



## Influence of solar collector surface on its thermal energy efficiency

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### ABSTRACT:

The manuscript compares the thermal efficiency of solar collectors with various types of the active surface. The research was carried out on a specially constructed measuring stand that maintains repeatable and constant conditions for measuring collectors' thermal parameters. The research results show that a collector's active surface roughening allows for about 12% increase in its thermal efficiency, regardless of whether the collector surface is metallic (raw) or coated with chromium black. The highest increase in thermal efficiency was observed for a collector covered with a chromium oxide plasma-coating, whereby the collector surface was subjected to abrasive blasting. Approximately 19% increase in thermal efficiency was achieved in comparison to the base-collector (copper with a smooth surface – raw surface).

### KEYWORDS:

solar energy; solar; photovoltaics

## 1. Introduction

A collector is a device with a compact, complex structure that uses solar energy to increase the temperature of the medium flowing through it [1]. The heat obtained in this way is transferred to the place of use. It is a device that forces designers to reconcile often-contradictory requirements in order to obtain the highest efficiency while ensuring an adequate price and high thermal efficiency [2]. Each of the collector's components fulfils a number of functions and must be properly selected and prepared. Due to the similar nature of the phenomena that occur during the operation of flat and vacuum collectors, one can focus only on analyzing the impact of surface condition on the overall performance of the collector [3, 4].

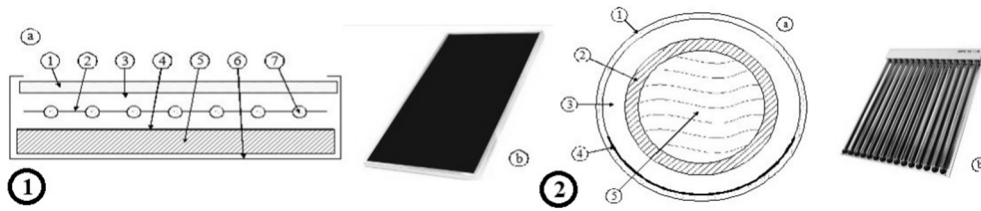
## 2. Construction and function of solar collectors

Two types of solar collectors are mostly used: a flat collector, or an irradiated-vacuum collector (Fig. 1). In both cases, the most crucial role is played by the heating surface that absorbs solar radiation. This surface must be able to withstand high temperatures and have a high ability to absorb solar radiation.

There are several methods to increase the surface absorption coefficient. One of the most frequently used is the blackening of the collector's active surface [1, 2]. However, this method does not provide the optimal value of the absorption coefficient. A much better method is to roughen the collector surface with shot blasting and then blacken the developed surface with chemical-galvanic methods [3-6].

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**Fig. 1.** Schematic view of a flat solar collector and vacuum solar collector construction 1(a): 1 – collector glass, 2 – absorber, 3 – nitrogen gas or air, 4 – aluminum foil, 5 – insulator, 6 – casing, 7 – absorber liquid channels; (b): general view of the flat plate collector; 2(a): 1 – glass pipes, 2 – absorber, 3 – vacuum area, 4 – reflective coating, 5 – absorber channel through which the cooling liquid flows; (b): general view of the vacuum collector [6]

Another more durable method of obtaining a more efficient active surface of the collector is spraying the plasma chromium oxide coating after roughening the surface. Chromium oxide has a high absorption coefficient (an over  $\alpha$  0,9) [7], and the sprayed coating provides high resistance to high temperature and protects the rough surface obtained in this way against corrosion and changes during operation.

### 3. Absorption and emission of thermal radiation by metals and non-metals

It is known that metals with a pure, non-oxidized surface have a low absorption coefficient ranging from a few hundredths to about 0.30. The absorption of non-metals (oxides) is much higher and ranges from 0.35 to 0.90 [8-10].

The absorption of non-metals (oxides) is much higher and ranges from 0.35 to 0.90 [6-8]. For metals, the absorption decreases, and for non-metals, it increases with an increasing wavelength of the incident radiation. If the state of the body surface does not change, it is commonly assumed that the course of the  $a_T$  function is independent of temperature [11, 12].

By roughening the surface or spraying coatings onto metal surfaces, the absorptivity of real bodies' surfaces can be significantly increased [7-9]. Roughening the surface by blasting with a properly selected abrasive causes many small and numerous depressions (cavities) on the treated surface. The shape of such a single cavity is similar to the shape of the blackbody model and, like it, has greater effective absorption than that of the raw material from which the cavity is made. The surface of the cavity opening (emitting opening  $S_o$ ) has a much greater effective absorption ( $\alpha_{T, e, ot}$ ) than the actual absorption ( $\alpha_{T, po}$ ) of the material of the cavity surface, the coefficient can be described by the function (1):

$$a_{T, Eot} = f(a_{T, po}, \vartheta, w) \quad (1)$$

where:  $\alpha_{T, po}$  – values of the cavity surface absorptivity,  $\vartheta$  – cavity shape factor,  $w$  – recess (in).

