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# EXPERIMENTAL INVESTIGATION OF A LINEAR FRESNEL COLLECTOR SYSTEM

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**Abstract:** In this study, linear Fresnel collector system is investigated experimentally. A solar tracking mirror mechanism to system was added. This tracking has been designed to maximize the reception of available solar radiation. The thermal performance of Fresnel solar collector for different operating conditions was obtained. The Fresnel collector system has been designed with sufficient flexibility to consider different geometries and thermal parameters, and may be used to simulate the performance of a proposed Fresnel collector system at any location.
**Keywords:** Solar energy, Fresnel collector, Thermal efficiency

## LİNEER FRESNEL KOLEKTÖR SİSTEMİNİN DENEYSEL ARAŞTIRILMASI

**Özet:** Bu çalışmada, lineer Fresnel kolektör sistemi deneysel olarak incelenmiştir. Sisteme, güneşi takip edebilen ve böylece aynaların konumunun ayarlanabildiği bir takip mekanizması eklenmiştir. Bu takip mekanizması sayesinde güneş radyasyonundan en maksimum şekilde faydalanılmaktadır. Farklı çalışma şartlarında Fresnel güneş kolektörün ısıl verimi belirlenmiştir. Fresnel kolektör sistemi, farklı çalışma şartlarında çalışabilecek şekilde dizayn edilmiştir. Bu yüzden Fresnel kolektör sistemi herhangi bir yerleşim yerinde çalıştırılabilir ve sistem verimi belirlenebilir.
**Anahtar Kelimeler:** Güneş enerjisi, Fresnel kolektör, Isıl verim

**Nomenclature**

| | |
|---|---|
| $A_c$ | Area of Fresnel mirrors [m$^2$] |
| $A_{nc}$ | Non-useful aperture area of the Fresnel collector [m$^2$] |
| $c_p$ | Specific heat of the fluid [kJ/kg/$^o$C] |
| CR | Concentration ratio |
| f | Height of the absorber above primary mirror reflector plane [m] |
| I | Solar radiation [W/m$^2$] |
| m | Fluid mass flow rate [kg/s] |
| RH | Relative humidity [%] |
| $T_i$ | Inlet fluid temperature [$^o$C] |
| $T_o$ | Outlet fluid temperature [$^o$C] |
| $T_a$ | Ambient temperature [$^o$C] |
| v | Wind velocity [m/s] |
| W | Width of a mirror reflector [m] |
| $Q_a$ | Heat absorbed by water [W] |
| $Q_n$ | Distance between the nth mirror and center [m] |
| $Q_r$ | Total energy incoming to receiver [W] |
| $S_n$ | Shift or space between nth and nth - 1 mirror [m] |
| $\theta_n$ | Tilt of the nth mirror |
| $\zeta_0$ | Half of the angular subtense of the sun at any point on the earth [=16$'$] |
| $E_f$ | Solar energy available to the absorber kept at focus [W] |
| $\rho$ | Specular reflectance of the reflecting mirror |
| $\gamma$ | Fraction of specularly reflected radiation intercepted by the absorber surface is the intercept factor |
| $\tau$ | Transmittance of the glass cover |
| $\alpha$ | Absorbance of the receiver surface |
| $\eta$ | Instantaneous thermal efficiency of the Fresnel reflecting solar concentrator–receiver system |

## INTRODUCTION

Linear concentrating solar thermal or photovoltaic technologies offer a promising method for large scale use of solar energy. With concentrating, the ratio of thermal energy loss to total solar radiation on the receiver will decrease significantly; hence this type of collector has higher efficiency at high temperature than those non concentrating collectors. Linear Fresnel collector technology relies on an array of linear mirror strips which concentrates light on to a fixed receiver mounted on a linear tower.

Some studies relating to types of Concentrating Solar Power technology are available in the literature. Gharbi et al. (2011) investigated the performance of parabolic trough collector and linear Fresnel reflector technologies. The influence of ambient conditions and the percent of different types of energy loss, etc., are analyzed. Sahoo et al. (2012) carried out analysis of heat losses from a trapezoidal cavity used for Linear Fresnel Reflector system. A steady state modeling and simulation of trapezoidal cavity with eight tubes was carried out using CFD. The results obtained by the model were compared with the experimental data. The correlation between the total average Nusselt number and its influencing parameters has been obtained for the proposed cavity.

