DEVELOPMENT AND INVESTIGATION OF SOLAR COLLECTORS FOR CONVERSION OF SOLAR RADIATION INTO HEAT AND/OR ELECTRICITY

by

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This article describes work on two projects of the National Energy Efficiency Program NEEP 709300036 and NEEP 271003 titled "The model of solar collector for middle temperature conversion of solar radiation in heat" and "Development and investigation on hybrid solar collector for heat and electricity generation", respectively.
This first project deals with solar collector that transfers solar radiation in heat in area of middle temperature conversion (at temperatures above 100 ºC). During entire year it can realize significant saving of electric energy used for preparation of warm water and in central and district heating.
During work on the second project, two hybrid solar collectors, their installation, mathematical model, software, and experimental set-up were designed and realized. The first collector had the photovoltaic panel located above the absorber and the second collector had the panel located on the absorber. For both collectors, the results show that efficiency of fossil fuel replacement is 85%.

Key words: *energy source, solar energy, concentrator, hybrid solar collector, heat, electricity, efficiency*

Introduction

Many factors have decided that between new (renewable and ecological), and conventional (non-renewable and non-ecological) energy sources, the first choice is always conventional energy source with profit as the only important criterion. For example, high profit is obtained by monopoly on strategic crude-oil reserves. New energy sources are hardly used.

It is known that solar energy of $175 \cdot 10^9$ MW reaches the earth, the power that is 10^5 times greater than that of all power plants on the earth. Is the used solar power at the order of one percent?

Can be mandatory to construct a residential house with solar collectors, and/or use incentives from government or municipalities?

Solar energy devices generate heat and/or electricity from "free" solar energy substituting fossil fuels. These devices do not emit SO_2, NO_x, and CO_2. In many countries such as EU, the use of solar energy is greatly supported. Participating organizations would acquire knowledge on the used technology and its mass production would help to protect environment and provide jobs solving social problems.

Here, we describe the research performed in two projects: NEEP 709300036 and NEEP 271003.

Project NEEP 709300036 (at University of Niš) was titled ”The model of solar collector for middle temperature conversion of solar radiation in heat”. The project deals with concentrating or evacuated solar collectors (PSE) that convert solar energy into heat that can be used in processes with the temperatures above 100 °C. Here, we describe solar collector CPC-2V and its measurement installation [1-2].

Project NEEP 271003 (at University of Kragujevac) was titled “Development and investigation on hybrid solar collector for heat and electricity generation“. To in crease solar energy transformation efficiency, we developed hybrid solar collectors that simultaneously generate heat and electricity and its installation. We built two different solar collectors. In addition, we designed software and measurement stand and these collectors are investigated for their energy characteristics. The investigation results are communicated in several reports, conferences publications [3-6].

Project NEEP 709300036 – Solar collector for middle temperature conversion

Basic features of the concentrating PSE

The device which increases the density of the solar radiation on the absorber of the collector above environment level is called solar energy concentrator (focusing PSE). Its major feature is concentration ratio (CR), as the ratio of effective surface of aperture and surface of PSE absorber. Concentration is done by using reflecting and refracting parts, to focus solar flux to a point or a line of a collector component. Because of this, their names are: point- and line-concentrator, respectively. The point concentrators belong to the group of PSE for high-temperature conversion of solar radiation into heat, whereas line-concentrators belong to the group of PSE for middle-temperature conversion (100-400 °C) of solar radiation into heat. Middle temperature-conversion concentrators don’t require either sharp focus or precise tracking of the apparent path of the Sun. They can be stationary or with occasional rotation of the collector or absorber.

Basic concept of CPC-2V collector

When choosing a design for the concentrating collector for middle temperature conversion of solar radiation into heat, the device must fulfill basic principle of “3E”, *i. e.* the device must be: Ecological, Efficient, and Economical in construction, and exploitation. Taking this into account, a concept of solar energy concentrator (labeled here as CPC-2V) based on Vinston concentrators has been suggested in [1]. CPC-2V cross-section presented in fig. 1 shows that the shape of its reflector is not parabolic. Geometry may achieve the reflector-curve design with CR up to 10. An increase in CR (good feature) results in a decrease of the reception angle of direct radiation $2\Theta_{max}$ (bad feature).