Cavity ( $w$ ), i.e. the ratio of the cavity opening area ( $S_o$ ) to the actual inner cavity surface ( $S_{rz}$ ) - this relationship is shown in formula (2) and shown in Figure 2 [1]:

$$w = \frac{S_{rz}}{S_o} \quad (2)$$

The effective absorption capacity of the cavity opening ( $\alpha_{T, ef}$ ) increases with an increase in the actual surface ratio to the surface of the cavity opening ( $w$ ) – called the cavity. The surface ( $S_{rz}$ ) should have a constant temperature  $T$  at every point – then its value is the temperature of the radiating surface ( $S_o$ ). The dimensions of the recesses should exceed the wavelengths of the absorbed radiation considerably. If this condition is not met, deviations from radiation laws (Planck, Stefan-Boltzman) may occur. Moreover, temperature measurement errors can be made, caused by, among others: non-isothermal properties of the chamber and other errors accompanying temperature measurements [2].

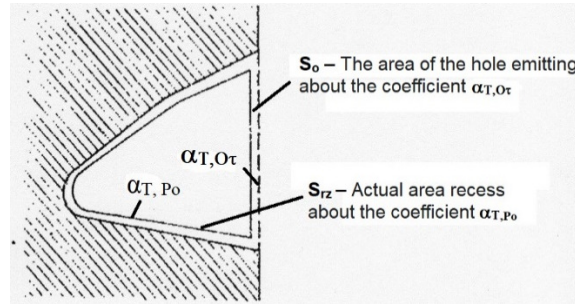


Fig. 2. The cavity constituting the model of the black body [6]

This increase in the sufficient absorption capacity of the rough surface ( $\alpha_T, E_{ot}$ ) caused by the cavity of the surface ( $w$ ) can be described by the formula (3), where the surface roughness  $R_z$  [2] was assumed as the measurable cavity parameter:

$$\alpha_{T,ot} = \frac{w \cdot \alpha_{T,Po}}{1 + (w - 1) \cdot \alpha_{T,Po}} = \frac{\alpha_{T,Po} \sqrt{1 + 4 \left(\frac{R_z}{S}\right)^2}}{1 + \left[ \sqrt{1 + 4 \left(\frac{R_z}{S}\right)^2} - 1 \right] \alpha_{T,Po}} \quad (3)$$

### 3.1. Absorption of metals

The processes of heat absorption by metals involve a thin surface layer several micrometers deep. This exchange is caused by oscillations of atoms and particles on the metal element's surface [4].

The absorptivity of the metal surface decreases with increasing wavelength (very unfavorable for infrared radiation). The total absorptivity ( $\alpha_{T,n}$ ) increases with the temperature increase, consistent with the Hagen-Rubens formulas [2]:

$$\alpha_{(\lambda)} = 0,365 \sqrt{\frac{\rho T}{\lambda_0}} \quad (4)$$

Simultaneously, the author of work [2] established that the reflectivity decreases with the temperature increase, and when the value is the smaller, the cavity ( $w$ ) of the surface is greater. The presence of an oxide layer (even of minimal thickness) on metals significantly increases their ability to absorb and emit thermal radiation, even for stainless steels.

The results of numerous studies [7-9] confirmed that non-metals have a much greater radiation absorption capacity ( $\alpha_T$ ) than metals. Their absorptivity increases with radiation wavelength, although this increase is not as apparent as for metals. The absorptivity of non-metals significantly decreases with increasing temperature. White oxides (Mg, Al, Th,) have relatively low absorption in the wavelength range from 1 to 5-6  $\mu\text{m}$ , however, for 10  $\mu\text{m}$  radiation, their absorption is close to that of the black body. Black oxides (Cr, Co, Ni, Cu, etc.) have a higher absorption value in the near-infrared wavelength range relative to white oxides.

## 4. Materials and method

Three different materials were used for the tests: copper, aluminum and stainless steel, from which model collectors in the shape of squares with a side of 200x200 mm were made. The collectors had one or two tubes through which liquid flowed (Fig. 3) [13-15].