Morin et al. (2012) compared the electricity generation costs for Linear Fresnel Collector and Parabolic Trough Collector. The calculations were carried out using cost and hourly simulation performance models. Depending on the assumptions, the costs for a linear Fresnel collector solar field should range between 78 and 216 €/m$^2$ to reach cost-parity at assumed reference solar field costs of 275 €/m$^2$ for the Parabolic Trough Collector. Xie et al. (2011) gave a review about the recent development of the concentrated solar energy applications using Fresnel lenses. During the recent two decades, such applications have been built and tested successfully to validate the practicality of Fresnel lens solar concentration systems. Although the present application scale is small, the ongoing research and development works suggest that Fresnel lens solar concentrators, especially non-imaging Fresnel lenses, will bring a breakthrough of commercial solar energy concentration application technology in the near future. The advantages and disadvantages of these systems are also summarized.

Zhai et al. (2011) investigated a concentrating solar collector based on linear Fresnel lens. Experimental results show that the thermal efficiency is about 50% when the conversion temperature (water) is 90 $^{o}$C. The test shows that the indication of lost energy is 0.578 W/m$^2$ K, which is much smaller than that of commonly used evacuated tube solar collector without concentrating. The influence of ambient conditions and the percent of different types of energy loss, etc., are also analyzed. Pino et al. (2012) carried out experimental validation of an optical and thermal model of a linear Fresnel collector system. The function of the model is to simulate the optical and thermal dynamics of a Fresnel system for heating water. The model is validated using real data gathered from a cooling plant with double effect absorption chiller located in the School of Engineering University of Seville, Spain. Comparison of calculated and plant measured data shows that the error is lower than 3% in the optical model and within 7% in the thermal model.

Grena and Tarquini (2011) proposed the use of molten nitrates as heat transfer fluid in a solar Fresnel Linear Concentrator. A system specifically designed to work with molten nitrates is presented, with an analysis of its optical and thermal properties and the discussion of advantages and disadvantages with respect to existing systems. Abbas et al. carried out study of the performance of an innovative receiver for linear Fresnel reflectors. The results are analyzed with a physics perspective of the process. It is found that this innovative receiver provides an optimum design for the whole day, even though impinging radiation intensity varies notably. Thermal features of this type of receiver could be the base of a new generation of concentrated solar power plants with a great potential for cost reduction, because of the simplicity of the system and the lower weigh of the components, plus the flexibility of using the receiver tubes for different streams of the heat carrier fluid. Dai et al. (2012) proposed and designed a new type of linear Fresnel reflector system, which contains three motional modes. Based on the theoretical design, the optical simulation has been done, and some motile laws and geometric relationship have been included. The laws would be helpful for advance research and to develop the tracking device fit for the system combined three-movement. Xie et al. (2012) obtained both theoretically and experimentally the efficiency factors and heat removal factors of Fresnel lens solar collectors using different kinds of point-focus cavity receivers. It is found that the theoretical results agree well with the test results. For the point-focus Fresnel lens solar collector, the conical cavity receiver showed the best thermal performance.Singh et al. (2010) investigated thermal performance of linear Fresnel reflecting solar concentrator with trapezoidal cavity absorbers. The thermal efficiency decreased with the increase in the concentration ratio of the Fresnel reflecting collector. The selective surface coated absorber had a significant advantage in terms of superior thermal performance as compared to ordinary black painted absorber.

In this paper, a Linear Fresnel collector, which works in one-axis tracking mode is developed and tested. The main objective of this paper is to report the performance of the linear Fresnel collector by means of experimental analysis.

## DESIGN AND THERMAL EFFICIENCY OF LINEAR FRESNEL COLLECTOR

Fig. 1 shows the cross-sectional schematic of linear Fresnel reflector with cavity absorber. An equal width (W) of the constituent mirror elements were considered in each case. The tilt of each constituent mirror element was so adjusted that ray incident to the aperture plane, reached to the focus point ‘F’ after a single reflection. An appropriate distance (called shift) was kept between two consecutive mirror elements so that a mirror does not shadows its adjacent mirror element. Each mirror may then be characterized by three parameters, namely; location ($Q_n$), tilt ($\theta_n$), and shift ($S_n$) as shown.

