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Energy efficiency analysis of flat and vacuum solar collector systems

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Summary. This paper presents the findings of analyses depicting changes in solar radiation conversion efficiency in flat and vacuum solar collectors. It also sets out the efficiency for the entire system based on a 24-hour cycle. On the basis of results models have been found which define these efficiencies through experience (storage tank fluid capacity, surrounding temperature and total solar radiation). This model has also been validated and confirmed as useful for estimating efficiency and therefore, for selecting surfaces of the analyzed types of collectors in systems using these kinds of devices. Concerning the approved conditions the time required for the reimbursement of investment costs has also been defined.

Key words: flat and vacuum solar collectors, conversion efficiency, solar radiation

1. INTRODUCTION

The growing cost of energy, fear associated with the possibility of exhaustion of fossil energy sources, the need to increase the security of fuel and energy supply and concern for environmental protection have led to rapid growth of interest in the use of renewable energy. Solar radiation energy, which is converted into heat in flat and vacuum solar collectors, is being used more and more often as a component of renewable energy resources.

Of its many possible applications, heat obtained from solar collectors is also used in horticultural production, primarily for: supplementing the heating of structures under cover [Kurpaska et al 2004, Vox et al 2007], supplementary or basic heating of plastic tunnel bedding with the purpose of accelerating crop growth, preparation of processing water for the watering of plants, preparation of seedlings for planting, heating requirements for the post-harvest preparation of fruit and vegetables and heat treatment of soil pathogens [Al-Karaghouli and Al-Kayssi 2010]. A number of research centres has analysed in detail matters relating to the conversion of radiation for various configurations and conversion system equipment. Adsten et al [2002] analysed the impact of solar collector locations (both flat and vacuum) in northern Europe for operating effectiveness. The impact of annual energy was determined and it was confirmed that the amount of obtained energy is closely related to surrounding climate conditions. Apart from research on the use of individual collectors for energy purposes, specialist literature also provides the findings of research focusing on the coupling of collectors with heat pumps (so-called bivalent or hybrid systems). Hawlader et al [2001] researched the energy effects of the system in which the heat pump was coupled with the solar collector. The researchers defined the Coefficients of Performance for given system constituents. They also defined the rate of return on financial outlay and the COP for the entire system. Kjellsson et al [2010] carried out an analysis of the use of renewable energy for a residential building, provided by solar collectors corresponding with a heat pump. They concluded that it was necessary to optimise system components because the configuration of the system and the dimensions of its components depend on local environmental conditions. Eisenmann et al [2004] analysed the possibility of saving materials in the production of collectors and, amongst other things, replacing them with other more available materials. Following research and the optimisation of collector construction, the above researchers noted a possible reduction of 25% in traditional material without negatively impacting the effectiveness of converting solar radiation energy into heat. Aye et al [2002] studied the use of a compressor heat pump coupled with solar collectors for the purpose of heating processing water in residential buildings. In their analysis they compared aspects of energy and cost-effectiveness of the system under consideration in relation to separate constituent parts and indicated the conditions for which the proposed solution may be used in other facilities. Sozen et al [2008] used neural networks for the purpose of analysing the work effectiveness of flat solar collectors; they used the following as input values: collector surface temperature, solar radiation intensity and duration, angle of declination, azimuth angle and inclination angle. In their summary they indicated their usefulness of the elaborated network architecture. Trillat-Berdal et al [2007] analysed the use of a heat pump coupled with solar collectors for the purpose of heating residential buildings. This system guaranteed the channelling of heated water (following the meeting of given conditions) through collectors to a buffer tank in which lower heat source exchangers were located. Heat exchanger performance and general system operating effectiveness were defined. They also analysed heat pump operation in which the lower heat source was the intake of geothermal water and solar collectors. When using the existing numeric model they defined the operating parameters of the system under consideration and presented the energy and economic effects and the quantity findings of reducing the emission of harmful substances into the atmosphere. Kaygusuz [1995] presented the findings of theoretical and experimental analysis of the heating system in which a heat pump (used for heating purposes) was coupled with solar collectors. The model took into account given system components, whilst experimental research demonstrated satisfactory comparison. The model permits the calculation of collector surface, their efficiency and heating medium temperature. Badescu [2002] presented the findings of theoretical analysis in which he considered two systems used for the heating of buildings, namely the hybrid system (solar collectors coupled with the heat pump) and the single system in which only the heat pump was used for heating the building. The coefficient of performance of the heat pump was defined and it was concluded that the hybrid system is more useful for the heating of facilities. Fuller [2007] carried out a theoretical analysis and performed an experimental verification of the system in which use was made of water heated up in solar collectors for the heating of plastic tunnels. The water was collected in a storage tank and from there channelled (in a closed system) for the washing of the surface covering the facility. The energy effects of the system were defined and its usefulness in areas of high radiation was indicated.