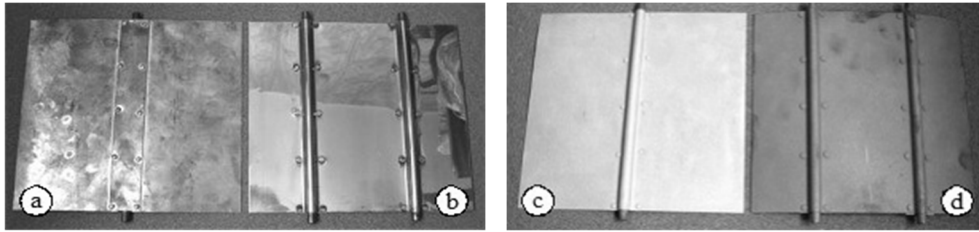


Fig. 3. View of the tested collectors – selected: a) aluminium collector with one tube, commercial surface – raw, b) steel collector with two pipes, commercial surface – raw, c) aluminium collector with one tube, matt surface – shot blasted, d) copper collector with two pipes, matt surface – shot blasted

Preliminary collector tests using the Sun have shown that it cannot be ensured that the experiment will be stable and repeatable. Therefore, it was decided to build a specialized measuring stand whose scheme and general appearance are presented in Figure 4.

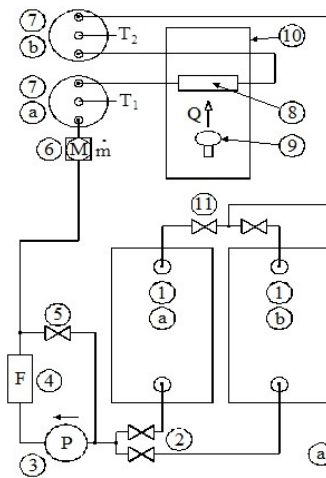


Fig. 4. Diagram of the stand, (1a), (1b) main tanks; (2) flow direction valves; (3) water pump; (4) filter and cooler; (5) pump flow control valve; (6) flow meter; (7a), (7b) buffer tanks measuring the temperature of the liquid flowing through the sample; (8) tested collector – absorber; (9) radiation source – light bulbs; (10) radiator column; (11) flow return valves

The following initial formula was used for the calculation of the size of the stream absorbed by the heated sample [12, 13]:

$$\dot{q} = \frac{\dot{m} \cdot c \cdot \Delta T}{\tau} \quad (5)$$

which, after development and substitution, has the following form:

$$\dot{q} = \frac{c \cdot \rho \cdot (V_A - V_B) \cdot (T_{BSR} - T_{ASR})}{\tau} \quad (6)$$

All the measurements that have been carried out are subject to a systematic error, resulting both from the inaccuracy of the measuring instrument and from the inaccuracy of the reading. Therefore, we are dealing with the following errors:

- $\Delta V_A = \Delta V_B = \pm 0,00001 \text{ m}^3$
- $\Delta T_A = \Delta T_B = \pm 0,01 \text{ K}$
- $\Delta \tau = \mp 0,5 \text{ s}$

The formula for the error value, calculated using the exact differential method.

5. Results

The obtained measurements are compared in Figure 5. In order to increase the influence of the surface condition and the source of the collector material on the choice of the best controller, the thermal efficiency coefficient of the entry panel model (2) was introduced:

$$\eta = \frac{\Delta\dot{q}}{\dot{q}_{bazowy}} = \frac{\dot{q}_{badane} - \dot{q}_{bazowy}}{\dot{q}_{bazowy}} \cdot 100\% \tag{7}$$

where:  $\eta$  – collector thermal efficiency;  $\Delta\dot{q}$  – heat difference between the examined collector and the base-collector;  $\dot{q}_{badane}$  – heat absorbed by the tested collector (test area);  $\dot{q}_{bazowy}$  – non-standard material absorbed by the base-collector (the same as the tested collector, but with a raw surface).

