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# INVESTIGATIONS ON EFFICIENCIES OF HT SOLAR COLLECTORS FOR DIFFERENT FLOW RATES AND COLLECTOR TILTS

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**Abstract** – Two HT solar collectors for solar heating plants from Arcon Solvarme A/S are tested in a laboratory test facility for solar collectors at Technical University of Denmark (DTU). The collectors are designed in the same way. However, one solar collector is equipped with an ETFE foil between the absorber and the cover glass and the other is without ETFE foil. The efficiencies for the collectors are tested at different flow rates and tilt. On the basis of the measured efficiencies, the efficiencies for the collectors as functions of flow rates are obtained. The calculated efficiencies are in good agreement with the measured efficiencies.

## 1. INTRODUCTION

A strongly increased number of solar heating plants have been built and are under construction in Denmark (<http://www.solar-district-heating.eu/SDH>). The solar collectors used in the solar heating plants are flat plate solar collectors and often the volume flow rate through the collector field is varying. If the solar irradiance is high the volume flow rate is high, if the solar irradiance is low the volume flow rate is low. When the efficiency of a solar collector is determined often only one volume flow rate is used. Actually the efficiency of a solar collector is influenced by the volume flow rate. Only if the influence of the volume flow rate on the collector efficiency is known, it will be possible to determine the optimal operation strategy for a solar collector field. Therefore two flat plate solar collectors used for solar heating plants from Arcon Solvarme A/S are tested side by side in a laboratory solar collector test facility at Technical University of Denmark (DTU) with different flow rates, see Fig.1. Evaluation of the test method for solar collector efficiency and the effect of the volume flow rate on the efficiency of a solar collector were discussed by Fan (Fan, 2006). Also the flow distributions in flat plate solar collectors under different conditions were studied by Jones (Jones, 1994) and by Weitbrecht (Weitbrecht 2002). Furthermore the performance and efficiency of flat plate solar collector arrays have been analyzed by Wang (Wang, 1990). In this paper, the tests on the efficiencies of two flat plate solar collectors at different flow rates have been carried out. The measured efficiencies are compared with the efficiencies calculated with the program SOLEFF which is a simulation program for flat plate solar collectors (Rasmussen, 1996). Based on the investigations efficiency expressions are determined for the collectors with different volume flow rates.



Fig.1 Photo of two HT solar collectors for tests

## 2. EXPERIMENTS

### 2.1 Experimental setup

The efficiency expressions and incidence angle modifiers for two flat plate solar collectors for solar heating plants are measured side-by-side with different volume flow rates at DTU according to European Committee for Standardization (2004), see Fig.1. The collectors are from Arcon Solvarme A/S. The collectors are identical with the exception that one collector is equipped with an ETFE foil between the absorber and the cover glass, while the other collector is without an ETFE foil. The test conditions for the collectors are listed in table 1. The aperture areas for the collector with ETFE foil and the collector without ETFE foil are  $12.55 \text{ m}^2$  and  $12.57 \text{ m}^2$ . The geometric dimensions for both collectors are  $5.96 \text{ m} \times 2.27 \text{ m} \times 0.14 \text{ m}$ . The absorbers are made with copper and aluminium with 18 parallel horizontal strips and with 2 vertical manifolds. The coating for the absorbers is a selective Tinox coating and the outer covers for the collectors are anti-reflective glass covers. The insulations for the collectors are mineral wool.

Table 1. Test conditions for two HT solar collectors

Test No.	Solar collector fluid	Volume flow rate (l/min)	Collector tilt, °
1	40% propylene glycol/water mixture	25	45
2	40% propylene glycol/water mixture	10	45
2	40% propylene glycol/water mixture	5	45
4	40% propylene glycol/water mixture	25	60

