QUALIFICATION OF A SMALL-SCALE PARABOLIC TROUGH COLLECTOR WITH DIRECT STEAM GENERATION FOR PROCESS HEAT AND SOLAR COOLING APPLICATIONS

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Abstract

A small-scale parabolic trough collector was further developed for use in process heat and solar cooling applications with an operating temperature between 140 and 200°C. Measurements of both the optical characteristics of the reflector and the thermal behavior of the collector operated in direct steam generation mode were carried out. Both tests show good results. The optical measurements of the collector geometric accuracy show that around 99% (depending on the angle of incidence) of the reflected rays actually hit the receiver. The thermal measurements were carried out with 10 collectors connected in parallel. Because of the direct steam generation mode the flow rate in the collector circuit is very small. Therefore, small pipe diameters and pumps can be used. The response time to heat the flow temperature from ambient temperature to 200°C operating temperature is very short (2 min). The flow temperature is kept constant thanks to the self regulating valve inside the collectors.

1. Introduction

The development of medium temperature solar thermal collectors opens up a new field of applications beyond domestic hot water preparation and space heating for the solar thermal industry. Collectors that provide heat efficiently in a temperature range between 150 and 200°C can be used for process heat and process steam generation in the industry. In addition, these kinds of temperatures are needed for the operation of highly efficient thermally driven cooling machines. One possibility is to use parabolic trough collectors for these applications. Small-scale parabolic trough collectors have the advantage compared to large parabolic troughs that are used for electricity generation, that they can easily be installed on factory roofs.

Within a previous research project [1] a parabolic trough collector developed and constructed by the company Button Energy (aperture width 0.5 m, length 4 m) was tested, analyzed and optimized by AEE INTEC. The optical efficiency of the parabola which was manufactured from curved glass, was satisfactory. A serious disadvantage of the construction was the complex and therefore costly manufacturing process where flat glass is bent under heat with high precision.

2. New Collector Construction

The prototype collector was completely reconstructed by the company Button Energy. The parabola shape of the enhanced prototype is now made out of deep drawn sheet aluminum (Fig. 1). The collector with an aperture area of 0.5 m x 4 m (nominal thermal capacity 1 kW) consists of eight segments which are molded and riveted with each other. The cover glass is bonded onto the parabola shape which gives the collector an excellent stiffness.

In view of a mass production of the collector, deep drawing of a whole collector of 4 m length would be desirable. However, financing of the necessary mold was not possible within the underlying project.

Fig. 1. Collector back made from profiled sheet aluminum.

Another advantage of the new construction is that it weighs only 17 kg/(m^2 aperture area) compared to 43 kg/m^2 of the previous glass construction.

The parabola shape is a crucial part of a parabolic trough collector because the optical precision of the concentration and therefore the efficiency of the collector depend strongly on the geometric properties. Therefore, the optical quality of the new construction was measured by the DLR (Deutsches Zentrum für Luft- und Raumfahrt, Institute of Technical Thermodynamics).

3. Measurement of the Geometric Accuracy of the Optical System

Geometric accuracy of the optics of the new collector design has been analyzed by a deflectometric technique [2] based on the evaluation of images of the mirror with reflected absorber tube. Red paint on the absorber tube results in enhanced contrast for the deflectometry evaluation (Fig. 2). A series of pictures taken from a distance of 7.7 m shows the absorber tube reflection in different locations of the mirror by varying the collector tilt angle. The pictures are then rectified and evaluated to show quantitative slope deviations of the reflector shape.

