Thermal performance analysis of a CPC solar collector array with series connection to the flat plate solar collector field in Sæby solar heating plant

Weiqiang Kong, Simon Furbo, Bengt Perers and Gerald Englmair
Department of Civil Engineering, Technical University of Denmark, Kgs. Lyngby 2800, Denmark

Abstract

A novel Compound Parabolic Collector (CPC) was developed and specially designed for operating in solar heating plants at the temperature range of 60 °C - 120 ºC. The prototypes of the collector were tested at Technical University of Denmark (DTU) in 2016. Four of the CPC collectors were then installed in series and connected to the flat plate solar collector field in Sæby solar heating plant in Denmark. The monitoring system was implemented for both the CPC collector array and a four flat plate collectors array in front. The thermal performance model was developed for both the CPC collector array and the flat plate collector array by using the QDT model and the tested collector parameters. The predicted annual thermal performance of both the CPC collector and the flat plate collector was calculated at different operating fluid temperatures under Denmark's weather condition. The conclusion is that the annual thermal performance of the new CPC collector will be higher than the annual thermal performance of the flat plate collector if the operating mean fluid temperature is higher than 78 °C in theory, in practice if the temperature is higher than 55 °C.

Keywords: solar heating plant, CPC solar collector, thermal performance analysis, flat plate solar collector

1. Introduction

Denmark has become the front runner in the solar heating plant market with large scale solar collector fields connected to district heating systems. An increasing number of large solar collector fields have been built in Denmark in the last years. 106 solar heating plants with a total solar collector area of 1,327,451 m^2 are in operation by the end of 2017 (Planenergi). Typically, large size flat plate solar collectors, with gross area up to around 15 m^2, are widely used in solar heating plants in Denmark. The operation temperature of solar collectors in solar heating plants in Denmark is in the range from about 40 °C to 95 °C. However, the efficiency of flat plate collectors decreases significantly in the range of 70 °C - 95 °C, while the concentrating solar collectors such as Parabolic Trough Collectors (PTC) and Compound Parabolic Collector (CPC) can keep relatively high efficiency in the range of 70 °C - 95 °C.

This paper will introduce a new concept of CPC solar collector, the CPC collector test results at laboratory and the in situ thermal performance of the CPC collector array connected to a solar heating plant.

1.1 PolyCSP CPC solar collector

A new concept of CPC solar collector has been developed by a Danish company PolyCSP A/S for solar thermal heating plants (Furbo et al., 2016). The CPC collector is specially designed by integrating the new wavelength selective absorber tubes in combination with multi-parabolic receivers into a robust flat panel, see Fig.1. The design is especially optimized for the temperature range of 60 ºC -120 ºC for district heating application.

Four identical parabolic-troughs are placed inside the flat panel with a width of 0.616 m and a length of 5.9 m each. The gross area and the aperture area of the collector are 15.4 m^2 and 13.9 m^2 respectively. The depth of the flat panel is 0.45 m. The flat panel is covered by an anti-reflection glass cover at the front and insulated by mineral wool at the back. The tube receiver is coated with selective layers on its outer surface. The collector is facing south and tube receiver orientates east-west direction. The whole collector panel is placed on a one-axis tracker, which can automatically adjust the tilt of the collector panel to track the sun direction aiming to minimize the

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transversal incident angle. See Fig. 2. The concentration ratio of the collector is 4.