### 2.1 Experimental results

Based on the measurements the efficiency expressions and the incidence angle modifiers were found for the collectors. The efficiency curves for a solar irradiance of 1000 W/m<sup>2</sup> and the incidence angle modifier for the two HT solar collectors at different flow rates and 45° tilt are shown in Fig.2 and Fig.3. Also the measurement data achieved for HT solar collectors at flow rate 25 l/min and 60° tilt are shown in Fig.2. The efficiency expressions are:

$$\eta_{1,w} = 0.811 - 2.60 \times (T_m - T_a) / G \quad (1-1)$$

$$\eta_{1,n} = 0.840 - 3.77 \times (T_m - T_a) / G \quad (1-2)$$

$$\eta_{2,w} = 0.80 - 2.16 \times (T_m - T_a) / G - 0.0119 \times (T_m - T_a)^2 / G \quad (1-3)$$

$$\eta_{2,n} = 0.828 - 3.26 \times (T_m - T_a) / G - 0.0086 \times (T_m - T_a)^2 / G \quad (1-4)$$

$$\eta_{3,w} = 0.806 - 2.13 \times (T_m - T_a) / G - 0.0172 \times (T_m - T_a)^2 / G \quad (1-5)$$

$$\eta_{3,n} = 0.827 - 2.94 \times (T_m - T_a) / G - 0.0146 \times (T_m - T_a)^2 / G \quad (1-6)$$

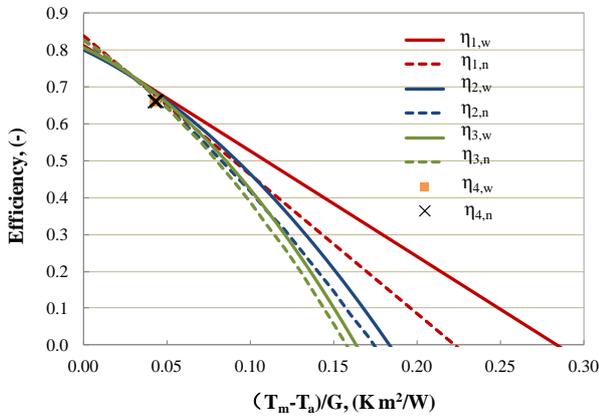


Fig.2 Efficiencies and efficiency curves for HT solar collectors at different flow rates and tilts

From Fig.2 and from equation (1-1) to equation (1-6), it is found that the start efficiencies both for the collector with ETFE foil and for the collector without ETFE foil increase with the increase of the flow rate while the tilts of solar collectors are 45°. The start efficiency for the collector without ETFE foil is 2-3 %-points higher than the start efficiency for the collector with ETFE foil at the same flow rate. The heat loss coefficient of the collector with ETFE foil is 0.4-1.0 W/m<sup>2</sup>K lower than the heat loss

coefficient of the collector without ETFE foil. For a certain solar irradiance and volume flow rate there exists one specific temperature T<sub>0</sub> at which the efficiency for the collector with ETFE foil equals the efficiency for the collector without ETFE foil. When the mean temperature of solar collector T<sub>m</sub> is lower than the temperature T<sub>0</sub>, the efficiency for the collector without ETFE foil is higher than the efficiency for the collector with ETFE foil. However when the temperature T<sub>m</sub> is higher than the temperature T<sub>0</sub>, the efficiency for the collector without ETFE foil will be lower than the efficiency for the collector with ETFE foil. For the same solar collector the efficiency at high flow rate are always higher than the efficiency at low flow rate. This is very obvious when the temperature T<sub>m</sub> is relatively high. The measurement data of efficiency for HT solar collectors with 60° tilt are not enough to decide the efficiency curves yet.

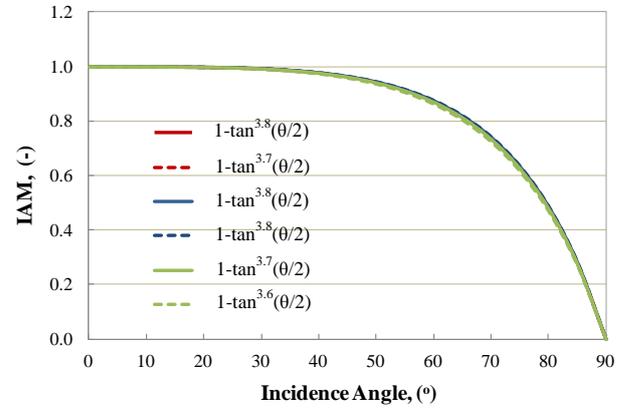


Fig.3 Incidence angle modifiers for HT solar collectors at different flow rates and 45° tilt

As shown in Fig.3, there are no big differences among the incidence angle modifiers for the collectors at different flow rates because the glass covers for both collectors are the same and the transmittance of the ETFE foil is very high.

