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EFFICIENCY AND LIFETIME OF SOLAR COLLECTORS FOR SOLAR HEATING PLANTS

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Abstract

The 12.5 m² flat plate solar collector HT, today marketed by Arcon Solvarme A/S, has been used in solar heating plants in Scandinavia since 1983. The collector is designed to operate in a temperature interval between 40°C and 90°C. The efficiency of the collector has been strongly improved since it was introduced on the market. The paper will present the increase of the efficiency of the collector due to technical improvements since 1983.

Further, measurements from the spring of 2009 of the efficiency of two HT collectors, which have been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate, will be presented. The efficiencies will be compared to the efficiencies of the collectors when they were first installed in the solar heating plants. The measurements are supplied with inspections of the collectors inclusive investigations of possible corrosion of the copper pipes of the absorbers of the collectors.

It is shown that from 2002 to 2007 the thermal performance of solar collector has been increased by 29%, 39%, 55% and 80% for a mean solar collector fluid temperature of 40˚C, 60°C, 80°C and 100°C respectively due to improvement of the collector design. The test of the two collectors shows that due to aging the Ottrupgård collector has a yearly thermal performance which is 4% lower than for the collector tested in 1991 for a solar collector fluid temperature of 45°C, while the Marstal collector has a yearly thermal performance which is 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgård collector and the Marstal collector is respectively 11% and 10% lower than the collector tested in 1991.

Keywords: *Flat plate solar collector*, *Collector efficiency*, *Efficiency test*, *Lifetime*, *Solar heating plants*.

1. INTRODUCTION

For evaluation and comparison of solar collectors, many factors need to be considered: collector thermal performance and costs, lifetime of the collectors and decrease of collector performance due to aging. The thermal performance of a solar collector is fairly easy to assess. There are a large amount of studies, both experimental and theoretical, on test of collector thermal performance in the literature, while a limited amount of literature can be found on evaluation of collector lifetime and deterioration of the collector thermal performance due to aging. Most of the studies concentrated on the durability of the solar absorber surfaces (Brunold et al., 2000; Carlsson et al, 2000; Pettit, 1983). The Working Group MSTC ('Materials in Solar Thermal Collectors') of the International Energy Agency – Solar Heating and Cooling Program (IEA-SHCP) identified aging of solar absorber surfaces as an important quality factor for collector degradation. Within the framework of the program, (Carlsson B. et al, 2000) and (Brunold, S. et al., 2000) described a test procedure developed based on the results of a comprehensive case study. The absorber surface should be considered qualified if it meets the requirement of a service life of 25 years with maximum loss in the optical performance of the absorber surface corresponding to a 5% relative reduction in the performance of a solar domestic hot water system. (Carlsson, Möller, et al., 2000) made a comparison between predicted and actually observed in-service degradation of a nickel pigmented anodized aluminium absorber coating for solar DHW systems. The investigation was carried out on

collectors used for a period of 10 years or more. It is expected that the estimated service life for the coating is of the order of 30-40 years in an airtight solar collector with controlled ventilation of air, while in a non-airtight collector, the estimated service life is shortened to 5-10 years.
Instead of focusing on components of the collector, several studies were carried out to investigate thermal performance of the whole collector. (Proctor and Czarnecki, 1985) tested a 22-year-old double-glazed ISC (Integral Storage Collector) type solar collector equipped with black painted absorber surface. They found that the degradation in thermal performance of the collector is mainly due to glazing seal failure allowing moisture into the insulation. (Rudnick et al. 1986) studied how aging effects the physical conditions and thermal behaviours of collectors by means of visual inspections, owner interviews, thermographic analysis of collectors, standard efficiency tests and dissection of solar collectors. They concluded that well made solar collectors can operate satisfactorily for periods in excess of 15 years with minimum maintenance and that many of the more serious problems found were either present at the time of installation or resulted from poor installation techniques.

The durability of the HT collector design in the Swedish climate was investigated for large modules from 4 collector fields. (Wennerholm and Kovacs 1998) They were from Lyckebo, Nykvarn, Ingelstad och Falkenberg. The age was between 8-14 years at the test. The performance was not significantly reduced within measurement errors. The main degradation was on rubber seals around the glazing and rupture of the Teflon convection barrier in some cases. The absorber surfaces showed no degradation. In practice the main lifetime problem in Swedish plants has been damage by children throwing stones at the glazing and solders with too low meting point in the absorber creating small leaks that were difficult to repair. In some cases also mistakes to adjust the glycol fraction before the winter after leaks during the summer, has caused expensive repairs.