Generalizing the results of research one may also state that the effectiveness of conversion depends not only on system configuration but also on the parameters of the surrounding climate.

The main purpose of research involved analysis of the effectiveness of conversion.

2. MATERIAL AND METHODS

2.1. EXPERIMENT SET-UP

Tests were conducted with the use of laboratory facilities located at the Agricultural University in Krakow (Figure 1).

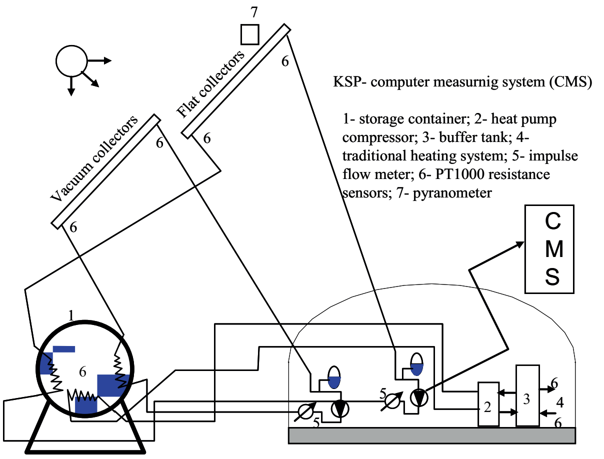

Fig. 1. Scheme of the laboratory stand

As indicated the laboratory facility comprises flat ($7.8m^2$ effective surface) and vacuum (surface of $4.3m^2$) solar collectors. The circulating medium flowed through a coil located in the buffer tank, which resulted in higher temperature of the water in the tank. Heat reception from the tank (1) was attained thanks to heat pump operation (2), in which the lower source constituted an additional heat exchanger located in the buffer tank. Heat was supplied to the plastic tunnel heating system (4) from the buffer tank (3). During the performance of the experiments, whose purpose was to analyse the effectiveness of collector operation, one of the collector types (liquid or vacuum) did not participate in the conversion of solar radiation.

During research the following was used for measuring the analysed values: the liquid stream flowing through the impulse flow meter (5), water (inside container, circulating liquid) and air temperature measured with the use of copper-constantan thermocouples (6) and solar irradiation by pyranometer (7).

All values were monitored and archived during sampling every 30 seconds with the use of the computer measurement system (CMS).

2.2. ANALYSIS

System efficiency analysis may be may be considered as instantaneous efficiency (depending on $d\tau$ sampling time and long-term efficiency.

- Instantaneous efficiency of solar collectors

Heat obtained from the collector during $d\tau$ is equal to:

$$Q(\Delta\tau) = \dot{m} \cdot c_w \cdot (T_z - T_p) d\tau, \quad \text{J} \tag{1}$$

In turn, conversion efficiency according to the standard expressed in the relationship between heat from the conversion and the sum of solar radiation energy, in other words:

$$\eta = \frac{Q(\Delta\tau)}{\Sigma R_{zewn} \cdot F_k \cdot d\tau} \tag{2}$$

where: $\dot{m}$ - stream of circulating medium mass, kg×s^{-1}; c_w- medium specific heat, J×kg^{-1}×K^{-1}; T_z, T_p- respective feed temperature (T_z) and return (T_p) of the circulating medium; $\sum R_{zew}$ - sum of solar radiation, W×h; Fk- surface of tested collectors, respectively 4.3 m^2 (vacuum) and 7.8 m^2 (liquid collector).

- Long-term efficiency

In the considered system this efficiency expresses the relationship between the quantity of energy stored in the storage tank i.e. the difference between useful collector heat and total heat loss from the tank into the environment and the sum of solar radiation energy which reaches the collectors. In consideration of the above this dependency is expressed as follows:

$$\eta_{med} = \frac{\int_{h_E}^{h_W} Q(\tau)d\tau - A_S U_S \int_{day} \left[T_S(\tau) - T_{ot}(\tau)\right] d\tau}{F_k \int_{h_E}^{h_W} R_{zew}(\tau)d\tau} \quad (3)$$

where: h_E, h_W- time of solar radiation penetration on the collector, A_S- surface heat loss of the storage tank, m^2; Us- replacement ratio of heat loss from the tank, W m^{-2} K^{-1}; T_S- instantaneous temperature of the liquid in the tank, °C; T_{ot}- tank surrounding temperature, °C, τ- time, s.