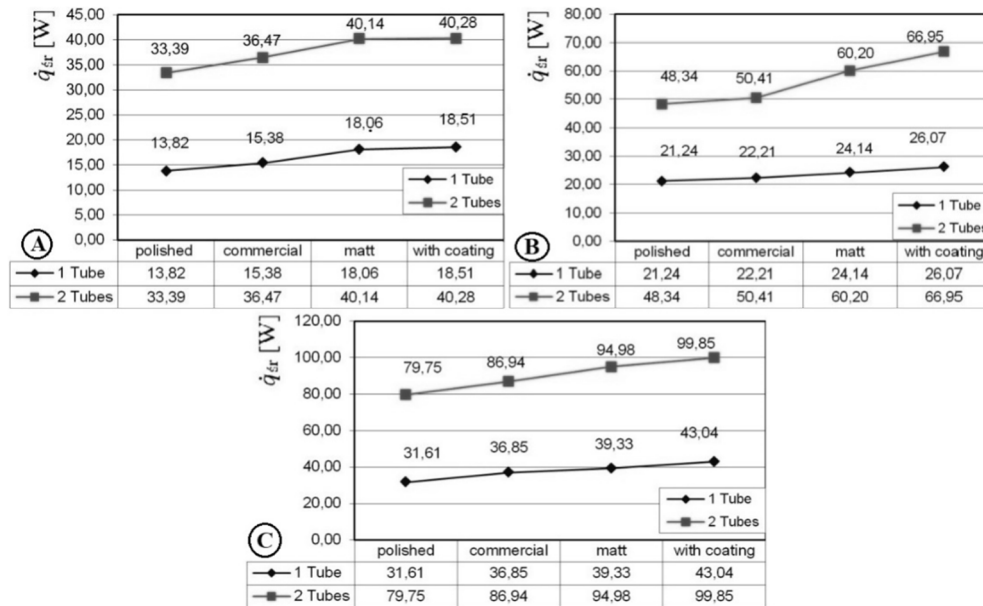


Fig. 5. Comparison of heat fluxes obtained in stainless steel samples (A), aluminium samples (B) and copper samples (C)

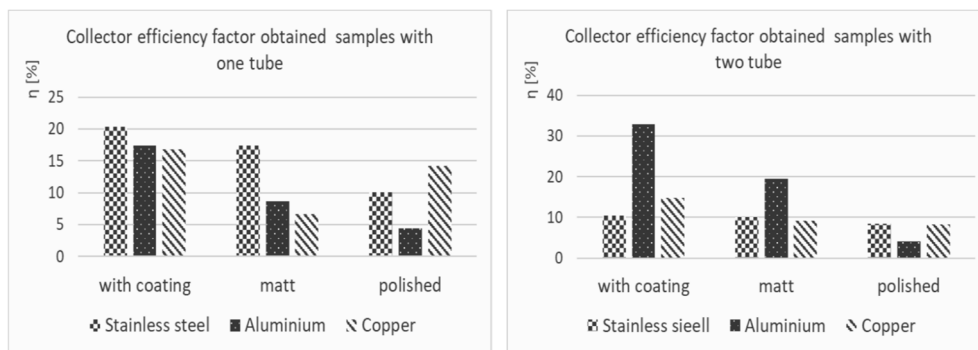


Fig. 6. Comparison collector efficiency factor obtained in stainless steel samples, aluminium samples and copper samples

Figure 6 shows that the most efficient collector is plasma-coated with chromium oxide, followed by a local collector with a roughened surface, and the collector that absorbed the least heat was with a polished surface. The collector with several tubes absorbed 18% more heat than the collector with one tube.

## 6. Conclusion

Results show that the amount of absorption depends on the material of the collector. The most significant amount of heat was absorbed by the collector made of copper, less absorption was shown by the collector made of aluminium, and the least absorption was by the collector made of stainless steel.

The most significant impact on the value of the absorbed material by the tested collector was tested by the volume of plasma-sprayed with chromium oxide into the harvest section, deposits over 30% increase absorption of a suitable base collector made of the same material without other modifications.

The effect of roughening the tested collector's surface was found to increase the update level by about 19% for copper, compared to the base-collector with a raw surface. Since spraying a plasma coating with chromium oxide is quite expensive, almost the same effects of increasing the absorbed final heat were obtained in a collector with a rough surface. Though it must be remembered that it should be abrasive blasting that improves the increase in production costs, but at about a 20% increase in the collector's thermal efficiency. Such an operation can lead to a 15÷20% reduction of the collector's active surface, thus reducing its dimensions and saving the materials used for its construction.

As a result of the conducted tests, the following statements can be made:

- the influence of surface condition within samples made of the same material is clearly visible in the capacity of the absorbed heat flux,
- when we sort the type of surface of the tested samples according to the increasing heat flux, we get the following series of effects of the surface condition:
  - polished surface (the worst results),
  - commercial surface – raw,
  - matt surface – shot blasted,
  - surface with sprayed coating (the best results),
- polishing the surface of the sample worsens the stream of the absorbed heat by an average of 8% compared to the commercial – raw sample,
- roughening the surface of the sample improves the absorbed heat flux by an average of 12% compared to the commercial – raw sample,
- spraying the coating causes an increase in the absorbed heat flux by an average of 7% in relation to the sample with a matt surface and an average of of 19% in relation to the sample with a commercial – raw surface.

