Field Study of Solar Bowl Under Malaysian Tropical Climate

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Abstract: - Results of a field study of a solar bowl operating under Malaysian tropical condition are presented. A total of 40 days data was collected over a period of four months. The solar bowl was capable of concentrating high amount of heat during solar noon up to about ± 20^o zenith angular deviation. The maximum temperature achieved was more than 200 ^{o}C. For global irradiance of less than 400 W/m^2, the temperature developed along the receiver was less than 100 ^{o}C. A correlation between the concentration ratio and the slope of the temperature–direct irradiance curve is presented which indicates that a high concentration solar collector has better potential in tropical area at the sampling time. The simulated maximum concentration ratio was 95 and together with the empirical observation, solar bowl concentrator should be able to produce power under Malaysian tropical climate.

Key-Words: - Field study, solar bowl, tropical climate, concentration ratio.

1 Introduction

This work presents a field test of a solar bowl, which employs concept of fixed spherical reflector with tracking absorber system. Solar bowl system is a solar collector technology that has been introduced in the late seventies for electric power generation. The mechanism of solar bowl is simple where a large and stationary spherical solar bowl serves to reflect and focus incident sunrays on a continuous tracking linear receiver to optimize the collection of solar energy [1]. The solar bowl system was developed and studied extensively at Crosbyton, Texas about 30 years ago [2, 3]. In 1997, a solar concentrator namely UPM Solar Bowl was initiated in Universiti Putra Malaysia (UPM) as a pioneer solar energy system for electric generation in Malaysia [4].

Malaysia is located in the equatorial region experiencing tropical climate, which is generally hot and wet throughout the year. The high frequencies of cloud cover and rainfall in the country may constraint the use of solar concentrator applications under outdoor environment. Some regions in the peninsula can have rainfall over 2.75 m per year. Besides, the diurnal variation can diverge at different places that ideal sine curve of global solar radiation is rarely observed [5]. The diurnal temperature range can reach about 7 ^{o}C [6].

Numerous studies have been conducted to investigate the characteristic and performance of solar bowl system [2-4, 7-12]. However, there is a lack in the literature investigation on solar bowl reported for different climates in particular tropical climate. The collector performance is influenced by weather pattern and that solar radiation pattern of tropical sky may show dissimilar performance profile compared to predicted clear sky condition. Rainfall and hazy weather are the key factors in decreasing daily solar radiation at the site. Cloudiness is the major element in the tropics that can obstruct solar radiation from reaching the earth's surface. According to Othman et al. [5], there is merely about 16% of clear sky available in Malaysia. In this respect, blue sky condition for system performance analysis may be useful, but in

Malaysia this is not fulfilled due to cloudy skies, and it is a major issue of the solar collector.

Although the geographical nature of country near the equator having tropical climate with ample sunshine provides great opportunity for harvesting solar energy, there is a need to explore its potential to justify further application. This study is carried out to examine the implication of local weather conditions on the collector performance with intention to serve as reference for local researchers who will be interested to employ this solar concentrating system.

2 Model Descriptions and Methodology

A small model of a solar bowl was constructed in Alternative and Renewable Energy Laboratory, UPM. Table 1 summarizes the parameters of the solar bowl.

Table 1 Geometry and physical parameters of a mini solar bowl

Parameter	Value
Rim angle (degree)	60
Radius of curvature (m)	0.29
Height of reflector (m)	0.15
Bowl aperture area (m^2)	0.20
Length of tubular receiver (m)	0.10
Diameter of tubular receiver (mm)	9
Ratio of solar receiver to reflector radius	0.015

Materials of solar reflectors hold the key performance of solar collector and thus the selection of suitable reflector material is important. In this work, 3M Silverlux aluminium film was used to shape the reflecting surface of the bowl. The specular reflectivity and diffuse reflectivity of the reflecting film are 85% and 2% respectively [13]. Film type reflecting material is chosen because of its relatively simple laying process and low cost [14, 15]. Segmental method was applied in the arrangement of the reflecting film for easy fabrication and assembly with minimal misalignment of the bowl surface resulting in good spherical reflective surface [14, 16]. Although the chassis structure of the bowl was made mainly from leftover of workshop materials to keep the cost down, the quality of the solar reflector was maintained by having detail measurement and systematic installation with the help of machinery tools. According to Palavras and Bakos [15], perfect optic maybe compromised for high solar flux concentration and therefore a low cost handmade collector model with reflection properties within tolerance limit should be acceptable for actual fabrication work.

In this work, calibrated type-K thermocouples with glass fibre insulation were used as thermal sensors to measure the heat temperature on the central receiver. Central receiver of a spherical concentrator is characterized by a line focus. In order to map the temperature distribution along the receiver as a result of different angular reflection from the spherical reflector, three sectional parts along the receiver were identified. Copper wires of diameter 0.79 mm were wound around each sectional part and a thermocouple attached. The three regions were categorized as high solar flux region, medium solar flux region and low solar flux region. Table 2 presents the locations of the regions. The normalized distance, *X* is the ratio of the distance of the reflected rays on the receiver (measured from the reflector surface) to the radius of the reflector. These three regions were determined from the simulation analysis according to the numerical models of El-Rafaie [11] and Sulaiman et al. [4]. The regions were investigated for their heat flux patterns and thermal gradient.

Table 2 Locations of high, medium and low solar flux regions on central beam receiver

Flux region	Normalized distance (*X*)	Actual distance from bowl surface (cm)
High	0.42	12.1
Medium	0.28	8.1
Low	0.14	4.0

The present field work investigates the performance of the solar bowl in terms of the thermal heat received by the central receiver under concentration. The experiment was located at latitude 2° 58’ N and longitude 101° 44’ E. The experiment was setup on the roof of a two floor building with an elevation of 69 m. Fig. 1 shows a snapshot of the outdoor experimental setup. It consists of a semi-hemispherical bowl, thermocouple wires, data logger, computer, pyranometer and thermo anemometer.

Pilot test was conducted for one month before the actual data collection to check for possible errors of the experimental setting and procedures. This is to verify the experimental setup for better accuracy and consistency in data collection. The experiment was conducted for four months from 1 July 2010 until 31 October 2010. These periods are conducive for solar energy work [6, 17]. Due to unpredictable precipitation, continuous bright sunny days are limited. Besides, regular servicing of the equipment and unexpected electricity blackout have affected data collection. Thus, the data were collected for only 40 days reading throughout the four months. The position of the collector was limited to these daily changes. For the tracking, actual local clock time corresponding to the solar time at the experimental site was calculated to enable manual solar tracking to be handled [18]. The operating duration of the field test was 8 hours starting from 08:00 to 16:00 solar hour corresponding to receiver movement in the zenith angle (angular deviation) from -60^o to +60^o.