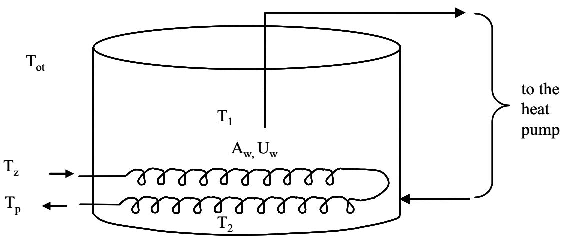

Fig. 2. Storage tank with coil: A_w- coil surface, m^2; U_w- ratio of heat penetration from the coil to water, W m^{-2} K^{-1}; T_1, T_2- tank liquid temperature, °C; m_w- stream of circulating medium flowing through the coil, kg s^{-1}.

For the purpose of the analysis a period of time equal to 24 hours was approved as the long-term storage period.

In the presented dependency a difficulty arises in indicating the penetration ratio of tank heat into the atmosphere (U_S). The diagram of this system is indicated graphically in Figure 2.

The following method was used for the purpose of designating the U_S coefficient. The tank is an exchanger in which there is liquid of a given mass (m) and specific heat (c_p). Water is heated in the tank following the transfer of heat from the medium which flows through the coil. There is thermal stratification in the tank, as a result of which a vertical temperature gradient takes place (t_1 and t_2 water temperature). In order to introduce the dependency defining change of tank water temperature, taking into account heat loss (Qstr), use has been made of standard heat balance. The dependency on indicating the U_S coefficient in $d\tau$ differential time was designated as follows (4):

$$U_S = \frac{m \cdot c_p \cdot \left(T_0 - T_{\Delta\tau}\right)}{A_S \cdot \left(T_{avg} - T_{ot}\right) d\tau} \quad (4)$$

where, T_{avg}- is average liquid temperature at the beginning and at the end of the dτ interval, °C; T_0, $T_{\Delta\tau}$- is liquid temperature at the beginning (T_0) and at the end of the interval ($T_{\Delta\tau}$), °C.

On the basis of findings a model dependency was established between efficiency defined through measurement and efficiency designated from the model. In order to define the differences application was made of relative differences and mean square error calculated from the dependence:

$$\sigma = \left(\sum_{i=1}^{n} \frac{\left(\eta_{calc} - \eta_{mod}\right)^2}{n} \right)^{0,5} \quad (5)$$

where: η_{calc}, η_{mod}- calculated (η_{calc}) and designated efficiency (η_{mod}) from the proposed model, n- number of comparisons.

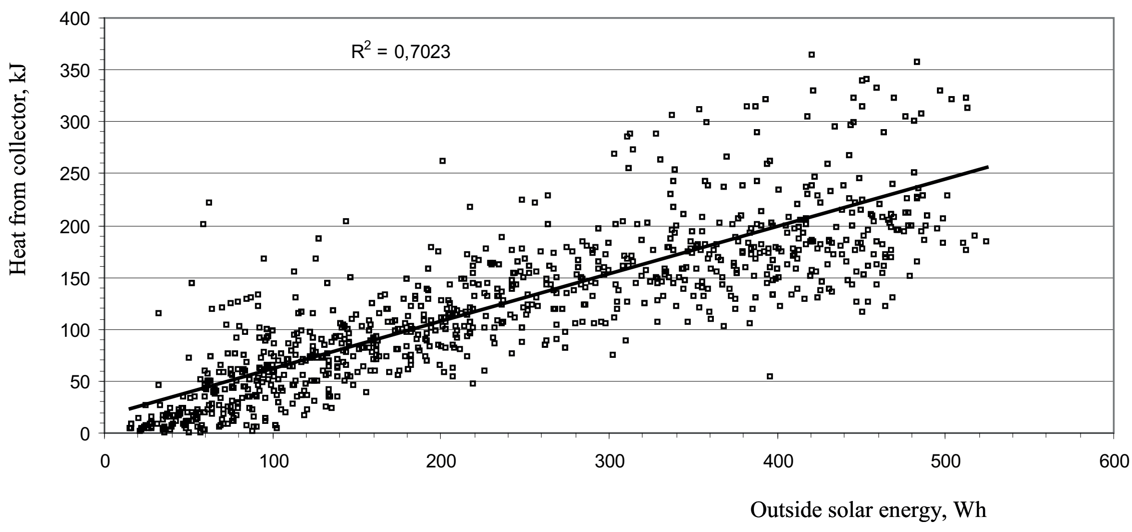

Fig. 3. Heat quantity generated in a solar vacuum collector in terms of total solar radiation.

