HYBRID SYSTEM SOLAR COLLECTORS-HEAT PUMPS FOR DOMESTIC WATER HEATING

by

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This paper deals with the use of solar energy, heat pumps, and solar system-heat pump combinations for domestic water heating. The testing of solar tiles, flat plate collectors as an autonomous system, as well as flat plate collector-heat pump and solar tile-heat pump combinations, are presented. Black-coloured water absorbs solar radiation flows through solar tiles made of transparent polymethyl methacrylate (CH2C(CH3)COOCH3). At the same time, solar tiles are used as a roof covering and as a solar radiation collector. Hot water from solar tiles or a flat plate collector is directed to the heat pump, which increases the temperature of water entering the boiler heating coil. The heat of water heated in solar tiles or in flat plate collectors serves as a source of energy for the heat pump. Since the goal was realistically evaluate the efficiency of solar tiles in comparison with the flat plate collector, extensive measurements of both systems under identical condition were carried out. The experiments were carried out in rainy, cloudy, and clear weather.

Key words: *solar energy, flat plate collector, heat pump*

Introduction

In the widest sense, solar energy comprises all types of energy arising from the Sun, including wind, biomass, water energy, and ocean energy.

The Sun, essentially an eternal nuclear reactor, is practically an inexhaustible source of renewable energy. In stars (the Sun, in our solar system), energy is generated by fusing hydrogen nuclei or protons into helium, whereby large amounts of energy are released [1-3].

Thus far, solar energy has been used in two ways: through thermal systems or using the photon effect, which is usually photovoltaics. The efficiency of commercially available photovoltaic systems ranges between 15% and 17%, whereas in practical applications it is from 10% to 12% due to the heating and ageing of photovoltaic material and dirt that collects on the surface [4-6].

Solar collectors are the key components of active solar-heating systems. They gather solar energy, transform its radiation into heat, then transfer that heat to a fluid (usually water or air). At present, mainly two types of liquid solar collectors for domestic heating and hot water production are used: flat plate collectors [7-14] and evacuated tube collectors [15-19].

For domestic heating and hot water production, a heat pump can be used [20-27]. Heat pumps are designed to move thermal energy in the opposite direction of spontaneous heat trans-

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fer by absorbing heat (energy) from a cold space and releasing it to a warmer one. A heat pump uses a small amount of external electric power (exergy) to accomplish the work of transferring energy from the heat source to the heat sink. Heat pumps are three to four times more effective at heating than simple electrical resistance heaters using the same amount of electricity. A heat source can be the surrounding air, water, or geothermal energy. The term COP is used to describe the ratio of useful heat movement per work input. The COP increases as the temperature difference decreases between heat source and destination. The COP can be maximised at design time by choosing a heating system requiring only a low final water temperature (*e. g.* underfloor heating), and by choosing a heat source with a high average temperature (*e. g.* the ground).

Conventionally, all types of collectors and heat pumps are used separately. In this paper, there is a suggestion to join both systems in a serial connection. Heated water coming from the collector is led directly into the inlet of the heat pump to reach higher temperatures.

Solar tiles

For domestic hot water heating, we developed a new solar tile that is made of transparent polymethyl methacrylate $CH2C(CH3)COOCH3$, fig. 1. At the same time, solar tiles are used as roof tiles and for domestic water heating. A solar tile has a typical shape of a roof tile and may be installed together with the usual commercially available roof tiles. We developed different shapes of solar tiles, all compatible with the standard shapes. Black-coloured water, absorbing the solar radiation energy, flows through the solar tiles. Solar tiles may be used for direct water heating or in combination with a heat pump.

