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PERFORMANCE OF SOLAR COLLECTORS UNDER LOW TEMPERATURE CONDITIONS:

Measurements and simulations results

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Abstract

The performance of four solar thermal collectors (flat plate, evacuated tube, unglazed with rear insulation and unglazed without rear insulation) was experimentally measured and simulated for temperatures below ambient. The influence of several parameters (e.g. collector inlet temperature, air temperature, condensation) is investigated under different operating conditions (day and night). Under some conditions condensation might occur and heat gains could represent up to 55% of the total unglazed collector energy by night. Two TRNSYS collector models including condensation heat gains are also evaluated and results compared to experimental measurements. A mathematical model is also under development to include, in addition to the condensation phenomena, the frost, the rain and the long-wave radiation gains/losses on the rear of the solar collector. While the potential gain from rain was estimated to be around 2%, frost heat gains were measured to be up to 40% per day, under specific conditions. Overall, results have shown that unglazed collectors are more efficient than flat plate or evacuated tube collectors at low operation temperatures or for night conditions, making them more suitable for heat pump applications.

Keywords: solar collectors, heat pump, condensation heat gains, measurements, simulations models.

1. Introduction

Combined solar and heat pump systems for domestic hot water (DHW) and space heating are increasingly demanded and advertised by manufacturers. Among the existing configurations [1], some systems use solar energy indirectly by delivering it to the evaporator of the heat pump (HP). This kind of utilisation may improve the coefficient of performance of the HP because the collector will be able to deliver higher temperature levels than other HP sources (e.g. ambient air or borehole heat exchanger). At the same time, solar collectors (SC) are also expected to increase their efficiency as they are operated at considerably lower temperatures than when in normal use.

There are four aspects bearing an impact on the performance of solar thermal collectors when employed as a heat source supply for heat pumps [2]:

- Condensation of water vapour on the absorber surface that is colder than the dew point temperature
- Frost accumulation on the absorber surface that is colder than the freezing point temperature

- Operation without solar irradiance (G)
- Rain on the absorber surface of the unglazed collector

These aspects are disregarded in the standard EN 12975 [3] and there is little information in the open literature on the behaviour of SC under such conditions. Therefore, it is the aim of this study to analyse the performance of different types of solar thermal collectors at temperatures below ambient and for cases without solar irradiance.

In this context, four different SC have been tested with low inlet temperature under various climate conditions. This data was, subsequently, used to evaluate and validate two TRNSYS [4] collectors' models, Type 202 [5] and Type 136 [6], that include the condensation effect. Furthermore, a mathematical model is also being developed to simulate other heat gains/losses, such as frost, rain and long-wave irradiation on the rear side of the SC.

2. Experimental measurements

A testing facility comprising the four solar thermal collectors under investigation is operational and equipped with different sorts of sensors for monitoring purposes. Several tests under different weather conditions have been performed with inlet collector temperatures varying from -10°C to 5°C. Table 1 presents the theoretical characteristics of the four solar collectors under investigation. All data is related to the absorber surface area.

Table 1: Theoretical characteristics of solar collectors tested on the bench test

	Flat plate [7]	**Evacuated tubes [7]**	**Unglazed without rear insulation [8]**	**Unglazed with rear insulation [8]**
η_0 (optical efficiency) [-]	0.791	0.821	0.959	0.959
a_1 (convective heat transfer coefficient) [W/m^2K]	3.104	2.824	12	8.91
a_2 (temperature dependence of the heat loss coefficient) [W/m^2K^2]	0.022	0.0047	-	0.047
Gross area [m^2]	2.53	3.51	1.87	1.87
Absorber area [m^2]	2.23	2.0	1.85	1.85

To characterise the thermal behaviour of the SC coupled as a source to the evaporator of a HP, two testing modes have been defined depending on the incident solar irradiance on the collector surface: "day mode" when radiation is above 150 W/m^2 and "night mode" when radiation is below 150 W/m^2.

FiguresFigure 1 and Figure 2 show the output power of the solar collectors for the two testing modes. It can be seen that for temperatures below ambient, the unglazed collectors are more efficient than the flat plate or the evacuated tube collector.