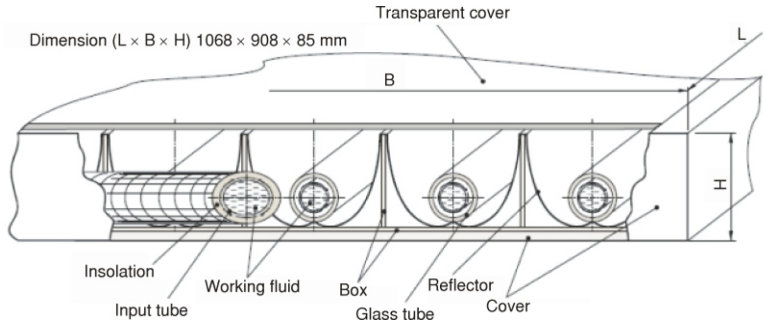

Figure 1. Part of cross-section of the collector CPC-2V for middle temperature conversion of solar radiation into heat

Basic features, and at the same time, advantages of CPC-2V in comparison to devices with similar purpose, are derived from the following requests: (1) to eliminate devices for collector motion – stationary; (2) to focus sun radiation along the pipe of absorber without complex optical instruments; (3) to receive solar radiation optimally for the annual period and for the position of 43° N – south orientation with collector inclination of 45°; (4) to use maximally direct solar radiation in December – with $2\Theta_{max} = 110°$, based on the average daily sun position (sunrise at 7 h 50', azimuth 125°, sunset at l6 h 10', azimuth 235°; day length 8 h 20', with angle of 45°); (4) to receive diffuse solar radiation optimally during the whole year, (5) to minimize heat losses – enabled by selection of the suitable selective absorber ($\alpha_a/\varepsilon_a > 4.5$) and evacuated glass shell, whereby conductive and convective losses from the pipe surface of absorber are eliminated, (6) to protect collector and its parts from external impact, and (7) to design the frame and casing by reducing mass and price of the device.

Particularly, sensitive aspect of PSE is possibility to receive diffuse solar radiation during its operation. With CPC-2V collector design, $2\Theta_{max} = 110°$ is provided. This enables that PSE would also receive diffuse radiation, especially because the specific curve of reflection would enable rays to reach absorber directly or after one or more reflections (fig. 2).

Geometrical analysis of the reflection curve of PSE for any reception angle –55-55° can prove that incident ray always falls at the absorber after one or more reflections.

Optical losses of calibrated CPC-2V collectors are negligible because of its wide reception range and possibility to use inaccurate optical elements, explained with the optical analysis in [1, 2]. Behavior of solar collector CPC-2V, can thereby be anticipated and calculated under specific conditions, but the real effect can be determined after measurements under real conditions.

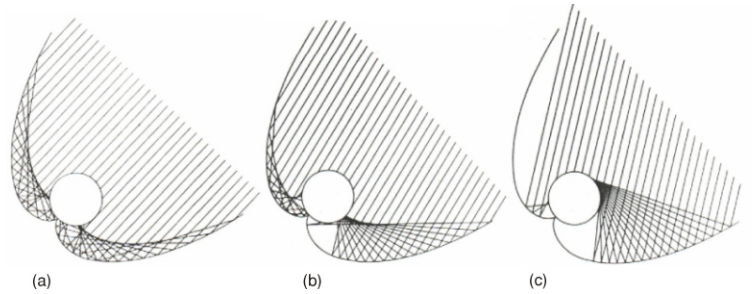

Figure 2. Path of the rays to the absorber can be direct or with one or more reflections

Regarding to ongoing selection of materials used for the parts of the device (reflector, absorber, and transparent cover), analysis of the heat transfer will be presented after prototype completion. For that purpose, tool for modeling and production of base reflection surface has been constructed, and the surface is going to be covered with reflection layer.