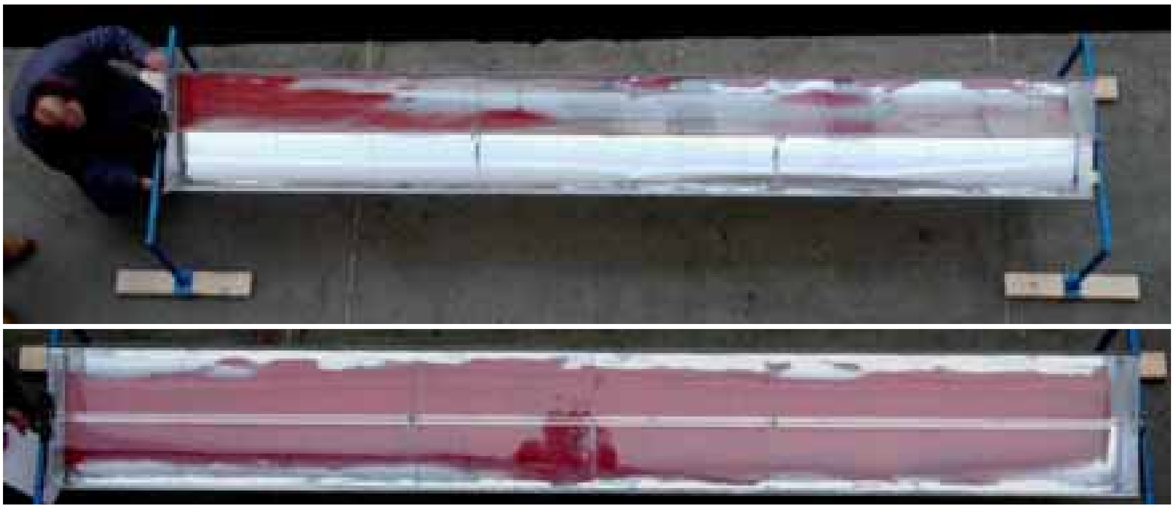

Fig. 2. Views onto the collector with red colored absorber tube. The extension of the red areas on the mirror is used to analyze the mirror shape. Measurement images from 7.7 m of distance.

4. Results and Findings from Deflectometry

Result from the photometric technique and subsequent evaluation with the DLR method is a map-like representation of the deviations of the mirror shape from the ideal parabolic shape. The so-called slope deviations of the reflector from its ideal cyclindrical parabola are measured in mrad (1 mm per 1 m) and shown on the color graph (Fig. 3). The reflector slope deviation has double effect because of the reflection of the light. The goal for the standard deviation of the slope deviation values depends on the concentration factor and should be in the range of 2 to 6 mrad.

The following graphs show the results of the measured module.

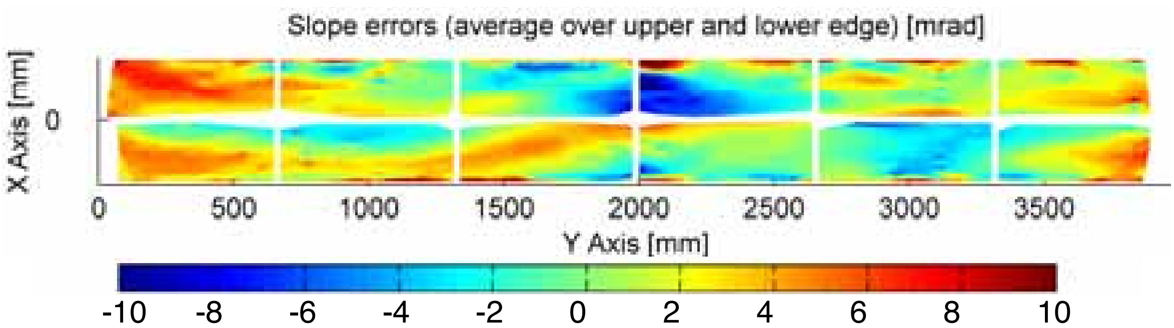

Fig. 3. Slope deviations of the reflector shape in mrad; positive values flatter than parabola.

Fig. 3 shows that wide areas of the collector have a maximum slope deviation from the ideal shape of not more than 5 mrad. Only the boundaries of the reflector have small regions with higher errors, but with low overall impact on the total results.

Ray tracing is used for interpreting which areas of the reflector have what amount of deviation of the reflected rays from the ideal focal line. The resulting graph is shown in Fig. 4. It reveals that deviations of the reflected rays from the focal line are small in comparison to the 5 mm absorber tube radius and thus yield a high intercept factor. As shown for the configuration with 30° of incident angle of the sunlight, the majority of the radiation hits the absorber tube.

Fig. 5 shows parameters and results from the measurement of slope deviations.