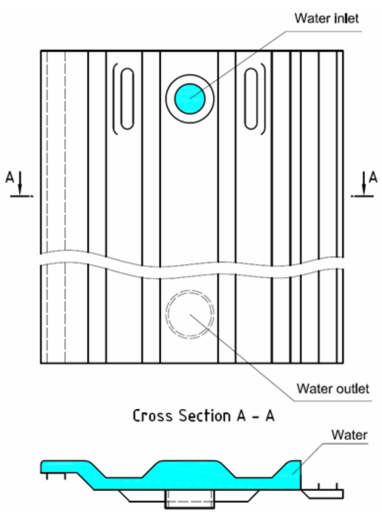


Figure 1. Solar tile

Experimental set-up

Improved efficiency of flat plate collectors and heat pumps may be achieved through their combined use. The COP of a heat pump can be increased by connecting the flat plate collectors and the water-water heat pump in series. The heat of water heated in solar tiles or in flat plate collectors serves as a source of energy. From the solar tiles or flat plate collectors, the water enters the heat pump evaporator, where it gives off its heat to the heat pump refrigerant. The higher the temperature of energy used by the heat pump is, the higher the COP of the heat pump is. Moreover, to raise the temperature of energy, we wished to use the visible solar and diffuse light. Therefore, a combination of solar tiles or flat plate collectors and the heat pump is used. In air-water heat pumps, the most widely used type of heat pump, the temperature of energy equals the ambient temperature, whereas in water-water heat pumps, using the groundwater, it equals the groundwater temperature. The advantage of groundwater heat pumps is that they can operate throughout the heating season, whereas it is practical to use the air-water heat pumps only down to a temperature of around –4 °C.

This paper presents the testing of solar tile-heat pump and flat plate collector-heat pump combinations connected in series. The measurements were made in sunny, cloudy, and rainy weather as well as at night.

Wishing to extend the heating season of a heat pump and increase the COP, we opted for a combination with solar energy, which represents an innovation in the market. In winter, sunlight may heat water in solar tiles or in the flat plate collectors to a temperature higher than the ambient air temperature, thus extending the heating season and improving, at the same time, the heat pump's COP.

Combining solar tiles and heat pump

This chapter comprises the results of the testing of a 1.5 kW water-water heat pump under standard conditions in a serial connection with solar tiles. The heat of water heated in solar tiles serves as a source of energy. The solar tiles are filled with black-coloured water to increase the sunlight absorption coefficient. From the solar tiles, the water enters the heat pump evaporator, where it releases its heat to the heat pump refrigerant. The measurements aimed at establishing the efficiency of the solar tile-heat pump combination and determining the required surface of solar tiles for the heat pump to be able to heat an energy-saving house.

One of the goals of this research was to find out the tile outlet water temperature in the case of low cloudiness, rain, and total darkness, when the share of radiant heat is practically zero. In clear weather, naturally, the tile outlet water temperature is considerably higher than the ambient temperature. We need this information to determine the size of heat pumps for residential systems because days are short in winter and there are few sunny days.

Figure 2(a) shows a measurement diagram and fig. 2(b) the installation of solar tiles. The surface area of tiles was 2 m^2. On the lower side, the tiles were insulated, resulting in a decrease by half of the contact surface of the air with the tiles in the case of cloudy weather and darkness, when convective heat transfer prevails. The insulation is appropriate when heat is generated from the radiant part of the heat transfer. The water-water heat pump had thermal power of 1.5 kW under standard conditions, and it heated a 300 L boiler. The measured parameters included:

- outlet water temperature from a solar tile, T_1,
- boiler water temperature, T_2,
- inlet water temperature to a solar tile, T_3,
- outlet water temperature from a heat pump, T_4,
- inlet water temperature to a heat pump, T_5,
- ambient air temperature, T_6, and
- water flow, Q.

