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Efficiency of solar conversion in flat plate and vacuum tube solar collectors

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Abstract. The paper presents results of efficiency of solar radiation conversion in flat plate and vacuum tube collectors. The research was carried out for uniform forced conditions and varied temperature in a hot water tank. Conversion efficiency, determined as a relation of the utility heat from collectors to the total solar radiation energy, was calculated for the varied water temperature in a hot water tank. Results of efficiency were presented as the reduced temperature function presenting a relation as a difference between the average temperature of the transfer fluid and the ambient temperature in relation to the solar radiation intensity. For the measured sizes, values of parameters were determined, based on which we may calculate the conversion efficiency according to the standard of investigation of collectors. Based on the obtained results, a model form which enables determination of the average temperature of the transfer fluid as a function of the ambient temperature and solar radiation intensity was found.

1. Introduction

The need to reduce fossil fuel consumption resulting from a risk of depletion, care for natural environment, induced to search for renewable energy sources. Except for the mentioned stipulations, also legal regulations accepted in the EU (packet of 3x20) oblige application of renewable energy sources. Solar collectors are one of such devices. The effect of their application and thus acceptability by a user follows from the efficiency of solar radiation conversion. This efficiency depends on the availability of solar radiation energy and the system structure. These issues were analysed in various scientific centres. Therefore, Ardente et al., [1] analysed the energy yield of collectors located in the south of Italy and the final thermal effect was calculated into savings in fossil fuel consumption. The procedure of the product life cycle, where they compared scenarios of construction and functioning of the solar system, was applied for calculation of the effect. Kalogiru [2] in his review paper made a synthetic division of structures of collectors along with their recommended use, mathematical relations for analyses in various systems and obtained effects of their application. Also Thirugnanasambandam et al., [3] in their paper discussed the existing technologies of solar energy use (both with technical devices and storing in a solar pond) and research trends. Hussein et al., [4] investigated operation of the liquid collectors with varied geometrical cross-section of tubes filled with a transfer fluid concluding that the elliptic shape will bring better results of solar radiation conversion than the round one. Yoo [5] determined financial and energy effects concerning satisfaction of demands for heating of water supplied from liquid collectors for a residential buildings complex, stating over 50% differences in energy yield



in comparison to the ones declared by the producer. Ladas et al., [6] analysed distribution of the wind speed on the surface of collectors mounted on the roof of the facility and heat losses, reporting that in the investigated range of speeds, relative differences in the amount of heat production in comparison to the control facility may reach even 21%. In laboratory conditions Riffat et al., [7] determined the impact of parameters of the surrounding climate, structure and applied materials on the performance of various types of solar collectors. Napauer and Magiera [8] presented the types of collectors used in practice with description of their operation and obtained performance as a function of the reduced difference of temperatures, concluding that the values of performance for vacuum collectors should be considered approximately. Kurpaska et al., [9] analysed the performance of solar collectors, which heated water in a hot water tank. A relation of the impact of the surrounding conditions (radiation, temperature) on the performance of the investigated system, where hot water from the tank was used as a bottom source of the compressor heat pump, was determined. Zima and Dziewa [10] developed a mathematical model for simulation of transitory states of the flat solar collector. As a result of the verification research, its usefulness for the system of collectors combined parallelly and in a hairpin bend manner was stated. Gao et al., [11] investigated the efficiency of solar radiation conversion for the flat and vacuum tube (U-pipe) solar collector reporting a higher value for the vacuum collector.

The presented review shows unanimously that the conversion efficiency issue, consequently obtained energy effects is a present research problem. The main objective of the paper will be determination of the quantity relation between the all-present solar energy and the obtained thermal effect.

2. Materials and methods

The investigations were carried out at a stand whose schematic representation was presented in figure 1.