The Lyckebo collector at the Älvkarleby laboratory in Sweden, has been retested 5 times since the operation start 1982. (Karlsson 2001), (Bröms 2003). No significant performance degradation of the test sample has been detected during the years. Some local Teflon rupture can be seen though. The large 4000 m^2 Lyckebo collector field had problems (Bröms 2003) with leaks of antifreeze fluid and severe damage of glass that made the operation too expensive finally. The problems are with rubber seals for the glass, rupture of the Teflon convection barriers, due to sharp metal edges, and wrong solder in the absorber. The plant was shut down 2000 after almost 20 years of operation.

The aim of this study is to investigate lifetime and efficiency of flat plate solar collectors used for solar heating plants. The 12.5 m^2 HT (high temperature) solar collector, marketed by Arcon Solvarme A/S, has been used in solar heating plants in Scandinavia since 1983. The collector is designed to operate in a temperature interval between 40°C and 90°C. The efficiency of the collector has been strongly improved since it was introduced on the market. The paper will present the increase of the efficiency of the collector due to technical improvements since 1983. Further, measurements from the spring of 2009 of the efficiency of two HT collectors, which have been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate, will be presented. The efficiencies will be compared to the efficiencies of the collectors when they were first installed in the solar heating plants. The measurements will be supplied with inspections of the collectors inclusive investigations of possible corrosion of the copper pipes of the absorbers of the collectors.

2. COLLECTOR DEVELOPMENT DURING THE PERIOD 2002-2007

The 12.5 m^2 HT flat plate solar collector has been used in solar heating plants in Scandinavia since 1983. Figure 1. shows the design of the HT solar collector. The collector panel consists of two manifolds (one dividing and one combining flow manifold) and 16 parallel connected horizontal fins.

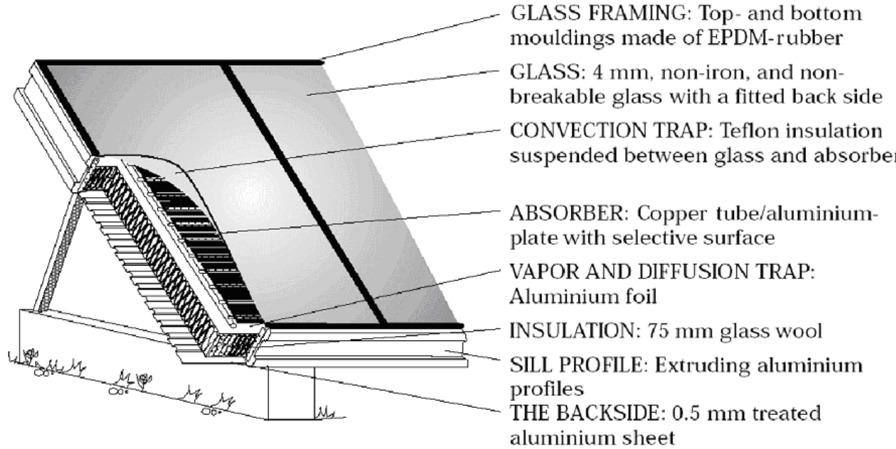

Figure 1. Design of the HT flat plate solar collector

The efficiency of the solar collector can be written as:

$$\eta = \eta_0 * k_\theta - a_1 * \frac{T_m - T_a}{G} - a_2 * \frac{(T_m - T_a)^2}{G} \quad (1)$$

where T_m is the mean solar collector fluid temperature, ˚C; T_a is the ambient air temperature, ˚C; G is the solar irradiance, W/m^2. η_0 is the maximum efficiency. a_1 and a_2 are the first order and the second order heat loss coefficients in W/m^{2}K and W/m^{2}K^2 respectively.

The incidence angle modifier of the solar collector is:

$$K_\theta = 1 - \tan^P(\theta/2) \quad (2)$$

where θ is the incidence angle of the solar ray; P is a constant determined by measurements.

The HT collector has been developed by Arcon Solvarme A/S in cooperation with the Department of Civil Engineering at the Technical University of Denmark during the period 2002-2007. The changes of the collector design is summarized in Table 1. The efficiency expressions and the constants for calculation of incidence angle modifiers for the HT collectors from 2002 to 2007 are listed in Table 2. In 2002, the HT collector was improved by changing the insulation materials from Isover glass wool to Rockwool industribatts 40. A better absorber was used with a reduction of the emittance from 0.12 to 0.06. The glass cover was changed from AFG Solite to AFG Solatex and the glass cover was antireflection treated by Sunarc Technology A/S which significantly increases transmittance of the glass. These changes in the collector design increases the efficiency of the collector, see Fig. 2. The collector tested in 2002 has an efficiency 5-10 percent points higher than the collector tested before 2002. In 2005 and 2007, the installation of the Teflon foil was improved and the insulation material Rockwool industribatts 40 was replaced by an even better insulation Rockwool industribatts 80 which decreases heat loss of the collector especially at higher temperature levels.

Table 1. A summary of design changes during the period 2002-2007.

