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OPTIMIZATION OF FLEXIBLE THIN-FILM PHOTOVOLTAIC CONVERTERS BASED ON CDS/CDTE HETEROSYSTEM FOR INTEGRATION WITH SOLAR THERMAL COLLECTORS

The paper introduces the concept of a photoenergy system based on film photovoltaic converters using the CdS/CdTe heterosystem. The goal is to develop a design solution for a flexible thin-film photovoltaic converter system that can be directly mounted on a heat collector plate, integrating photovoltaic converters with thermal collector systems. The paper highlights the limitations of traditional silicon-based photovoltaic converters and propose using flexible photovoltaic converters based on CdS/CdTe, which have concentrated absorption within the visible range and allow unobstructed flow of long-wave solar radiation for efficient thermal energy generation. The paper discusses the methods of obtaining samples of flexible photovoltaic converter ITO/CdS/CdTe/Cu/Au solar cells, including the deposition of layers on polyimide films, chloride treatment, and annealing processes. Analysed the impact of the "chloride" treatment on the structural and optical characteristics of the base layers and present the overall appearance of the thin-film photovoltaic converter samples. The structural analysis of the cadmium telluride films is conducted using X-ray diffractometry techniques, while the optical properties are investigated using a spectrophotometer. The light-voltage characteristics of the photovoltaic converter samples are measured under illumination conditions, and various output parameters and characteristics of the photovoltaic converter are determined. The authors emphasize the significance of optimizing the performance of the cadmium telluride layer in the flexible photovoltaic converter structure and discuss the variation of technological parameters to enhance efficiency. Paper presents the output parameters and light diode characteristics corresponding to different thickness ranges of the CdS layer. Overall, this paper provides valuable insights into the development of flexible film photovoltaic converters based on the CdS/CdTe heterosystem for integrated photovoltaic and thermal collector systems. The experimental methods and results contribute to the understanding of optimizing the performance of the photovoltaic converters and offer potential applications for autonomous heat supply systems.

Keywords: photoenergy system, thin film photovoltaic converters, CdS/CdTe heterosystem, flexible thin-film solar cell, heat collector plate, integration of photovoltaic converters and thermal collector systems, absorption within the visible and infared range.

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ОПТИМІЗАЦІЯ ГНУЧКИХ ТОНКОПЛІВКОВИХ ФОТОЕЛЕКТРИЧНИХ ПЕРЕТВОРЮВАЧІВ НА ОСНОВІ ГЕТЕРОСИСТЕМИ CDS/CDTE ДЛЯ ІНТЕГРАЦІЇ З СОНЯЧНИМИ ТЕПЛОВИМИ КОЛЕКТОРАМИ

Стаття наводить концепцію фотоенергетичної системи на основі плівкових фотоелектричних перетворювачів з використанням гетеросистеми CdS/CdTe. Метою є розробка конструктивного рішення для гнучкої тонкоплівкової системи фотоелектричних перетворювачів, яка може бути безпосередньо встановлена на колектор тепла, інтегруючи фотоелектричні перетворювачі з системами теплозбору. Стаття наголошує на обмеженнях традиційних фотоелектричних перетворювачів на основі кремнію та пропонує використовувати гнучкі фотоелектричних перетворювачі на основі CdS/CdTe, які мають концентроване поглинання в межах видимого діапазону та дозволяють неперешкоджений потік довговалового сонячного випромінювання для ефективного генерування теплової енергії. У статті обговорюються методи отримання зразків гнучких сонячних елементів на основі фотоелектричних перетворювачів ITO/CdS/CdTe/Cu/Au, включаючи нанесення шарів на поліімідні плівки, обробку хлоридами та процеси відпалу. Аналізується вплив «хлоридної» обробки на структурні та оптичні характеристики основних шарів та презентується загальний вигляд зразків тонкоплівкових фотоелектричних перетворювачів. Структурний аналіз плівок кадмію телуру проводиться за допомогою технік рентгенівської дифрактометрії, тоді як оптичні властивості досліджуються за допомогою спектрофотометра. Світловольтові характеристики зразків фотоелектричних перетворювачів вимірюються за умов освітлення, і визначаються різні вихідні параметри та характеристики фотоелектричних перетворювачів. Окремий наголошується значущість оптимізації продуктивності шару кадмію телуру в гнучкій конструкції фотоелектричних перетворювачів і обговорюють варіацію технологічних параметрів для покращення ефективності. У статті презентуються вихідні параметри та світлодіодні характеристики, що відповідають різним діапазонам товщини шару CdS. Загалом, ця стаття надає цінні уявлення про розвиток гнучких плівкових фотоелектричних перетворювачів на основі гетеросистеми CdS/CdTe для інтегрованих фотоелектричних та теплозбірних систем. Експериментальні методи та результати сприяють розумінню оптимізації продуктивності фотоелектричних перетворювачів та пропонують потенційні застосування для автономних систем теплопостачання.