Fig. 1 Outdoor experimental set up

The recorded quantities for the experimental study of the solar bowl are date, time, temperature, global irradiance, ambient temperature, wind speed and relative humidity. A data acquisition system was used with a pyranometer and thermocouples to record the solar irradiance and temperature. Setting of the data logger to measure acceptable data was performed before starting the experiment. The trigger rate for data recording was 30 seconds. For a particular zenith position of the receiver, data was recorded for every 30 seconds continuous interval within a ± 5 minutes timeframe and the average reading was computed. This timeframe is equivalent to ±1.25^o of solar radiation incident angle. The deviation of incident angle was kept low in this experiment to achieve satisfactory accuracy. Concurrently, thermo anemometer was used to measure the humidity and wind speed at the experimental site for the same time interval. Fruchter et al. [19] used the same timeframe in taking the average readings, but data was recorded for every one minute interval.

Another experiment was conducted to strengthen the experimental data. Infrared thermal imager was employed to capture thermographic images of the receiver in a large view to obtain better visualization of the data to strengthen the overall data. It helps to display the heat flux distribution pattern on the entire receiver. By this method, the exact heat distribution on different regions of the receiver surface can be viewed visually. The central receiver was exposed to the concentrated solar radiation for about one minute for a specific zenith angle. Then, the reflector surface was covered by a cloth before capturing the image to avoid excessive interference from sunrays reflected from the bowl. The infrared images of the receiver ware analyzed using SmartView software to reveal the temperature profiles of the images.

Direct solar radiation is an essential component in modelling a concentrating solar collector. Since global radiation is the measured solar radiation data at the experimental site in the present work, the beam radiation has to be estimated from the measured global radiation. The beam radiation data was extracted from the measured global radiation data using Maxwell model. This model is helpful because it requires merely global solar radiation and zenith angle as the input parameters without taking the data for cloud cover, precipitant water vapour and atmospheric turbidity that are usually not recorded in the place [20]. Perez et al. [21] evaluated three models [20, 22, 23] and found out that Maxwell model performs better overall. In specific, it offers more accurate prediction for high and low zenith angle in clear sky conditions.

3 Results and Observations

The experimental data of available heat at high flux region, medium flux region and low flux region was collected to analyze the thermal gradient of the collector model. Outdoor ambient conditions such as wind speed, relative humidity and air temperature were also measured. These variables were not analyzed in this study, instead, they were used to identify the weather condition at the site.

Figs. 2 and 3 show two samples of experimental results recorded on 8 July and 10 August 2010. The level of solar irradiation at the site was fluctuating due to intermittent breaks of cloud formation during the duration of the measurement. From the displayed pattern, the concentrated thermal heat on the central receiver is highly affected by variation of the solar radiation intensity. As the global radiation increases, heat flux rises for the entire region of the receiver and vice versa. The rate of the increment of the heat available at the high flux region was strong as shown during 11:20 am and 2:30 pm on 8 July. The average ambient temperature at the site during the test was 32 °C.

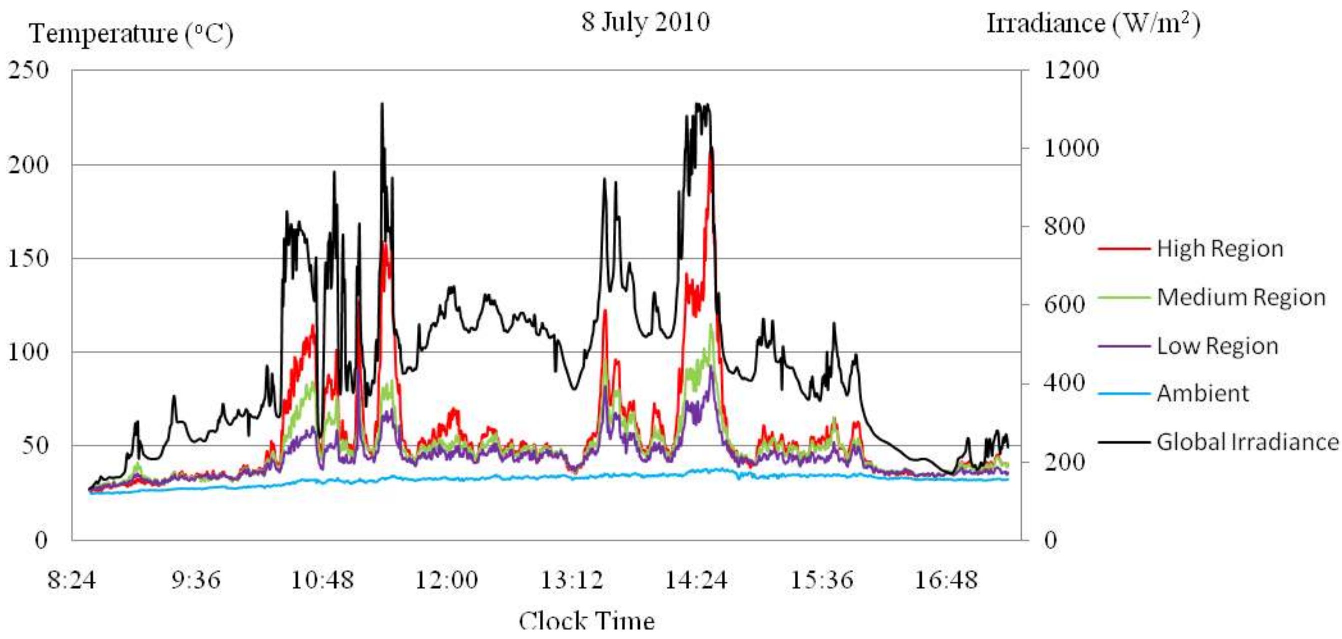

Fig. 2 Continuous experimental data recording on 8 July 2010 from 8:34 am to 5:24 pm