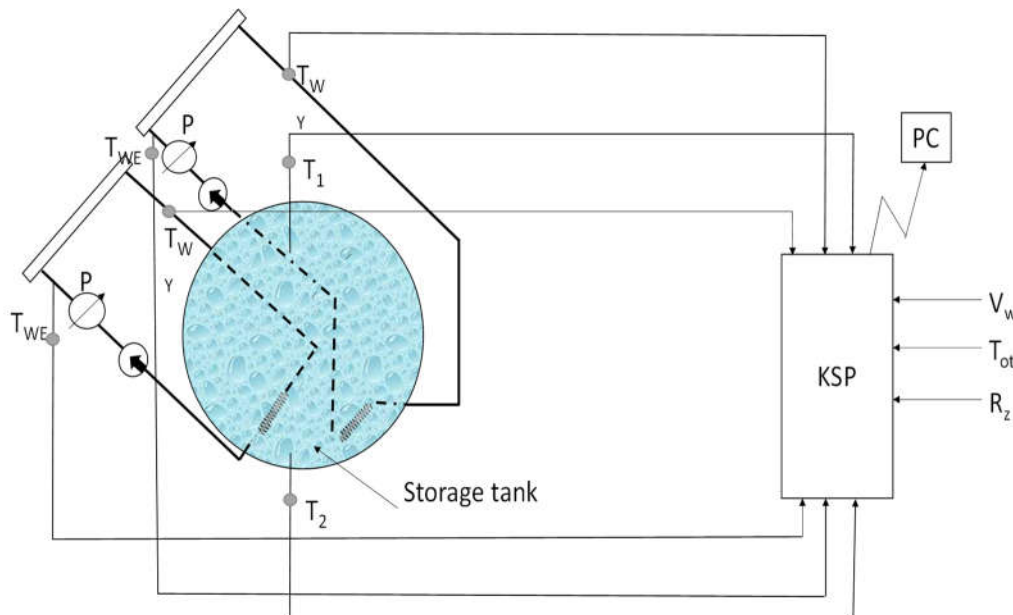


Figure 1. Schematic representation of the measurement stand.

The following were measured during tests: air temperature (T_{ot}), wind speed (V_w), solar radiation intensity (R_z), transfer fluid temperature (T_w , T_{WE}) and fluid in the hot water tank (T_1 , T_2). The following sensors were used in the measurements: temperature - with measurement device PT1000, wind speeds - with time anemometer MAX 40H, intensity of solar radiation with pyranometer LP PYRA 02AV, flow of the transfer fluid with impulse flow-meters Type ALV3.

Circuit pumps installed in the heat receipt system pumped the transfer fluid (30% water glycol solution) and the mounted impulse flow meters (P) indicated the flowing factor stream. Diaphragm

exchangers were installed inside the tank (a pipe coil made of a copper pipe), which were connected to both solar collectors. The total area of solar collectors was respectively: flat collectors (7.8m²) and vacuum collectors (heat pipe) 4.3m². In the system of pumping fluid through collectors, circuit pumps were installed. All values were monitored with the use of the original computer measurement system with 30 s frequency and archived in the computer.

The tests were carried out in April-October and the effective operation time of circuit pumps was included in analysis. Control of circuit pumps operation took place based on the difference of temperatures between the average water temperature in the hot water tank and the temperature of supply of collectors. Analysis included measurement data for the recommended days of particular months when experiments were carried out.

3. Theoretical analysis

Efficiency of solar radiation conversion was computed as a ratio of utility energy collected in the transfer fluid to the amount of solar energy radiation on the collector, namely in the differential time $d\tau$ defined as:

$$\eta = \frac{\int_0^{\tau} q_u d\tau}{F_k \cdot \int_0^{\tau} R_z d\tau} \quad (1)$$

This equation after the assumed time of sampling ($\Delta\tau$) may be written as:

$$\eta = \frac{q_u \cdot \Delta\tau}{\sum R_z^{\Delta\tau} \cdot F_k} \quad (2)$$

where the utility heat stream (q_u) was calculated from the following relations:

$$q_u = m_{cz} \cdot c_w \cdot (T_{WY} - T_{WE}) \quad (3)$$

and the above symbols mean: m_{cz} - transfer fluid stream, kg/s; c_w - specific heat of factor, J/kg/K; T_{WY} and T_{WE} - temperature of factor respectively at the inflow (T_{WE}) and on the outflow from the collector (T_{WY}), °C.

