Sławomir KURPASKA, Hubert LATAŁA, Stanisław KOKOSZKA

University of Agriculture in Krakow, Faculty of Production and Power Engineering

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Comparison of the radiation conversion efficiency of flat plate and vacuum tube solar collectors

***Abstract**. The paper analyses the efficiency of three types of collectors: flat plate collectors and vacuum tube collectors (flow and heat pipe). Based on measured and calculated values, the influence of ambient temperature and solar radiation intensity on the change in efficiency was presented in the form of graphic dependencies. Using the recommendations of the standard for testing collectors, the values of the parameters of the quadratic polynomial as well as the change in efficiency as a function of the reduced temperature were found.*

***Streszczenie.** W artykule przeanalizowano efektywność trzech rodzajów kolektorów: płaskich kolektorów i próżniowych kolektorów rurowych (rura przepływowa i ciepła). Na podstawie zmierzonych i obliczonych wartości przedstawiono wpływ temperatury otoczenia i natężenia promieniowania słonecznego na zmianę wydajności w postaci zależności graficznych. Korzystając z zaleceń normy dotyczącej testowania kolektorów, znaleziono wartości parametrów wielomianu kwadratowego oraz zmianę wydajności w funkcji obniżonej temperatury. (**Porównanie efektywności konwersji promieniowania płaskich i próżniowych kolektorów słonecznych**)*

Słowa kluczowe: kolektor słoneczny, efektywność, konwersja promieniowania
Keywords: solar collectors, efficiency, radiation conversion

Introduction

The necessity to reduce the consumption of fossil fuels resulting from the fear of their exhaustion, concern for the surrounding natural environment, impose the necessity to search for renewable energy sources. In addition to the above-mentioned premises, also the legal regulations adopted in the EU (3x20 package) oblige the use of renewable energy sources. Among the devices using renewable energy resources, apart from heat pumps, photovoltaic panels, biomass burning boilers are solar collectors. The efficiency of solar radiation conversion determines the effect of their use and the same acceptability by the user. This efficiency depends on the availability of solar energy, the type of solar collectors and the system construction. There is a number of studies in the literature that analyze these issues, however the difference in climatic conditions and research positions cause that the transfer of the obtained results may be fraught with errors. Knowledge of the efficiency of solar radiation conversion is indispensable both at the stage of determining the surface of the collectors as well as when estimating the resulting financial effects and reducing the impact of traditional heat carriers on the surrounding environment. The issue of efficiency was the subject of analysis in various environmental conditions and for differentiated collector structures. And so, Bhowmik and Amin [1] analyzed the efficiency of collectors equipped with a movable solar reflector integrated with the collector whose task, through the concentration of radiation, is to increase the supply of radiation. The constructed prototype made it possible to improve the collector's efficiency by nearly 10% compared to the standard design. Chen et al. [2] compared the efficiency of flat collectors, where in one of them between the glass and the absorber they installed a transparent polymer foil. The tests were carried out at various flow rates of the circulating medium, stating in conclusion that the installed foil allows for increased efficiency and reduced heat losses to the environment. Weitbrecht et al. [3] presented the results of experimental research at a differentiated stream of the circulating medium. The applied analytical description of the flow enables the analysis of pressure losses caused by the flow of the medium. Vafeli and Sah [4] have developed a fuzzy inference system to forecast solar collector efficiency. The system uses the ambient temperature, the inlet and outlet temperature of the solar heating system. The comparison between the measured and calculated values was characterized by satisfactory compliance, noting that the proposed fuzzy inference system can provide high accuracy and reliability to predict the efficiency of the solar collector. Methods using artificial intelligence algorithms are characterized by increasing practical application and can be an alternative to existing computational algorithms [5,6]. Lee and Beal [7] in the modified equation to assess the efficiency of the solar collector instead of the inlet fluid temperature introduced a heating load. Parameters of the modified equation were estimated using test data from selected measurement days. The applied equation took into account the shape of the hot water tank in the solar heating system. The conducted comparison between measured and calculated values was characterized by high correlation. Sozen et al. [8] used artificial neural networks to analyze the thermal efficiency of flat collectors. Meteorological data from the summer period (from July to September) were used as learning sets. The resulting input data included data related to the operation of collectors and ambient parameters. Based on the analysis, it was found that the method used, compared to the traditional one, is characterized by speed and simplicity. Riffat et al. [9] determined in laboratory conditions the influence of parameters of the surrounding climate, structure and used materials on the efficiency of work of various types of solar collectors. Neupauer and Magiera [10], presented the types of collectors used in practice along with a description of their operation and efficiency achieved as a function of the reduced temperature difference, stating in conclusion that efficiency values for vacuum collectors should be treated as approximate. Kurpaska et al. [11] analyzed the efficiency of solar collectors that heated the water in the storage tank. Kurpaska et al. [12] presented the results of research on the efficiency of solar radiation conversion in flat and vacuum solar collectors. The tests were carried out for the same conditions of forcing and different temperature in the storage tank for heated water. The review of the literature shows that the efficiency of solar radiation conversion in solar collectors depends on the ambient conditions and their construction.