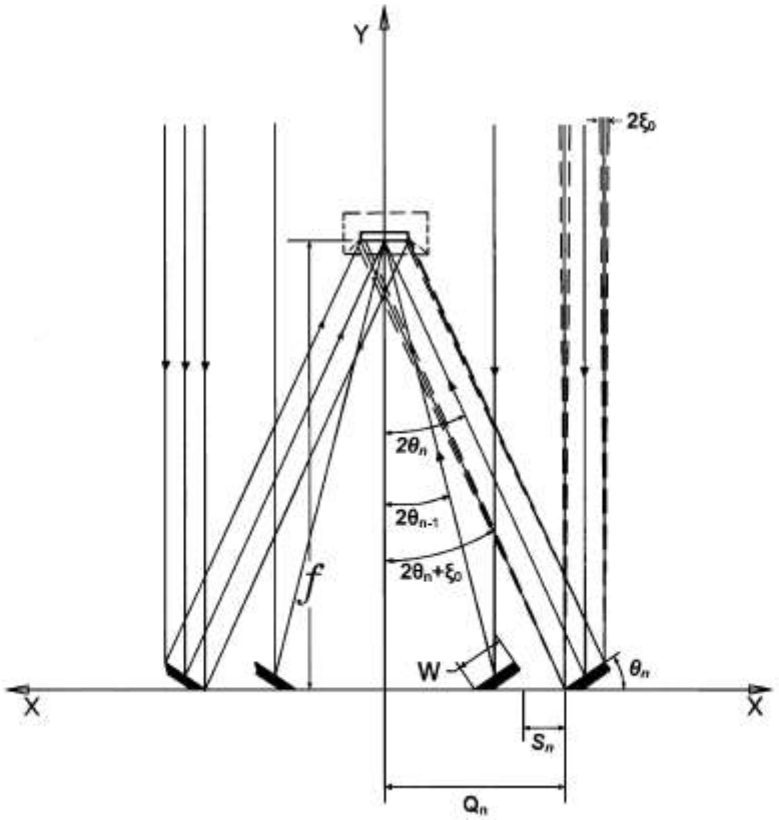


**Figure 1**. Schematic of linear Fresnel reflecting solar concentrator with cavity absorber

The following expressions were used to obtain these parameters using simple geometrical optics (Mathur et al., 1990; Singh et al., 1999; Singh et al., 2010; Mathur et al., 1989):

$$\theta_n = 1/2\tan^{-1}\left[\left\{Q_n + (W/2).\cos\theta_{n-1}\right\}/\left\{f - (W/2).\sin\theta_{n-1}\right\}\right] \tag{1}$$

$$S_n = W.\sin\theta_{n-1}.\tan(2\theta_n + \xi_0) \tag{2}$$

$$Q_n = Q_{n-1} + W.\cos\theta_{n-1} + S_n \tag{3}$$

where W is width of each mirror element, and $\xi_0$ is half of the angular subtense of the sun at any point on the earth ($=16^0$).

With $\theta_0 = 0$, $S_1 = 0$, $Q_0 = -W/2$, $Q_1 = W/2$ as initial values for the iteration and n= 1, 2, . . ., m, where, 'm' is the total number of mirror elements placed on each half of the reflector.

The Fresnel reflecting device has been designed assuming width of mirror (W) = 38 cm, and height of the absorber above primary mirror plane (f) = 180 cm. The location (Q), tilt (θ) and shift (S) of each mirror element either side from center was calculated with help of the above Eqs. (1-3).

Concentration ratio (CR) of the Fresnel collector was obtained by summing up the concentration contribution of the nth mirror element. Contribution of concentration of nth mirror element ($CI_n$) to the local concentration ratio distribution on flat absorber plane was calculated as (Sharma et al., 1990; Choudhury and Sehgal, 1986; Singh et al., 2010).

$$CR = 2\sum_{n=1}^{n=m} Cl_n \tag{4}$$

$$Cl_n = W.\cos\theta_n / (U_n + D_n + I_n) \tag{5}$$

where values of the portion of reflected rays width on the absorber $U_n$, $D_n$, and $I_n$ are calculated as:

$$U_n = \left[(f - W.\mathrm{Sin}\theta_n)\sec 2\theta.\sin\xi_0\right]/\left[\cos(2\theta_n - \xi_0)\right] \tag{6}$$

$$D_n = \left[W.\cos\theta_n.\sec 2\theta_n\right] \tag{7}$$

$$I_n = \left[f.\sec 2\theta.\sin\xi\right]/\left[\cos(2\theta_0 + \xi_0)\right] \tag{8}$$

The concentration ratio of Fresnel collector was estimated with help of the Eqs. (4-8) for different sets of reflecting mirrors.