Year	Changes
2002	Insulation material: Rockwool industribatts 40 instead of Isover glass wool Absorber: Absorptance still 0.95. Emittance reduced from 0.12 to 0.06 Glass: AFG Solatex instead of AFG Solite Antireflection treated glass: Glass surfaces etched by Sunarc Technology A/S
2005	Installation of Teflon foil improved to decrease thermal bridges
2007	Insulation material: Rockwool industribatts 80 instead of Rockwool industribatts 40 Improved edge insulation

Fig.3 shows the calculated yearly thermal performance of the collectors as a function of a constant mean solar collector fluid temperature throughout the year. The calculations are carried out with weather data from the Danish Design Reference Year based on the efficiency expressions and the constants for calculation of incidence angle modifiers shown in Table 2. Fig. 4 shows the relative performance of the HT collectors as a function of the mean solar collector fluid temperature. The relative performance is the ratio between the yearly thermal performance of the collector in question and the yearly thermal performance of the collector tested before 2002. It is seen that from 1991 to 2007 the thermal performance of solar collector is increased by 29% for a mean solar collector fluid temperature of 40˚C. The increase of thermal performance is larger with an increased solar collector fluid temperature., see Table 3.

Table 2. Test conditions and efficiency of the collectors during the period 2002-2007.

Year	η_0	a_1	a_2	P	Collector fluid	Flow rate
-	-	W/m^2K	W/m^2K^2	-		l/min
2002	0.75	3.05	0.0051	2.7	40% Glycol/water	25
2002	0.81	2.57	0.0079	3.7	40% Glycol/water	25
2005	0.81	2.91	-	4.4	40% Glycol/water	25
2007	0.81	2.89	-	4.4	40% Glycol/water	25

Table 3. Improvement of collector thermal performance from 2002-2007.

Mean solar collector fluid temperature	40°C	60°C	80°C	100°C
Improvement of thermal performance of solar collector from 2002 to 2007	29%	39%	55%	80%

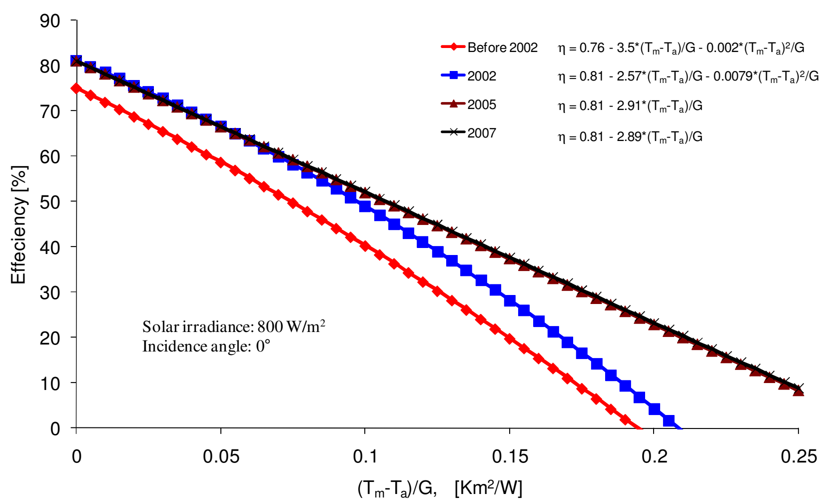

Figure 2. Efficiency of the collectors at small incidence angles during the period 2002-2007

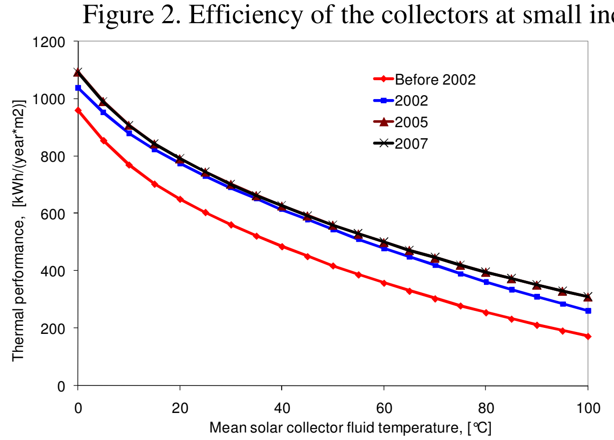

Figure 3. Yearly thermal performance of the collectors during the period 2002-2007

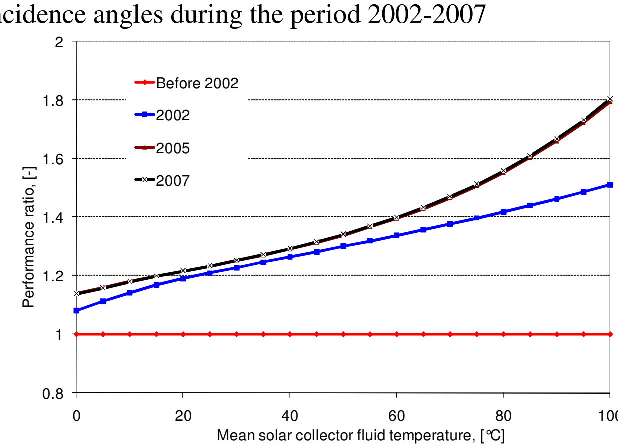

Figure 4. Performance ratio of the collectors during the period 2002-2007.