Ключові слова: фотоенергетична система, тонкоплівкові фотоелектричні перетворювачі, гетеросистема CdS/CdTe, гнучка тонкоплівкова сонячна батарея, пластина збору тепла, інтеграція фотоелектричних перетворювачів і теплових колекторів, поглинання в межах видимого та інфрачервоного діапазону.

Introduction. Currently, solar collectors with high efficiencies of 70–80 % are employed for converting solar energy into heat. These efficiencies are achieved by utilizing selective coatings with exceptional absorption coefficients of 95–98 % within the spectral range of solar irradiation, along with low reflection coefficients of 5–7 % in the infrared range. The prevailing trend in automated heat collector systems, which feature forced circulation of heat carrier, is to generate the required electrical energy using conventional silicon solar modules. However, this conventional setup, where solar modules are placed separately from solar thermal collectors, does not lead to an enhanced utilization of solar energy.

To address this limitation and optimize space utilization, there is a growing focus on integrating photovoltaic converters with thermal collector systems. This integration is made possible through the utilization of flexible film photovoltaic converters that can be directly applied to the surface of the collector plate, mirroring its microrelief features and ensuring efficient thermal contact. The primary optimization objective in developing such a system is to assess the impact of the collector's operating temperature on the reduction in film photovoltaic converter (PVC) efficiency.

Purpose of the article. Contribute to the development of efficient and cost-effective photovoltaic-thermal hybrid systems by exploring the integration of flexible PVCs with solar thermal collectors. The findings have implications for various applications, including military and civil installations, and can potentially lead to advancements in the utilization of solar energy.

Concept of a photoenergy system based on film PVC based on the CdS/CdTe heterosystem. The primary objective is to develop a design solution for a flexible thin-film PVC system based on the CdS/CdTe system. This system aims to directly mount a solar panel made of this PVC onto a heat collector plate as part of an autonomous combined photovoltaic installation suitable for military and civil applications, using standard solar thermal collectors. The installation's key component is a photoenergy module, which comprises a standard solar thermal collector with a flexible solar panel based on the CdS/CdTe system placed on its photodetector surface.

According to [1], traditional PVCs based on monocrystalline silicon have significant absorption of the near-long-wave component of solar radiation beyond 1000 nm, which is photoelectrically inefficient and leads to unwanted heating of the PVC and reduced efficiency of the thermal aspect of the hybrid installation. Consequently, efficient heat dissipation from the PVC to the heat exchanger is necessary through intermediate thermal interfaces, resulting in a more complex and costly installation design. Additionally, the high cost of monocrystalline silicon-based PVC contributes to the high price of hybrid thermophotovoltaic modules, reaching $1,200 per module. In contrast, flexible thin-film PVC based on the CdS/CdTe system exhibits concentrated absorption within the range of 400–800 nm, while being nearly transparent to the near-infrared component. This characteristic allows for the unobstructed flow of long-wave solar radiation to the heat exchanger of the installation, enabling efficient generation of thermal energy.