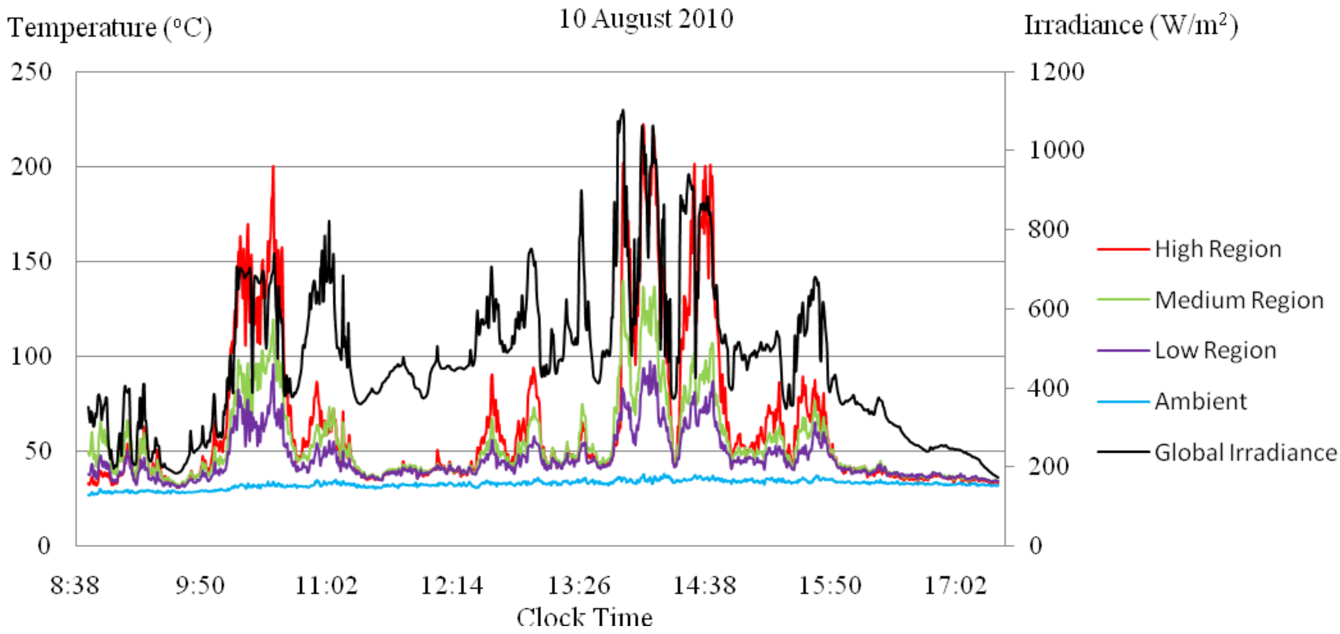

Fig. 3 Continuous experimental data recording on 10 August 2010 from 8:45 am to 5:27 pm

The global radiation measured at the site was erratic and dissimilar to the clear sky global radiation. Due to the inherent meteorological factor in tropical country, cloudless sky throughout daytime is rare. The intermittent nature of the solar irradiance at the site induces this fluctuation and conventional prediction of the continuous collector performance under blue sky for each day may not be practical. Figs. 4 and 5 present the dynamic direct irradiance estimations of the sample days. The results indicate the cloud cover during noon period has made the less availability of beam radiation on the ground. In contrast, off noon period may capable of contributing more radiation energy if the cloud is absent. Fig. 6 illustrates this observation during the noon time. The expected highest performance of the collector at solar noon might not be seen often. The heat concentrated on the receiver during morning and evening was relatively low. On average, it was less that 50 °C at all regions of the receiver surface due to the cosine effect of the collector and atmospheric attenuation at that moment.