3. EFFICIENCY OF THE HT COLLECTORS AFTER 13-15 YEARS OF OPERATION

The HT collector has been developed in Sweden since the1980s. A prototype of the HT collector installed in the Lyckebo solar heating plant has been in operation for 25 years in the Vattenfall's test platform in Älvkarleby, Sweden. Efficiency of the collector was tested in 2008. The test shows that the yearly thermal performance of the HT collector decreases by 2-5% for a mean solar collector fluid temperature between 30˚C and 100˚C (Chen et al, 2009).

Further in 2009 with the aim to investigate efficiency deterioration of the HT collector due to aging, two HT collectors were tested after 13-15 years of operation in a solar heating plant. One of them has been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and the other has been in operation in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate. Collectors from the end of collector rows were chosen so that the temperature in the collector has been the highest during operation. The same type of collector has been tested with water as collector fluid in 1991 at the Laboratory of Thermal Insulation, Technical University of Denmark (Kristiansen 1993). The collector was tested with a collector tilt of 40˚ and a volume flow rate of 7.2 l/min, see Table 2. The wind speed is approx. 1 m/s during the test.

In the spring of 2009, the two collectors were tested side by side in the test facility at the Department of Civil Engineering. For the sake of fair comparison, water is used as the solar collector fluid in the test. The solar collector fluid is forced to circulate through the collector panel by a pump. The circulating flow rate, in the range of 7.2 l/min, is measured using a Grundfos VFS (vortex flow sensor) type flow meter. The difference between the solar collector fluid inlet and outlet temperatures is measured with a copper-constantan thermopile, type TT. Solar irradiance on the collector panel is measured using a pyranometer type CM11 from Kipp & Zonen. The data collection and control program IMPVIEW is used to measure the collector fluid flow rate, the inlet fluid temperature to the collector panel, the difference between the solar collector inlet and outlet temperatures, the ambient temperature and the solar irradiance during the steady state test period. The accuracy of the measuring equipment is given in Table 4.

Table 4. Accuracy of measuring equipment.

Grundfos VFS Flow meter	± 2 %
Kipp & Zonen pyranometer	± 2 %
Thermocouples Type TT	± 0.5 K
Thermopile Type TT	± 0.1 K

Results of the test of the collector from Ottrupgård at small incidence angles are shown in Fig. 5. Each point stands for an averaged value over 15 min steady period. The collector is tested with four mean solar collector fluid temperature levels: 22˚C, 40-49˚C, 68˚C and 87-89˚C. During the measurement, the average ambient air temperature is 14.7˚C. The average wind speed at the same height of the collector panel is 1.2 m/s. The efficiency expression (equation 3), obtained by regression, is shown in Fig. 5 for a total solar irradiance of 986 W/m^2 which is the average solar irradiance during the test. There is a good fit of the efficiency expression to the measurement points.
The incidence angle modifier of the collector is measured with a mean solar collector fluid temperature of 22˚C. Fig. 6 shows measured incidence angle modifiers for the Ottrupgård collector in the morning and in the afternoon. For the same operation conditions, the incidence angle modifier is higher in the afternoon than in the morning due to thermal capacity of the collector. The coefficient of the incidence angle modifier is determined by regression based on the measurement points, see equation 4.

$$\eta = 0.76 * K_\theta - 3.72 * \frac{T_m - T_a}{G} - 0.0122 * \frac{(T_m - T_a)^2}{G} \quad (3)$$

$$K_\theta = 1 - \tan^{3.1}(\theta / 2) \quad (4)$$

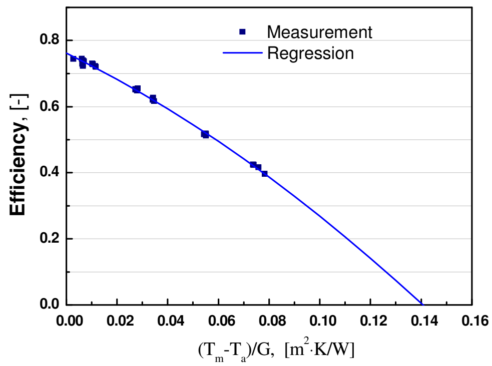

Figure 5. Measurement points and the efficiency expression of the Ottrupgård collector.