### 3. THEORETICAL INVESTIGATIONS

The efficiencies for the two HT solar collectors are calculated with a simulation program for flat plate solar collectors SOLEFF. The calculated efficiencies are compared with the measured efficiencies. The yearly thermal performances of the solar collectors in Denmark are also calculated for different mean solar collector fluid temperature on the basis of the calculated and measured efficiencies.

In order to know how well the calculated efficiencies are in agreement with the measured efficiencies the root mean square deviation (RMSD) is introduced to evaluate the differences between calculated and measured results. It is defined as:

$$RMSD = \sqrt{\frac{\sum_{i=1}^N (X_{c,i} - X_{t,i})^2}{N}} \quad (2)$$

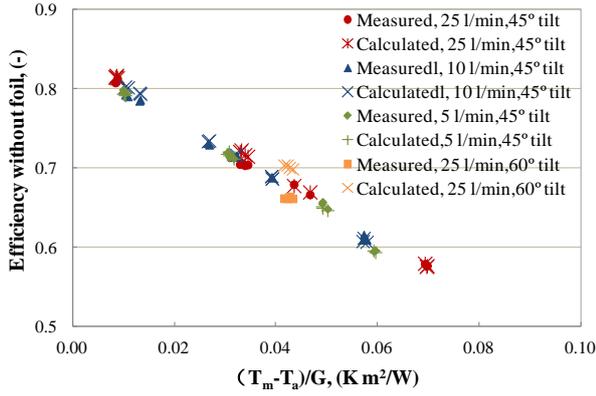


Fig.4 Measured and calculated efficiencies for HT solar collector without foil at different flow rates and tilts

### 3.1 Theoretical efficiencies of HT solar collectors

Based on the measured data of total solar irradiance, diffuse solar irradiance, volume flow rate of collector fluid, ambient temperature, mean temperature of collector fluid, wind speed as well as the geometric and physical parameters of the HT solar collectors, the efficiencies are calculated with SOLEFF. The measured and calculated efficiency points for the collector without ETFE foil and for the collector with ETFE foil under the same conditions are shown in Fig.4 and Fig.5. The *RMSD* for efficiencies for the collector without ETFE and the collector with ETFE at different flow rates are 0.013 and 0.011. That is: There is a good agreement between measured and calculated efficiencies.

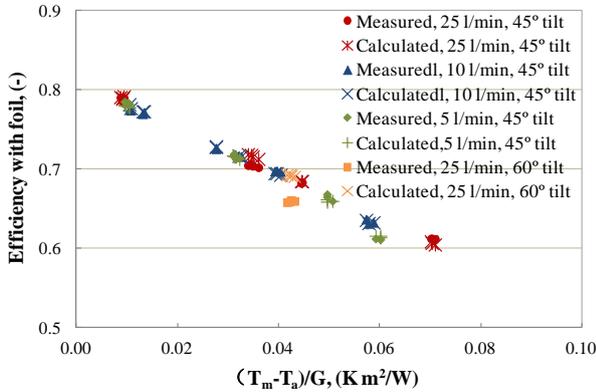


Fig.5 Measured and calculated efficiencies for HT solar collector with foil at different flow rates and tilts

On the basis of the calculated efficiency points with SOLEFF in Fig.4 and in Fig.5, the theoretical efficiency expressions for the HT solar collectors for an incidence angle of 0° and 45° tilt are:

$$H_{1,w} = 0.817 - 1.93 \times (T_m - T_a) / G - 0.0028 \times (T_m - T_a)^2 / G \quad (3-1)$$

$$H_{1,n} = 0.848 - 3.80 \times (T_m - T_a) / G - 0.0012 \times (T_m - T_a)^2 / G \quad (3-2)$$

$$H_{2,w} = 0.808 - 2.64 \times (T_m - T_a) / G - 0.0064 \times (T_m - T_a)^2 / G \quad (3-3)$$

$$H_{2,n} = 0.844 - 3.85 \times (T_m - T_a) / G - 0.0042 \times (T_m - T_a)^2 / G \quad (3-4)$$

$$H_{3,w} = 0.802 - 2.16 \times (T_m - T_a) / G - 0.0153 \times (T_m - T_a)^2 / G \quad (3-5)$$

$$H_{3,n} = 0.822 - 2.77 \times (T_m - T_a) / G - 0.0170 \times (T_m - T_a)^2 / G \quad (3-6)$$