The measurements shown in fig. 3 were made at 13:00 in clear sunny weather. The difference between temperatures, T_1 (outlet water temperature from a solar tile) and T_6 (ambi-

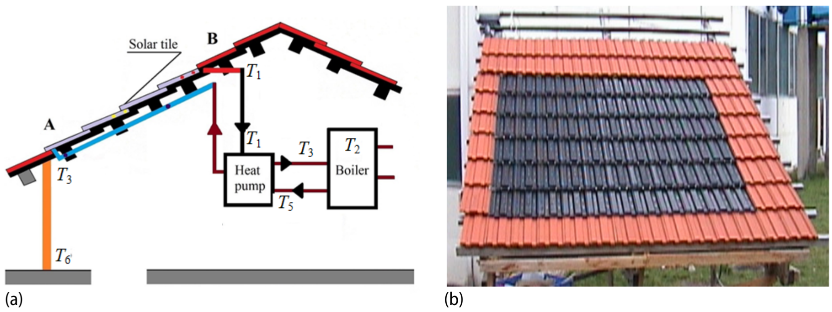


Figure 2. (a) Measurement diagram, (b) installation of solar tiles

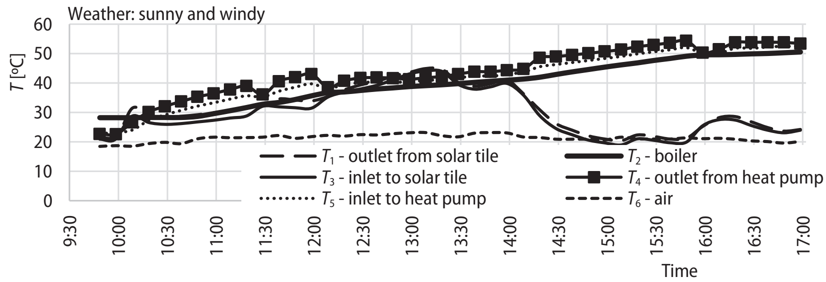


Figure 3. Temperature measurements – Weather: sunny and windy

ent air temperature) was as high as 20 °C. Between 13:00 and 15:30, it was extremely cloudy, which is why the T_1-T_6 difference dropped to 0 °C. At 15:30, the sky fully cleared and the temperature difference increased again to 8 °C. From an energy point of view, the solar tile-heat pump combination is certainly the best solution in clear weather for the heating of residential houses and domestic water.

The measurements shown in fig. 4 were made in low-level cloudiness, fog, and rain. The greatest undercooling (between T_1 and T_6) of 4.5 °C, fig. 4, was measured at 11:00. The sky cleared that day between 2 p. m. and 3 p. m., which is immediately reflected in temperatures T_1 and T_3. As the radiant part of heat transfer increased, the aforeindicated temperatures immediately rose above the ambient temperature T_6. The T_1-T_6 difference increased to 6 °C. This shows that in partly sunny weather the solar tile-heat pump combination is better than the air-water heat pump. The measurements shown in fig. 5 were made in low-level cloudiness, fog and rain. The undercooling ranged between 2 °C and 3 °C. The measurements shown in fig. 6 were made in complete darkness. The greatest undercooling T_1-T_6 was 4 °C.

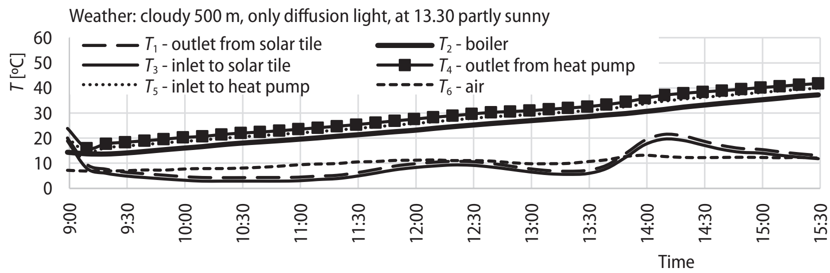


Figure 4. Temperature measurements - Weather: cloudy 500 m, at 13.30 partly sunny

For residential house heating purposes, a heat pump is the most efficient in combination with underfloor heating. The COP of the heat pump is calculated using the eq. (1):

$$\mu = \xi \frac{T_H}{T_H - T_A} \tag{1}$$

where T_H is the temperature of heating water and T_A the temperature of energy or the medium from which energy is extracted. By agreement, T_A = 7 °C is taken for the comparison of both systems. The ξ is the exergetic efficiency of an irreversible heat pump. In real heat pumps, the measured exergetic efficiency amounted to 0.4.