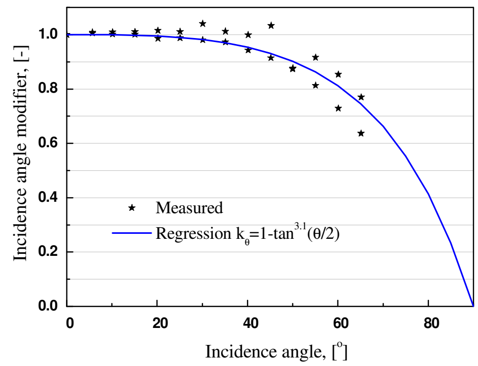

Figure 6. Measurement points and the incidence angle modifier for the Ottrupgård collector.

Measurements of collector efficiency and incidence angle modifier for the Marstal collector are shown Fig. 7 and Fig. 8 respectively. The test conditions are the same as the collector from Ottrupgård. The efficiency expression and the equation of incidence angle modifier are as follows:

$$\eta = 0.78 * K_\theta - 3.00 * \frac{T_m - T_a}{G} - 0.0261 * \frac{(T_m - T_a)^2}{G}$$

$$K_\theta = 1 - \tan^{2.8}(\theta / 2)$$

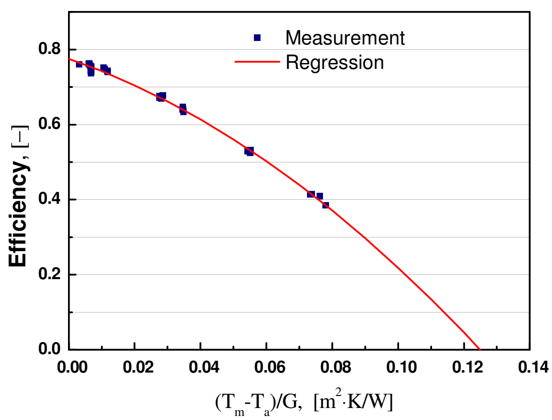

Figure 7. Measurement points and the efficiency expression of the Marstal collector.

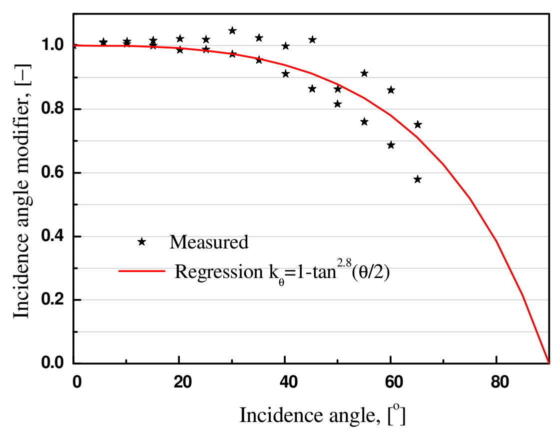

Figure 8. Measurement points and the incidence angle modifier of the Marstal collector.

The efficiency of the Ottrupgård collector and of the Marstal collector at small incidence angles are compared to the efficiency of the collector tested in 1991, see Fig. 9. It can be seen that the maximum efficiency is almost the same for the three collectors. The Marstal collector has a maximum efficiency of 78% while the Ottrupgård collector and the collector tested in 1991 have a maximum efficiency of 76%. The difference can be due to the measurement inaccuracy and variation of the absorber quality. The Ottrupgård collector and the Marstal collector have a larger slope than the collector tested in 1991, which means that the two collectors after 13-15 years of operation have a significant increase of the heat loss coefficient. For a X-axis value $(T_m-T_a)/G$ up to 0.05 m^2K/W, the Marstal and Ottrupgård collectors have efficiencies almost the same as the efficiencies of the collected tested in 1991. For higher X-axis values, the efficiencies of the Marstal and Ottrupgård collectors are much lower than the efficiencies of the collector tested in 1991.

Fig.10 shows the calculated yearly thermal performance of the collectors as a function of a constant mean solar collector fluid temperature throughout the year. The calculations are carried out with weather data from the Danish Design Reference Year based on three efficiency expressions shown in Fig. 9. The incidence angle modifier is 3.1 and 2.8 for the Ottrupgård and the Marstal collector respectively. Since the incidence angle modifier is not measured for the collector tested in 1991, the yearly thermal performance of the collector is obtained by averaging the thermal performance calculated with an incidence angle of 3.1 and the thermal performance calculated with an incidence angle of 2.8.