Hence, the main aim of the research was to determine the efficiency of radiation conversion for various types of collectors. The analysis was carried out for flat and vacuum collectors, both heat pipe and flow type.

Material and method

The tests were carried out at the measurement stand, the diagram of which is shown in Fig. 1.

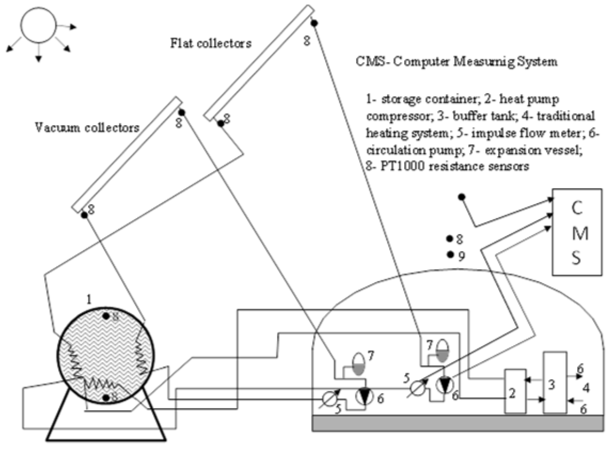

Fig. 1. Diagram of the measurement stand

During the tests, the following parameters were measured: air temperature (Tamb), solar radiation intensity (Rz), temperature of the circulating medium (TW, TWE) and liquid in the accumulation tank (T1, T2). The following sensors were used in the measurements: temperature- using PT1000 meters, intensity of solar radiation with the help of the LP PYRA 02AV pyranometer, flow of the medium- by means of pulse flow meters- Type ALV3. The circulating pumps installed in the heat collection system pumped the circulating medium (30% aqueous glycol solution), while the impulse flow meters (P) indicated the stream of the flowing medium. Inside the tank there were installed diaphragm exchangers (coils made of copper pipes) that were connected to both solar collectors. The total area of solar collectors was respectively: flat plate collectors (7.8 m^2) and 4.3 m^2 vacuum tubes (heat pipe) and a vacuum flow collector with an area of 2.15 m^2. Collector pumps have been installed in the system of circulating liquids through the collectors. All values were monitored using the proprietary computer measurement system (CMS) with a frequency of 30s and archived in a computer. During the experiments, the heat removal system constituted a compressor heat pump (2) cooperating with a buffer tank (3). The tests were carried out over a two-year period between April and October. In the first year, flat and vacuum collectors (heat pipe type) were installed in the system, whereas in the following year the vacuum flow collector was installed instead of the heat pipe one. The analysis took into account the effective working time of circulating pumps. Control of circulation pumps was based on the temperature difference between the average water temperature in the storage tank and the collector supply temperature. The analysis included measurement data for recommended days of individual months of experiments.

The efficiency of solar radiation conversion was calculated as the quotient of useful energy accumulated in the storage tank to the amount of solar radiation energy incident on the collector, i.e. in the differential time $d\tau$ is 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, at the adopted sampling time ($d\tau$) can be written as:

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

where the useful heat flux (q_u) was calculated from the dependence:

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

The obtained results were converted into efficiency in accordance with the applicable EN 12975 standard [13], resulting in a functional relationship in the form of:

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

$$t_m^* = \frac{\left(\frac{T_{WE}+T_{WY}}{2} - T_{amb}\right)}{R_z}$$

The above symbols mean: F_k- area of collectors, m^2; R_z- intensity of solar radiation, $W \cdot m^{-2}$; τ- time, s; m_{cz}- flow of the circulating medium, $kg \cdot s^{-1}$; c_{cz}- specific heat of the medium, $J \cdot kg^{-1} \cdot K^{-1}$; T_{WY} and T_{WE}- medium temperature, respectively at the inlet t (T_{WE}) and at the outlet of the collector (T_{WY}), ^oC, t_m^* - reduced temperature, $K \cdot m^2/W$, T_{amb}- ambient temperature,

In accordance with the procedure for determining the efficiency of collectors with the above standard, for the values found (in the function of the so-called reduced temperature), the required parameters of the quadratic polynomial were found using the nonlinear estimation method.

