A PROTOTYPE RECEIVER FOR MEDIUM TEMPERATURE CONVERSION OF SOLAR RADIATION TO HEAT [*]

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Abstract. *Solar energy can be utilized as the energy source for many high quality processes operating at temperatures above 100 oC. The efficient conversion of solar radiation to these temperature levels into the heat requires the use of concentrating or evacuated solar collectors. In this paper, a concept of solar receiver prototype (marked as CPC-2V) is described for area of middle temperature conversion of solar radiation in heat. The prototype has high efficiency, low price, possibility of its production in small and middle companies, and wide distribution. Its application in a good part of year (or entire year) would mean significant savings of electric energy which is now used for preparation of warm water, and in central and long-distance heating systems.*

Key words: *energy source, solar radiation, solar energy concentrator, prototype*

1. INTRODUCTION

Critical energy situation forces mankind to reconsider thoroughly all possibilities given by renewable energy sources, and our present knowledge and technology. Unfortunately, many factors have decided that between renewable and ecological, and non-renewable and expensive energy sources, the first choice is always non-renewable energy source. The second half of the last century and the beginning of this century clearly show that high profit is the only important criterion, crucial to project a global energy image

and to set trends. Of course, high profit is gained by monopoly on strategic quantities and reserves. For example, fossil fuels, as the most important conventional fuels, are usually in possession by a small group of undeveloped countries.

For example, only 0.5 billionth part of radiated solar energy reaches the Earth, which equals the power of 175×10^9 MW. This power is 10^5 times greater than that of the all power plants on earth. How much of this energy is used effectively? Is there a number small enough to describe this? If we add the energy produced from wind, geothermal potential, biomass, sea waves, etc., the number would not be much bigger. How can we change this fact? How can we improve our environment?

Is it possible to construct a new building, for example, a residential house, with an obligation to install solar energy collectors and benefit from state, government, competent ministries, or town (municipalities) together? Would it be useful for the society?

In this paper it is proposed to use solar energy as it would be proposed to use other ecological and renewable energy resources. When considering utilization of solar energy, the important weather data are the duration of isolation, and the total and diffuse solar radiation at horizontal (vertical or inclined) surface.

High-quality solar energy can be utilized as energy source for many processes with the temperatures above 100°C. The efficient conversion of solar radiation into heat at these temperature levels requires the use of solar thermal collectors (STC) of concentrating type.

Tchinda et all [1] studied heat transfer in the compound parabolic concentrator (CPC). They developed a model, which in a numerical analysis of heat transfer takes into account the axial heat transfer in the CPC. Then, they studied the effect of various parameters, such as the inlet heat transfer fluid temperature and the mass flow rate, on the dynamic behavior of CPC. The predicted results were compared with experiments.

Norton et all [2] developed a theoretical numerical model of heat transfer that describes the steady-state thermal behavior of a symmetric CPC. For the first time, they investigated the effect of the axial inclination of an east-west oriented CPC and hence the effect of the latitudinal and tracking configuration of the CPC on its performance.

Oommen and Jayaraman [3] designed a system to use a CPC to collect solar energy and to generate steam. They experimentally studied the CPC with water as a heat transfer fluid. A CPC efficiency was tested with different inlet water temperatures. In addition, the CPC efficiency was tested for different conditions of steam generation.

Amaral et all [4] worked on the *SolAgua* project, which aims at the design, development and conception of a concentrating solar collectors that maximally capture solar energy. The CPC developed during this project may heat the water from 45ºC to 60ºC. These results can be achieved to a great extent due to the rotation of the CPC provided by its innovative automatic support. This movement enables it to follow the sun.

Souliotis and Tripanagnostopoulos [11] worked extensive experimental study on solar water heater, which were developed in their laboratory, is presented. These solar devices are integrated collector storage (ICS) systems with single horizontal cylindrical storage tank properly placed in symmetric CPC type reflector trough. In this paper we study ICS solar systems, which differ in storage tank diameter and correlate they thermal performance and the ratios of the stored water volume per aperture area and also per total external surface area.