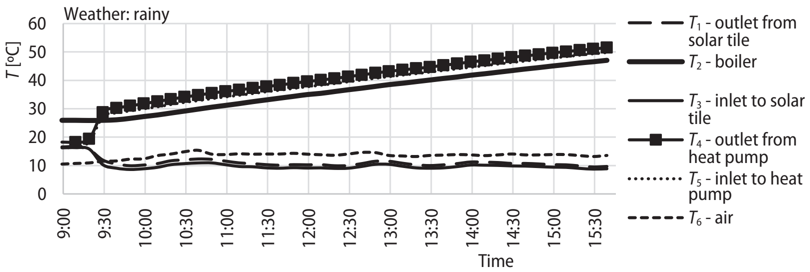


Figure 5. Temperature measurements - Weather: rainy

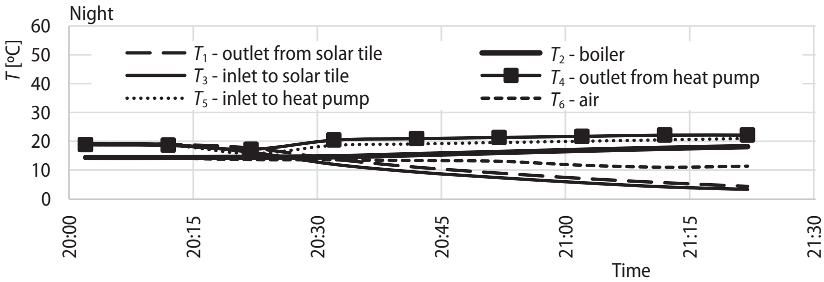


Figure 6. Temperature measurements - Weather: night

In underfloor heating, the heating water heating regime is 35/30 °C, where the COP at T_A = 7 °C = 4.4, whereas in the radiator heating system, the 35/45 °C regime is usually applied, where COP = 3.34. The temperature of energy and the temperature of heating water have a decisive influence on the COP. If the temperature of energy T_A is increased by 5 °C in the underfloor heating-heat pump combination, the COP raises to 5.35 and to 6.84, if the temperature increases by 10 °C.

Combining flat plate solar collector-heat pump and solar tile-heat pump

This section contains the testing results of two different sanitary water heating systems. Both systems operated at the same time and under identical conditions, thus allowing a direct comparison of the test results, fig. 7. The boiler capacity was 300 L. The two systems were tested under various weather conditions, *i. e.* in sunny, cloudy and rainy weather. The water in both boilers was changed so that before any measurement the water temperature was 18 °C. In this way, testing under identical conditions was ensured in order to allow a direct comparison of both systems. Figure 7(b) shows that the surfaces of both collectors, radiated by the sunlight, were identical. The following systems were tested:

– Flat plate collector Lentherm NSL 2005 Tinox, effective surface 2 m^2, in combination with a heat pump and without it.
– Solar tiles in the form of roof covering of 2 m^2 and filled with a black liquid, in combination with a heat pump or without it.
– Applied was a 1.5 kW water-water heat pump at standard conditions.

Figure 7(a) shows a diagram of the connection of the sanitary water heating systems. Both systems can heat the sanitary water directly so that the water flows from the collectors directly to the boiler heating coils or so that the hot water flows from the collectors to the heat pump, which raises the temperature of water from the solar system to an even higher level.

Then, the heated water flows from the heat pump to the boiler heating coil, which heats the sanitary water. Figure 7(a) shows all measuring points where the temperature was measured:
– Solar tile: inlet (cold water) temperature, T_1, outlet (hot water) temperature, $T_{2.}$
– Heat pump: inlet (cold water) temperature, T_3, outlet (warm water) temperature, $T_{4.}$
– Temperature of heated sanitary water in the boiler, $T_{5.}$
– Ambient air temperature, $T_{\mathrm{ok.}}$
– Collector: inlet (cold water) temperature, T_6, outlet (hot water) temperature, $T_{7.}$
– Heat pump: inlet (cold water) temperature, T_8, outlet (warm water) temperature, $T_{9.}$
– Temperature of heated sanitary water in the boiler, $T_{10.}$