Description of the measurement installation

Installation for experimental measurements shown in fig. 3 is completed at the Faculty of Mechanical Engineering in Niš, within the Laboratory for Thermal Engineering. Thermal investigations of a solar energy collector with water as a heat transmitter are provided.

Investigations of thermal features of PSE (according to JUS M.F5.110, point 4.6) are performed at the experimental installation for external tests by using a closed circulation loop. Its scheme is presented on fig. 4.

Figure 3. Test installation

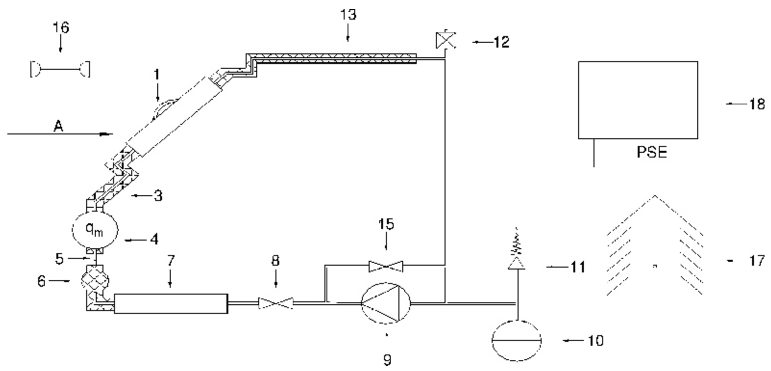

Figure 4. Test installation for external tests with a closed circulation loop
1 and 2 – pyranometer, 3 – temperature probe at PSE input, 4 – flow meter, 5 – transparent tube, 6 – filter, 7 – temperature controller, 8 – valve, 9 – pump, 10 – expansion vessel, 11 – safety valve, 12 – purge valve, 13 – temperature probe at PSE output, 14 – isolation, 15 – counterflow valve, 16 – anemometer, 17 – surrounding temperature

In the installation in fig. 4, pump (9) pushes water through valve (8), temperature controller (7), filter (6), transparent tube (5), and flow meter (4). At the level of the collector median, a pyranometer (1) for measuring solar radiation is set together with the anemometer (16). At the input and the output of the collector are temperature probes (3) and (13). For safety of the installation, the safety valve 11 and the expansion vessel 10 are added. With a particular probe, within the TESTO 454 system, surrounding temperature is measured.

For the purpose of measuring the flow rate of working water at the PSE input, TA-STAD measuring valves are used. Temperature measurements are performed with temperature sensors Pt100, and previously calibrated chromel-alumel thermocouples (the diameter of thermocouples was 0.2 mm). External temperature is measured with a system TESTO 454 and checked with a mercury thermometer.

Wind velocity, relative humidity, and temperature, as relevant parameters used to represent the state of environment conditions, are determined with the measuring system TESTO 454 with anemometer, relative humidity, and temperature probes. Accuracy of each probe is 1% according to manufacturer. Measurement of isolation is performed with Kipp&Zonen CM11 pyranometer, with 3% accuracy.

Project NEEP 271003 – Hybrid solar collectors

The deliverables of this research are the following: (1) prototypes, (2) demonstration plant, (3) measurement set-up, (4) simulation software, and (5) testing and monitoring data.

Prototype construction [3]

Two prototypes of hybrid solar collectors would be constructed. The prototypes would consist of glass cover, photovoltaic panel, absorber, and thermal insulation. They will differ in location of the photovoltaic panel. In SVPA prototype, the photovoltaic panel will be put directly on the absorber as it is shown in fig. 5a, and in SPVA prototype, the photovoltaic panel will be put above the absorber as it is shown in fig. 5b. Here, we will describe the characteristics of the applied photovoltaic panel, applied absorber and entire prototype of the solar collector.