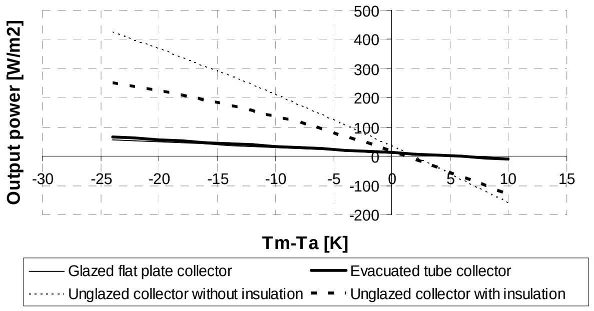

Figure 1: Output power of solar collectors under “day mode” conditions (~950 W/m^2)

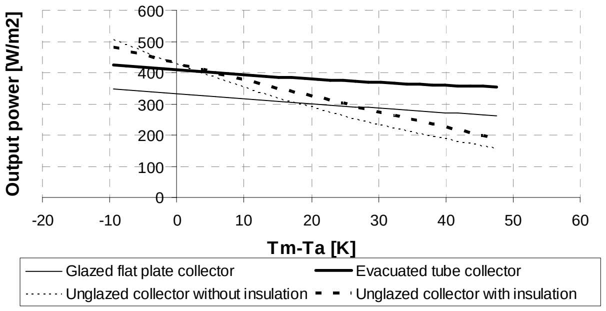

Figure 2: Output power of solar collectors under “night mode” conditions (0 W/m^2)

2.1. “Day mode” testing

“Day mode” results are shown to be close to the theoretical efficiency curve provided by the manufacturer even for temperatures below ambient, see FiguresFigure 3 toFigure 6. These curves only take into account the solar irradiance, the air convection effect and the temperature dependence of the heat loss. As a result, solar heat gains and wind speed have the most important influence on the collector’s output power while other parameters such as relative air humidity or long-wave radiation bear no significant impact.