The experimental results show that ICS system with selective absorbing surface, high transmissivity of the transparent cover and high reflectance of its reflector surface performs efficiently enough, both during the day and night operation, approaching the ther-

mal performance of the corresponding thermosiphonic unit of flat plate collector with selective absorber.

Praumang and Exell [5] developed a method for measuring the performance parameters of a solar thermal collector under non-steady conditions has been applied to an air heater with a truncated compound parabolic concentrator having an aperture area of 1.44 m^2 and a flat absorber with concentration ratio three. These parameters were determined individually in separate experiments, some with and some without solar radiation falling on the collector.

Brunold, Frey and Frei [6] conducted a comparison of three different collectors for process heat applications. A critical point however, is that most of the common transparent insulating materials cannot withstand high temperatures because they consist of plastics. One possibility is to use capillaries made of glass instead of plastics. In this paper measurement results of the collector efficiency and the incident angle modifier (IAM) will be presented for an experimental flat plate collector with a glass capillary transparent insulation.

The so-called middle (medium) temperature systems are suitable for cooling and industrial processes. The aim of this research is to obtain the experimental data in the field of heat transfer inside concentrating solar collectors. The results of this research may have a direct application in the construction of small solar systems but also in the design and construction of large polygeneration systems.

In this paper we describe a concept of solar receiver CPC-2V for area of medium temperature conversion of solar radiation in heat [7-8]. The receiver is designed to collect the both direct and diffuse solar radiation. The receiver is in a prototype phase. Description of measurement installation with its elements is also presented.

2. BASIC FEATURES OF THE CONCENTRATING STC

A. System description

The device which increases the density of solar radiation on the absorber of the receiver above environmental level is called concentrator. Frequent name for solar energy concentrator is also 'focusing STC'. One of the major features of the focusing systems is ratio of concentration CR, which represents the ratio of effective surface of aperture and surface of the absorber of STC. The concentration is improved by using reflecting and refracting parts. They focus solar flux into a point or a line. Because of this, their names are either point-concentrator or line-concentrator. The first can provide much higher temperatures than the second. They belong to a group of STC for high-temperature conversion of solar radiation into heat (indirectly in electric energy), but they demand more complex optical and moving devices. Practically, when it operates, every focusing STC requires change in position to get maximal heat effects from sun radiation. This navigation to sun is automatically done with special devices. This radically increases the price of the STC. Rotation can be done manually, when terms of use are allowing so. The shortcoming of mobile focusing collectors is that they are using only direct sun radiation, and in (most cases) they don't use diffuse solar radiation.

Concentrators of solar energy used in middle temperature conversion of solar energy (100-400°C) 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.

Potential use of these concentrators is very wide: for heating of sanitary water or water for technology and rooms, for metallurgy or industry etc. Devices for middle (medium) temperature conversion with occasional or continual motion include:

- Parabolic Through Concentrator – PTC
- Evacuated Tubular Collector
- Compound Parabolic Concentrator – CPC
- Fresnel Mirror or Lens Collector
- Spiral focusing collector (Fig. 1.)
- Trapezoid focusing collector (Fig. 2.)
- Various types of solar ovens etc.(Fig. 3.)

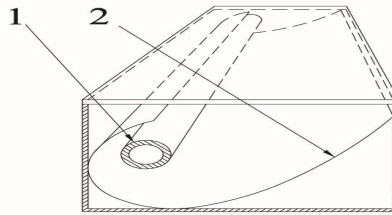Some examples of focusing solar collectors are shown on Figs.1 to 4:

Fig. 1 Spiral focusing collector: 1. absorber's pipe, 2. Spiral reflector
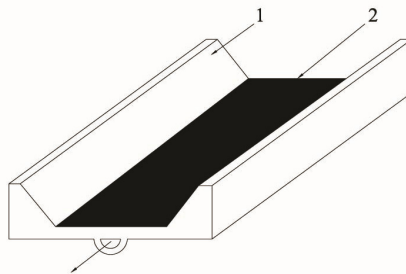