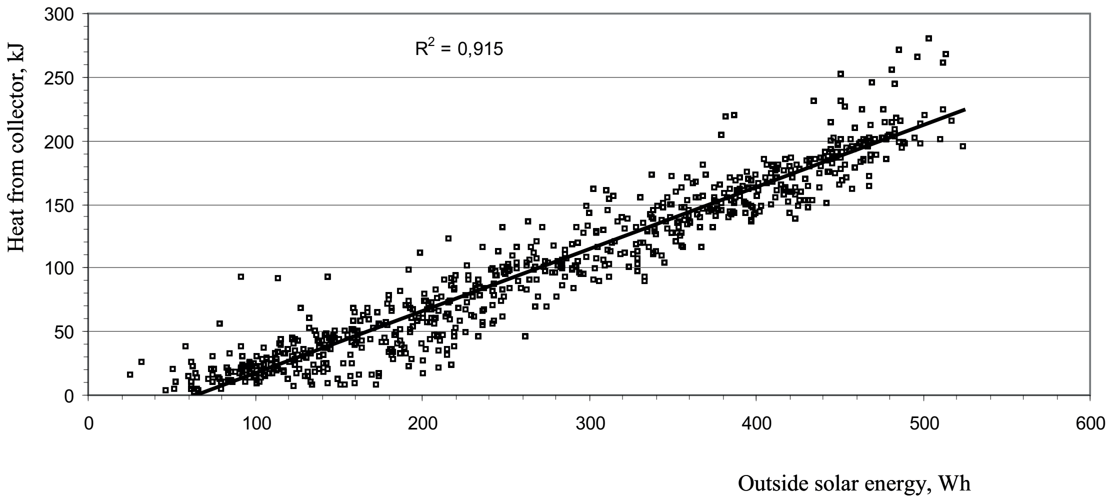

Fig. 4. Heat quantity generated in a flat vacuum collector in terms of total solar radiation.

3. RESULTS AND DISCUSSION

Tests were carried out on varying volumes of water in the tank, between 1.25 m^3 and 1.78 m^3 (vacuum collectors) and between 2.22 m^3 and 3.75m^3 for flat collectors. The quantity of test liquid for flat collectors was respectively: 2.22 m^3, 2.58 m^3, 2.9 m^3 and 3.22 m^3; and for vacuum collectors: 1.25 m^3, 1.4 m3, 1.6 m^3 and 1.78 m^3. Figures 3, 4 and 5 present examples of measured amounts.

The dependency, which arose as a result of solar radiation conversion, between the quantity of heat generated in the collectors (in relation to unit surface) in terms of total solar radiation energy, is depicted in Figures 3 and 4, respectively for vacuum collectors (Figure 3) and flat collectors (Figure 4).

Under test conditions the scope of heat quantity change spanned between 0.2 to 364.2 kJ×m^{-2} ,(vacuum collectors), and between 2.6 to almost 280 kJ/m^2 for flat collectors. In turn, average quantities of obtained heat stood at 130 kJ×m^{-2} ,(vacuum collectors), and 103 kJ×m^{-2} (flat collectors). Taking into account the above data it stems that from the unit surface of a vacuum collector (based on average values) almost 18% more heat is obtained in comparison to flat collectors. This analysis was carried out for similar surrounding conditions (the sum of solar radiation energy, surrounding temperature).

Assuming the futility of providing all possible approaches, Figures 5 and 6 illustrate the impact of surrounding temperature and the sum of solar radiation on the change of effectiveness of the conversion of radiation for flat collectors. Calculations were performed in relation to the unit surface of flat collectors (Figure 5) and for storage tank fluid capacity at 2.25 m^3. The same course of change of effectiveness for vacuum collectors (for tank capacity equivalent to 1.25 m^3) is presented in Figure 6.

For maximum liquid volumes applied in the buffer tank (flat collectors, 3.22m^3 and vacuum collectors, 1.78m^3) the obtained calculations have been presented graphically in Figures 7 and 8.

In analyzing the obtained values one may state unequivocally that conversion effectiveness grows together with the growth of the sum of solar radiation and sur-

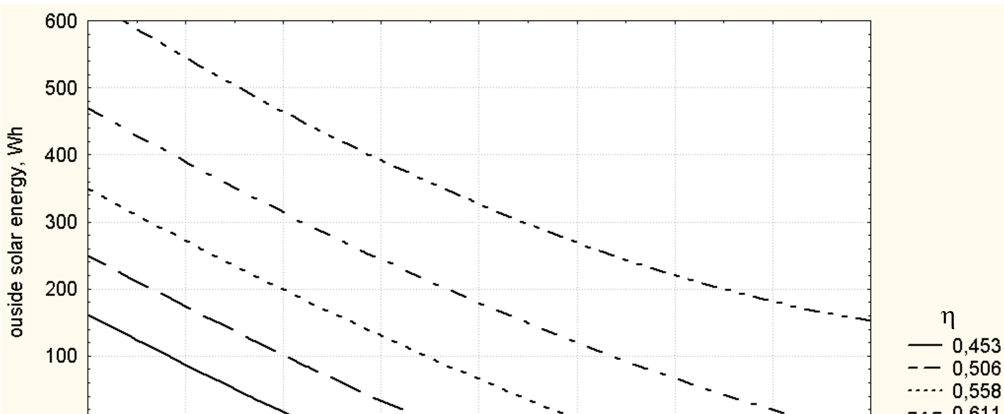

Fig. 5. Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for flat collectors (liquid volume equivalent to 2.25m^3).