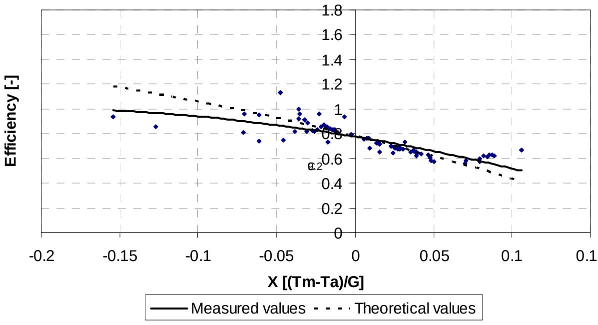

Figure 3 : Efficiency of the flat plate collector

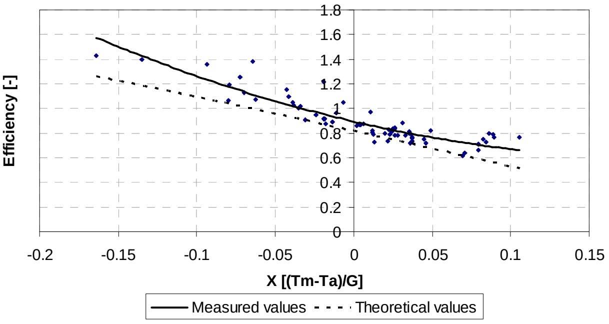

Figure 4 : Efficiency of the evacuated tube collector

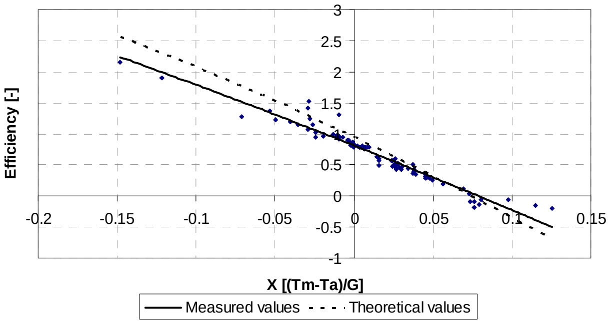

Figure 5 : Efficiency of the unglazed collector without insulation

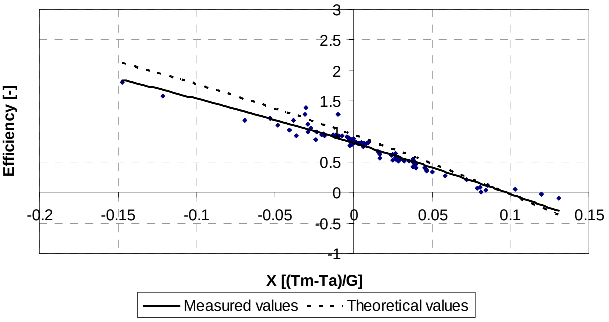

Figure 6 : Efficiency of the unglazed collector with insulation

2.2. “Night mode” testing

Without solar irradiance, measurements have showed that important heat gains are still possible for unglazed collectors, see Figure 2. These heat gains have been found to be primarily influenced by two parameters: ambient air temperature (T_a) and long-wave radiation.

For large differences between the mean collector temperature (T_m) and T_a, it is the air temperature that contributes most to the measured heat gains. In this case, convective heat exchange is increased and condensation (eventually frost) is also likely to occur.

In cases where the temperature difference between the collector and the surrounding air is small, long-wave radiation predominates. Under these conditions the convective exchange rate and condensation effect is reduced. However, when condensation occurs, the impact of long-wave radiation on the heat gains is increased due to increased thermal emissivity of the wet surface of the collector.

For this testing mode and under any temperature condition, the impact of the long-wave radiation from the rear side of SC was also found to be important for collectors without insulation.

Condensation was visually detected on the unglazed collectors but not on the flat plate or evacuated tubes due to their glass shield acting as insulation. To experimentally estimate the amount of condensation on the unglazed collectors, a large bucket was placed underneath the collectors in order to recover the condensed water. The uncertainty of the condensation heat gains measurements was determined to be 8% by night. The measured yield for the conducted tests varied from 0.5 kWh to 3.3 kWh for the insulated SC and from 1.3 kWh to 4.8 kWh for the non insulated SC. It was observed that the condensation yield can vary from 23 to 55% of the total collector’s yield for these tests depending on the weather conditions.

3. TRNSYS simulations

As seen in section 2, glazed collectors provide no additional benefit when operated at low temperatures. Therefore, the following discussion will focus on unglazed collector models, because it is here that most significant changes are expected to occur. In this section, only the unglazed collector with rear insulation will be analysed. Two TRNSYS collectors’ models, Type 136 and Type 202, have been tested under real weather conditions in Yverdon-les-Bains (CH). Type 202 is applicable to unglazed collectors while Type 136 applies to both glazed and unglazed collectors.

In addition to the parameters defined by the EN 12975, these models use an extra term for the condensation effect. The simulation results were then compared to the field measurements. Time resolution of the measurements is 10 seconds and for simulations a time step of 30 seconds was chosen.

3.1. Day and night testing with or without condensation

For daytime tests, both models show good agreement with measurements (within 5%), see Figure 7. Without solar irradiance, discrepancies arise for nights where the ambient temperature is close to the collector’s temperature; see last couple of nights on Figure 7. These discrepancies happen mostly because of changes of emissivity when condensation occurs, as in this case, the main energy transfer mechanism is long-wave radiation. Nevertheless, this corresponds to low absolute energy differences.