The calculated value of the efficiency was also presented in the recommended form by standard EN 12975 as [12]:

$$\eta = a - b \cdot t_m^* - c \cdot R_z \cdot (t_m^*)^2 \quad (4)$$

where the reduced difference of the temperature (t_m^*) was calculated as:

$$t_m^* = \frac{\left(\frac{T_{WE} + T_{WY}}{2} - T_{amb}\right)}{R_z} \quad \text{m}^2\text{K/W} \quad (5)$$

In order to generalize the obtained results which define the average temperature of the transfer fluid in the investigated collectors as a function of the measured parameters of the system (T_{WE} , T_{WY} , R_z) multiple regression equations were found and the difference between the calculated and measured values was determined, with the average radical square error known from the error account, (σ).

4. Results and discussion

Figure 2 shows graphic course of the measured parameters.

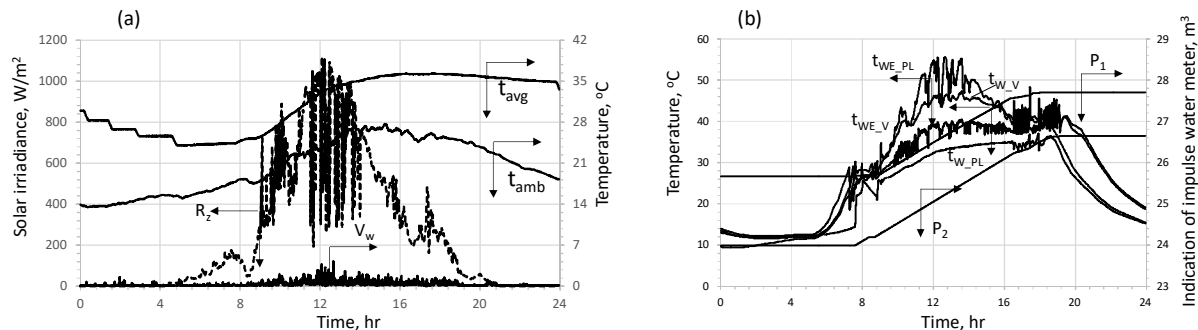


Figure 2. A daily course of the measured parameters: intensity of solar radiation: ambient temperature, wind speed and average temperature of fluid in a tank (a), temperature of a transfer fluid and values of the impulse flowmeter (b).

It may be reported that on that day, a flat collector converted solar energy into heat in 10.4 hours and the vacuum one in more than 11.5 hours. In the course of the operation of a flat collector, 2.04m³ of fluid flow through the pipe coil, the average temperature of the transfer fluid was 36.6°C, the ambient temperature 23.49°C and the total solar radiation was 5.29 kWh. On the other hand, during the operation of the vacuum collector, the circuit pump pumped 2.63m³ of the agent, the average ambient temperature was 23.46°C, the transfer fluid - 37.66°C and the total energy of radiation was almost 5.6 kWh. During the operation of both solar collectors, the average water temperature in the hot water tank (with the volume equal to 4.5m³) increased from 17.1 to 25°C. Differences in the amount of the pressed transfer fluid result from the varied length of an exchanger of the operation time of collectors.

The detailed analysis included 805 (vacuum collectors) and 596 (flat collectors) measuring cycles. Experiments were carried out for variable conditions of the surroundings and varied initial temperature of water in the hot water tank.

Fig. 3 presents the relation of the calculated efficiency of solar radiation conversion as a function of the solar radiation sum for the varied initial water temperature in the reservoir.