Fig. 11 shows the relative performance of the HT collectors as a function of the mean solar collector fluid temperature. The relative performance is the ratio between the yearly thermal performance of the collector in question and the yearly thermal performance of the collector tested in 1991. For a solar collector fluid temperature of 45°C, the Ottrupgård collector has a yearly thermal performance 4% lower than the collector tested in 1991 while the Marstal collector has a yearly thermal performance 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgård collector and the Marstal collector is respectively 11% and 10% lower than the yearly thermal performance of the collector tested in 1991, while the reduction of performance of the Ottrupgård collector and the Marstal collector are respectively 23% and 27% with a mean solar collector fluid temperature of 80°C.

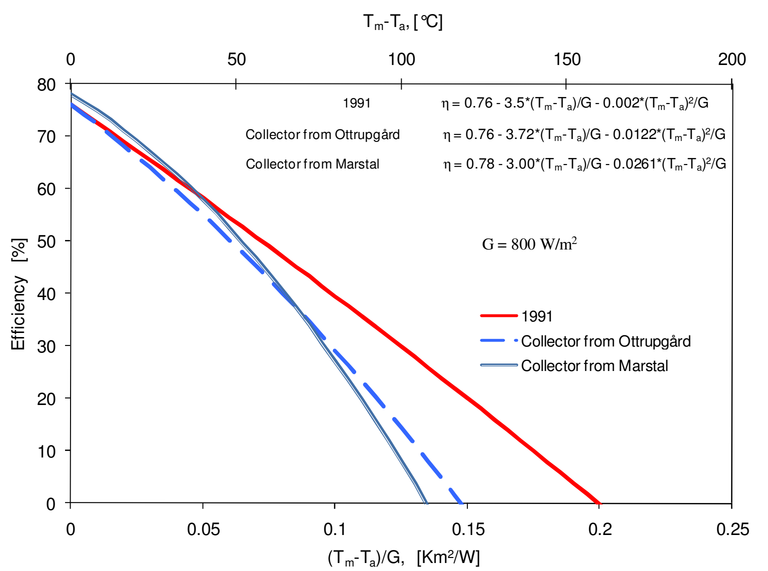

Figure 9. Efficiency curves of the collectors tested in 1991 and in 2009.

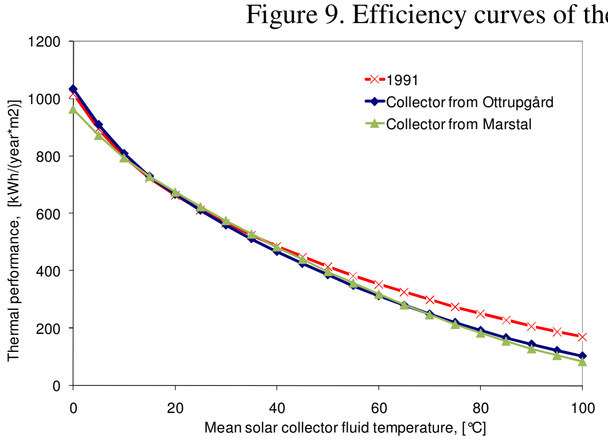

Figure 10. Yearly thermal performance of the collectors tested in 1991 and in 2009.

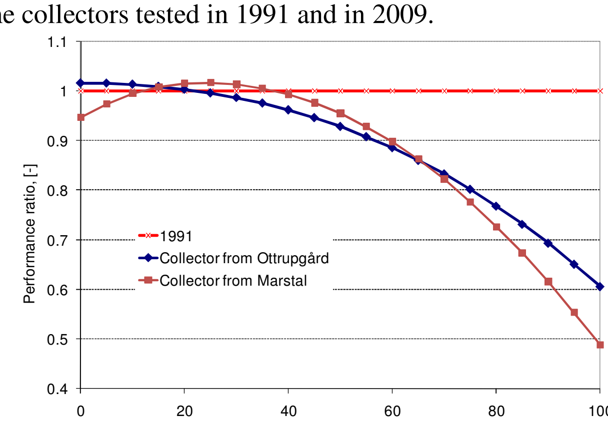

Figure 11. Performance ratio of the collectors tested in 1991 and in 2009.

4. DISSECTION OF THE COLLECTORS

A physical examination of the collectors is carried out after completion of the efficiency test. It is observed that all the glass covers of the two collectors, the rubber band and the casing of both collector panels are in good conditions. The Teflon layer in between the glass cover and the absorber plate, as shown in Fig. 1, is partly damaged for both the Ottrupgård collector and the Marstal collector. Fig. 12 shows an illustration of the damages of the Teflon layer in the Ottrupgård collector. The Teflon layer is installed vertically in the left two modules and horizontally in the other three modules. In the three modules to the right, the Teflon layer is observed to be so loose that either it is very close to the absorber plate or it touches the absorber plate. The space between the Teflon layer and the absorber plate has a significantly influence on the heat loss from the top of the collector especially if the distance is smaller than 1 cm (Duffie and Beckman, 1991). There is space between the Teflon layer and the top edge of the collector panel which allows free air flow through the crack. The crack facilitates the air circulation in the collector panel thus increasing heat loss from the top of the collector. In the first module to the left, Teflon foil is broken at the right corner, creating a hole of 25% of the module area. These damages of the Teflon layer significantly increase heat loss from the top of the collector.