Fig. 2 Absorber of the trapezoid focusing collector: 1. reflector, 2. absorber
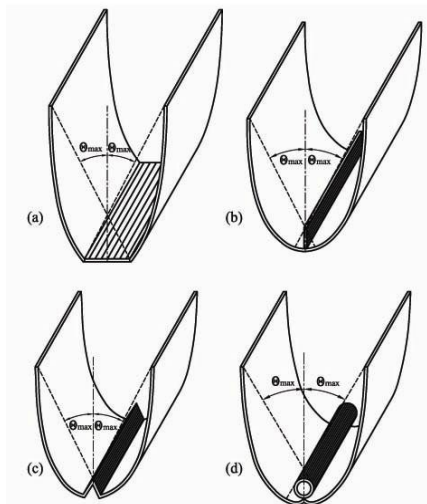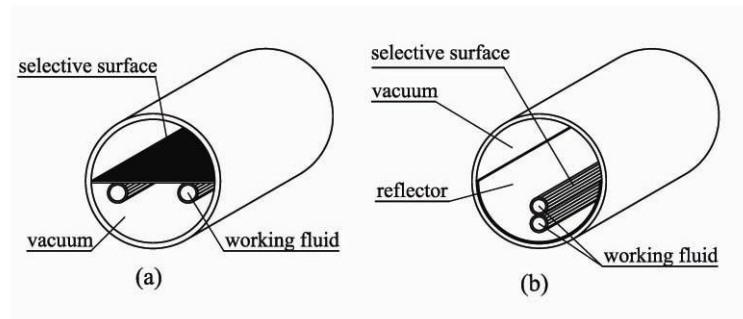

Fig. 3 Variations of CPC collectors

Fig. 4 Various commercial types of the evacuated tubular collectors

3. BASIC CONCEPT OF CPC-2V RECEIVER

When choosing a design approach for the concentrating receiver for middle temperature conversion of solar radiation into heat, the device must fulfil the basic principle of "**3E**", i.e. device must be:

- **E**cological – when it integrally function, and with its components,
- **E**fficient – even when it is not expected from it,
- **E**conomical - in construction and exploitation.

Concerning all of these demands, previous steps, analysis and experiences in the field, a concept of solar energy concentrator has been accepted globally. It is labelled here as **CPC – 2V** [7-8].

Concept of CPC-2V concentrator is originally based on Winston and other complex parabolic concentrators. The shape of reflector is not parabolic, but the nomenclature CPC has been used to label this type of collector. Figure 5(a) shows a cross-section of investigated concentrator CPC-2V. This concentrator also has a tubular receiver and two identical reflectors, one from each side of the tubular receiver. The tubular receiver is a metal tube in the glass tube. The reflector curve at the right hand side consists of three curves A'B', B'C' and C'D. The curve A'B' is located at the top of the reflector curve and the curves B'C' and C'D are located at its bottom. The A'B' is a parabolic curve. The B'C' and C'D are circle parts (Fig. 5a). At Fig.5a, the center of B'C' circle is denoted as O_I', and the center of C'D circle is denoted as O_{II}'. Similar description is valid for the reflector curve at the left hand side in Fig.5a. The actual designs of these curves were obtained by using optical analysis, and graphical methods. The propagations of the incident beams 1, 2 and 3 from the concentrator aperture to the concentrator absorber are also given in Figure 5(a).
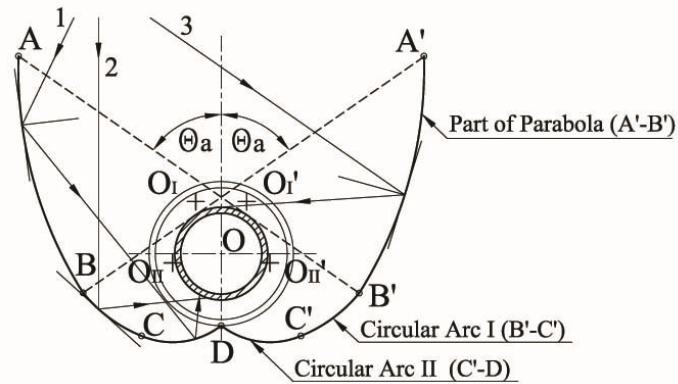
Fig. 5a The construction of the CPC-2V