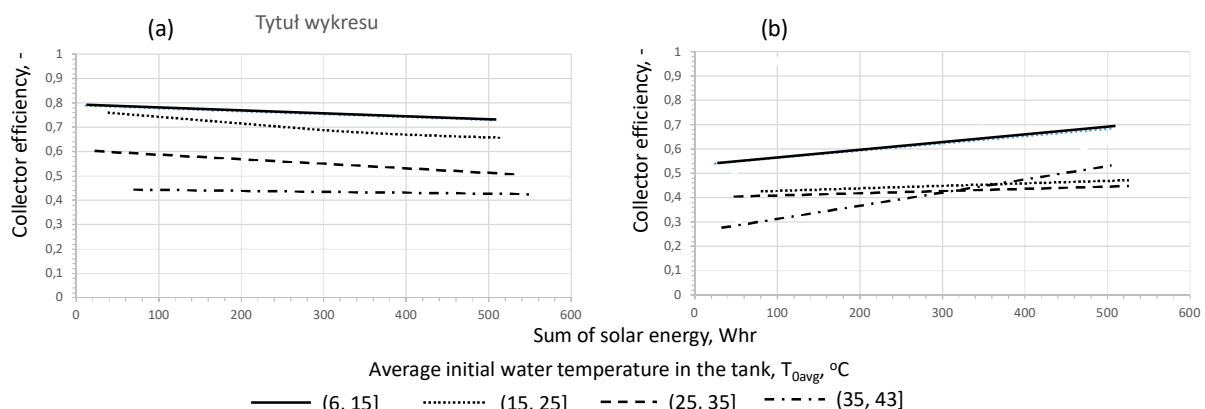


Figure 3. The course of the solar collectors efficiency as a function of the solar radiation sum (a) vacuum and (b) flat.

As it can be noticed along with the increase of water temperature in the hot water tank the efficiency of collectors decreases. It may be justified with the reduced intensity of heat exchange between the

surface of the pipe coil and transfer liquid in the hot water tank. In the entire range of temperature in the tank, the average efficiency of flat collectors was 0.42 and vacuum collectors 0.58. The analysis showed that these differences are statistically significant at the level of significance which is 0.05. The analysis also proved that for example with 95%, probability the average performance of the vacuum collector is within 0.564 to 0.593 and in case of a flat collector within 0.412 to 0.434.

Figure 4 presents the course of performance of collectors in the function of the reduced temperature difference.

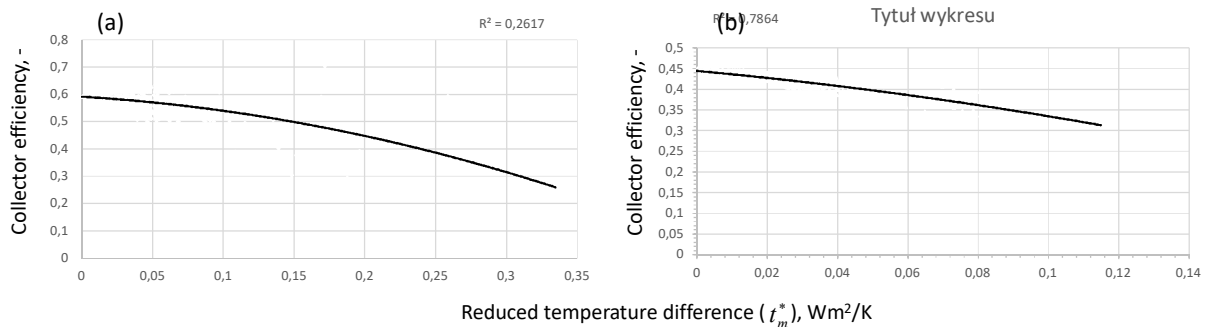


Figure 4. Curve of performance of analysed solar collectors, (a) vacuum collectors, (b) flat collector.

Table 1 presents the coefficients found for the equation which determines the relations of performance to the reduced temperature difference.

Table 1. Values of parameters for determination of performance of collectors.