The solar energy available to the absorber ($E_f$) at different concentration ratio of the Fresnel concentrating collector was estimated considering various radiative absorber parameters as follows (Singh et al., 2010).

$$E_f = (A_c - A_{nc}) I\rho\gamma\tau\alpha \tag{9}$$

The instantaneous collector thermal efficiency (η) of solar concentrator–receiver system was computed by the following equation (Singh et al., 1999; Zhai et al., 2010):

$$\eta = \frac{\dot{m}.c_p.(T_o - T_i)}{I.A_c} \tag{10}$$

where $T_o$ is the outlet temperature, $T_i$ is the inlet temperature, $c_p$ is the specific heat of fluid, $A_c$ is the area of Fresnel mirrors, I is the global solar radiation.

## EXPERIMENTAL SET-UP AND ERROR ANALYSIS

The Linear Fresnel collector system was tested outdoors at Isparta. The schematic of experimental set-up is shown in the Fig. 2. The Linear Fresnel collector system has three main parts: the first part consists of the 10 rows of mirrors located at the lower end of the collector. These mirrors have one axis of rotation. Incident radiation is directed by the mirrors to reflect radiation towards the receiver located at the highest point, which is the second part. Finally, heat energy is gathered from the pipe using a continuous working fluid (water). The mass flow rate of water in the system is 0.025 kg/s. The set-up consisted of 10 reflecting mirrors, each having 180 cm length and 38 cm width. Each row of mirrors is moved by a solar tracking system working in an autonomous way with an electric motor. The absorber is composed of a copper U-shape tube. The absorber pipe was placed at upper portion of the trapezoidal cavity. Glass wool insulation was provided at the upper top and sides of the absorber pipe to reduce heat loss. A photograph of the Linear Fresnel collector system is shown in the Fig. 3. Further details of the experimental procedure can be found in Dostuçok (2012). The Linear Fresnel collector system has several sensors:

- Solar sensor: There are solar sensors to detect the solar radiation (Accuracy: <1%). Solar radiation was measured with a pyranometer AHLBORN FLA 613 GS during our studies. Signal range of this pyranometer is 0-1200 W/m$^2$. Operating temperature is -20 to +60 °C.

- Temperature sensor: Temperature at input and output of the absorption pipe were monitored using K type thermocouple (Accuracy: ± 0.8% $^o$C).
- Mass flow meter: Located at inlet of absorption pipe (Accuracy: ±1%).
- Weather station: It has an environmental humidity and temperature sensor (accuracy: ±2% R.H.), and a wind velocity sensor (Accuracy: ± 0.5 m/s). Total uncertainty can be written as below (Genceli, 2005):

$$w_R = \left[\left(\frac{\partial R}{\partial x_1}.w_1\right)^2 + \left(\frac{\partial R}{\partial x_2}.w_2\right)^2 + ... + \left(\frac{\partial R}{\partial x_n}.w_n\right)^2\right]^{1/2} \tag{11}$$

where $x_1$, $x_2 \ldots x_n$ are the physical variables (directly measured data), $w_1$, $w_2, \ldots w_n$ are uncertainties of the physical variables. Substitute Eq. (10) into Eq. (11), the relative error of thermal efficiency is obtained. The minimum average temperature difference in a period of time is 2$^o$C and average radiation is 890 W/m$^2$. Substitute above measured data and error of measurement instrument, the maximum relative error is 10 %.