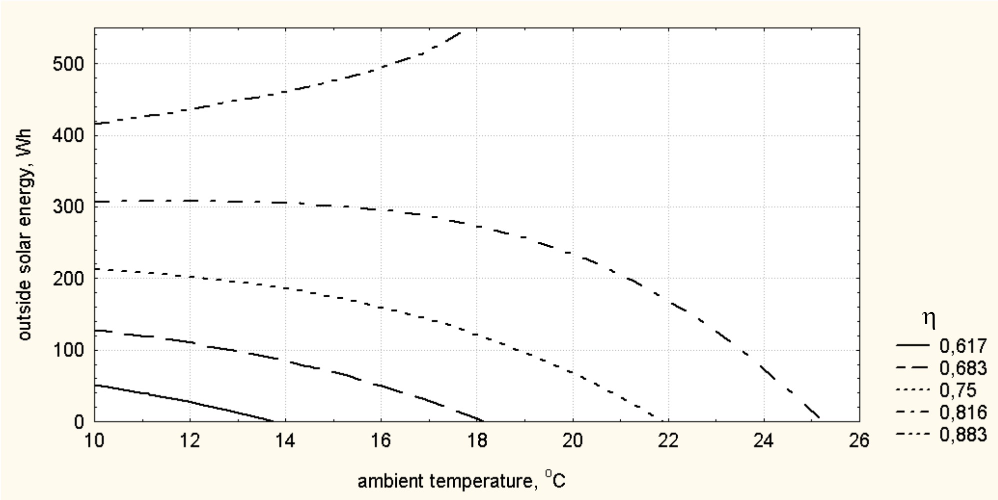

Fig. 6. Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for vacuum collectors (liquid volume equivalent to 1.25m^3).

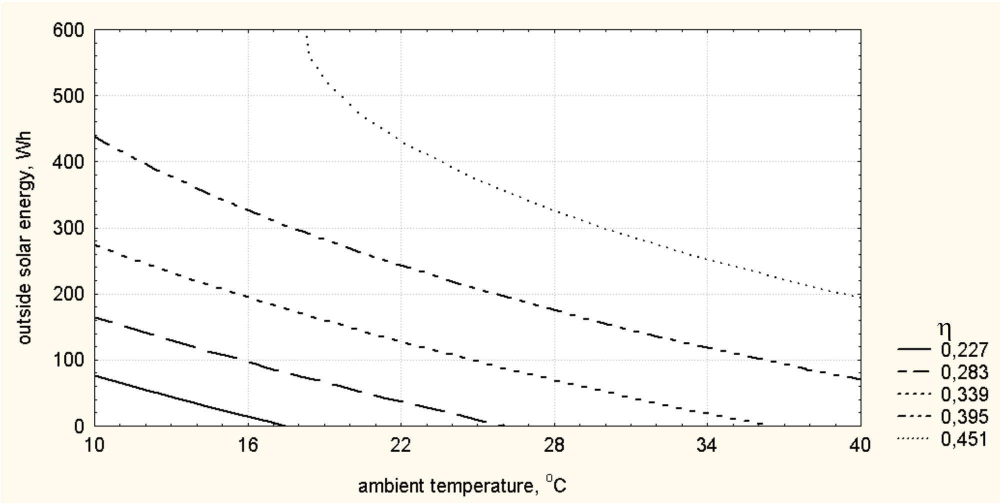

Fig. 7. Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for flat collectors (liquid volume equivalent to 3.22m^3).