It should be noted that this concentrator is different to that of Rabl [10]. Figure 5(b) shows a cross-section of CPC adapted from Rabl [10]. This concentrator has a tubular receiver and two identical reflectors, one from each side of the tubular receiver. The tubular receiver in CPC is a metal tube while the tubular receiver in CPC-2V is a concentric tube. Each reflector curve in CPC only consists of a parabola [10], while each reflector curve in CPC-2V consists of parabola and two parts of circles.

The method of generation of the shape CPC in illustrated by Figure 5b, which shows a special case of interest, a cylindrical absorber. Parts *AB* and *AC* of the reflector are convolutes of parts *AF* and *AG* of the absorber [9].
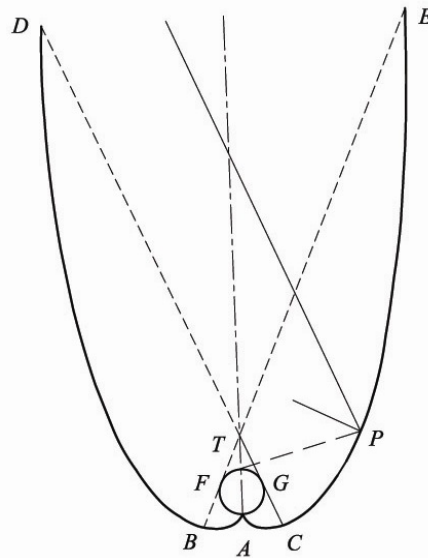

Fig. 5b A CPC for a tubular receiver. Adapted from Rabl (1978) [10]

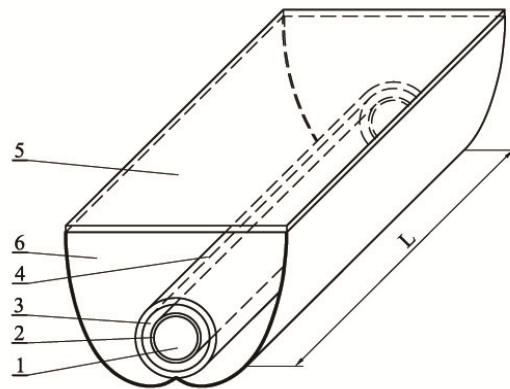Schematic with cross-cut of a CPC-2V module is presented in Fig. 6

Fig. 6 Cross-cut of a CPC collector module: 1. working fluid, 2. absorber,
3. vacuum, 4. glass tube, 5. transparent cover, 6. reflector

Geometry sets conditions for design of the reflector curve (modification of CPC from the Fig. 3. a,b,c,d) which allow the ratio of concentration up to CR=10 by different maximal reception angles of direct radiation $2\Theta_{max}$. An increase in the ratio of concentration (good feature) results in a decrease in the reception angle of direct radiation $2\Theta_{max}$ (bad feature) and vice versa. The increase of $2\Theta_{max}$ leads to the decrease in CR. Established demands for the design of collectors sets the limit for the reception angle and the ratio of concentration, and hereby determine geometry of the reflecting surface, selection of absorber assembly etc.

Basic features (and at the same time, advantages of CPC-2V in comparison to devices with similar purpose) are the following:

- eliminates devices for collector motion - stationary;
- line focus along the pipe of absorber without complex optical instruments essential for sharp focus definition;
- optimal reception of solar radiation for the annual period and for the position of 43° N with south orientation and collector inclination of 45°;
- maximal exploitation of the direct solar radiation in December – which determines the reception angle of $2\Theta_{max}$=110°, based on the average daily sun position (sunrise at 7^{50}h, azimuth 125°, sunset at 16^{10} h, azimuth 235°; day length 8h 20', with vertical position of absorber pipes with angle of 45°)
- optimal reception of the diffuse solar radiation during the whole year (very important during winter)
- maximized cut of 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
- Compactness and preservation of collector and its parts from external impact – selection of transparents, design of the frame and casing, reduction in mass and the price of the device by selection of suitable materials and design simplification.