## References

- [1] Müller S., Giovannetti F., Reineke-koch R., Kastner O., Hafner B., Simulation study on the efficiency of thermochromic absorber coatings for solar thermal flat-plate collectors, *Solar Energy* 2019, 188, 865-874.
- [2] Wang C., Shi J., Geng Z., Ling X., Polychromic Al – AlN cermet solar absorber coating with high absorption efficiency and excellent durability, *Solar Energy Materials and Solar Cells* 2016, 144, 14-22.
- [3] Neto J., Torres S., Gomes K., Filfo M., Gomes R., Chromium silica co-sputtered graded Cermet for solar thermal collectors, *Solar Energy* 2019, 193, 212-219.
- [4] Dan A., Barshilia H., Chattopadhyay K., Basu B., Solar energy absorption mediated by surface plasma polaritons in spectrally selective dielectric-metal-dielectric coatings : A critical review. *Renew., Renewable and Sustainable Energy Reviews* 2017, 79, 1050-1077.
- [5] Teixeira V., Sousa E., Costa M., Nunes C., Rosa L., Carvalho M., *et al.*, Chromium-based thin sputtered composite coatings for solar thermal collectors, *Vacuum* 2002, 64, 299-305.
- [6] Wang X., Gao J., Hu H., Zhang H., Liang L., Javaid K., *et al.*, High-temperature tolerance in WTi-Al<sub>2</sub>O<sub>3</sub> cermet-based solar selective absorbing coatings with low thermal emissivity, *Nano Energy* 2017, 37, 232-241.

- [7] Vijaya G., Muralidhar, M. Krupashankara M., Srinivas M., Kulkarni R., Development and Analysis of Tungsten-Aluminium oxide based solar thermal multilayer Coating, *Materials Today: Proceedings* 2018, 5, 2547-2554.
- [8] Nunes C., Teixeira V., Collares-pereira, M. Monteiro A., Roman E., Martin-Gago J., Deposition of PVD solar absorber coatings for high-efficiency thermal collectors, *Vacuum* 2002, 67, 623-627.
- [9] Suriwong T., Banthuek S., Bunmephiphit C., Wamae W., Andemeskel A., The effect of annealing temperature on selective solar absorptance of Ni-Al coating prepared by flame spray technique, *Materials Today: Proceedings* 2018, 5, 14886-14891.
- [10] Soum-glaude A., Gal A., Bichotte M., Escape C., Dubost L., Optical characterization of TiAlN<sub>x</sub>/TiAlNy/Al<sub>2</sub>O<sub>3</sub> tandem solar selective absorber coatings, *Solar Energy Materials and Solar Cells* 2017, 170, 254-262.
- [11] Selvakumar N., Barshilia H., Review of physical vapor deposited ( PVD ) spectrally selective coatings for mid- and high-temperature solar thermal applications, *Solar Energy Materials and Solar Cells* 2012, 98, 1-23.
- [12] Soum-glaude A., Bousquet I., Bichotte M., Quoizola S., Thomas L., Flamant G., Optical characterization and modeling of coatings intended as high temperature solar selective absorbers, *Energy Procedia* 2014, 49, 530-537.
- [13] Hobler T., *Ruch ciepła i wymienniki*, WNT, Warszawa 1986.
- [14] Drzymała A., Knap T., Sanecki P., Więcek P., Szymański A., *Przyjazne środowisku źródła energii*, Fundacja N, Rzeszów 2002.
- [15] Morel S., Jasinski J., Zloto T., Stryjewski P., The influence of a radiated heat exchanger surface on heat transfer, *TEKA Comm Mot Energ Agric* 2015, 15, 51-56.

## Wpływ stanu powierzchni kolektorów słonecznych na ich sprawność cieplną

### STRESZCZENIE:

W artykule wyznaczono i porównano sprawność cieplną kolektorów słonecznych o różnej powierzchni czynnej wykonanej z miedzi, aluminium i stali nierdzewnej o różnym stanie powierzchni: polerowanej, handlowej, chropowatej i z natryskaną powłoką. Badania przeprowadzono na specjalnie zbudowanym stanowisku pomiarowym, pozwalającym zachować powtarzalne i stałe warunki pomiarów parametrów cieplnych kolektorów. Z badań wynika, że samo schropowacenie powierzchni czynnej kolektora spowodowało około 12% wzrost jego sprawności. Największy wzrost sprawności cieplnej otrzymano dla kolektora miedzianego pokrytego plazmowo tlenkiem chromu, otrzymano 19 % wzrost sprawności cieplnej w porównaniu do kolektora bazowego (miedzianego o powierzchni handlowej – „surowej”).

### SŁOWA KLUCZOWE:

energia słoneczna; solary; fotowoltaika