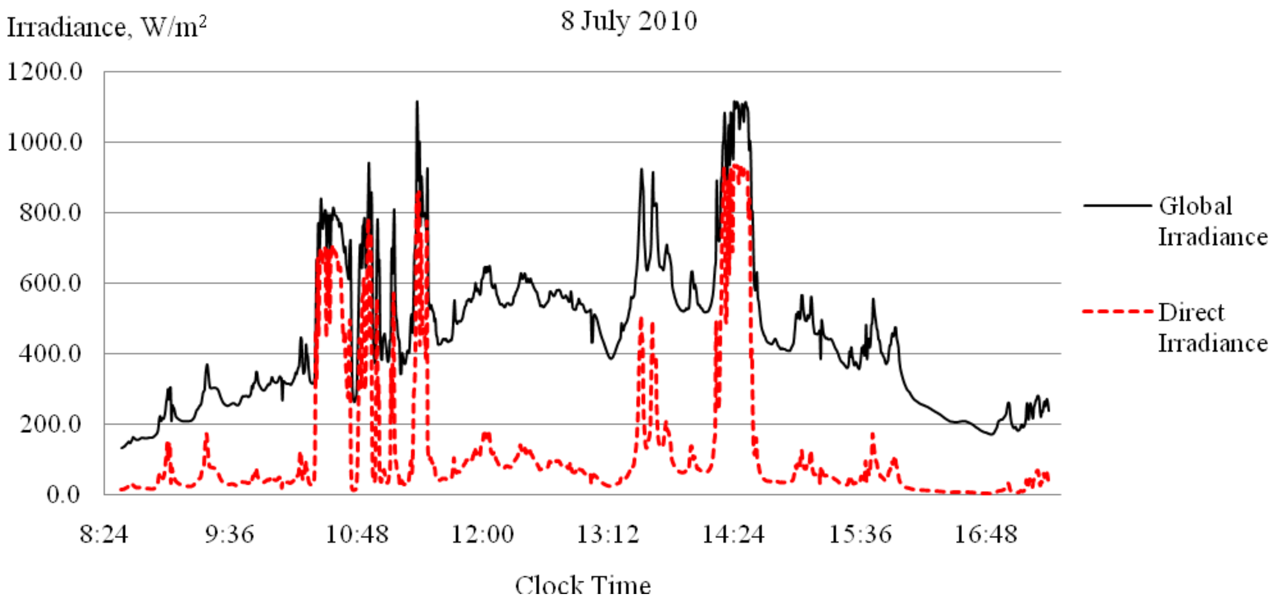

Fig. 4 Dynamic direct irradiance estimation on 8 July 2010

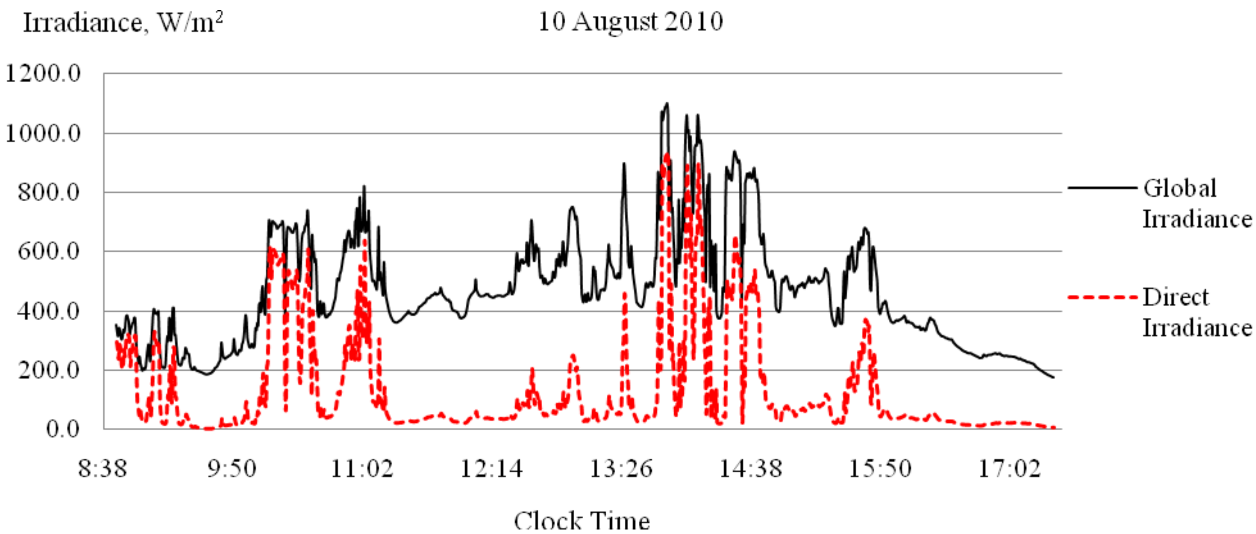

Fig. 5 Dynamic direct irradiance estimation on 10 August 2010

Fig. 6 Cloudy skies at the site

Solar bowl model is very dependent on the available solar irradiance. Figs. 7 and 8 show the analysis for the effect of the global and beam solar irradiances on the heat flux generated on the three regions of the receiver. From the diagram, high flux region can collect most of the thermal heat as the solar irradiance increases. This is followed by medium flux region and low flux region of the receiver. The medium part of the receiver can collect a significant energy with temperatures averagely exceeding 100 °C at global irradiance more than 800 W/m^2 or direct irradiance greater than 350 W/m^2. The low portion of the receiver records a relatively low temperature with less than 100 °C even at a higher solar irradiance. The important observation from this analysis is that the solar bowl may under perform at global irradiance less than 400 W/m^2 due to the low concentrated solar energy with most of the recorded temperatures not exceeding 100 °C for all regions of the receiver. There is virtually no temperature gradient along the receiver under this condition. As the irradiance increases, the temperature gradient along the receiver increases.

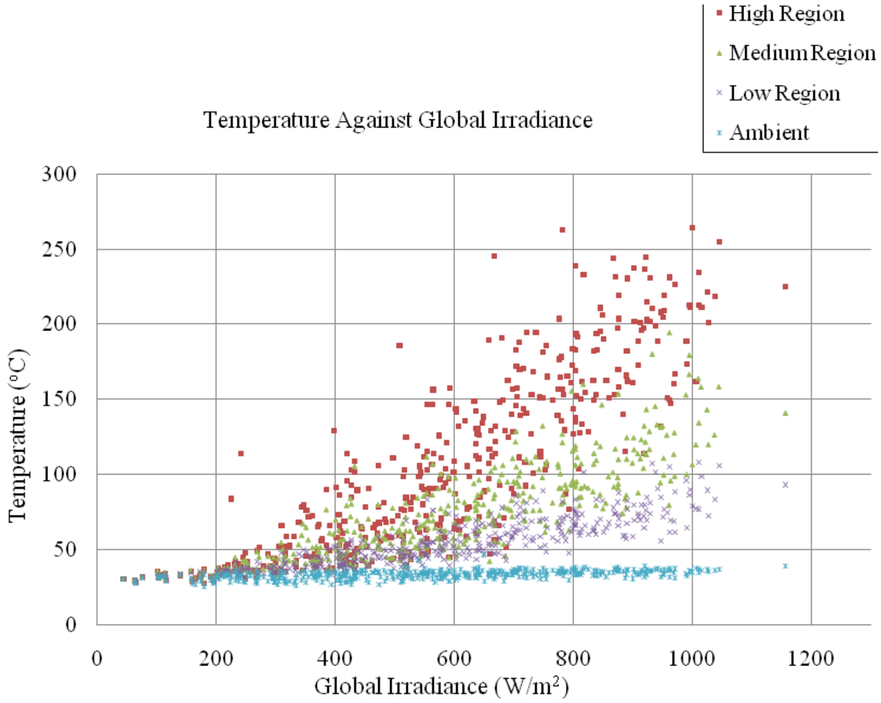

Fig. 7 Distribution of temperature on three regions of the receiver by variation of global solar irradiance

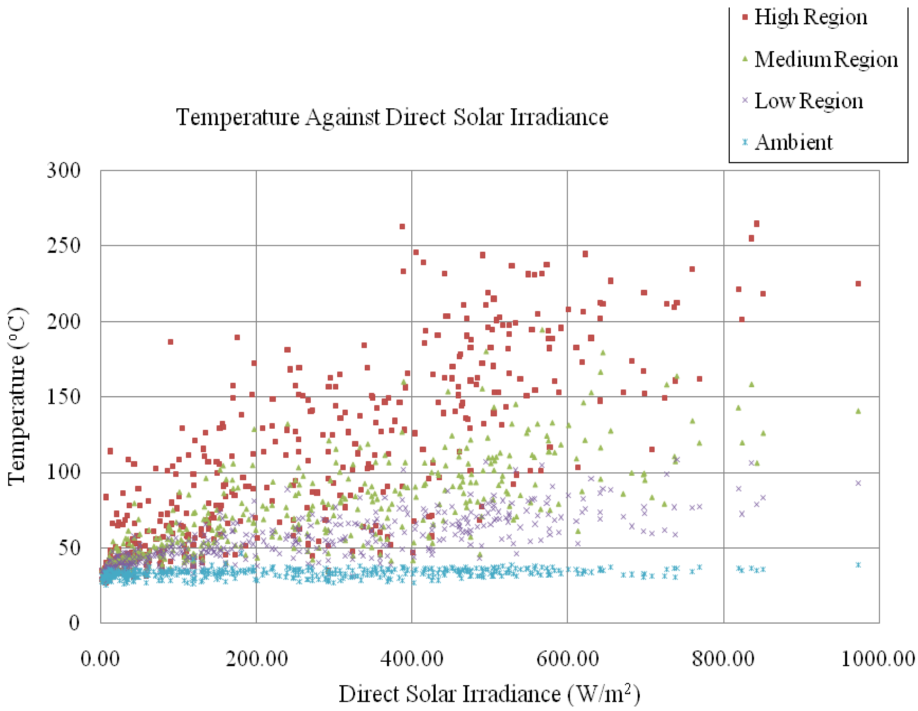

Fig. 8 Distribution of temperature on three regions of the receiver by variation of direct solar irradiance

Plots of the effect of global and beam irradiances on the solar bowl for different angular deviations are given in Figs. 9 to 15. The results show the decrease in heat collection as the angular deviation increases. During angular deviations 0°, 10° and 20°, the receiver can collect a fairly similar amount of heat when the solar radiation is high. It is seen that the increased angular elevation reduces the performance of the bowl. This is caused by the atmospheric attenuation and the cosine effect that results in low concentration ratio of the collector. The statement is consistent with the finding of other researchers [2, 3, 10, 12]. The lowest average temperature was recorded for angular deviation of 60° that was less than 60 °C for all regions.