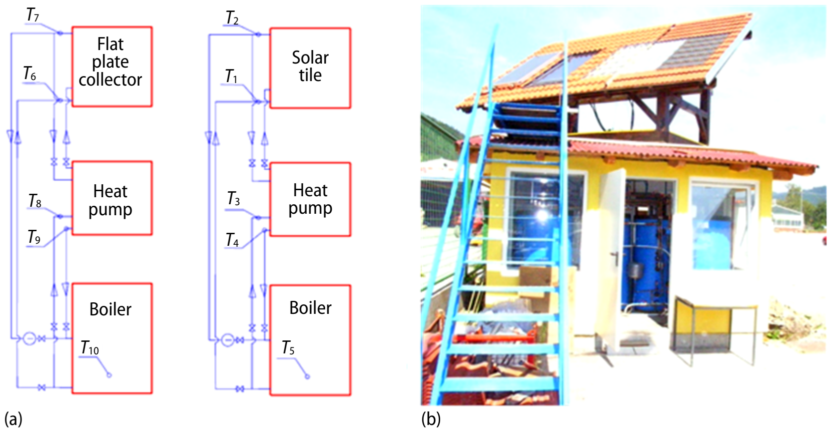
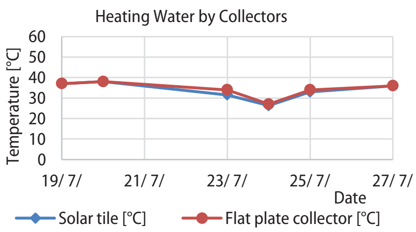


Figure 7. (a) Connection diagram of sanitary water heating systems, (b) solar collector test line

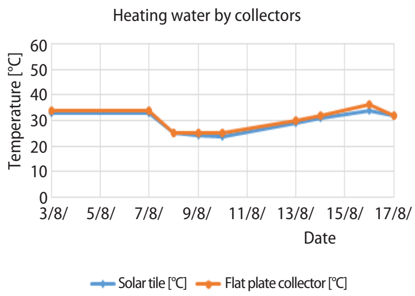
Figures 8 and 9 show the temperature T_5 of the water in the boiler, achieved by the collectors through direct heating between 9:40 and 15:40 on different days. The measurements were made in sunny, cloudy, and rainy weather. Temperature T_5 was measured at 15:40. All boilers were emptied before each measurement so that the initial water temperature at the beginning of the measurement was always 18 °C. The flat plate collector achieved on average a temperature by 1 °C to 2 °C higher than the solar tiles (which is very little) under any weather conditions. The exceptions were the measurements on July 23, 2015 and August 16, 2015, made in sunny weather. The flat plate collector achieved a temperature higher by 4 °C on both days.

Moreover, the measurements clearly showed that the solar system efficiency is very low in very cloudy and rainy days. When the measurements were carried out, the boiler water temperature T_5 was always lower than the ambient air temperature in cloudy weather. The measurements showed that in cloudy weather the contribution of diffusive light to efficient sanitary



Date	Temperature at 3 pm and weather
19/7/2015	36, sunny
20/7/2015	37.5, sunny
23/7/2015	36.8, partly cloudy/sunny
24/7/2015	30.7, cloudy
25/7/2015	24.8, partly cloudy
27/7/2015	33.75, sunny

Figure 8. Water heating using solar tiles and a collector

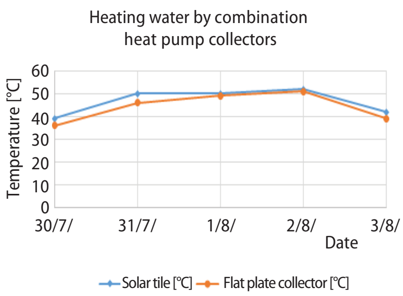


Date	Temperature at 3 pm and weather
3/8/2015	30.75, clear
7/8/2015	32.25, clear
8/8/2015	27, cloudy
9/8/2015	23.31, cloudy
10/8/2015	18.75, rainy
13/8/2015	25, partly sunny
14/8/2015	29.75, partly cloudy
16/8/2015	32.82, clear
17/8/2015	28.5, partly cloudy

Figure 9. Water heating using solar tiles and a collector

water heating is small. This is also in line with the measurements of illumination, which ranged from 95000 to 100000 lux in completely clear weather and from 3000 to 5000 lux in cloudy weather.