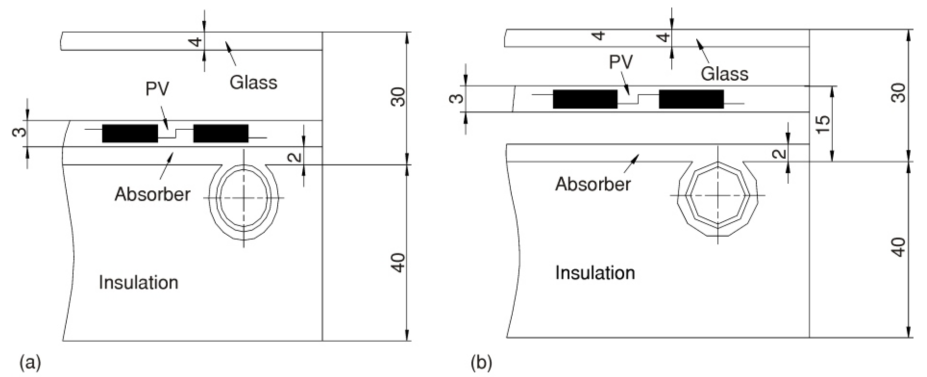

Figure 5. Cross-section of hybrid collectors of types (a) SVPA and (b) SPVA

As a photovoltaic panel, the bifacial panel is used with two faces. It is transparent as the part of solar radiation is transferred through the panel. Its both faces react to light and transform solar energy to electric energy. Because of this property, this panel differs from the conventional photovoltaic panels that have only one face and are not transparent. At the front side of bifacial panel, the solar cells are protected with glass resistant to braking. On the beck side, these cells are protected with a transparent protection film. At their front side, solar cells produce twice more electrical energy than that at the back side. From the photovoltaic panel, the obtained electric energy is transferred via cables and connectors to the battery.

To obtain needed electric energy, we use one bifacial photovoltaic panel of type MSWb 40(12)125 per one hybrid solar collector. Its dimensions are $598 \times 587 \times 38$. Some characteristics of electrical energy generated by this panel are given in tab 1.

An absorber transfer solar energy (heat) to water that circulates inside the absorber. Absorber has the same dimensions as corresponding photovoltaic panel. The absorber is made from 6 special aluminum profiles with the coefficient of absorption of 0.95, and coefficient of reflection of 0.14. Al profiles are specially modeled and electrochemically covered by selective film. There are 6 parallel copper pipes (15/ 13) inside the absorber. These pipes start from a common copper pipe (22/ 20) outside the absorber and return to other common copper pipe outside the absorber. Thermal insulation is hard-pressed mineral wool covered by reflective Al plate. Bottom protection plate is 0.5 mm Al plate. Water volume in absorber is 0.538 liters.

Table 1. Parameters of electrical energy generated by MSWb 40(12)125

Parameters	Front	Back
Power 5%, [W]	40	24
Rated current, [A]	2.35	1.41
Current of short circuit, [A]	2.70	1.75
Voltage of open circuit, [V]	21.6	21.2

Rated voltage is 17 V and nominal voltage is 12 V

Construction of demonstration plant with assembled prototypes [4]

Figure 6 shows the outdoor part of installation for use of hybrid solar collectors. The collector faced south side with the slope of 34° which was the best position of collector for summer.

Figure 7 shows the indoor part of installation of hybrid solar collectors. The installation has two parts: one for heating of domestic water and another for using of generated electricity. In the first installation part, pump pushes collector water (mixed with glycol) to collectors. In the collector absorbers, this water is heated by sun and then in the water tank, the water is cooled by tank water. In addition, in the circuit of the collector water, there are different valves, purge valve, expansion valve, and expansion tank. Water from main is heated in tank by the collector water and directed where needed. In the second part the direct current electricity generated by photovoltaic panels goes to regulator to fill the battery. From the battery, electricity may be taken to device that transforms direct current to alternate current as is used to run a fluorescent light bulb or refrigerator.