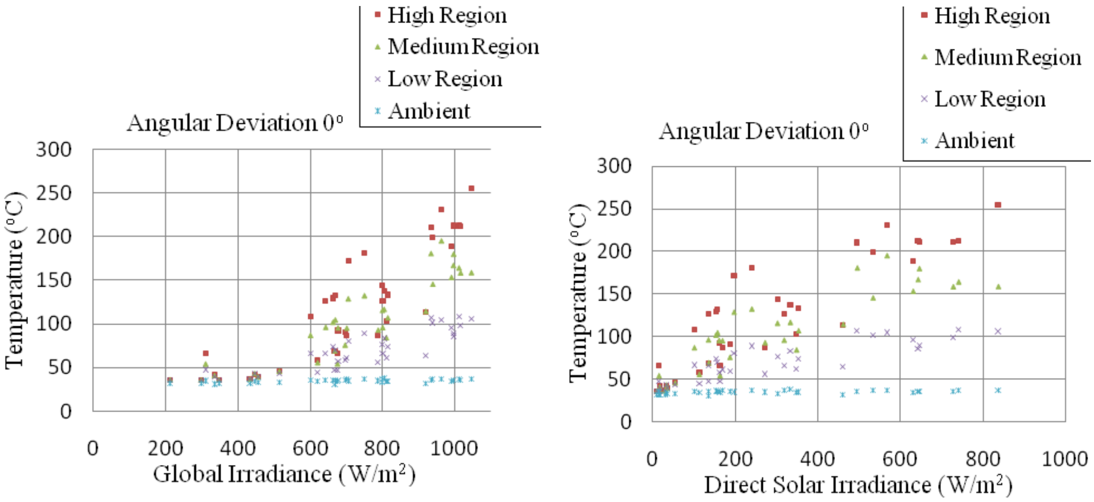

Fig. 9 Distribution of heat flux generated on receiver for angular deviation 0°

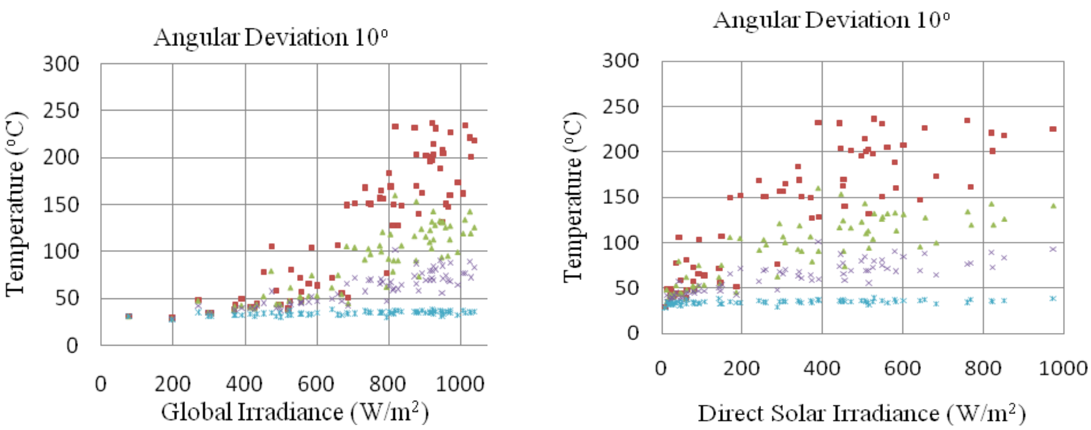

Fig. 10 Distribution of heat flux generated on receiver for angular deviation 10°

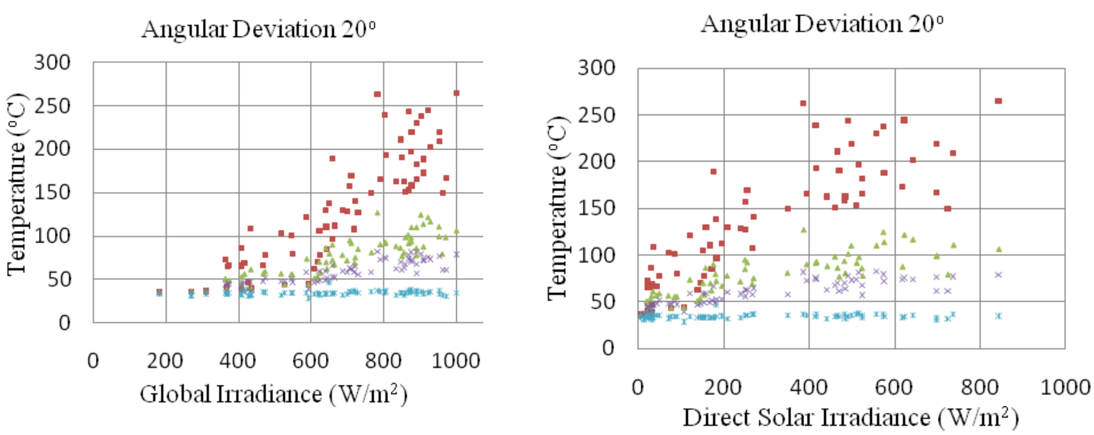

Fig. 11 Distribution of heat flux generated on receiver for angular deviation 20°