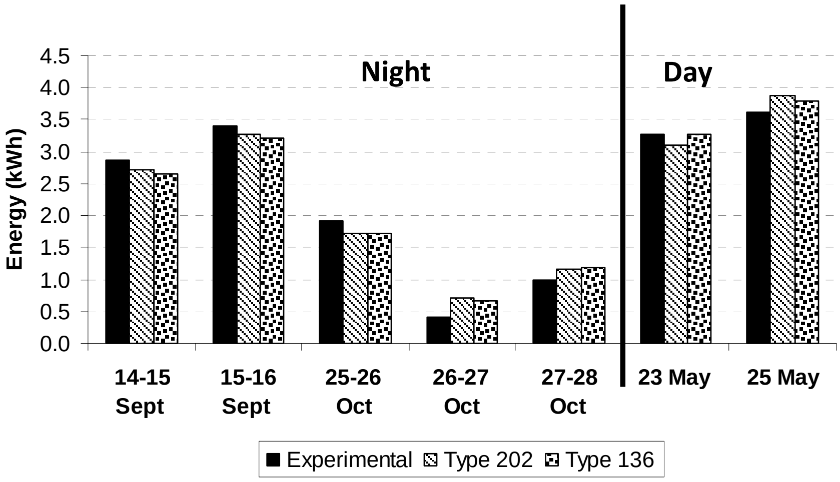

Figure 7: Comparison between measured and simulated unglazed collector yield for different testing conditions

The condensation energy measurements were also compared to the condensation energy given by the two TRNSYS models, see Figure 8.

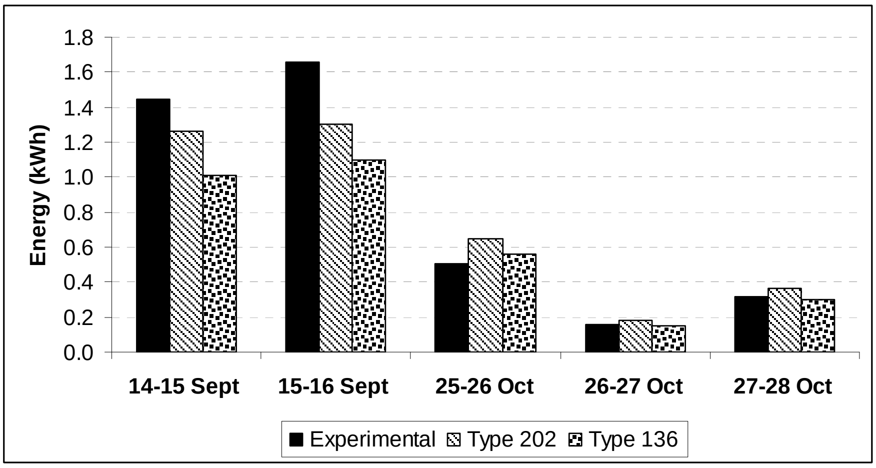

Figure 8: Comparisons of condensation energy of the insulated unglazed collector for different nights

For large temperature differences (>10 K) between the collector and the ambient air (first couple of nights in Figure 8) simulation predicts less condensation energy than measured. However when the collector's temperature is close to the ambient temperature, both models agree well with the measurements (last couple of nights in Figure 8).

Due to changes of the SC physical properties during the condensation phase, tuning of the parameters related to condensation (e.g. surface emissivity, internal thermal heat conductivity or convective heat loss coefficient of absorber) was seen to be of great importance. Thus, simulations of the condensation energy can be closer to measurements for one given condition. However, results revealed that condensation parameters are very much dependent on the operating conditions so that no general parameters could be found leading to acceptable simulation results under all investigated conditions.

A test over 136 hours (day and night) between 15th and 21st of May with variable weather conditions (e.g. wind, solar irradiation, condensation) was performed and compared to the simulations. Time resolution in data and time step for simulation is 30 seconds. Figure 9 and Figure 10 show that the two models give good results for the whole test duration with a tendency to provide more energy for output powers beyond 1.5 kW and for high collector temperature, see encircled areas of Figure 9 and Figure 10. In this case, differences from measurements appear because the long-wave irradiation heat losses are defined, according to EN 12975, as a function of the ambient temperature and not of the collector's temperature [3].

