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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.

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 m² and
12.57 m². The geometric dimensions for both collectors are 5.96 m×2.27 m×0.14 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.

Fig. 1 Photo of two HT solar collectors for tests
Table 1. Test conditions for two HT solar collectors

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

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/m² 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:

\[
\eta_{1, w} = 0.811 - 2.60 \times \frac{(T_m - T_a)}{G} \quad (1-1)
\]

\[
\eta_{1, n} = 0.840 - 3.77 \times \frac{(T_m - T_a)}{G} \quad (1-2)
\]

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

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

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

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

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:

\[
RMSD = \sqrt{\frac{\sum_{i=1}^{N} (X_{ij} - X_{ij})^2}{N}}
\]
### 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.

#### Efficiency expressions

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:

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

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

\[
H_{3,w} = 0.802 - 2.16 \times \frac{(T_m - T_a)}{G} - 0.0153 \times \frac{(T_m - T_a)^2}{G} \quad (3-3)
\]

\[
H_{1,n} = 0.848 - 3.80 \times \frac{(T_m - T_a)}{G} - 0.0012 \times \frac{(T_m - T_a)^2}{G} \quad (3-4)
\]

\[
H_{2,n} = 0.836 - 3.85 \times \frac{(T_m - T_a)}{G} - 0.0042 \times \frac{(T_m - T_a)^2}{G} \quad (3-5)
\]

\[
H_{3,n} = 0.822 - 2.77 \times \frac{(T_m - T_a)}{G} - 0.0170 \times \frac{(T_m - T_a)^2}{G} \quad (3-6)
\]
agreement with the efficiencies calculated with SOLEFF when the reduced temperature difference is not larger than 0.1 (K m²/W).

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 45º. 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 45º tilt. Assuming a 40% concentration of propylene glycol/water mixture, 1000 W/m² of total solar irradiance, ambient temperature of 20°C, wind speed of 2 m/s and a diffuse irradiance of 110 W/m², mean temperature of collector fluid lower than 100°C and a volume flow rate between 5 l/min and 25 l/min for 45º tilt, the efficiencies for the collector without ETFE foil and the collector with ETFE foil can be expressed as:

$$H_n = (0.8143 + 0.2199F - 0.5680F^2 + 0.5177F^3)$$

$$- (3.1226 + 1.1189F - 1.4588F^2) T^*_m$$

$$- (13.4233 - 0.5756F - 0.5756F^2) T^*_m + 35.5255T^*_m^3$$

$$H_n = (0.7923 + 0.1672F - 0.4357F^2 + 0.4005F^3)$$

$$- (2.3956 + 0.8537F - 1.0865F^2) T^*_m$$

$$- (9.1450 - 0.9949F - 1.9908F^2) T^*_m + 17.45T^*_m^3$$

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%.

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

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 45º tilt

Fig.11 Measured efficiencies and calculated efficiencies with Eq.(4) for the HT solar collector without foil at different flow rates and 45º 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/m²K 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/m²)
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)

T₀ specific temperature (°C)
Tₘ reduced temperature difference 
= (Tₘ-Tₐ)/G, (K m²/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

REFERENCES


http://www.solar-district-heating.eu/SDH/LargeScaleSolarHeatingPlants.aspx