Particularly sensitive work aspect of CPC concerns the possibility to receive diffuse solar radiation. With CPC-2V receiver design, a reception angle of solar radiation $\Theta_{max}=110°$ is provided.

Geometrical analysis of the reflection curves for the CPC for any reception angle -55° ÷ 55° can prove that an incident ray always falls at the absorber after one or more reflections.

Optical energy losses are negligible with CPC-2V because of the wide reception range and the possibility to use inaccurate optical elements, explained in the optical analysis [7-8]. Behaviour of the solar radiation receiver CPC-2V, can thereby be anticipated and calculated under specific conditions, but the real effect can be determined after measurements under real conditions.

In regard to ongoing selection of materials used for the parts of the device (reflector, absorber, transparent), the analysis of heat transfer will be presented after the prototype completion. For that purpose, a tool for modelling and production of base reflection surface has been constructed, and the surface is going to be covered with reflection layer. Part of cut of CPC-2V is presented in Fig.7.
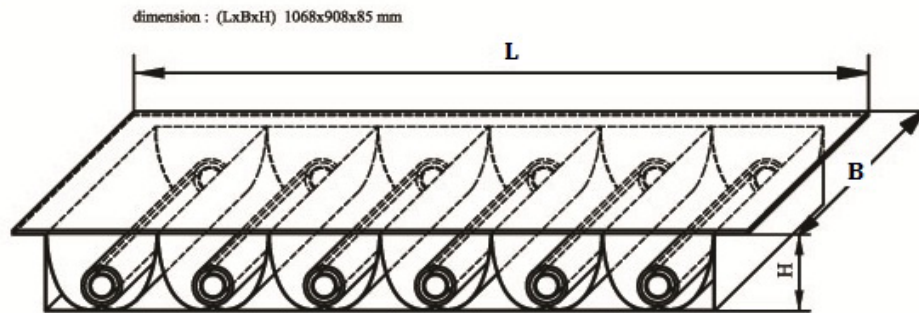

dimension : (LxBxH) 1068x908x85 mm

Fig. 7 Cut through the receiver CPC-2V for medium temperature conversion of solar radiation into heat

4. MEASURING INSTALATIONS

An installation for experimental measurements is completed at the Faculty of Mechanical Engineering in Nis, within the Laboratory for Thermal-technique. Thermal and hydraulic investigations of a solar energy receiver with water as a transmitter of heat are performed.

4.1. Hydraulic tests

a) The Resistance to pressure

As for the hydraulic tests, the first focused on examining the resistance to pressure. Were not observed not tightness and heat damage to the channel transmitters. Then focused on examining the hydraulic resistance of the receiver CPC-2V. The results of this study are shown in Figure 8. Figure 9 is the dependence of pressure drop Δp of the mass flow of fluid $\dot{m}$.

Hydraulic tests of STC include (scheme at Fig. 8):
- Testing of the pressure resistance (according to SRB (JUS) M.F5.110, point 4.1)
- Testing of the hydraulic resistance of STC (according to SRB (JUS) M.F5.110, point 4.2)
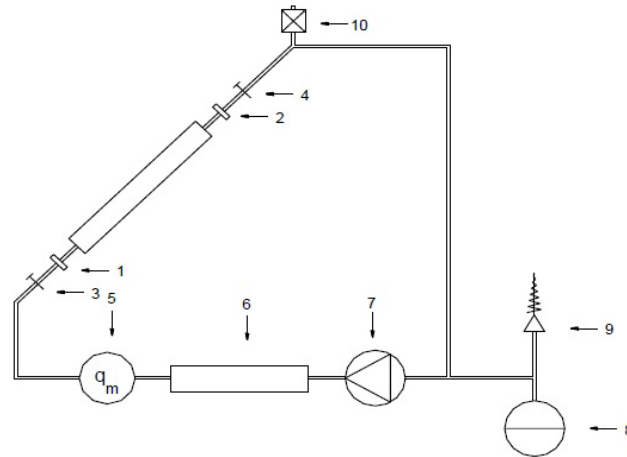
Fig. 8 Testing installation for determining hydraulic resistance of STC – closed (1. and 2. Connection points for differential manometer; 3. and 4. Temperature meter at input and output of STC; 5. Calorimeter; 6. Heater; 7. Pump; 8. Expansion vessel; 9. Safety valve; 10. Purge valve)