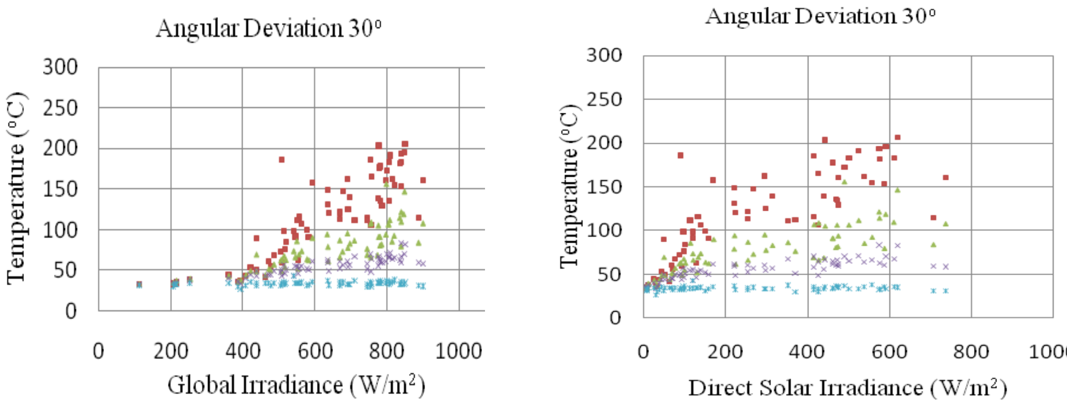

Fig. 12 Distribution of heat flux generated on receiver for angular deviation 30°

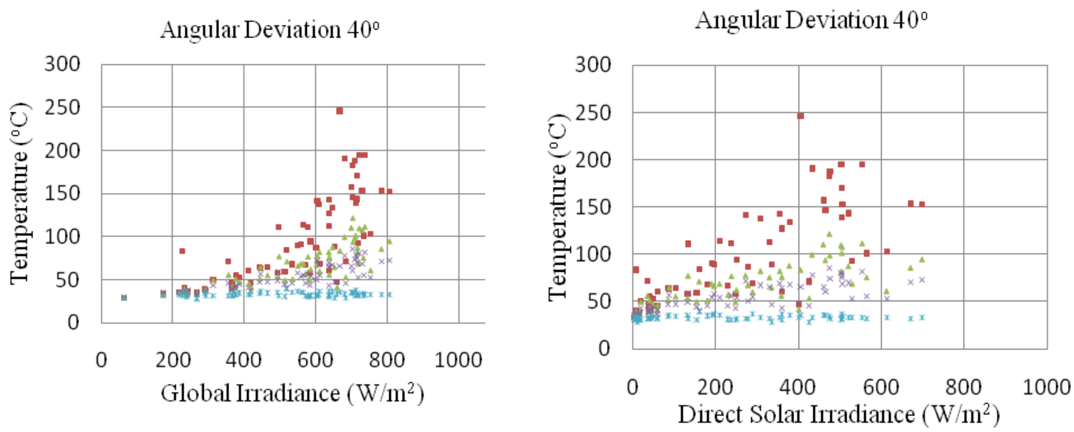

Fig. 13 Distribution of heat flux generated on receiver for angular deviation 40°

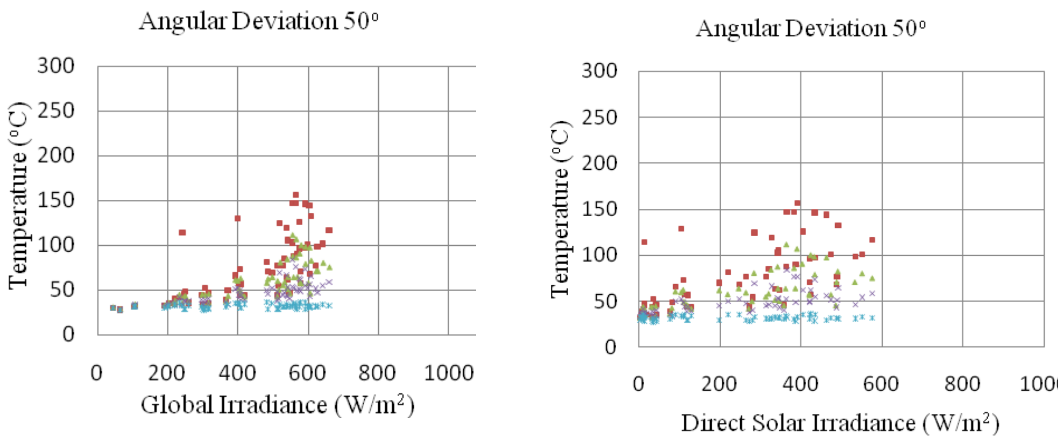

Fig. 14 Distribution of heat flux generated on receiver for angular deviation 50°

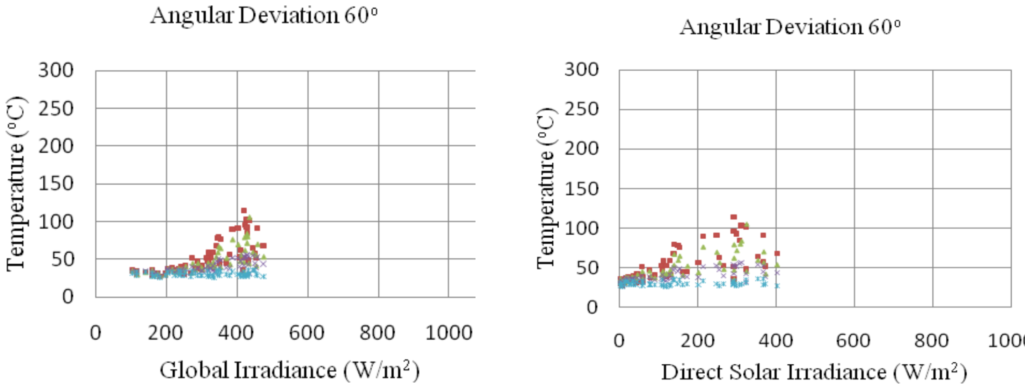

Fig. 15 Distribution of heat flux generated on receiver for angular deviation 60°

Fig. 16 displays the frequency of temperature distribution for different angular deviations on the three flux regions. The temperatures are categorized into five intervals; (i) less than 50 °C, (ii) from 50 °C to less than 100 °C, (iii) from 100 °C to less than 150 °C, (iv) from 150 °C to less than 200 °C, and (v) 200 °C and above. It was observed that only at the high flux region the heat caused the temperature to exceed 200 °C. At angular deviations 0°, 10° and 20°, the percentage of the temperature exceeding 200 °C are 17.5%, 21.25% and 15% respectively. The collector is therefore able to collect good thermal heat at high flux region from solar noon until an angular deviation of 20°. For the same region, there seems to be an increase in the lower temperature occurrences as the elevation of the angular deviation increases from 30° to 60°. The medium and low flux regions show similar trend as well. For the medium flux region, the temperature lies between 50 °C and 100 °C is prevailing for most of the time. The same trend is seen at the low flux region. One can see, the temperature intervals (i) and (ii) are present at all regions during high angular deviations. For the low flux region, very small heat is developed for angular deviations of 40°, 50° and 60° with about 40%, 51.25% and 60% of the temperature is below 50 °C.