To improve the efficiency of the solar systems in clear and cloudy weather, in rain and in darkness, we used the solar system-sanitary water heating heat pump combination. This combination produced good results when the previous measurements of the solar tile-heat pump system were carried out. The solar tile-heat pump combination heats the water in the boiler in any weather by 1 to 5° C, fig. 10, higher than the flat plate solar collector-heat pump system does. The highest difference of 5° C is in rainy weather, in which the transfer of heat from the air and rainwater to the solar tile is better than in the flat plate solar collector, where a layer of air between the glass and the collector absorber acts as an insulator. In cloudy, and especially in rainy weather, the transfer of heat through radiation no longer prevails; rather, the prevailing heat transfer is through convection. In this case, a solar tile has a decisive advantage of having direct contact with air and rainwater.



Date	Temperature at 3 pm and weather
30/7/2015	14.9, rainy
31/7/2015	23.31, rainy
1/8/2015	25.37, clear and cloudy
2/8/2015	28.8, mostly clear
3/8/2015	17.93, rainy

Figure 10. Water heating using the heat pump-solar tile and collector combination

Figures 11 and 12 show the measured temperatures for solar tiles and the flat plate collector in rainy weather. Characteristic temperatures are the solar tile cold water inlet temperature T_1 and the flat plate collector cold water inlet temperature T_6 as well as the solar tile warm water outlet temperature T_2 and the flat plate collector warm water outlet temperature T_7. A comparison of the aforeindicated temperatures shows that undercooling of water in the flat plate collector (T_7-T_{ok}) over the entire area is by 3 to 7 °C higher than in solar tiles (T_2-T_{ok}). As warmer water enters the heat pump, the solar tile-heat pump combination operates at a higher COP than the flat plate collector-heat pump combination, resulting in the temperature of water in the boiler being higher by 3 °C.

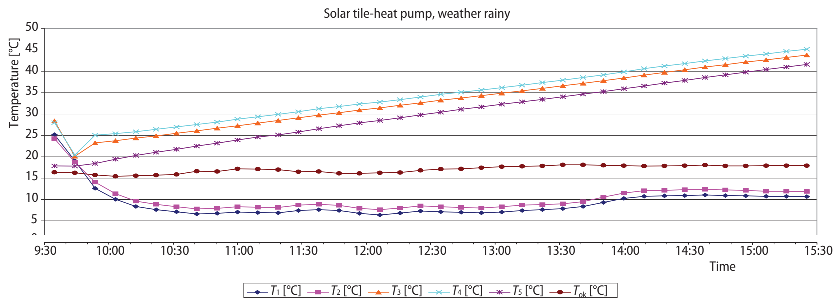


Figure 11. Solar tile-heat pump combination temperature readings

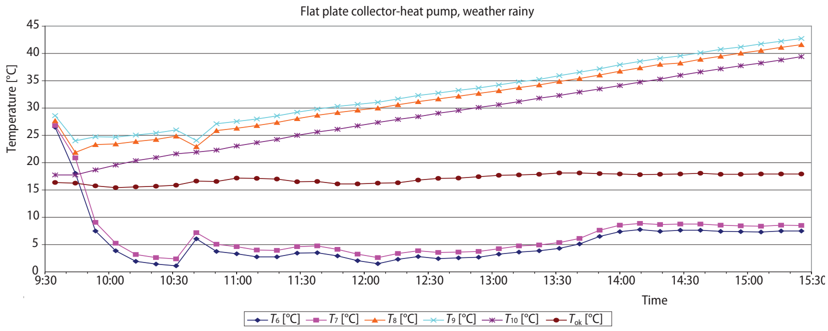


Figure 12. Lentherm collector-heat pump combination temperature readings

In partly cloudy weather, fig. 13, the solar tile outlet temperature T_2 is higher than the ambient air temperature, which means that the heat pump in combination with solar tiles operates at a higher COP than the air-water heat pump. Figure 14 shows that the outlet temperature T_7 is lower in the flat plate collector-heat pump combination than the ambient temperature. The undercooling varies between 1 to 3 °C.