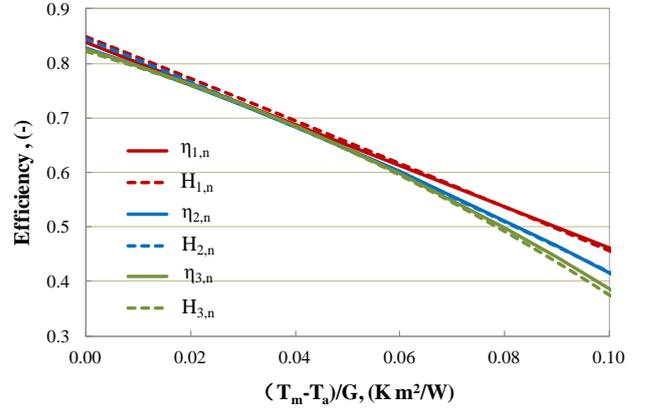


Fig.6 Efficiency curves from measured and calculated results for the HT solar collector without foil at different flow rates and 45° tilt

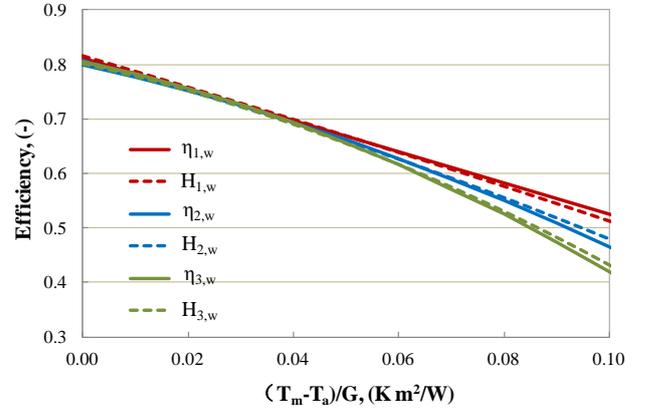


Fig.7 Efficiency curves from measured and calculated results for the HT solar collector with foil at different flow rates and 45° tilt

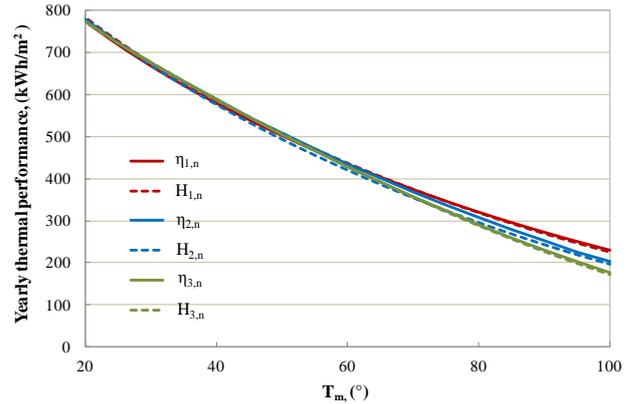


Fig.8 Yearly thermal performance for the HT solar collector without foil at different flow rates and 45° tilt

The comparisons of efficiency expressions, which are obtained from the measured efficiencies and from the calculated efficiencies at different flow rates and 45° tilts both for the collector without ETFE foil and for the collector with ETFE foil, are shown in Fig.6 and Fig.7. The efficiencies from measurements are in very good

agreement with the efficiencies calculated with SOLEFF when the reduced temperature difference is not larger than 0.1 (K<sup>2</sup>/W).