The profiles of the predicted solar flux and recorded temperature at different regions on the receiver are clearly influenced by the available solar radiation at that instant. From the data collected for 40 days, it was found that during solar noon, which is expected to show the best performance due to the highest concentration ratio, is not always true in tropical region. Instead, off solar noon irradiance is higher and produces higher concentrated heat at the receiver as shown in Fig. 17. The angular deviation of ± 20° contributes to 77.5% in achieving peak temperature at the sampling time. For high zenith angle, the solar irradiance is low resulting in low concentrated heat at the receiver and this is true for tropical climate. The high zenith angular deviations correspond to the morning and evening periods.

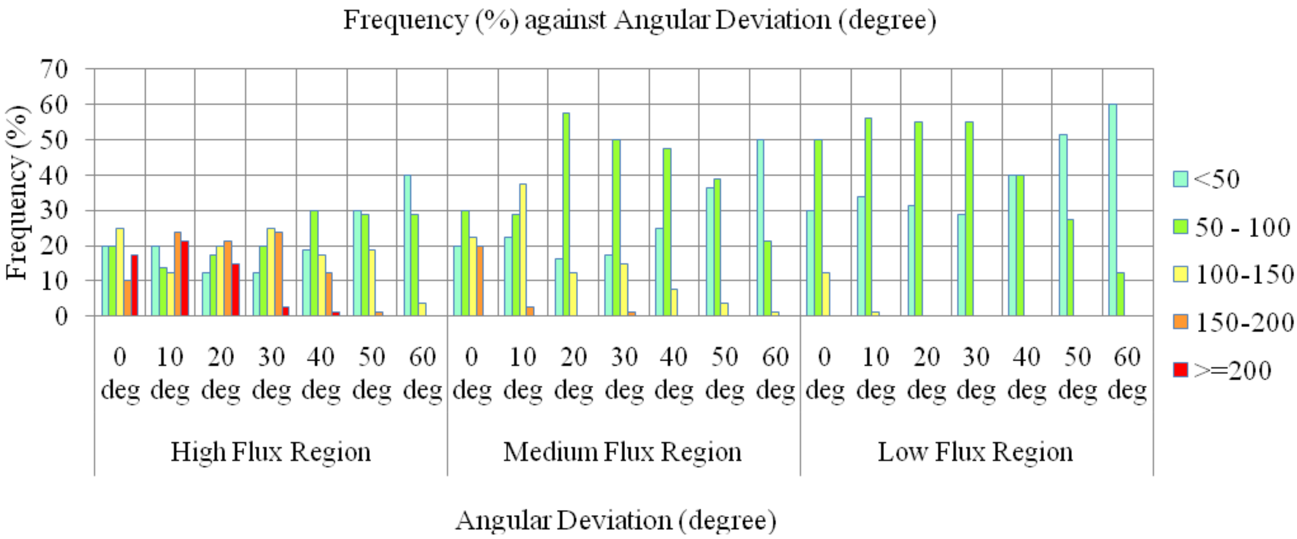

Fig. 16 Frequency of temperature distribution for different angular deviations on three flux regions

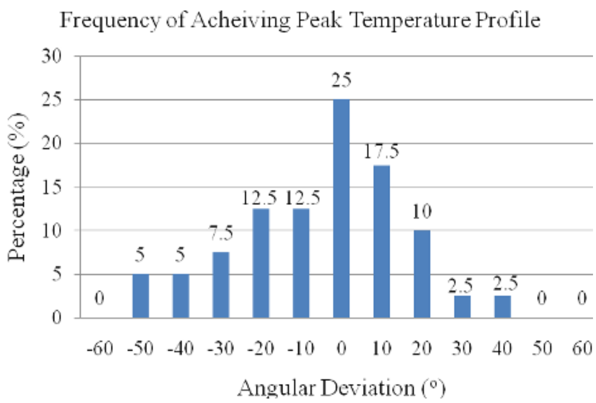

Fig. 17 Frequency of achieving peak temperature profile at different angular deviations

One additional experiment was conducted using the infrared thermal imager. Fig. 18 and Fig. 19 show the results which can provide further validation of the thermal gradient of the solar bowl. The results were analyzed on the heat distribution of the entire receiver part. Temperature gradients presented by the thermographic images and 3-D diagrams were in good agreements with literatures [4, 8-11] and available experimental data. Analyzing temperature distribution in the figures, the high flux region is close to the maximum temperature value, with deviations of 0.6 °C and 1 °C respectively. These results are significant in the validation of the coordinate of the high flux region, showing the outcome of the solar bowl in this work is agreeable and can be used for future reference if the work is to be pursued further.

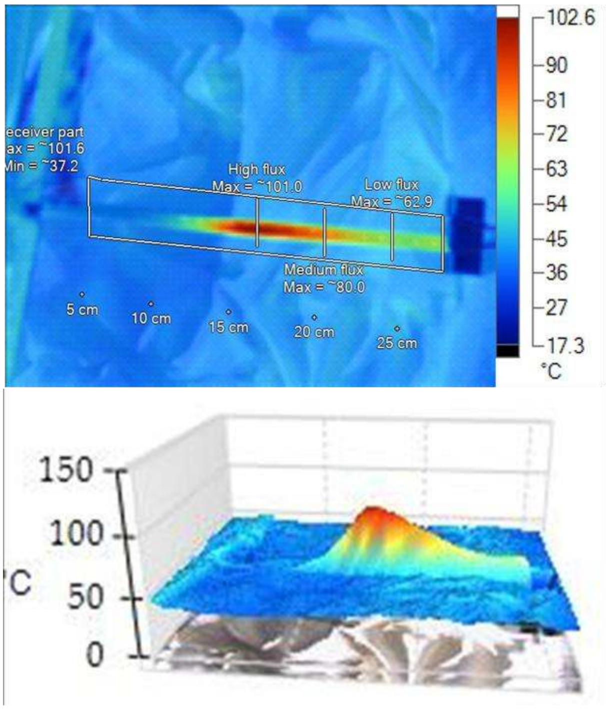

Fig. 18 Thermographic image and 3-D view of the receiver part on 16 November 2010 at 10:21:18 am