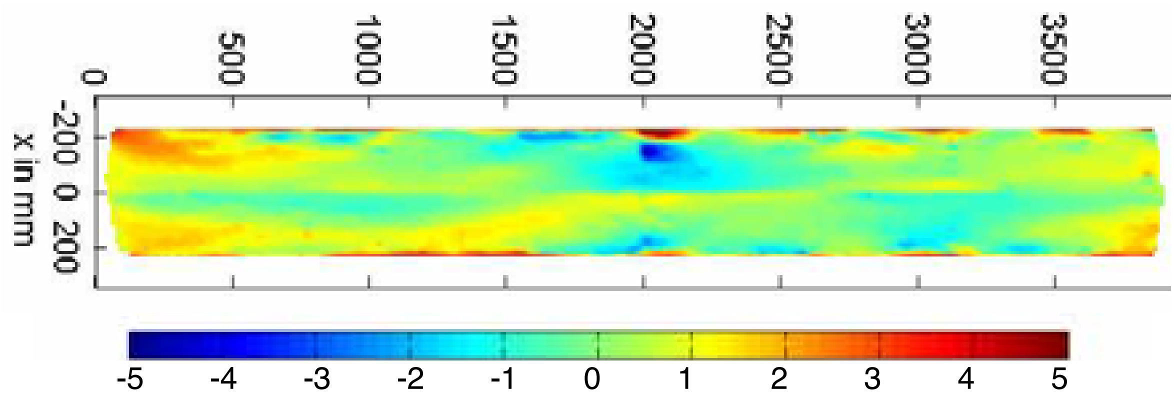

Fig. 4. Focus deviation map for the reflected rays, in mm. Positive values: reflected rays above the focal line.

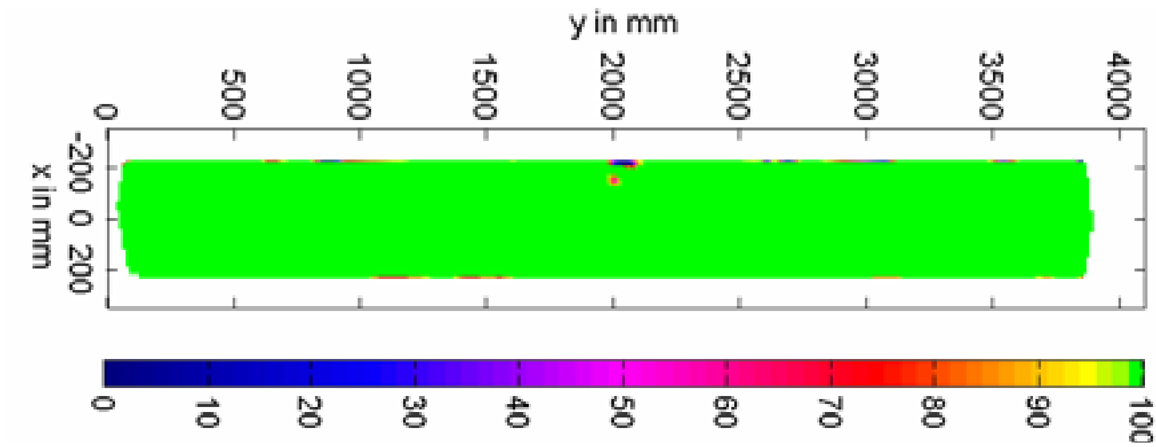

Fig. 5. Intercept factor distribution on the reflector area at 30° incident angle.

Table 1. Results of the slope deviations of the examined collector module.

		Mean Error	RMS Error
Total [mrad]		**0.00**	**3.19**
Column No., [mrad]			
	1	1.04	4.06
	2	0.19	2.52
	3	-1.89	3.13
	4	-1.26	3.80
	5	1.51	2.55
	6	0.57	2.78
Row No., [mrad]			
	1	0.77	3.50
	2	-0.78	2.84
Mirror area No. , [mrad]			
	1	4.39	4.69
	2	1.18	2.26
	3	-1.71	3.02
	4	-2.33	4.98
	5	1.27	2.30
	6	2.29	2.77
	7	-2.47	3.27
	8	-0.80	2.77
	9	-2.08	3.23
	10	-0.21	2.08
	11	1.76	2.79
	12	-1.17	2.79

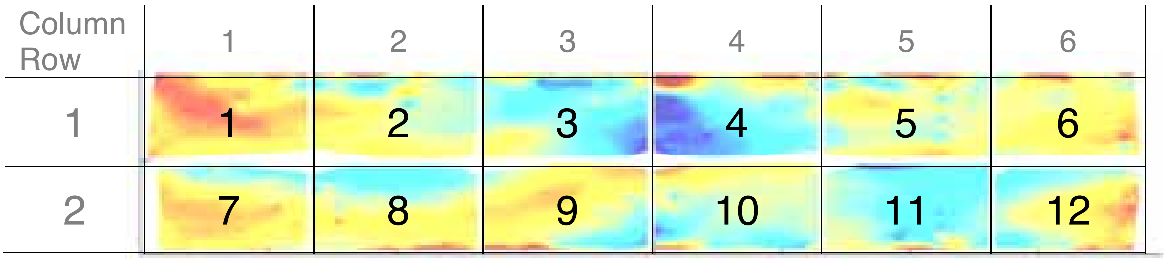

Fig. 6. Numbering of the mirror sections from left end, see Fig. 3.