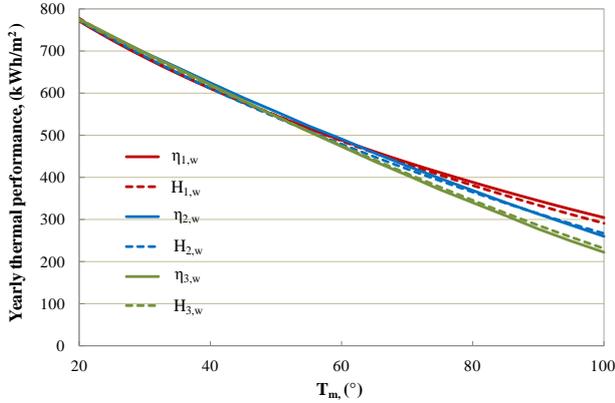


Fig.9 Yearly thermal performance for the HT solar collector with foil at different flow rates and 45° tilt

### 3.2 Yearly thermal performances of HT solar collectors

The yearly thermal performances of flat plate solar collectors in Denmark are calculated for different mean solar collector fluid temperatures with the weather data of the Danish reference year and with the above efficiency and incidence angle modifier equations. The yearly thermal performances calculated with the efficiency equations from measurements and from calculations both for the collector without ETFE foil and for the collector with ETFE foil are compared and shown in Fig.8 and Fig.9 as a function of the mean solar collector fluid temperature.

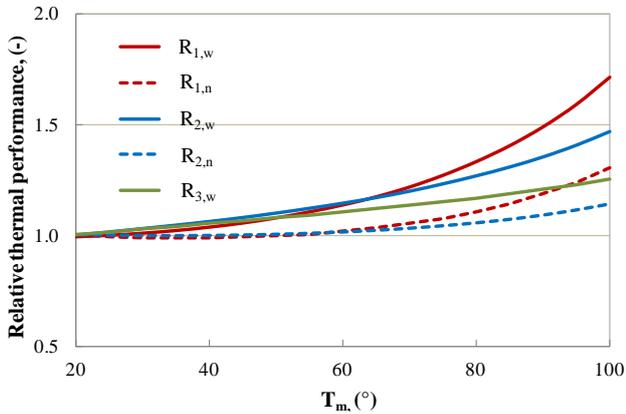


Fig.10 Relative yearly thermal performance for the collectors without and with ETFE foils at different flow rates and 45° tilt

The maximum deviations between the yearly thermal performances calculated with the efficiency equations from measurements and the efficiency equations from calculations for the collectors without ETFE foil at flow rates of 5 l/min, 10 l/min and 25 l/min are 3%, 6% and 3%. Correspondingly, the maximum deviations for the collectors with ETFE foil are 4%, 5% and 4%.

Comparing the yearly thermal performances of the collectors without and with ETFE foil at different flow rates with the yearly thermal performances of the collector without ETFE foil at flow rate of 5 l/min for different mean collector fluid temperatures is shown in Fig.10 on the basis of the measured efficiencies. It can be seen that the collector with ETFE foil has higher yearly thermal performance than the collector without ETFE foil when the mean solar collector fluid temperature is higher than 30°C. When the mean collector fluid temperature is 60°C, the yearly thermal performance of the collector with ETFE foil is approximately 10% higher than that of the collector without ETFE foil.

### 3.3 Efficiency of HT solar collector as a function of flow rates

As shown above there is a good agreement between measurements and calculations while the tilt is 45°. Therefore the efficiencies both for the collector without ETFE foil and the collector with ETFE foil as a function of the volume flow rate and the reduced temperature difference  $T_m^*$  can be developed with SOLEFF for 45° tilt. Assuming a 40% concentration of propylene glycol/water mixture, 1000 W/m<sup>2</sup> of total solar irradiance, ambient temperature of 20°C, wind speed of 2 m/s and a diffuse irradiance of 110 W/m<sup>2</sup>, mean temperature of collector fluid lower than 100°C and a volume flow rate between 5 l/min and 25 l/min for 45° tilt, the efficiencies for the collector without ETFE foil and the collector with ETFE foil can be expressed as:

$$H_n = (0.8143 + 0.2199F - 0.5680F^2 + 0.5177F^3) - (3.1226 + 1.1189F - 1.4588F^2) T_m^* - (13.4233 - 0.5756F) T_m^{*2} + 35.5255T_m^{*3} \quad (4)$$

$$H_w = (0.7923 + 0.1672F - 0.4357F^2 + 0.4005F^3) - (2.3956 + 0.8537F - 1.0865F^2) T_m^* - (9.1450 - 0.9949F) T_m^{*2} + 17.45T_m^{*3} \quad (5)$$