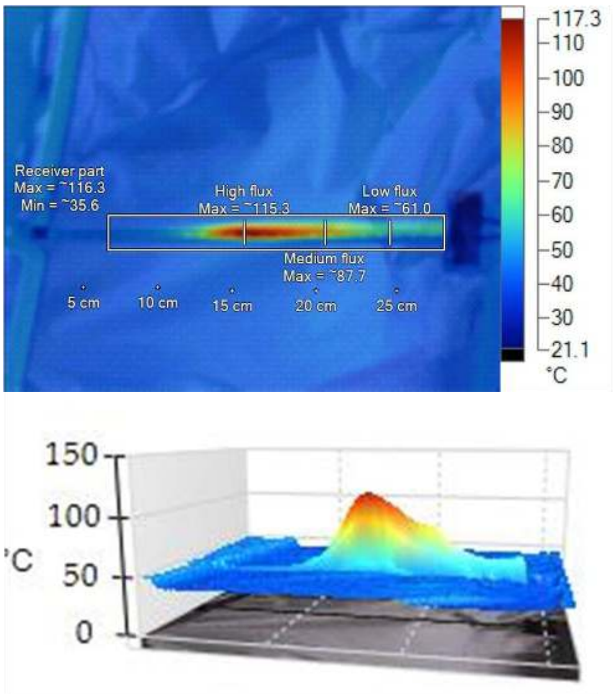

Fig. 19 Thermographic image and 3-D view of the receiver part on 16 November 2010 at 10:58:42 am.

The experimental results were analyzed by incorporating the simulated concentration ratio to study the influence of local solar radiation on the quality of the solar concentration. Table 3 shows the concentration ratio at three regions on the central receiver.

Table 3 Simulated concentration ratio at three flux regions on central beam receiver

Angular Deviation (^{o})	Flux regions High	Medium	Low
0	95.1	39.8	22.6
10	95.1	39.8	14.9
20	95.1	28.4	12.4
30	95.1	23.6	11.3
40	67.5	20.9	10.5
50	55.8	18.8	9.8
60	43.3	16.8	9.1

In the analysis, the concentration ratios are sorted into five ranges to describe their relations to the concentrated heat and beam radiation. Fig. 20 presents the result that depicts the linear relation between temperature and direct solar radiation under different range of concentration ratio. These distributions show that there exists a correlation between the concentration ratio and the slope of the temperature–direct irradiance curve. For sun concentration of less than 15, the heat focused on the receiver may be not more than 100 ^{o}C even though the radiation energy at the site is high. The greater concentration ratio shows a strong tendency of achieving quality heat, despite a lower grade of beam radiation. It can be concluded that a high concentration solar collector could have a relatively larger potential to perform better in term of getting thermal heat as compared to a solar collector with low concentration for tropical areas.

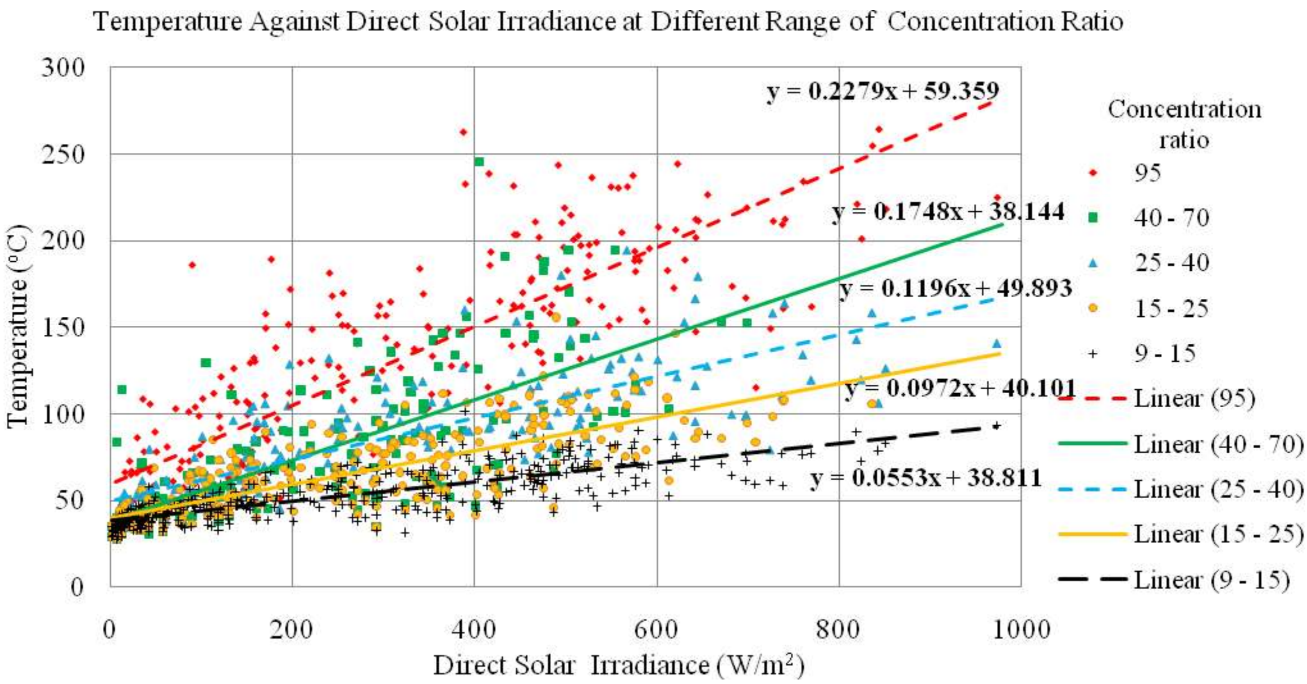

Fig. 20 Distribution of temperature as a function of direct solar irradiance and linear relation between temperature and direct solar radiation under different range of concentration ratio

4 Conclusion

The behaviour of the tropical sky in Malaysia has significant effect on the performance of solar bowl. The results showed that the solar irradiation level at the site was fluctuating due to intermittent breaks of cloud formation during the study period. It was discovered that, under tropical sky of the present work, solar noon might not always contribute to the best performance of the solar collector. This observation is in contrast to other places having blue sky throughout the day. According to the experimental data, the heat collected is low for global irradiance less than 400 W/m^2. As the solar irradiance increases, the heat flux and temperature gradient along the receiver rise. The increase in the elevation of the angular deviation from the normal plane decreases the performance of the bowl and this is in agreement with published results. The results revealed the drawback of the solar bowl collector performance during the morning and evening periods. Low solar irradiance couples with frequent rain during that time have contributed to the low performance of the solar bowl. The linear relation curve of temperature–direct solar irradiance showing that high concentration ratio was desirable for thermal concentration in tropics. From the analysis, the collector was capable to concentrate high amount of heat during the off solar noon up to about ±20^o angular deviation corresponding to solar time between 10:40 and 13:20. The finding is essential for the local researchers as a recommendation to optimize the thermal harnessing not only at solar noon, but also beyond the solar noon under tropical sky.

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