Collector type	Values of parameters			Range of use
	a	b	c	
vacuum	0.591	-2.025	-0.3147	$-0.01 \leq t_m^* \leq 0.33^\circ\text{C}$; $23 \leq R_z \leq 1061 \text{ W/m}^2$
flat	0.444	-3.078	-0.7892	$-0.02 \leq t_m^* \leq 0.115^\circ\text{C}$; $50 \leq R_z \leq 1061 \text{ W/m}^2$

Analysis of courses presented in figure 4 shows that for the same conditions of the surroundings, the range of the reduced difference of temperature for vacuum collectors is almost 3 times higher. The comparison of the changes of performance of both analysed collectors shows that for the same range of values of the reduced temperature difference in case of flat collectors there is almost 30% reduction of performance and for vacuum collectors the performance (in both cases towards the maximum value) decreases only by 10%. It may be justified with varied values of the average temperature of the transfer fluid.

Having the measured analysed values (ambient temperature and solar radiation intensity) for the entire range of water temperature in the hot water tank, the multiple regression equation which serves for determination of the average temperature of the transfer fluid (t_m) takes the following form:

a) vacuum collectors

$$t_m = 9.62 \cdot t_{amb}^{0.38} + 0.18 \cdot R_z^{0.89}$$

Within the range of use: $10.29 \leq t_{ot} \leq 55^\circ\text{C}$; $24 \leq R_z \leq 1061 \text{ W/m}^2$

b) flat collectors

$$t_m = 4.43 \cdot t_{amb}^{0.47} + 0.506 \cdot R_z^{0.53}$$

Within the range of use: $12.1 \leq t_{ot} \leq 55^\circ\text{C}$; $50 \leq R_z \leq 1061 \text{ W/m}^2$

Results of comparison of the temperature value calculated from the above relation and measured were presented in figure 5.

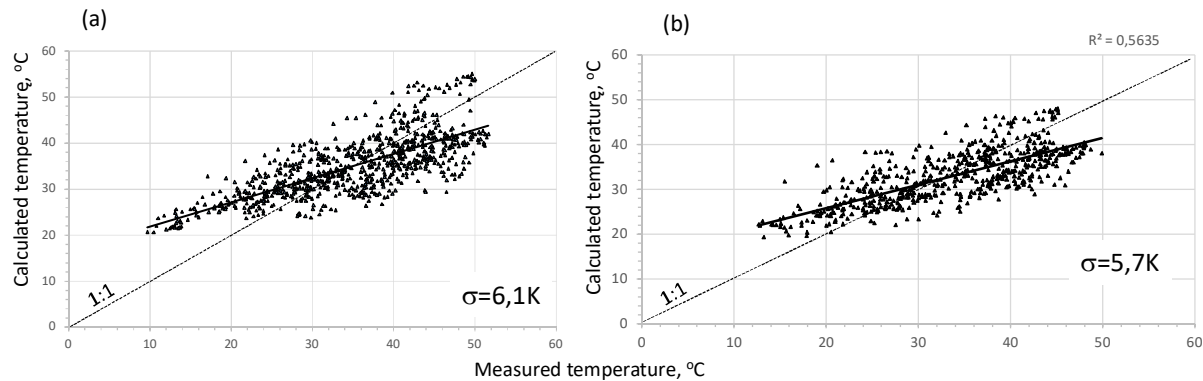


Figure 5. Comparison between the measured and calculated average temperature of the transfer fluid in collectors: (a) vacuum, (b) flat.

The statistical analysis showed that for uniform enforcing conditions (temperature of the surroundings, intensity of solar radiation), these differences are statistically significant.

5. Conclusions

1. The average performance of flat collectors was 0.42 and vacuum collectors was 0.58.
2. For the uniform range of values of the reduced temperature difference, in case of flat collectors there is almost a 30% reduction of performance and for vacuum collectors only by 10%.
3. Equation of multiple regression which serves for determination of the average temperature of the transfer fluid (t_m) takes the following form: (vacuum collectors) and for flat collectors:

$$t_m = 9.62 \cdot t_{amb}^{0.38} + 0.18 \cdot R_z^{0.89}$$
 (vacuum collectors) and for flat collectors:

$$t_m = 4.43 \cdot t_{amb}^{0.47} + 0.506 \cdot R_z^{0.53}$$
. These formulas are real for the range of variables which occur during experiments.

Acknowledgements

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