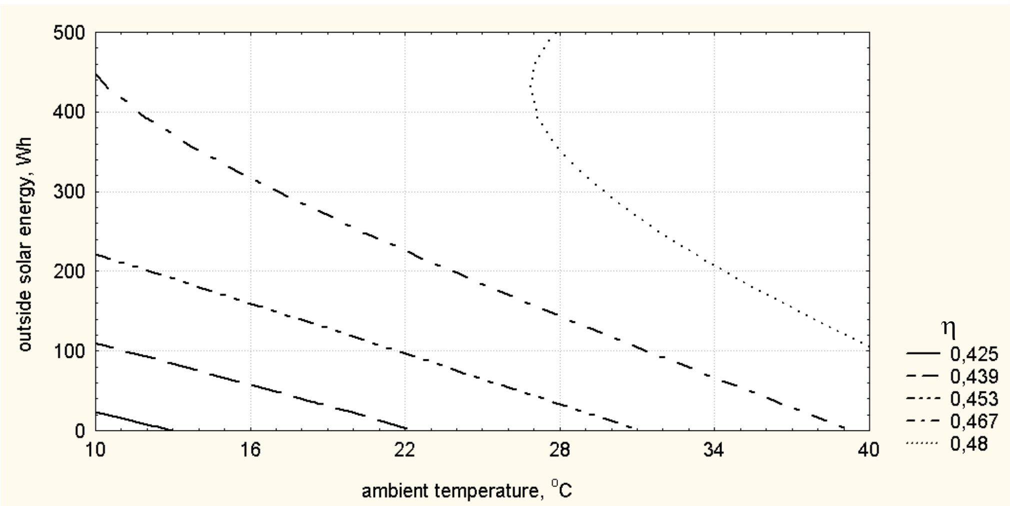

Fig. 8. Impact of surrounding temperature and the sum of solar radiation on the effectiveness of radiation conversion for vacuum collectors (liquid volume equivalent to 1.78m^3).

rounding temperature. Under test conditions, the average efficiency value for tested collectors kept changing depending on liquid volume in the storage tank for: vacuum collectors – from 0.46 to 0.72 (respectively for tank capacity of 1.25 and 1.78 m^3), and ion the case of flat collectors from 0.4 (tank capacity of 2.25m^3) to 0.6 (for capacity of 3.22m^3). On the basis of obtained data it stems unequivocally that in order to obtain the highest level of efficiency through a solar collector system it is necessary to apply the above indicated liquid volumes in storage tanks. It was also noted that under the same conditions (for vacuum collectors almost 900 measure cycles were performed and 840 cycles for flat collectors), conversion effectiveness for vacuum collectors is on average 18% higher than in the case of flat collectors. The increase in conversion effectiveness as a positive function of temperature increase and the sum of solar radiation is the outcome of the growth in direct radiation share and reduced heat losses from the collector casing into the surroundings.

Following the performance of a series of tests, using non-linear estimation by means of the quasi-Newton method whilst retaining rates of convergence at 0.001, a dependence was found between independent variables (liquid volume in the tank - V_{zb}, surrounding temperature - t_{ot} and the sum of solar radiation energy – R_{sl}). This connection for vacuum collectors is defined by the following dependence:

$$\eta = -0.5 \cdot V_{zb} + 1.24 \cdot t_{ot}^{0,023} + 3.85 \cdot 10^{-5} \cdot \sum R_{sl}^{1,19}; \quad R^2 = 0.87$$

for the scope of application: $1.25 \leq V_{zb} \leq 1.78$ m^3; $10.3 \leq t_{ot} \leq 37.5^oC$; 1.78; $15.2 \leq R_{sl} \leq 525$ Wh

In turn, for flat collectors this connection is expressed as follows:

$$\eta = -0.22 \cdot V_{zb} + 0.52 \cdot t_{ot}^{0,162} + 0.0168 \cdot \sum R_{sl}^{0,448}; \quad R^2 = 0.82$$

for the scope application: $2.25 \leq V_{zb} \leq 3.22$ m^3; $10.3 \leq t_{ot} \leq 37.5^oC$; 1.78; $15.2 \leq R_{sl} \leq 525$ Wh

These forms of dependence were selected on the basis of the largest coefficient of determination. In order to compare measured and calculated efficiency according to the proposed dependencies, in Figures 9 and 10 a global comparison between these values has been presented (for vacuum collectors Figures 9 and Figures 10 and for flat collectors).

Calculated heat penetration coefficient form the tank to the surroundings (from model 4) stood at 2.4 W/m^2K. This illustrates unsatisfactory storage tank insulation.

Assuming the futility of providing all possible approaches, it has been decided to present in Figure 11 sample changes of long-term efficiency ($\square_{med}$) calculated from the model (3) in terms of independent variables (surrounding temperature and sum of solar radiation). These dependencies are obtained for flat collectors and water volume in tanks equivalent to 2.22m^3. Under the test conditions this efficiency changes from 0.21 to 0.52. When analysing all combinations (type of collector, tank liquid volume), this scope ranges between 0.18 to 0.52 (flat collectors) and from 0.23 to 0.61 (vacuum collectors). Smaller values were obtained for larger liquid capacity in the storage tank.

Changes in analysed efficiency are the outcome of reduction in temperature differences (collector temperature, tank temperature – surrounding temperature) and the larger share of direct radiation. The greater the values of these independent variables the smaller the heat loss from the collector, the storage tank and the more efficient conversion of direct radiation.