A pump 7 pushes a cold water through a heater 6, and calorimeter 5. After that, the cold water enters the STC. At the STC input, as well as at the output, there are the connection points 1 and 2 for measuring pressure with a differential manometer (CBI Hydronics). Nearby to these points, there are temperature sensors (PT100 probe) 3 and 4. At the top of the collector is a purge valve 10, which removes air out of the installation.

Tests are performed at a pressure up to 2.5 bar for collectors operating at atmospheric pressure. For collectors working with pressure of 6 bar, the test is done at a twice bigger pressure. For collectors working with pressure bigger than 6 bar, the tests are done at a pressure 50% bigger than working pressure, but minimally 12 bar.

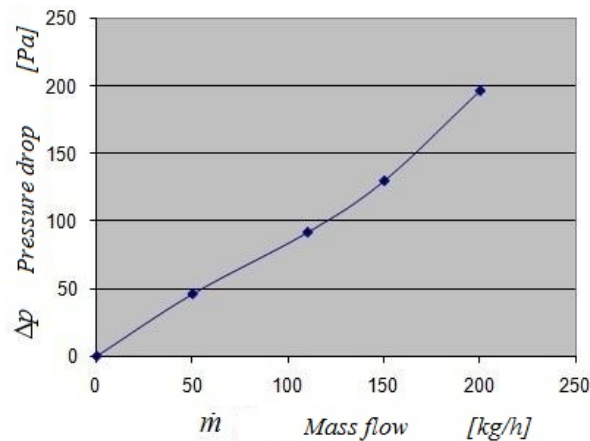To avoid damage, expansion vessel 8 and safety valve 9 are installed in the system

Fig. 9 Pressure drop as a function of mass flow rate of water in the CPC-2V

4.2. Thermal tests

Examinations of thermal features of STC (according to SRB (JUS) M.F5.110, point 4.6) are performed at the line for external tests with a closed circulation loop. Its scheme is presented in Fig. 10.

In the installation on Fig. 10., pump 8 pushes the water through valve 7 (TA-STAD), heater 6, filter 5, transparent tube 4 (for visual control of existing air bubbles in the installation) and calorimeter 3 in STC. At the middle level of the STC, a device 1 for measuring solar radiation is put. If global solar radiation is measured, the device will be pyranometer, direct pirheliometer, and diffuse pyranometer with a shield. In the vicinity of the STC, anemometer 14 (anemometer probe within the system TESTO 454) is set. At the input and the output of the collector, there are temperature sensors 2 and 12 (PT100 probe), and at the highest point of the installation is purge valve 11. For safety of the installation, the pump may close the circulation loop over a counterflow valve 13. The safety valve 10 and the expansion vessel 9 are also added. With a special probe 15, or in this case anemometer-within the TESTO 454 system, the environmental temperature is measured. To assure the safety of the system, an electric boiler has been built to stabilize the system.
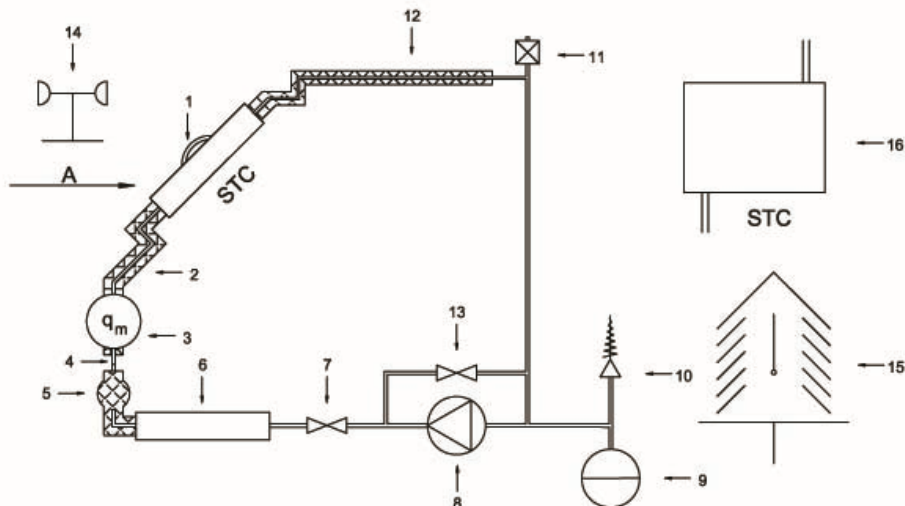