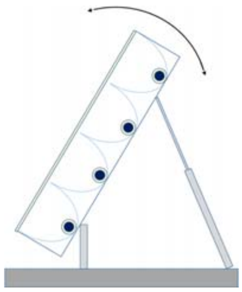

Fig. 1: The diagram of cross-section of PolyCSP CPC collector

Fig. 2: Photograph of the PolyCSP CPC collector testing at DTU

1.2 PolyCSP CPC solar collector array and monitoring system in Sæby solar heating plant

Four CPC solar collectors were installed in series as the last array and connected to the solar collector field in Sæby solar heating plant (http://www.saebyvarmevaerk.dk/), see Fig. 3. The CPC collector array connects the front flat plate collector array in series, which means the working fluid will first go through the flat plate collector array and then go to the CPC collector array. Therefore, the inlet fluid of the CPC solar collector array comes from the outlet of the flat plate array, which means the CPC solar collectors work at higher temperature than the flat plate collector. Two pyranometers were installed on the CPC collector plane. One measures the total irradiance on the collector plane and the other equipped with a shadow band measures the diffuse irradiance. Other measurements were also monitored by a data logger such as the inlet and outlet temperature, the flow rate, the ambient temperature and the four CPC collectors' tilt angles. In order to compare the thermal performance of the CPC collector and the flat plate collector, the thermal behaviour of four flat plate solar collectors in series were also monitored. Measurements include the total solar irradiance on the tilted surface, the inlet and outlet temperature and the flow rate.

Fig. 3: The CPC solar collector array connecting to flat plate solar collector field in Sæby solar heating plant

2. PolyCSP CPC COLLECTOR TESTING AT TECHNICAL UNIVERSITY OF DENMARK

The PolyCSP CPC collectors were tested at Technical University of Denmark (DTU) in 2016 according to the Quasi-Dynamic Testing (QDT) method (Fischer et al., 2004). The glycol-water mixture as working fluid was pumped to the collectors at a constant flow rate of 11 l/min. The fluid inlet temperature was regulated by an electrical heating element and the backward fluid from collector was cooled by a water cooling heat exchanger. The monitoring measurements were recorded by a data logger every 10 second including the inlet and outlet temperature, the total and diffuse solar radiation on the collector surface, the ambient temperature and the fluid rate.

The QDT (Quasi-dynamic test) model as shown in Eq. (1) was used to determine the thermal performance of the solar collector.

$$q_u = \eta_0 k_b(\theta) G_b + \eta_0 k_d G_d - a_1(T_f - T_a) - a_1(T_f - T_a)^2 - a_5 dT_f/dt \quad \text{(eq. 1)}$$

$$K_b(\theta) = 1 - b_0\left[\frac{1}{\cos(\theta)} - 1\right]$$

Where,

q_u is thermal performance of solar collector, W/m²

$K_b(\theta)$ is incidence angle modifier for beam radiation, -

K_d is incidence angle modifier for diffuse radiation, -

θ is incidence angle for direct radiation, °

η_0 is peak collector efficiency, -

a_1 is heat loss coefficient of collector at ambient temperature, W/(m²K)

a_2 is temperature dependence of heat loss coefficient of collector, W/(m²K²)

a_5 is the thermal capacity of the collector, J/m²K

T_f is the mean solar collector fluid temperature, °C

T_a is the ambient air temperature, °C

G_b is the beam irradiance on the collector, W/m²

G_d is diffuse radiation on the collector, W/m²

t is time, s

b_0 is a constant for the incidence angle modifier, -

The measured data were re-averaged to 5 min and calculated according to the international standard ISO 9806 (2013). The parameters were then obtained and shown in Table 1. The parameters of the flat plate solar collector operating in Sæby solar heating plant were also shown in Table 1 for comparison. The data was extracted from the data sheet tested by SP Sweden (2010).

From Table 1 it can be seen that the flat plate collector has higher peak efficiency but also higher heat loss coefficient than the CPC solar collector which accords to the properties of the two kinds of solar collectors. In the next section, the in situ thermal performance of the two kinds of solar collector will be calculated and compared and the pros and cons will be analysed.

Tab. 1: CPC collector and flat collector parameters

Parameter/collector	CPC Collector	Flat plate collector (from data sheet)
Peak collector efficiency η_0(-)	0.65	0.815
Incident angle modifier for beam radiation b_0 (-)	0.25	0.11
Incident angle modifier for diffuse radiation K_d (-)	0.27	0.90
Heat loss coefficient a_1 (W/m^2 K)	0.92	3.43
Temperature dependence of the heat loss coefficient a_2(W/m^{2}K^2)	0.0148	0.0145
Effective thermal capacity a_5 (J/m^{2}K)	7518	8028
Collector aperture area (m^2)	13.91	13.88

3. THERMAL PERFORMANCE ANALYSIS OF THE CPC COLLECTOR ARRAY AND THE FLAT PLATE COLLECTOR ARRAY AT SÆBY SOLAR HEATING PLANT

The measurement of the CPC collector array and the flat plate collector array started from May 2017 and are still going on. The measured data used for analysis in this paper were taken from May to August 2017.