Figure 6. Outdoor part of installation of hybrid solar collectors

Figure 7. Indoor part of installation for use of hybrid solar collectors

Measurement set-up[5]

The measurement system was constructed to measure the available global solar radiation, generated electrical energy, and generated heat. These quantities were necessary to calculate the heat efficiency, electrical efficiency, and efficiency to replace fossil fuel. The schema of the measurement system is given in fig. 8.

First, global solar radiation in W/m^2 was measured by pyranometer connected to SOLRAD integrator 990301.

Second, the generated electrical energy was measured for both solar panels: SP1 and SP2. SP1 is the solar panel of hybrid solar collector 1, and SP2 is the solar panel of hybrid solar collector 2. SP1 supplies the electricity to consumer PT1 and SP2 supplies electricity to consumer PT2. For each panel, the generated electrical energy was calculated by from the measured values of the electrical voltage and electrical current.

Third, the domestic hot water was heated in the boiler by using water heated by sun in the hybrid solar collector inside the absorber. Heat is calculated from the measured values of temperatures and flow rate. The measured temperatures were inlet and outlet temperatures of water to solar collector (Tu, and Ti). The volume flow rate for this water is obtained by turbine flow meter.

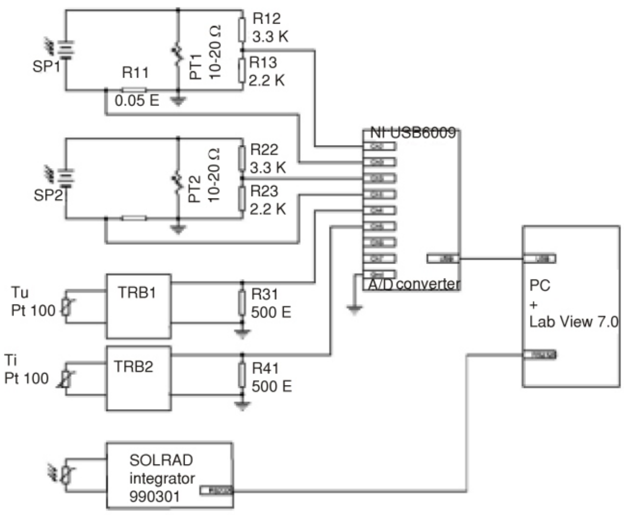

Figure 8. Schema of measuring system
SP1 – hybrid solar collector 1, SP2 – hybrid solar collector 2, PT1 – electricity consumer 1, PT2 – electricity consumer 2, Tu – temperature of inlet water (from hybrid solar collector), Ti – temperature of exit water (after heat exchanger), TRB1 and TRB2 – converters of temperature to electricity signal

Analog signals of current, voltage, Tu, and Ti were transformed to digital signals in A/D converter NI USB 6009 and recorded in the computer by using software Lab View 7.0.

Construction of software and software simulation of operation of demonstration plants and prototypes [5]

We performed three software simulation analyses.

– Comparison of heat energy efficiency of hybrid solar collector and common solar collector for different construction parameters by using developed analytical formulas.
– Comparison of energy gain of five different collectors at yearly level.
– Analyses of yearly operation of installation of hybrid solar collectors.

For the first analyses, the general conclusion is that heat energy efficiency (η) of hybrid solar collector is lower than that of common solar collector. The following construction parameters are investigated.

– Coefficient of emission of photovoltaic panel of hybrid solar collector and absorber of common solar collector. Higher coefficient of emission yields lower η.
– Coefficient of absorption of photovoltaic panel of hybrid solar collector and absorber of common solar collector. Higher coefficient of absorption yields higher η.
– Quality of thermal contact between absorber and pipes with flowing water. Better thermal contact yields higher η.
– Thickness of the heat insulation at the bottom of the solar collector. Its higher value yields higher η.
– Temperature coefficient of photovoltaic panel. Its lower value yields higher η.
– Efficiency of photovoltaic panel. Its lower value yields higher η.