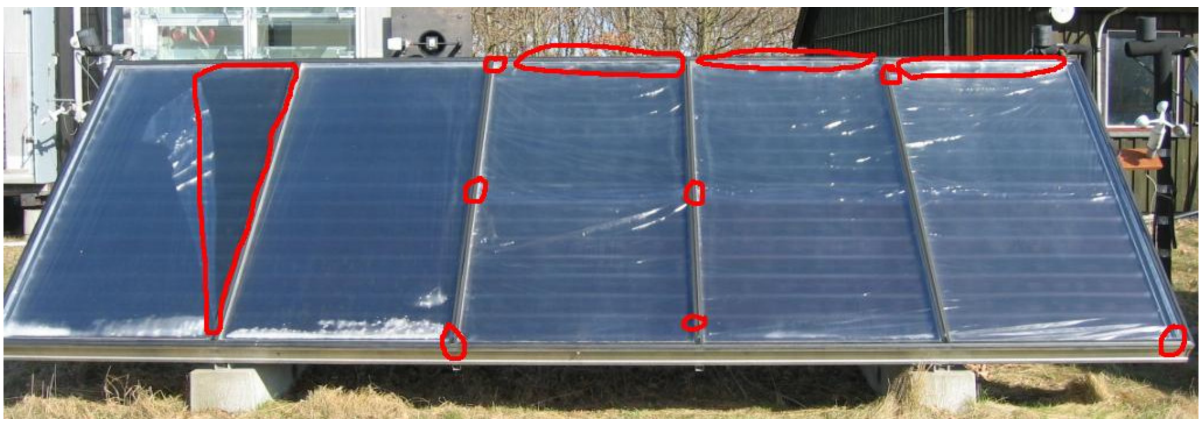

Figure 12. Damage of the Teflon layer in the collector from Ottrupgård.

The damages of the Teflon layer in the Marstal collector is shown in Fig. 13 with red marks. Although there are only small cracks or holes in the Teflon layer at the top and the bottom of the collector panel, the Teflon layer is so loose that it is very close to the absorber plate in the centre part of the module. This can explain the increased heat loss coefficient of the collector.

Figure 13. Damage of the Teflon layer in the collector from Marstal.

Absorptance and emittance of the absorber plates from the two collectors are measured which shows no significant changes of the absorptance and the emittance of the absorber plates. There is no visual damages to the coating of the absorber plate. The collectors are dissected in order to investigate the corrosion of the absorber tubes and the manifolds. Fig. 14 shows the bottom half of the absorber tubes close to the outlet side of the Ottrupgård collector. The 16 absorber tubes from the top of the collector to the bottom of the collector are shown sequentially. There is no corrosion detected in the manifold while there is only corrosion of minor importance on the inner tube surfaces. Fig. 15 shows the upper half and the bottom half of the absorber tubes close to the inlet side of the Marstal collector. Apparently the upper half of the absorber tube has severe corrosion on the surfaces with some brown dots, but close examination of the dots shows that the corrosion is only superficial. Detailed analysis is needed in order to estimate how long it takes for the corrosion to penetrate the tube wall.