Fig. 10 Testing installation for external tests with a closed circulation loop
(1. Pyranometer Kipp&Zonen CM11; 2. Thermometer at STC input;
3. Calorimeter; 4. Transparent tube; 5. Filter; 6. Heater; 7. Valve; 8. Pump;
9. Expansion vessel; 10. Safety valve; 11. Purge valve; 12. Thermometer at STC
output; 13. Counter-flow valve; 14. Anemometer; 15. Environmental
temperature; 16. STC-Solar thermal collector)

4.3. Flow measurement

For measuring of the flow of working fluid and water at input, TA-STAD measuring valves are used. Measuring paths are produced with a sufficient length of straight sections before and after the valve to stabilize water stream. Measuring consist of determining the pressure drop. The processing of the obtained data is done with acquisition system TA-CBI[II] (Computerized

Balancing Instrument). Valves and acquisition system are from the well-known manufacturer Tour&Andersson Hydronics. To achieve additional accuracy, flow meter 4 Krohne H250 and calorimeter Kamstrup Multical 66CDE are installed within the system.

4.4. Temperature measurement

Temperature measurements are performed with temperature sensors Pt100, and previously calibrated thermocouples chromel-alumel, with diameter of 0.2mm. "Cold" ends of all thermocouples are immersed into a thermostatic bowl with a mixture of water and ice. For determining potential of thermocouples, voltmeter Hewlett-Packard 3468A is used. The external temperature is measured with a system TESTO 454 and checked with a mercury thermometer. Order of magnitude of errors showing thermocouples is 0.1 ^{0}C.

4.5. Measuring of the environmental air parameters

As relevant parameters to represent environmental conditions, the wind velocity, relative humidity, and temperature are determined with the measuring system TESTO 454. The system has a probe for measuring velocity, relative humidity, and temperature. An accuracy of the mentioned probes is 1% according to manufacturer. The measuring system TESTO 454 uses the measured variables and with its software it calculates and finally displays the value of absolute humidity.

4.6. Solar energy measurement

Measurement of global solar radiation is performed with pyranometer Kipp&Zonen CM11, with 3% accuracy, and range of radiation energy in the range $0 \div 1400 W/m^2$ (max. $4000 W/m^2$), spectral range $305 \div 2800 nm$ and sensitivity $4 \div 6 \mu V/(W/m^2)$, which can measure both direct and diffuse solar radiation.