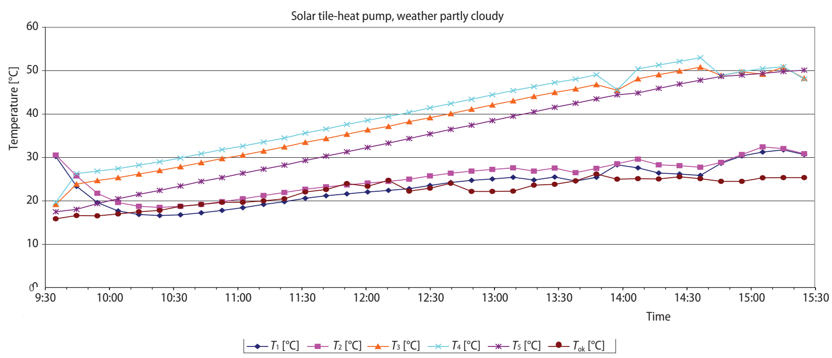


Figure 13. Solar tile-heat pump combination temperature readings

Figures 15 and 16 show the same measurements in clear weather. The inlet temperature T_1 and outlet temperature T_2 are the same or higher than the ambient air temperature T_{ok} in the solar tile-heat pump combination, fig. 15. At 15:14, temperature T_2 is by 5 °C higher than the ambient temperature T_{ok}. In the flat plate collector-heat pump combination, fig. 16, however, the undercooling of temperatures T_6 and T_7 is lower than the ambient temperature. Moreover,

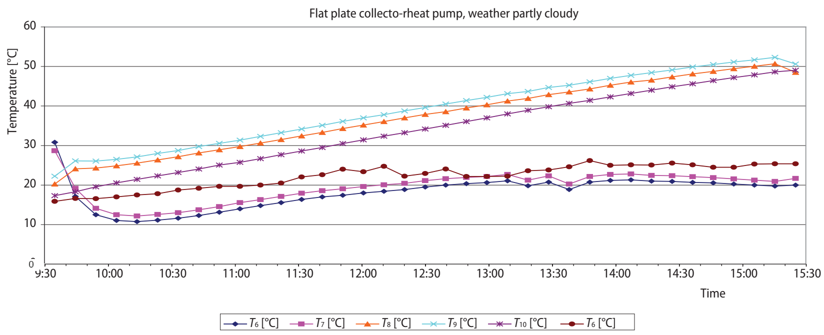


Figure 14. Lentherm collector-heat pump combination temperature readings

fig. 15 shows that the heat pump outlet temperature T_4 is 53 °C, at which the heat pump control system switches off the heat pump.

The aim of the solar tile-heat pump combination is to increase the heat pump inlet water temperate T_2 above the ambient air temperature. In this way, the temperature of energy and the air-water heat pump COP increase. The solar tile-heat pump combination is very appropriate for sunny winter days, when the air temperature is low and solar radiation is intense.

A higher solar tile outlet temperature T_2 and flat plate collector outlet temperature T_7 may be achieved through a correspondingly larger solar tile and flat plate collector surface.