Summing up the research findings one may state that, apart from their cognitive values (defined under operating conditions), could also be applied. This stems from the fact that in each designed system which stems from its specifics, it is necessary to have an understanding of the efficiency of converting solar radiation into heat. The analysis also shows that vacuum collectors are more effective in converting radiation into useful heat. Conversion efficiency obtained through research demonstrates somewhat lower values than the parameters indicated by the producers of this equipment. However, the difference in the operating effectiveness of flat and vacuum collectors (higher efficiency) analyzed during

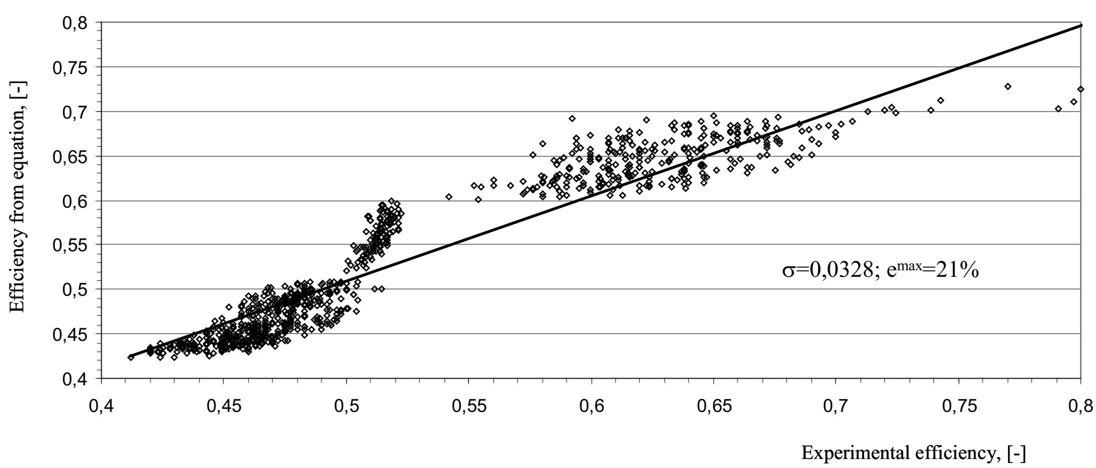

Fig. 9. Comparison between efficiency calculated from the proposed model and efficiency designated from vacuum collector tests.

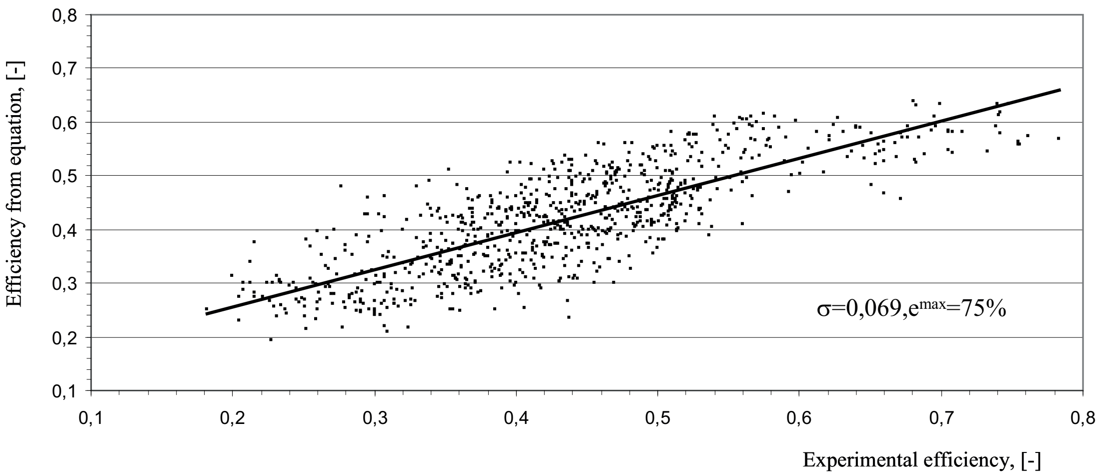

Fig. 10. Comparison between efficiency calculated from the proposed model and efficiency designated from flat collector tests.