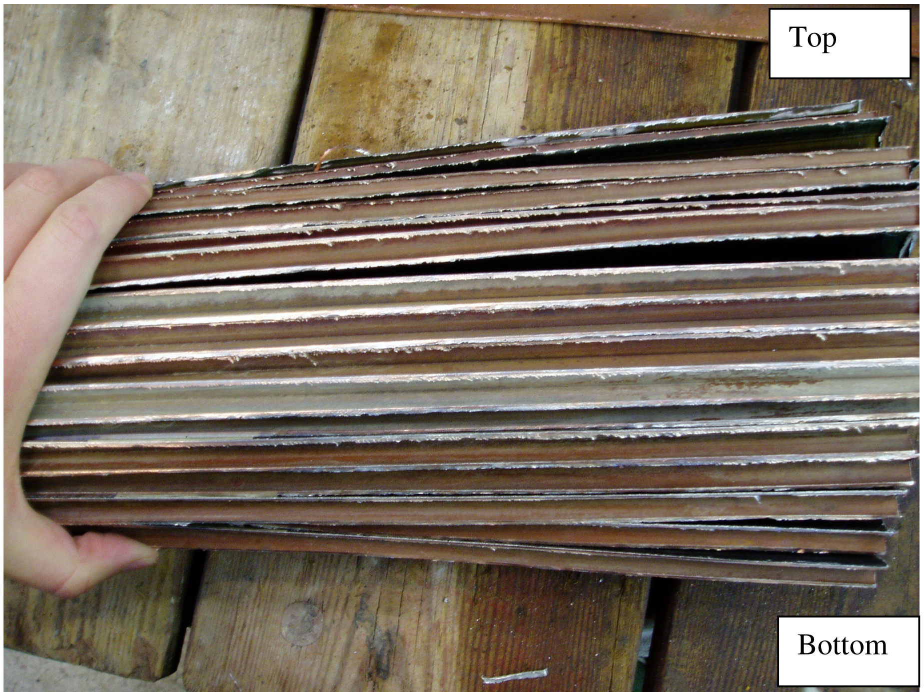

Figure 14. The bottom half of the absorber tubes close to the outlet side of the Ottrupgård collector.

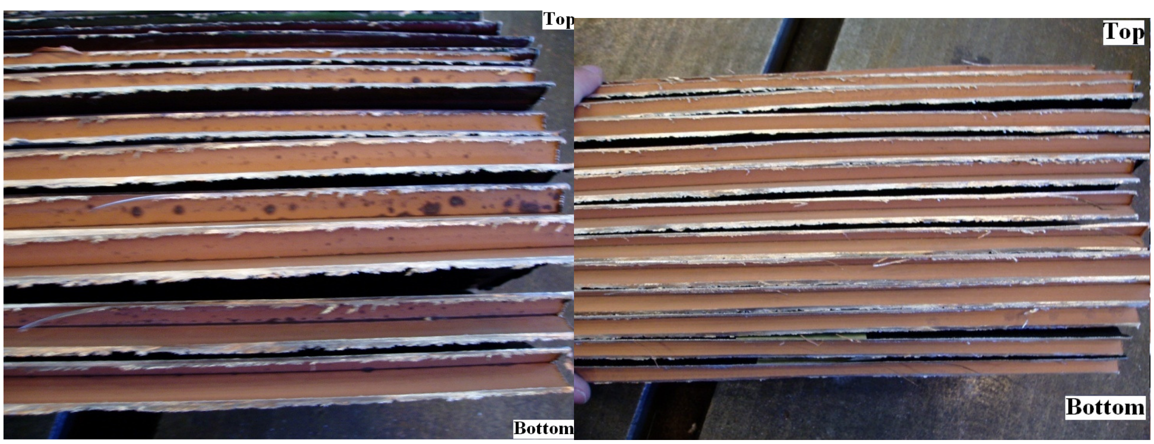

Figure 15. The upper half (to the left) and the bottom half (to the right) of the absorber tubes close to the inlet side of the Martal collector.

5. CONCLUSION

The 12.5 m² HT flat plate solar collector has been used in solar heating plants in Scandinavia since 1983. During the period 2002-2007, the HT collector has been developed by Arcon Solvarme A/S in cooperation with the Department of Civil Engineering, Technical University of Denmark. The development of the collector design and improvement of the collector performance are summarized. From 2002 to 2007 the thermal performance of solar collector has been increased by 29%, 39%, 55% and 80%

for a mean solar collector fluid temperature of 40˚C, 60°C, 80°C and 100°C respectively. The increase of thermal performance is more significant for an increased solar collector fluid temperature.

In the Spring of 2009, measurements of the efficiency of two HT collectors, which have been in operation in the solar heating plant Ottrupgaard, Skørping, Denmark since 1994 with a constant high flow rate and in the solar heating plant Marstal, Denmark since 1996 with a variable flow rate, are carried out. The efficiencies are compared to the efficiencies of the collectors when they were first installed in the solar heating plants. The results show that for a solar collector fluid temperature of 45°C, the Ottrupgård collector has a yearly thermal performance which is 4% lower than for the collector tested in 1991 while the Marstal collector has a yearly thermal performance 1% lower than the collector tested in 1991. With an increase of the solar collector fluid temperature to 60°C, the yearly thermal performance of the Ottrupgård collector and the Marstal collector is respectively 11% and 10% lower than the collector tested in 1991, while the reduction of performance of the Ottrupgård collector and the Marstal collector are respectively 23% and 27% for a mean solar collector fluid temperature of 80°C.

Physical examination of the collector shows that the absorber surfaces, the glass covers, the rubber band and the casing of both collector panels are in good conditions while the Teflon foil is damaged with holes in the Teflon foil and cracks between the Teflon foil and the edge of the collector. The Teflon foil is so loose that the Teflon foil is very close to the absorber plate or even it touches the absorber plate in some parts of the collector. These damages of the Teflon foil can explain the increasing heat loss coefficient of the collector, especially at high temperature levels. Dissection of the absorber tubes does not show severe problems with corrosion of the inner surface of the tubes, however detailed analysis is needed to estimate lifetime of the absorber tubes.

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