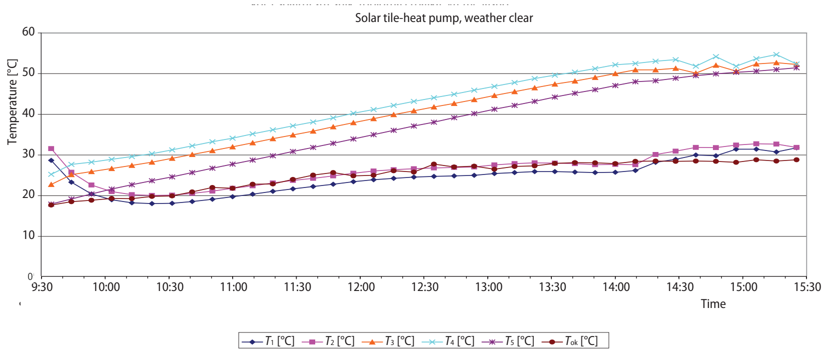


Figure 15. Solar tile-heat pump combination temperature readings

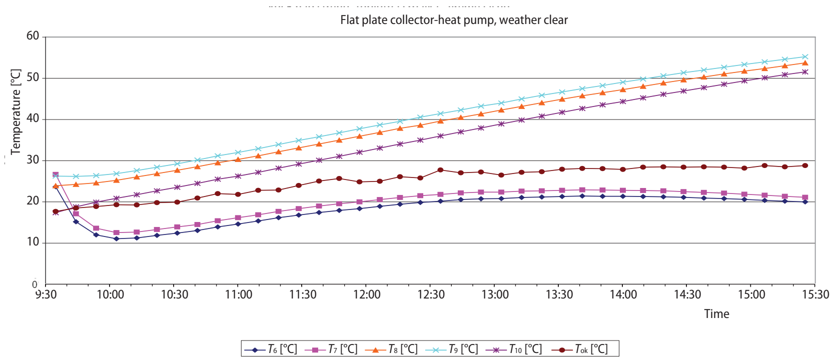


Figure 16. Lentherm collector-heat pump combination temperature readings

Conclusions

This paper deals with the use of solar energy, heat pumps and solar system-heat pump combinations for domestic water heating. Solar tiles made of transparent polymethyl methacrylate (CH2C(CH3)COOCH3) are analysed. Black-coloured water which absorbs solar radiation flows through the solar tiles. Testing of solar tiles was carried out as an autonomous water heating system and in combination with a heat pump. In the solar tile-heat pump combination, warm water enters the heat pump from the solar tiles, and the heat pump raises the water temperature to a higher level. In this case, the solar tiles increase the temperature of water entering the heat pump and the energy of water. When an air-water heat pump is used, the ambient air (heating energy) temperature is low in winter months. The solar tiles can increase the temperature of water exiting the tiles and entering the heat pump above the ambient temperature, thus increasing the heating energy temperature. To evaluate the efficiency of solar tiles in comparison with the flat plate collector realistically, the extensive measurements of both systems under identical conditions were carried out. The surface of both systems was 2 m^2, they could heat the water directly or in combination with a heat pump. The boiler capacity was 300 L. The experiments took place in rainy, cloudy, and clear weather. In the case of direct heating, the flat plate collector achieved on average by 1 °C to 4 °C higher temperature of water in the boiler than the solar tiles under any weather conditions. The experiments showed that the efficiency of solar systems was very low in very cloudy and rainy weather. The contribution of diffuse light to sanitary water heating is small, and consequently, it is reasonable to use the solar tile-heat pump and flat plate collector-heat pump combinations.

The solar tile-heat pump combination heats the water in the boiler in any weather by 1 to 5 °C, fig. 10, higher than the flat plate solar collector-heat pump system does.

A higher heating water temperature in the boiler is a consequence of a higher solar tile outlet water temperature T_2 than the flat plate collector outlet water temperature T_7. Since energy entering the heat pump of the solar tile-heat pump combination has a higher temperature than in the flat plate collector-heat pump combination, the heat pump in the solar tile-heat pump combination operates at a higher COP.

Higher solar tile and flat plate collector outlet temperatures T_2 and in T_7 are achieved by increasing the surface of solar tiles and of the flat plate collector. On the basis of the research presented in the paper, we plan to cover the entire roof of the house with solar tiles and carry out the measurements in all weather conditions.

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