5. RESULTS

5.1. The results of measuring the effectiveness

Measurement tests of thermal characteristics of concentrating solar collector CPC-2V are conducted at the external testing installation with a closed circulation loop (Figs 8 and 10). Efficiency test were conducted in-situ following the Sun, with water as the heat transfer fluid. The test results of thermal performances are as shown on Fig. 14. This figure show efficiency η as a function of the reduced temperature $t^* = (t_m - t_a)/G$. An equation for the curve is obtained using the standard technique of a least squares fit. Here, η is insantenious efficiency of solar collector defined as the ability of receivers to a certain amount of radiant solar energy converted into useful heat, t_m stands for average collector fluid temperature, t_a stands for ambient temperature,G stands for total (direct plus diffuse) solar energy incident on the collector aperture. The figure 11. shows that efficiency decreases with the reduced temperature.
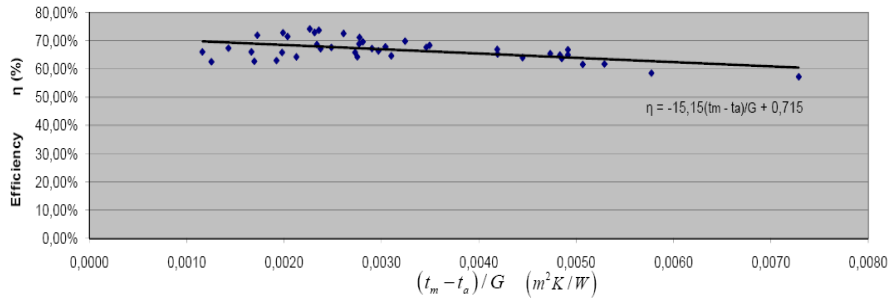
Fig. 11 The instantaneous efficiency of the solar collector CPC-2V

6. CONCLUSION

The demonstrated design of the focusing STC enables to receive incident solar radiation with an angle of 110° (**E**fficient), without extra-complex optical devices and elements (**E**conomical) at CR=1.38, with the possibility of significant reception of diffuse radiation. At first sight, it seems that the ratio of concentration is small, but here we had an idea to receive diffuse radiation with the biggest possible reception angle, which is very important during colder months (not in summer), when the demands for efficient utilization of solar radiation are bigger. With additional upgrade of deflecting (declined) reflection surfaces, which are set at the rim of collector field, solar flux can be additionally increased and thereby, if necessary, small ratio of concentration can be recompensed. It should be emphasized that the present geometrical and physical similarity of some types of focusing STC doesn't have to imply in similar optical and thermal behaviour, but it can be used for initial analysis.

Required thermal engineering and hydraulic examinations of the solar energy collectors at demonstrated installation for experimental measurements at Faculty of Mechanical Engineering in Nis will reveal the real optical and thermal effects of STC.

Measurement tests of thermal characteristics of the solar collector were conducted at the test installation at Faculty of Mechanical Engineering in Nis. Then, the efficiency of solar receiver CPC-2V was measured. This receiver has proved effective. We should organize its serial production.

The basic structural advantage receiver CPC-2V is that it eliminated the need for tracking system and thus lowered price system. Then enabled the production of a prototype receiver reflector plastic vacuum extraction, which further lowers the price of the receiver. On the surface of plastic is applied reflective layer. He also eliminated the use of insulation on the back and lateral side of the receiver.

On the basis of the reviews and performed measurements led to the following conclusion:
- STC construction is such that under normal conditions of use are nowhere made permanent deformation or damage to any individual elements,
- all elements of the STC are so connected that during operation there was no deformation,
- elements of the STC without permanent deformation withstand the test pressure of 10 bar.
- On the basis of the above stated may suggest that the STC fully meet its basic purpose, so that they can be used as devices to heat hot water, pool water, heating and so on.

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PROTOTIP PRIJEMNIKA ZA SREDNJETEMPERATURNU KONVERZIJU SUNČEVOG ZRAČENJA U TOPLOTU

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Visokokvalitetna sunčeva energija može se koristiti kao energetski izvor za mnoge radne operacije na temperaturama iznad 100 oC. Efikasna konverzija sunčevog zračenja u toplotu, na tim temperaturnim nivoima, zahteva korišćenje fokusirajućih ili fokusirajuće vakuumiranih prijemnika sunčeve energije. U ovom radu je predstavljen koncept solarnih prijemnika (označen kao CPC-2V), za oblast srednje temperaturne konverzije sunčevog zračenja koji ima visoki učinak, nisku cenu, mogućnost proizvodnje u malim i srednjim preduzećima, široku distribuciju, sa jasnom težnjom da se njegovom primenom u velikom delu godine ili celogodišnje ostvare značajne uštede električne energije koja se sada koristi za pripremu tople potrošne vode i u sistemima centralnog i daljinskog grejanja.

Ključne reči: *izvori energije, prijemnik solarne energije, sunčevo zračenje, prototip*