The measured thermal performance of both the CPC and the flat plate collector arrays were calculated by the measured data while the modelled thermal performance was predicted by the QDT model and the measured weather data with implementing the collector parameters obtained from Table 1.

The modelled power output will be compared to the measured power output from daily to monthly thermal performance point of view in order to validate the QDT model. Then the validated collector model will be used to predict the annual thermal performance of the CPC collector and the flat plate collector under Denmark's typical weather condition (Furbo et al., 2018).

3.1 Daily thermal performance comparison

One typical sunny day on 13-06-2017 and one typical cloudy day on 23-05-2017 were chosen to compare the measured power output with the modelled power output both for the CPC collector array and the flat plat collector array. The total and diffuse solar irradiance on the CPC collector surface for the two days are plotted in Fig. 4 and Fig. 7.

Fig. 5 and Fig. 8 show the power output comparison of the CPC collector array. The blue curve is the measured power output. The orange and green curves are the modelled power output. The CPC collector array has two modelled power outputs because the control software for the collector tilt tracking system had a small error in that period which caused a relative big deviation between the measured and targeted transversal angles in the early morning and in the late afternoon. Therefore in order to give the impression of the potential power output, the orange curve of the modelled power output with the best tilt angle is plotted together with the green curve which is the modelled power output with the measured tilt angles. It can be seen from the figures that the green curve has small deviation with the blue curve while the orange curve has larger deviation with the blue curve in the early morning and the in the late afternoon which shows that the CPC collector array can produce more power output after the small tracking error fixed. But the conclusion is that the QDT model with tested collector parameters can predict the collector power output in an accurate way.

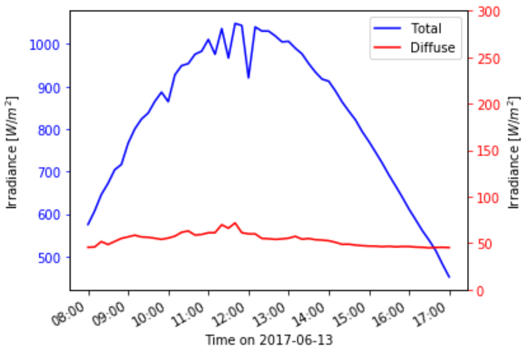

Fig. 4: Total and diffuse solar irradiance on CPC collector surface on 2017-06-13

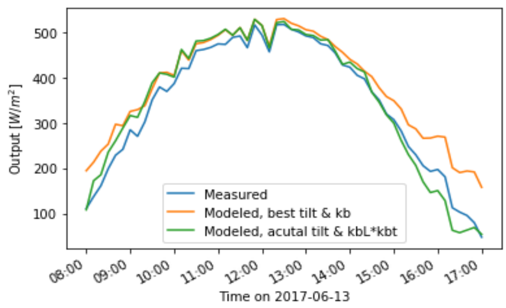

Fig. 5: Measured and modelled power output of the CPC collector array on 2017-06-13

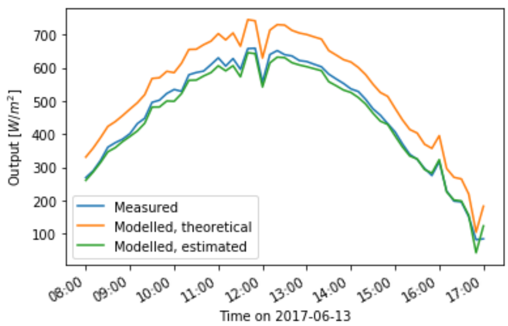

Fig. 6: Measured and modelled power output of the flat plate collector array on 2017-06-13

Fig. 6 and Fig. 9 show the power output comparison of the flat plate collector array. The blue curve is the measured power output. The orange curve is the modelled power output calculated by the QDT model with the collector parameters taken from the data sheet. It can be seen from Fig. 6 that the modelled power output of the orange curve is much higher than the measured power output of the blue curve. The reason could be that the flat plate collector degraded from its original status. However, a set of estimated collector parameters was used to predict the power output which is drawn as the green curve. From Fig. 6 and Fig. 9 it can be seen that modelled power output with estimated collector parameters coincide well with the measured power output which validated the model.