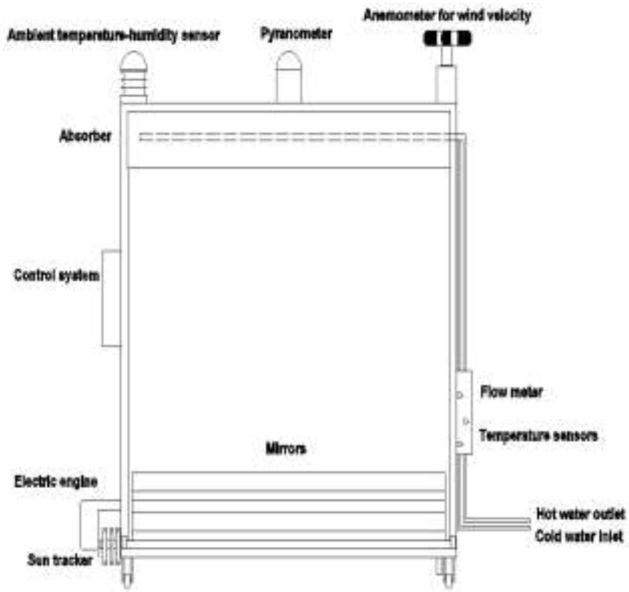


**Figure 2**. Schematic of experimental set-up

**Figure 3**. Photograph of experimental set-up

## RESULTS AND DISCUSSION

In this paper, a Linear Fresnel collector, which works in one-axis tracking mode is developed and tested. The Linear Fresnel collector system was tested for August at Isparta. In Table 1, tilt angle of the ten mirrors rows of Fresnel collector at different times are shown. For each row and time, the tilt angle is calculated by the optical model. The presented data was obtained on the day 2th of August 2012.

Table 2 shows the results of the thermal model for different times for the same day. For each time is presented: water input temperature, output water temperature, water mass flow, relative humidity of ambient, ambient temperature, wind velocity, global radiation incident in the reception pipe and heat absorbed by water.

Fig. 4 shows the variation of the solar radiation for different times for the same day. As expected, solar radiation is the highest at midday.

Fig. 5 shows temperature difference ($T_i$-$T_o$) values for different times for the same day. As can be seen in Fig. 5, the maximum temperature difference at 14:00 has been obtained as about 23$^o$C. The minimum temperature difference at 8:00 has been obtained as about 2$^o$C.

**Table 1**. Tilt angle of mirror rows of Fresnel Collector at 2th of August 2012

| **Local Time** | **ROW1 (°)** | **ROW2 (°)** | **ROW3 (°)** | **ROW4 (°)** | **ROW5 (°)** | **ROW6 (°)** | **ROW7 (°)** | **ROW8 (°)** | **ROW9 (°)** | **ROW10 (°)** |
|---|---|---|---|---|---|---|---|---|---|---|
| **08:00** | -20 | -22 | -27 | -31 | -33 | 39 | 43 | 47 | 50 | 54 |
| **09:00** | -14 | -15 | -21 | -24 | -27 | 32 | 37 | 41 | 45 | 47 |
| **10:00** | -7 | -9 | -14 | -17 | -21 | 26 | 31 | 35 | 39 | 41 |
| **11:00** | -1 | -3 | -7 | -11 | -16 | 20 | 25 | 29 | 32 | 35 |
| **12:00** | 6 | 1 | -1 | -4 | -9 | 13 | 18 | 22 | 25 | 28 |
| **13:00** | 14 | 10 | 7 | 4 | -1 | 6 | 11 | 15 | 18 | 21 |
| **14:00** | 21 | 18 | 15 | 11 | 6 | -1 | 4 | 7 | 10 | 14 |
| **15:00** | 28 | 25 | 22 | 18 | 13 | -9 | -4 | -1 | 1 | 6 |
| **16:00** | 35 | 32 | 29 | 25 | 20 | -16 | -11 | -7 | -3 | -1 |
| **17:00** | 41 | 39 | 35 | 31 | 26 | -21 | -17 | -14 | -9 | -7 |
| **18:00** | 47 | 45 | 41 | 37 | 32 | -27 | -24 | -21 | -15 | -14 |
| **19:00** | 54 | 50 | 47 | 43 | 39 | -33 | -31 | -27 | -22 | -20 |

**Table 2**. Experimental results of the thermal model of Fresnel Collector at 2th of August 2012

| **Local Time** | **$T_i$ ($^o$C)** | **$T_o$ ($^o$C)** | **RH (%)** | **$T_a$ ($^o$C)** | **v (m/s)** | **I (W/m$^2$)** | **$Q_r$ (W)** | **$Q_a$ (W)** |
|---|---|---|---|---|---|---|---|---|
| **08:00** | 18,7 | 20,9 | 35,2 | 28,3 | 0,80 | 890 | 5193,61 | 230,175 |
| **09:00** | 18,9 | 24,8 | 40,8 | 29 | 1,20 | 985 | 5899,50 | 617,288 |
| **10:00** | 19,1 | 28,8 | 46,2 | 29,7 | 0,96 | 1060 | 6218,24 | 1014,862 |
| **11:00** | 19,2 | 32,6 | 49,6 | 31,6 | 1,40 | 1090 | 6800,32 | 1041,975 |
| **12:00** | 19,7 | 36,2 | 51,5 | 31,9 | 0,50 | 1099 | 6519,20 | 1736,775 |
| **13:00** | 19,8 | 42,3 | 53,5 | 31,9 | 0,70 | 1086 | 6628,64 | 2249,438 |
| **14:00** | 19,6 | 42,5 | 50,4 | 31,6 | 0,50 | 1096 | 7147,11 | 2395,913 |
| **15:00** | 19,5 | 42,6 | 42,9 | 31,4 | 0,90 | 1095 | 7012,36 | 2374,988 |
| **16:00** | 19,7 | 39,8 | 36,8 | 29,6 | 0,60 | 1099 | 6880,35 | 2102,963 |
| **17:00** | 19,6 | 36,3 | 34,5 | 27,9 | 0,47 | 1097 | 6622,48 | 1747,234 |
| **18:00** | 19,3 | 33,5 | 31,7 | 26,8 | 1,2 | 996 | 5812,63 | 1506,6 |
| **19:00** | 19,2 | 26,6 | 27,9 | 26,5 | 0,9 | 799 | 4536,97 | 774,225 |