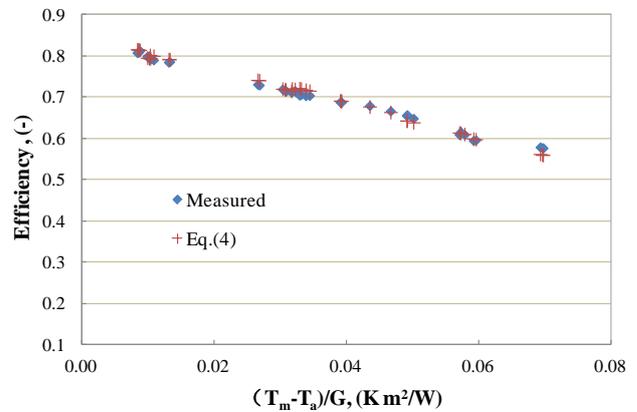


Fig.11 Measured efficiencies and calculated efficiencies with Eq.(4) for the HT solar collector without foil at different flow rates and 45° tilt

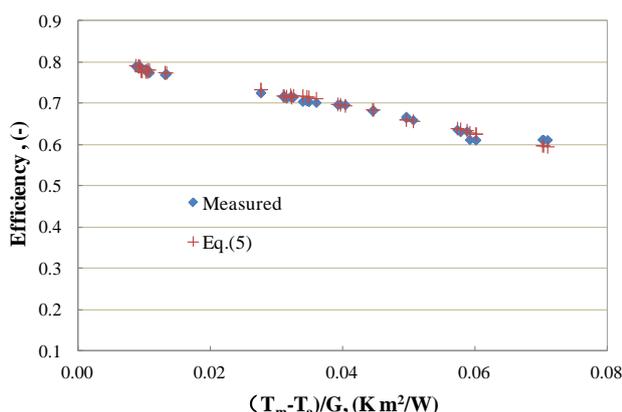


Fig.12 Measured efficiencies and calculated efficiencies with Eq.(5) for the HT solar collector with foil at different flow rates and 45° tilt

The comparisons of the measured efficiencies with the efficiencies calculated with Eq.(4) and Eq.(5) for the collector without ETFE foil and for the collector with ETFE foil at different flow rates and 45° tilt are shown in Fig.11 and Fig.12. The *RMSD* of the efficiency points for the collector without ETFE and the collector with ETFE are 0.009 and 0.008.

### 3. CONCLUSIONS

The start efficiency for the collector without ETFE foil is 2-3% points higher than the start efficiency of the collector with ETFE foil. The heat loss coefficient of the collector with ETFE foil is about 0.4-1.0 W/m<sup>2</sup>K lower than the heat loss coefficient of the collector without ETFE foil. The incidence angle modifier is almost identical for the collectors without and with ETFE foil.

If the volume flow rate of solar collector fluid is increasing, the efficiency, the start efficiency and the incidence angle modifier are increasing and the heat loss coefficient is decreasing.

The yearly thermal performance for the collector with ETFE foil is higher than the yearly thermal performance for the collector without ETFE foil when the mean solar collector fluid temperature is higher than 30°C. When the mean collector fluid temperature is 60°C, the yearly thermal performance of the collector with ETFE foil is approximately 10% higher than that of the collector without ETFE foil.

### NOMENCLATURE

F	volume flow rate (l/s)
G	total irradiance (W/m <sup>2</sup> )
H	calculated efficiency of solar collectors (-)
IAM	incidence angle modifier (-)
N	number of values (-)
RMSD	root mean square deviation, defined in Eq.(2)
T	temperature (°C)

T <sub>0</sub>	specific temperature (°C)
T <sub>m</sub> *	reduced temperature difference = (T <sub>m</sub> -T <sub>a</sub> )/G, (K m <sup>2</sup> /W)
X	variable (-)
η	measured efficiency of solar collector (-)

### Subscript

1	flow rate at 25 l/min and 45° tilt
2	flow rate at 10 l/min and 45° tilt
3	flow rate at 5 l/min and 45° tilt
4	flow rate at 25 l/min and 60° tilt
a	ambient
c	calculated
m	mean value
n	collector without ETFE foil
t	measured
w	collector with ETFE foil

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