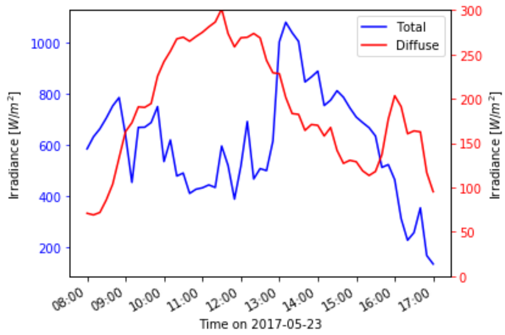

Fig. 7: Total and diffuse solar irradiance on CPC collector surface on 2017-05-23

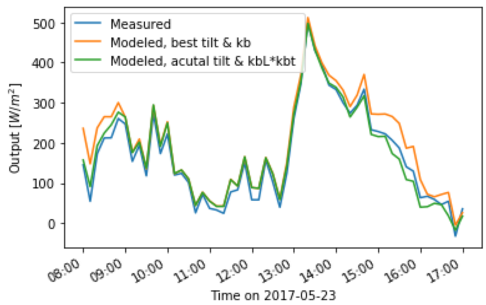

Fig. 8: Measured and modelled power output of the CPC collector array on 2017-05-23

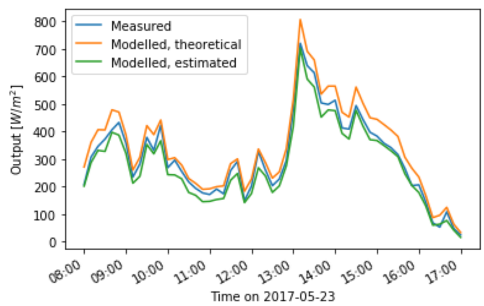

Fig. 9: Measured and modelled power output of the flat plate collector array on 2017-05-23

3.2 Monthly thermal performance summary

The monthly energy output of both the CPC collector array and the flat plate collector array are summarized in Table 2 and Table 3. The measurement was not continuous by days because of some practical problems like sensors connections, power cut off, etc. However, the selected days for calculation had full data of 24 hours. From the third and fourth column of Table 2 it can be seen that the measured energy output in each month is always slightly lower than the modelled energy output which indicates that the CPC collector array could have dust on their glass surface or there could be tracking errors. The last column shows the ratio of the modelled energy output with measured tilt angles and the modelled energy output with the best tilt angles. The average ratio is 74.2% which means there is around 25% potential improvement of the energy output for the CPC collector array without tracking error.

Tab. 2: Monthly energy output summary of the CPC collector array

Month/ Measured days	Total/ Diffuse solar irradiance	Measured energy output	Modelled energy output with actual/best tilt angles	Ratio of the actual and the best tilt angles of the modelled energy output
	(kWh/m^2)	(kWh/m^2)	(kWh/m^2)	(%)
May/5	29/8	7.4	8.3/9.5	77.9
June/30	162/45	41.2	48.6/55.7	74.0
July/7	36/10	9.0	11.2/12.6	71.4
August/17	83/22	21.7	27.0/29.2	74.3
Total/59	310/85	79.3	95.2/106.9	74.2

Table 3 shows the monthly summarized energy output of the flat collector array. It can be seen from the table that the modelled energy output with theoretical collector parameters is much higher than the measured energy output while the difference decreases by implementing the model with estimated collector parameters. The reason could be the degraded collector performance, moisture inside the collector and dust on the collector surface. The last column shows that there is around 26% deviation between the modelled energy output with estimated collector parameters and the modelled energy output with theoretical collector parameters.