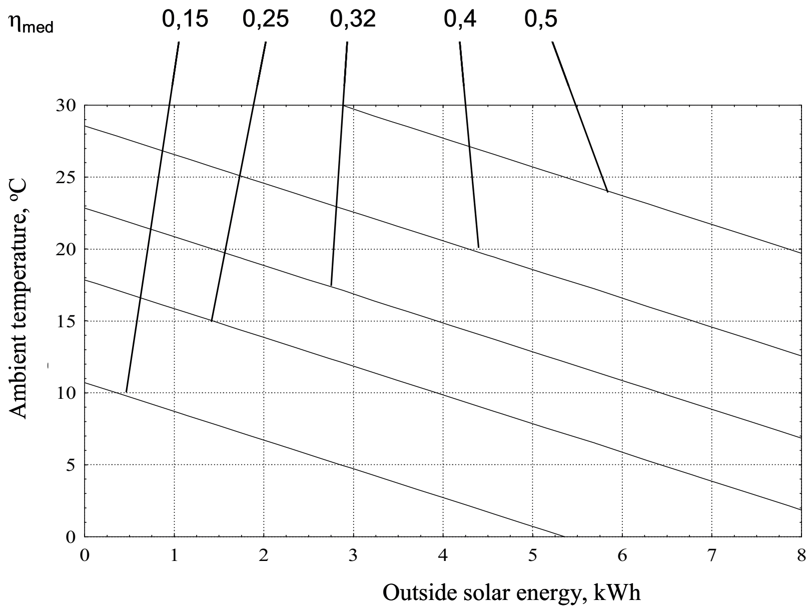

Fig. 11. Long-term efficiency ($\square_{med}$) concerning surrounding temperature and sum of solar radiation energy.

the summer (May - September) depended primarily on the surrounding temperature and solar radiation.

Of course, the attractiveness of the solution and the recommendation of a given type of collector depend on financial analysis. For this reason, in order to illustrate this topic, a calculation was made of payback on financial investment. The analysis took into account the following: The cost of purchasing the installation in entirety (vacuum or flat collectors included), average quantity of solar radiation (according to latitude of 54°), installation operating time and cost of electricity. For calculation purposes, tank capacity corresponding to maximum collector efficiency and total respective solar collector surface (4 flat collectors) of 7.8 m^2 and 4.3m^2 (flat collectors). Analysis findings, assuming that a flat collector set costs PLN 9,000 and a vacuum collector set costs PLN 12,000, indicate that return on investment would be 6.7 years and 6.5 years respectively.

4. CONCLUSIONS

The following conclusions are based on the above analysis:

1. Depending on storage tank liquid volume solar radiation conversion efficiency is between 0.46 and 0.72 for vacuum collectors and between 0.4 and 0.6 for flat collectors.
2. Under comparable experimental conditions, conversion efficiency for vacuum collectors is on average 18% higher than in the case of flat collectors.
3. The model defining the efficiency of solar radiation conversion in vacuum collectors is expressed as follows:

$$\eta = -0.5 \cdot V_{zb} + 1.24 \cdot t_{ot}^{0,023} + 3.85 \cdot 10^{-5} \cdot \sum R_{sl}^{1,19}; \quad R^2 = 0.87$$

for the scope of application: $1.25 \leq V_{zb} \leq 1.78$ m^3; $10.3 \leq t_{ot} \leq 37.5$°C; 1.78; $15.2 \leq R_{sl} \leq 525$ Wh for flat collectors:

$$\eta = -0.22 \cdot V_{zb} + 0.52 \cdot t_{ot}^{0,162} + 0.0168 \cdot \sum R_{sl}^{0,448}; \quad R^2=0.82$$

for the scope of application: $2.25 \leq V_{zb} \leq 3.22$ m^3; $10.3 \leq t_{ot} \leq 37.5^{o}$C; 1.78; $15.2 \leq R_{sl} \leq 525$ Wh

4. Depending on the type of collector and liquid capacity in the storage tank, the daily efficiency of the analysed conversion system is between 0.18 and 0.61.
5. The payback period on financial investment in a solar radiation conversion system depending on the type of collector is respectively as follows: 6.5 years for vacuum collectors and 6.7 years for flat collectors.

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ANALIZA EFEKTYWNOŚCI ENERGETYCZNEJ PŁASKICH I PODCIŚNIENIOWYCH UKŁADÓW KOLEKTORA SŁONECZNEGO

S t r e s z c z e n i e. W artykule przedstawiono wyniki analiz obrazujących zmiany sprawności konwersji promieniowania słonecznego w płaskich i próżniowych kolektorach słonecznych. Określono również wydajność całego systemu opartego na cyklu 24-godzinnym. Na podstawie wyników zostały znalezione modele, które eksperymentalnie określają te efektywność (zbiornik pojemność płynu, temperatura otoczenia i całkowite promieniowanie słoneczne. Modele te zostały również zatwierdzone i potwierdzone jako przydatne do oszacowania wydajności, a zatem przy wyborze powierzchni analizowanych typów kolektorów w systemach korzystających z tego rodzaju urządzeń. Określono również czas potrzebny na zwrot kosztów inwestycji.

S ł o w a k l u c z o w e: płaskie i próżniowe kolektory słoneczne, wydajność konwersji, promieniowanie słoneczne.