Results and discussion

The research was carried out in the months of April-October, while in the effectiveness analysis, recommended days were taken into account. Fig. 2 presents exemplary results obtained for two days with different solar insolation and variable installation of collectors. During those days, in a system where flat and vacuum flow collectors were installed (Fig. 2a), the sum of solar radiation was 4.2kWh, whereas for a system in which flat and vacuum (heat pipe) collectors were installed, the sum of solar radiation energy amounted to nearly 6.5kWh.

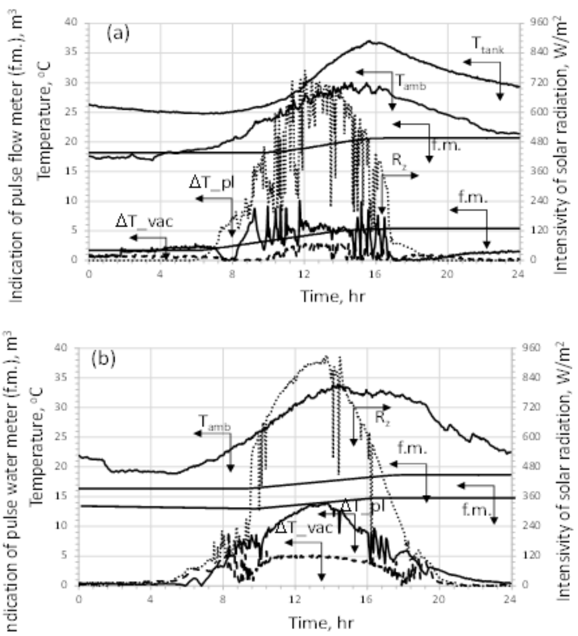

Fig. 2. The course of measured values for a system equipped with flat and vacuum (flow) collectors (Fig. 2a) and flat and vacuum (heat pipes) collectors (Fig. 2b)

The variation in the amount of circulating medium and temperature values results from the diversity of ambient climate conditions and the surface area used in solar collector tests. With the temporal variability of the measured parameters, Fig. 3 and 4 present the effect of the intensity of solar radiation and ambient air temperature on the efficiency of the analyzed solar collectors.

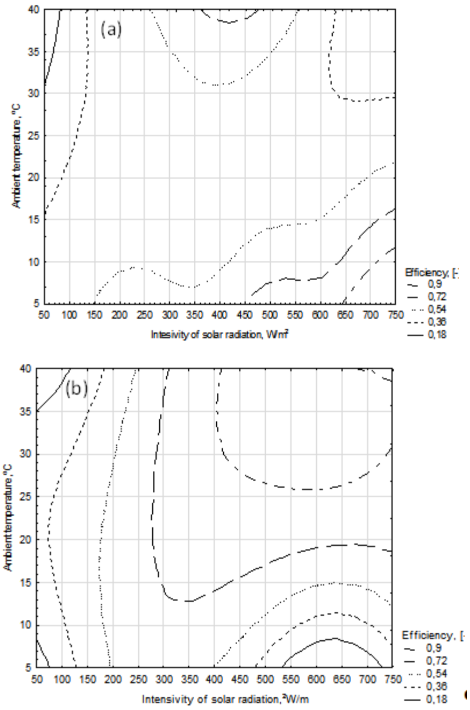

Fig. 3. Influence of solar radiation intensity and ambient temperature on the efficiency of flat plate collectors (Fig. 3a) and vacuum collectors (Fig. 3b)

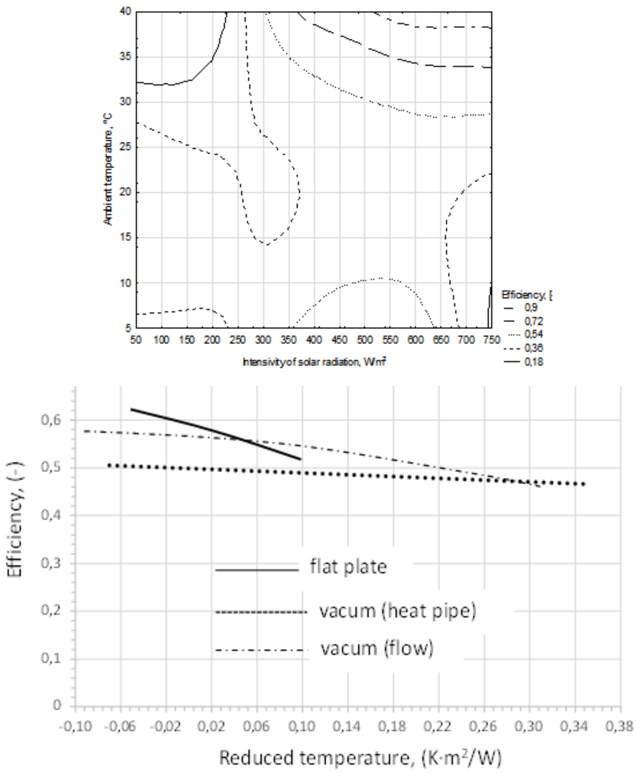

Fig. 4. Influence of the intensity of solar radiation (a) and Efficiency of collectors in function ambient temperature on the efficiency of the reduced temperature vacuum collectors (b)

Analyzing the obtained waveforms, it can be concluded that the efficiency reaches the highest values for the maximum values of solar intensity and at lower ambient temperatures.