For the second analyses, we investigated the operation of five different solar collectors and their energy gain at the yearly level. It is found that the highest quantity of heat is obtained with common plane solar collector. The highest yearly quantity of electricity is obtained by hybrid solar collector that has transparent photovoltaic panel that covers collector instead of glass cover. The same is valid for the total energy (heat + electricity).

For the third analyzes, we analyzed operation of hybrid solar collector at yearly level for water tanks of different characteristics. It is found out that when the volume of storage tank is higher and nominal heating temperature lower then the used solar energy to heat water in the tank is higher.

Testing and monitoring data on the prototype and demonstration plant for different properties of prototype [4]

The two prototypes were developed where in both of them one photovoltaic panel was put in front of the absorber. In the first prototype the panel was on the absorber and in the second prototype the panel was put on the absorber. The second solution proved more effective in electricity production. The measurement results show that efficiency of electricity production is around 14% and efficiency of heat production is around 54%, and efficiency of fossil fuel replacement is around 85%. The efficiency of the electricity production proves to be higher than that of electricity production by photovoltaic panels, whereas efficiency of heat production proves to be lower than that with single absorber. The efficiency of fossil fuel replacement is definitely higher than that for the both devices.

Conclusions

This article describes research on two projects NEEP 709300036 and NEEP 271003.

In the first project, the demonstrated design of the focusing PSE enables to receive incident solar radiation with an angle of 110° at CR = 1.38 specially adapted to operate during colder months. With additional upgrade of reflection surfaces, solar flux can be additionally increased. Required thermal examinations of this collector at experimental installation at Faculty of Mechanical Engineering in Niš will reveal the real optical and thermal effects of PSE.

In the second project, two hybrid solar collectors are constructed together with their installation, mathematical model, and experimental set-up. These collectors had a photovoltaic panel in front of the absorber. The developed installation enabled the solar energy to heat water in the boiler and to produce electricity that will run fluorescent lumps and/or a refrigerator. The measurement results show that efficiency of electricity production is around 14% and efficiency of heat production is around 54% and finally efficiency of fossil fuel replacement is around 85%.

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References

[1] Nikolić, B., Laković, S., Stefanović, V.: Utilization of Solar Energy Concentrators in the Area of Middle-Temperature Conversion (in Serbian), *Proceedings*, 26th Air Conditioning, Heating and Cooling Congress, Belgrade, 1995, pp. 29-40

[2] Stefanović, V., *et al*., Report I, II, and III (in Serbian), National Project NEEP 709300036, Faculty of Mechanical Engineering, University of Niš, Niš, Serbia, 2004-2005
[3] Bojić, M., Despotović, M. Development of Hybrid Plane Solar Collector (in Serbian), *Proceedings on CD*, 12th Symposium of Heat Engineers of Serbia and Montenegro, Soko Banja, Serbia, 2005
[4] Bojić, M., Taranović, D., Demonstration Installation for the Hybrid Plate Collector (in Serbian), in: Alternative Energy Sources and Future of Their Application, Montenegro Academy of Science, Podgorica, Montenegro, 2005, pp. 97-103
[5] Bojić, M., *et al.*, Hybrid Solar Collector: Realization and Measurements (in Serbian), Elaborate #4 of Project 271-003: Development and Investigation on Hybrid Solar Collector for and Electricity Generation, Faculty of Mechanical Engineering, University of Kragujevac, Serbia, 2005
[6] Bojić, M., *et al*., Simulation of Operation of Hybrid Solar Collector with Results (in Serbian), Elaborate of Project 271003: Development and Investigation on Hybrid Solar Collector for and Electricity Generation, Faculty of Mechanical Engineering, University of Kragujevac, Serbia, 2005

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