Thermal efficiency is presented in Fig.6 for different hours on August 2th. As can be seen in Fig. 6, the maximum thermal efficiency has been obtained as about 34%. The minimum thermal efficiency has been obtained as about 4%.

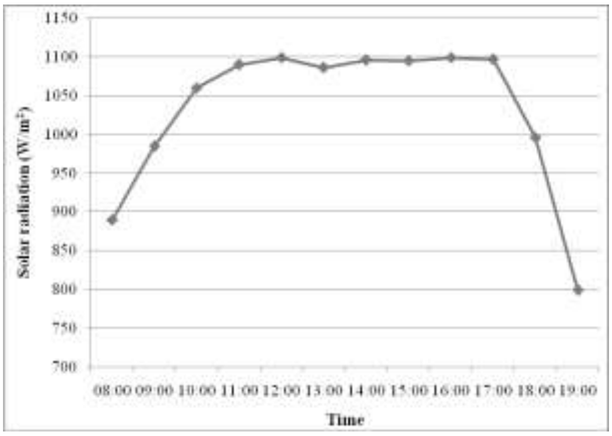


**Figure 4**. Solar radiation variation on August 2th

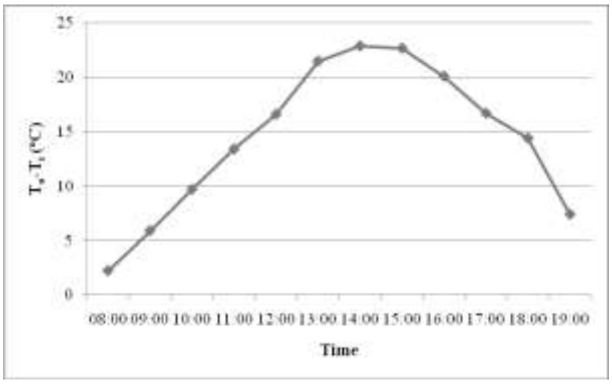


**Figure 5**. Temperature difference ($T_i$-$T_o$) values on August 2th.

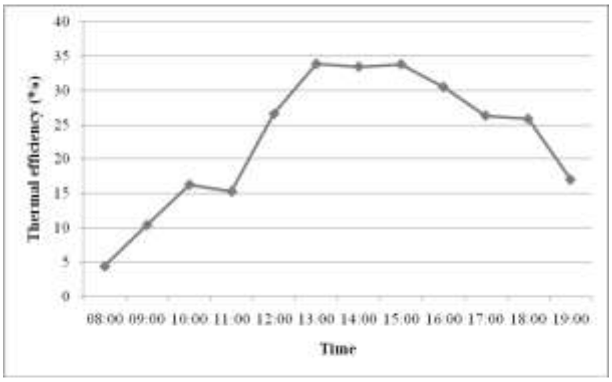


**Figure6**. thermal efficiency curve on August 2th.

## CONCLUSION

In this paper, the thermal efficiency of linear Fresnel collector system is investigated experimentally. From the experimental results, the thermal efficiency curve of linear Fresnel collector was plotted. It is found that for water heating, the thermal efficiency of this collector can reach 34.1%. The thermal efficiency varies a little with the ambient conditions. Therefore, ambient conditions have been neglected in the thermal efficiency calculations. Thermal efficiency of linear Fresnel collector is higher than the non concentrating collector the commonly used. Thermal efficiency of linear Fresnel collector system can be increased by developing control system and receiver.

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