\eta$ = 44.2% . The efficiency value is slightly lower comparing to those of the aluminum prototype concentrator system. This might be because the mirror glass used in the 2nd prototype had a slightly lower reflectance and the finned plate solar receiver had a larger thermal resistance than the concentric pipe used in the 1st prototype. It is worthwhile to point out that both of the prototype trough concentrators could get over 95 °C solar heat in winter in the northern China with a fairly low ambient temperature.

### *Summary of comparative testing results*

The experimental results are summarized in tab. 1 in order to compare the effect of orientation, reflector, and receiver on the thermal efficiency of the new-type trough concentrator system.

**Table 1. Summary of experimental results**

| Concentrator surface type | Orientation | Receiver type | Efficiency prior to 70 °C, [%] | Daily efficiency, [%] |
|---|---|---|---|---|
| Coating glass reflectivity ~85% | East-west | Flat | 41.4 | 35.9 |
|  | East-west | Cylinder | 43.3 | 38.7 |
| Reflecting aluminum sheet reflectivity ~92% | East-west | Cylinder | 47.1 | 46.7 |
|  | North-south | Cylinder | 40.7 | 40 |
|  | East-west | Flat | 48.3 | 43.0 |

The following conclusions may be reached according to tab. 1:

(1) For the same reflector, the east-west orientated installation can give a higher thermal efficiency than the north-south orientation in winter. This is because the edge loss is larger for the north-south orientated installation due to lower solar altitude in winter particularly for higher local latitude.

(2) As it had a lower reflectance of about 82 ~ 85%, the glass reflector gave a worse efficiency than the aluminum reflector.

(3) Although reflectance is the most important influence factor for the trough concentrating solar collection system, the thermal efficiency of system could be significantly improved if the concentrator had better geometric and Sun-tracking accuracy and the receiver and tank had good thermal insulation. The efficiency of the system was up to 45.3% and the water temperature was over 90 °C in winter sunny day when the aluminum reflector with the reflectance of 92% was used. In addition, for the east-west orientated system, its efficiency did not largely change with the hot water temperature even in the low ambient temperature period.

### *Performance testing of the system in higher temperature range*

In all before-mentioned experiments, the working fluid is water so that the temperature in tank only can reach about 100 °C. This temperature is not able to reflect the middle temperature characteristics of this new-type concentrator. Recently, a small size concentrator of the same structure was constructed, as shown in fig. 14. The reflection material in the new one was aluminum sheet with the reflectance of 92%.

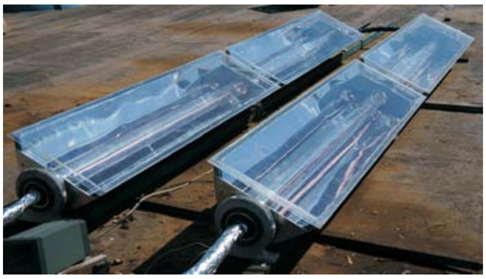

**Figure 14. A small scale new-type trough concentrator**

This latest trough concentrator has an aperture with 0.45 m width and 2 × 1.9 m length. To be protected from dust, the entrance was cover by 3 mm thick super white glass. Corresponding to fig. 1, $l = 0.18$ m, the upper parabolic curves equation of AG and BH is:

$$y = -24.4286 + 0.45051x + 0.00324x^2$$

and the base parabolic curve equation of CED is:

$$x^2 = 300y.$$

The origin of the co-ordinates is at the lowest point of the trough concentrator.

The receiver used in the system is a 4 m long evacuated-tube finned plate absorber, same as shown in fig. 5. The experiments were carried out in the outdoor with the heat conduc-

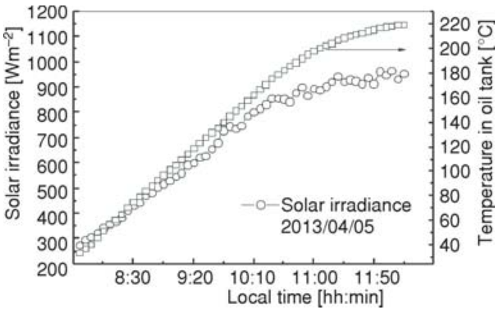

**Figure 15. Variation of solar irradiation and oil temperature in tank at local time (west-east orientated, flat receiver)**

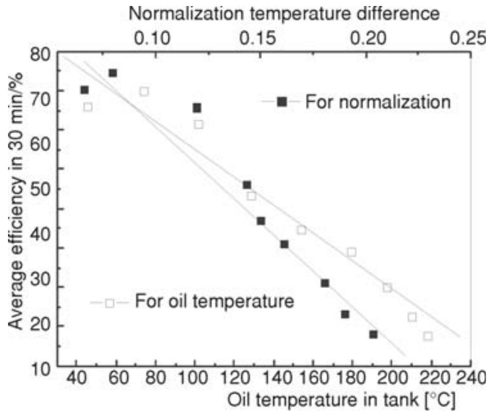

**Figure 16. Variation of the transient efficiency of the small size prototype with the oil temperature and normalization temperature difference**

tive oil as the working fluid. The total oil amount in tank was 15 kg. The flow rate of working fluid is 4.0 ~ 4.3 liter per minute. Two concentrators were placed in the east-west direction in series connection to heat the oil. The temperature of the oil in tank and solar irradiation changing with the local time are shown in fig. 15. The change of the efficiency at the 30 minutes interval with the oil temperature in the tank and normalization temperature difference is shown in fig. 16. The experimental results tell us that the concentrator can produce 220 °C solar heat. The efficiency is over 40% when the temperature in the tank is less than 140 °C. This result shows the characteristics of the concentrator as a medium temperature solar collector. From the normalization temperature difference curve, the efficiency of this small scale concentrator solar collector can be approximately described:

$$\eta = 0.82 - 3.64T^*$$

where $T^*$ is the normalization temperature difference of the system and given by:

$$T^* = \frac{T_i - T_\mathrm{a}}{I}$$

where $T_i$ is the oil temperature entering collector, $T_\mathrm{a}$ – the ambient temperature, and $I$ – the solar irradiation.

## Conclusions

This paper has presented the performance testing results about a new-type trough solar concentrator in combination with a glass evacuated-tube concentric pipe solar receiver and a finned plate receiver, respectively. The proposed trough concentrator comprises of a main paraboloid, a paraboloidal bottom, and a planar mirror connecting them. The main paraboloid has its mirrored focus overlapping with that of the paraboloidal bottom. The configuration of the proposed concentrator provides an advantage of reflecting the incident sunlight to both the top and bottom surfaces of the solar receiver. For the presented design, the Sun tracking accuracy required is 1.6° if using a concentric pipe solar receiver and 2° if using a finned plate receiver. Two prototype concentrators made of a polished aluminum sheet and a mirror glass, respectively, have been constructed and tested. Both of the prototypes had the same aperture area of 0.7 m × 4.0 m. For the ambient temperature below 0 °C in winter, the prototype concentrator systems have heated 55 kg water up to 80 °C with an average efficiency around 40%. To evaluate the medium temperature performance of this kind concentrator, a small scale prototype trough concentrator has been also made and tested with conductive oil. The field experiment proved that the concentrator system can be used to provide about 80 °C ~ 200 °C solar heat.

## Acknowledgment

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