Analyzing the graphical results presented in detail, it can be stated that for the analyzed types of collectors, an increase in collector temperature stimulates an increase in the intensity of heat loss to the environment. Then, the resulting temperature gradient stimulates an increase in the heat transfer coefficient from the housing to the environment. Under the conditions under test, the average efficiency values are: η=0.6 (flat), η=0.56 (vacuum-flow) and η=0.48 (vacuum-heat pipe).

The calculated value of efficiency can be used for many engineering purposes, ranging from the selection of collector surfaces, by determining the instantaneous yields and ending with the operational issues of installations in which solar collectors are used. These systems, in the era of concern for the environment and reduced operating costs, are widely used not only for the heating needs of facilities, preparation of hot utility water but also to determine the surface of collectors in the construction of swimming pools. The given range of independent variables in which the conversion efficiency was determined takes into account the wide range of environment variables.

Figure 5 shows the course of efficiency (determined in accordance with EN 12975) in the function of reduced temperature. In the analyzed types of collectors, the efficiency decreases with the increase of the reduced temperature. The analysis of the obtained results shows that for the same ambient conditions, the value of the reduced temperature difference for the analyzed types of collectors, in comparison to a flat collector, is from 2 (vacuum-flow collector) to 3-times (vacuum-heat pipe collector) higher. Comparing the change in efficiency, it can be noticed that for the same range of reduced temperature difference, in the case of flat collectors there is a 28% decrease in efficiency, whereas for tested types of vacuum collectors the efficiency (in both cases in relation to the maximum value) decreases from 10 (heat pipe collector) to 18 % (flow collector). This can be explained by the different values of the average temperature of the circulating medium. Table 1 presents the values of coefficients occurring in the equation describing their variability.

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

Collector type	Values parameters			Range of use
	a	b	c	
plate	0.62	0.21	0.089	46≤Rz≤850 W/m^{2}K; $-0.06 \leq t_m^* \leq 0.08$ K·m^2/W
vacuum (flow)	0.51	0.029	0.008	30≤Rz≤750 W/m^{2}K; $-0.09 \leq t_m^* \leq 0.31$ K·m^2/W
vacuum (heat pipe)	0.57	0.07	0.023	16≤Rz≤850 W/m^{2}K; $-0.07 \leq t_m^* \leq 0.35$ K·m^2/W

The analysis clearly shows that in comparable environmental conditions the highest efficiency was recorded for flat collectors. It is also a recommendation for engineering practice that such collectors will bring the best effect when used in an energy installation. From the many years of operational experience carried out at the Faculty of Production and Energy Engineering of the University of Agriculture in Krakow, this conclusion also follows (on the recommendation for the installation of flat collectors). The analyzed collectors in real conditions were characterized by either failure rate (vacuum collectors) or relatively higher purchase costs (flow collectors). Hence, both the efficiency calculations carried out and the experience acquired from the use of the tested collectors) recommend this type of collector for engineering use.

Conclusions

1. The average efficiency of the analysed collectors is 0.6 (flat), 0.56 (flow) and 0.48 (heat pipe).
2. With the increase of solar radiation intensity and the decrease of the ambient temperature, the efficiency of collectors decreases.
3. For the same ranges of changes in the reduced temperature, the greatest reduction in efficiency was observed for flat collectors, followed by flow vacuum collectors and the smallest for vacuum tube with heat pipe technology.

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Authors:
Prof. dr hab. inż. Sławomir Kurpaska, University of Agriculture in Krakow, Faculty of Production and Power Engineering, ul. Balicka 116B. 31-149 Krakow, E-mail: rtkurpas@cyf-kr.edu.pl; dr hab. inż. Hubert Latała, University of Agriculture in Krakow, Faculty of Production and Power Engineering, ul. Balicka 116B. 31-149 Krakow, E-mail: rtlatala@cyf-kr.edu.pl; Prof. dr hab. inż. Stanisław Kokoszka, University of Agriculture in Krakow, Faculty of Production and Power Engineering, ul. Balicka 116B. 31-149 Krakow, E-mail: stanislaw.kokoszka@urk.edu.pl;

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