Tab. 3: Monthly energy output summary of the flat plate collector array

Month/ Measured days	Total/Calculated diffuse solar irradiance	Measured energy output	Modelled energy output with estimated/theoretical collector parameters	Ratio of estimated and theoretical modelled energy output
	(kWh/m^2)	(kWh/m^2)	(kWh/m^2)	(%)
May/5	29/10	12.6	13.2/16	78.8
June/30	159/53	67.9	76.2/92	73.8
July/7	35/12	14.6	17.6/21	69.5
August/17	83/26	34.7	38.9/47	73.8
Total/59	306/101	129.7	146/176	73.7

4. Predicted annual thermal performance comparison

In order to have a comprehensive thermal performance comparison between the CPC collector and the flat plat collector at different operating fluid temperatures, the predicted annual thermal performance was calculated for both the collectors by implementing a standardized collector performance calculation method (Perers et al., 2012) with the tested collectors' parameters and the typical weather conditions of the north Jutland of Denmark (Furbo et al., 2018) where the Sæby solar heating plant located.

The predicted annual thermal performance comparison can be seen in Fig.10. The blue curve is the predicted annual thermal performance of the CPC collector under different operating mean fluid temperatures with optimal tracking tilt. The red and green curves are the predicted thermal performance of the flat plate collector with theoretical and estimated collector parameters, respectively.

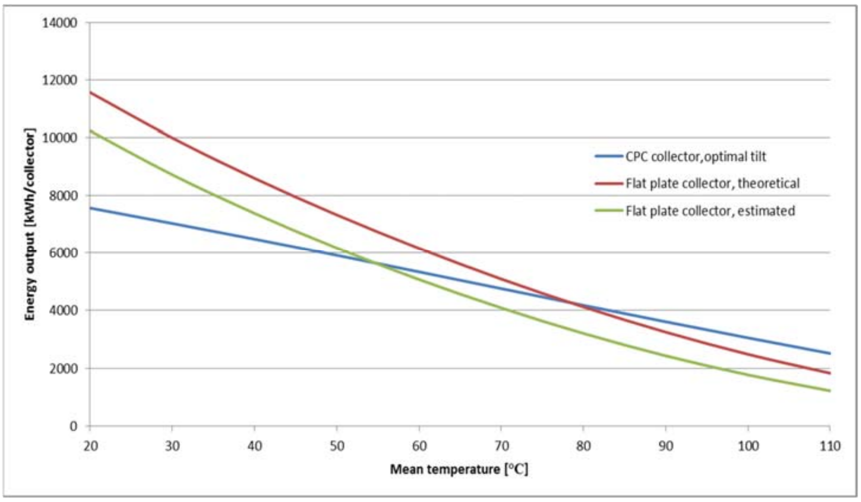

Fig. 10: Predicted annual thermal performance comparison under Denmark's weather condition

It can be seen from the figure that two cross points are created by the three curves. The two points represent the equivalent annual thermal performance of the two collectors at the mean fluid temperature of 55 °C and 78 °C. It means that when the operating mean fluid temperature is higher than 55 °C, the CPC collector with optimal tracking tilt angle has thermal advantages than the flat collector with estimated collector parameters while the CPC collector with optimal tracking tilt angle will have thermal advantages than the flat plate collector with theoretical parameters when the operating mean fluid temperature is higher than 78 °C.

5. CONCLUSIONS

A new concept of CPC solar collector was designed and the prototype collectors were developed by a Danish company PolyCSP A/S. The new CPC collector was optimized for operating at the temperature range of 60 °C - 120 °C aiming to be utilized in solar heating plant.

The CPC collectors were tested at the Technical University of Denmark for obtaining the collector parameters. Then four CPC collectors were installed as an array and connected to the solar collector field in Sæby solar heating plant in Denmark. The operating behavior of the CPC collectors and other four flat plate solar collectors in front were monitored.

The thermal performance model was developed for both the CPC collector and the flat plate collector by using the QDT model and the tested collector parameters. From the daily and monthly thermal performance calculation and comparison it can be seen that the developed QDT model for both the CPC solar collector array and the flat plate collector array is valid and can be used for predicting the collector's thermal performance.

The annual thermal performance of the CPC collector and the flat plate collector was calculated at different operating fluid temperatures under the typical weather condition of north Jutland of Denmark. The conclusion is that the annual thermal performance of the CPC collector is higher than the annual thermal performance of the flat plate collector if the mean fluid temperature is higher than 78 °C in theory, in practice if the temperature is higher than 55 °C.

6. ACKNOWLEDGEMENT

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