Table 2. Results of the intercept factor, exemplarily for 0°, 30° and 60° of incidence angle.

Collector	Absorber tube height above parabola in mm	Average focus deviation in mm	Standard focus deviation in mm	**Intercept-Factor %**
AEE_1_I0	108.4	0.79	1.02	**99.55**
AEE_1_I30				**99.43**
AEE_1_I60				**98.80**

The major tendency of the shape is towards slightly too long focal length. It is obvious from the result that the boundaries of each submodule are the most difficult parts for maintaining the shape accuracy.

5. Direct Steam Generation

An advantage of steam generation in the collector is that lower flow rates are needed in the collector circuit because the phase change contains a lot of energy. Therefore, pipes can be dimensioned significantly smaller which also reduces heat losses from the pipes. In addition, the necessary pumps can be small which reduces the electricity consumption of the pump.

The receiver (developed and built by the company Button Energy Energiesysteme GmbH) consists of a concentric stainless steel pipe surrounded by a glass cover tube which should ideally be evacuated. The advantage of the concentric construction compared to a simple tube with inlet on one side and outlet on the other side is that only one glass-metal-bond is necessary to seal the cover tube with the absorber tube. The glass cover tube is somewhat longer than the absorber tube which leaves room for linear thermal expansion of the absorber tube.

The receiver for direct steam generation developed by Button Energy is shown in Fig. 7. This receiver has a valve at the end of the inner absorber tube which opens and closes depending on the temperature. Thereby the flow rate through the collector is controlled and a constant outlet temperature is reached.

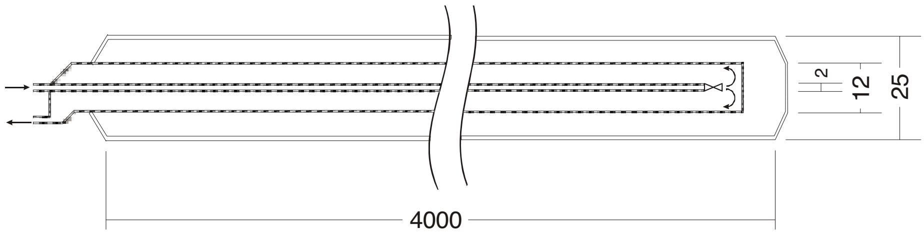

Fig. 7. Receiver for direct steam generation.

6. Thermal Measurements

Ten parabolic trough collectors connected in parallel were tested in direct steam generation mode at the test facility of AEE INTEC in Gleisdorf (see Fig. 8).

Fig. 8. 10 parabolic trough collectors at the test facility in Gleisdorf.

Fig. 9 shows the flow temperature of all 10 collectors as well as the volumetric flow rate in the return line (liquid). In this test, the pump was started just before 10 o'clock. The volumetric flow rate goes from zero to about 4 l/h. This is the leakage flow rate that goes through the valves inside the receiver even if they are closed as long as the pump keeps the pressure in the return line at a certain level.

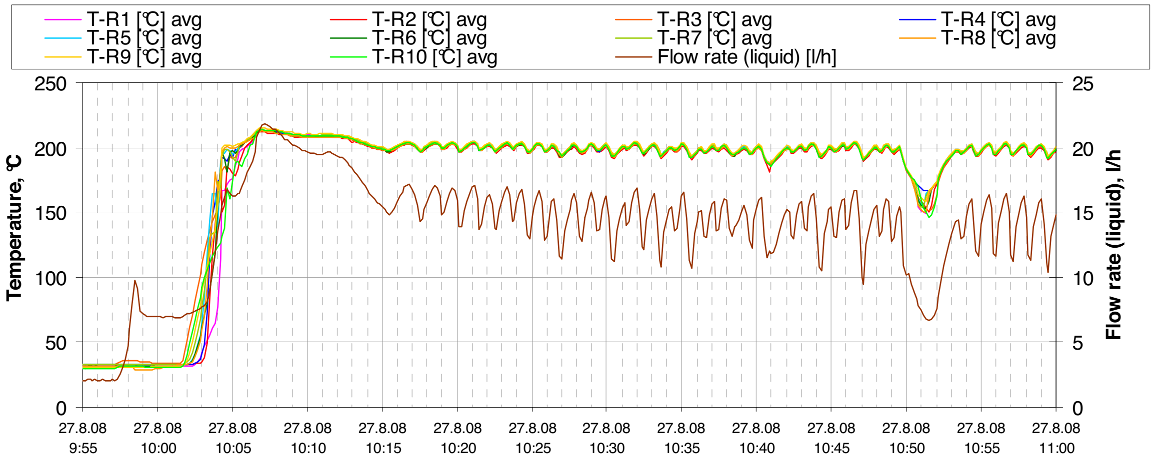

Fig. 9. Temperatures and flow rate of 10 parabolic trough collectors during a test run.