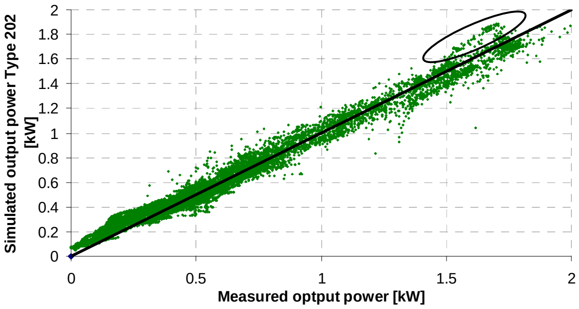

Figure 9: Measured output power versus simulated output power with Type 202

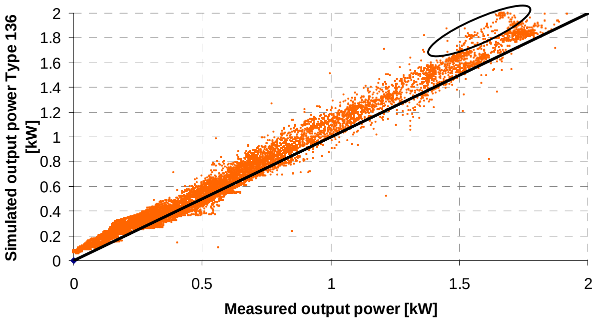

Figure 10: Measured output power versus simulated output power with Type 136

For these specific test conditions, Type 202 seems to provide better agreement with measurements than Type 136 and this due to a better fit of the different parameters integrating the model. It should be noticed that Type 136 has been built so that parameters can be derived from tests similar to EN 12975. However, measurements in our case were performed for conditions other than those specified by the standard and the required parameters derived from it. In any case it can be said that results from both collector models are in good agreement with the measurements excepting for frost and rain conditions.

3.2. Tests with frost and rain

Some preliminary tests have been conducted with frosting occurring at the surface of the absorber. First results over a 24 hours test in December showed that heat gains of 6.3 kWh/m^2 can be achieved (cloudy conditions). As collectors models do not take into account frost, simulation results obtained are 40% lower than measured values.

The effect of rain was also investigated. The annual potential rain yield near Yverdon-les-Bains was estimated to be around 2% of the annual yield for an unglazed collector, about 10 kWh/m^{2}a. However, for an accurate representation of the thermal behaviour of the collector, the effect of the rain must also be included in the numerical model. Preliminary tests to estimate the amount of energy from rain have not been conclusive and due to the small annual rain yield, no further investigation will be undertaken.

As simulations cannot integrate the frost gains, rain heat loss/gain or the rear side long-wave irradiation loss/gain, a simplified mathematical model is being developed taking into account all these energy transfers. The equation will be based on the quasi-dynamic collector efficiency equation defined by EN 12975 with three additional terms:

- A simplified term for condensation [6]
- A simplified term for heat exchange between the collector and the water rain
- A long-wave irradiation term for the rear side of the non insulated collector.

Some terms defined in EN 12975 will also be modified to better model the test bench measurements and some particular operating conditions. The parameters values required to adequately represent all heat gain/loss contributions will be derived from further measurements. This simplified model, implemented in a first stage as an equation module in a TRNSYS file, will enable to specify and quantify each thermal flux going through the SC. This should provide a very interesting feature, particularly when choosing the appropriate SC for a given utilisation.

4. Conclusions

HP applications combined with SC can considerably change the operating range of collectors to lower temperatures. Under these conditions, not many information is available in the open literature regarding the thermal performance of SC. Therefore, it is the focus of this article, to experimentally and numerically analyse the thermal behaviour of different types of SC for conditions with no solar irradiance and for temperatures below ambient, for which particular phenomena such as condensation, and frost might occur.

Experimental results have shown that for temperatures below ambient and for cases without irradiance, unglazed collectors performed better than glazed ones, with considerable heat gains from condensation and frost. Due to their design, glazed collectors are not suitable to operate at temperatures below the dew point as condensation and frost conditions might lead to deterioration of materials, compromising the reliability and durability of this type of collector.

Work on the validation of two TRNSYS models including condensation heat gains was conducted and both model results shows good agreement with measurements not only for normal day test conditions but also for cases without solar irradiance and even when condensation appears on the unglazed collectors.

Available glazed and unglazed solar thermal collector’s models exist but currently none takes into account the effects of frost or rain in their calculations. To tackle this problem, a simplified mathematical model is being developed, based on modifications to the quasi dynamic collector efficiency equation of EN 12975. The required performance parameters will be derived from measurements.

Acknowledgements

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