The collectors were turned into focus shortly after 10 o'clock. The flow temperatures of all 10 collectors increase quickly to about 200°C. It takes only 2 minutes to reach this temperature at the outlet of the collector. The temperature is then kept constant to a few degrees Celsius. The flow rate fluctuates between around 14 and 18 l/h. The reason for that is that the valves inside the collector are not all opened at the same time but depending on the temperature in each single collector.

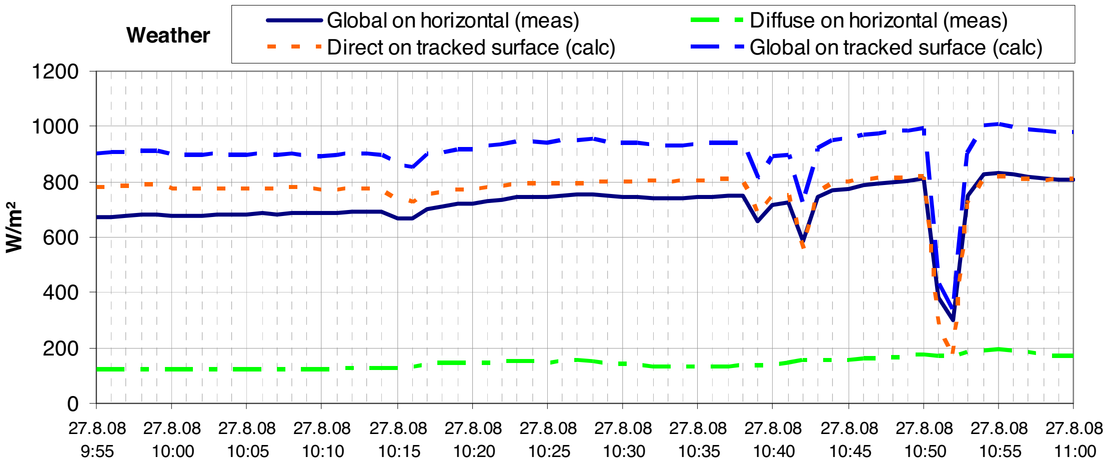

Fig. 10. Radiation on the horizontal and on the tracked collector.

Fig. 10 shows the measured radiation on the horizontal plane as well as the calculated global and direct radiation on the tilted (tracked) collector for the same test run. At this time of the day, the radiation on the tracked surface is significantly higher than on the horizontal. The curve shows also two drops in radiation. The first smaller one is due to a small cloud or possibly a condensation trail of an airplane. The second one lasts about 3 minutes.

A shown in Fig. 9, the first drop in radiation does not affect the flow temperatures at all, but it reduces the flow rate. During the second longer drop in radiation the flow temperatures decrease by about 50 K an also the flow rate drops significantly. But as soon as the radiation is again high, the system reaches its operating temperature within 2 minutes.

7. Summary

The evaluations have shown that the collector design and the manufacturing give ideal results of the geometric accuracy and thus the energetic output of the collectors.

The reflector shape fulfills effectively the desired parabolic shape. Deviations of the mirror slope of the parabolic shape vary 2 - 5 mrad. The standard slope deviation SDx of the mirror of 3.19 mrad and the concentration factor of 48x enable good intercept factors. The concentration factor and the reached reflector precision match so that intercept factors of 99% are possible provided that a good quality tracking system is used.

The optical efficiency of a clean collector of this construction can reach values around 65%.

The collectors have a very short response time. It takes only 2 minutes to heat the flow temperature from 30°C ambient temperature to 200°C operating temperature. The flow rate of 15 – 20 l/h for 20 m^2 aperture area is very low.

The low weight of the collector (17 kg/m^2) and its good optical properties make it possible to design process heat applications in a temperature range between 140 and 200°C. Typical applications will be office buildings, hotels and recreation centers, laundries and industries where fossil fuel can be replaced by solar energy entirely during the summer months.

8. Acknowledgements

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