Film PVC based on the CdS/CdTe heterosystem, comprising cadmium sulfide and telluride, presents an alternative to the widely used silicon crystalline PVC for autonomous terrestrial and transatmospheric applications. Advanced high-performance film PVC based on CdS/CdTe are typically manufactured in a rear configuration on a glass substrate, allowing solar radiation to enter the base layer. These PVCs have a theoretical efficiency of 29 % and excellent radiation resistance [1, 2]. However, in industrial production, First Solar (USA), a major manufacturer of CdS/CdTe-based PVC, has achieved an efficiency of 11 %. It's important to note that traditional CdS/CdTe-based PVCs are significantly inferior to crystalline silicon-based PVCs in terms of their mass-power characteristic, which refers to the amount of electrical power produced per unit weight of the PVC. This discrepancy is primarily due to the use of glass substrates, which account for 98 % of the PVC's weight [1]. By replacing the bulky glass substrate with a thin and transparent polyimide film [3], the weight of CdS/CdTe-based PVC can be reduced by a factor of 50, allowing for the creation of flexible structural elements [4, 5]. These flexible PVCs, capable of being mounted on surfaces of any shape, show promise for integration into autonomous heat supply systems based on heat collectors.

Several companies, including Apical, Kapton, Kaptrex, Meldin, Vespel, Plavis, and Upilex, have started manufacturing transparent polyimide films with excellent thermal stability. Among them, Upilex-S polyimide films exhibit the highest thermal stability, capable of withstanding temperatures up to 450 °C. These films possess a remarkable average transmittance of 80 % in the visible region, making them highly promising as substrates for creating efficient flexible PVCs based on cadmium telluride. With a thickness of 7 microns, substituting the glass substrate with a polyimide film enables the development of flexible PVCs based on cadmium sulfide and telluride, achieving a record-specific power per unit weight of over 2 kW/kg. This breakthrough emphasizes the significance of this scientific and technical problem in the industrial production of a new type of PVC.

Considering the thermal resistance of the polyimide film, characterized by a coefficient of thermal conductivity (κ) of 0.14–0.20 W/(m·K), it exhibits lower thermal conductivity than PVC films used in silicon-based modules. However, due to the thinness of the polyimide film (7 microns), it allows for a temperature difference within the thin-film PVC in the range of 0.6–0.9 °C. Copper's high thermal conductivity facilitates a transverse temperature gradient of the collector plate not exceeding 1.0–1.5 °C. By optimizing the thermal resistance of the system, it is possible to achieve a temperature difference of approximately 2.5 °C between the film PVC and the coolant.

However, replacing the glass substrate with a flexible polyimide film, which possesses different thermophysical and mechanical properties, necessitates the optimization of photoelectric conversion for flexible PVCs based on CdS/CdTe. These structures can be obtained through precipitation of photosensitive cadmium telluride films using advanced industrial methods such as condensation in a quasi-closed volume and non-reactive magnetron sputtering with direct current [6]. Nonetheless, the development of flexible PVCs based on cadmium sulfide and telluride through these methods, except for a few exceptions, is not extensively pursued, and there are no industrial technologies for producing flexible PVCs based on the CdS/CdTe heterosystem. Economically viable solutions could involve integrating such industrial installations into existing production lines that manufacture CdS/CdTe-based PVCs on glass substrates.

The current development of flexible PVCs based on the CdS/CdTe system demonstrates an exceptional mass-power characteristic of 2.5 kW/kg and an efficiency of 10-

11 %. By utilizing flexible thin-film PVCs based on the CdS/CdTe system on a polyimide substrate in the electrical part of the PVC, they can be directly attached to the photodetector surface of standard solar thermal collectors [7]. These collectors typically cost no more than $1130 per module. A typical unit comprises 4–5 collectors, each with a photodetector surface area of 2 m², providing heating for a room up to 200 m² and water heating of approximately 300 liters/day. Equipping such collectors with a solar battery based on flexible thin-film PVC with the aforementioned output parameters would generate around 200 W of electrical power, sufficient to meet the unit's energy requirements.

Methods of obtaining samples. To obtain experimental samples of flexible PVC/CdS/CdTe/Cu/Au solar cells, the following procedure was followed:

1. ITO layers were deposited on 12.5 µm thick polyimide films from Upilex. Magnetron sputtering at direct current was used, employing a target containing a mechanical mixture of In_2O_3 (90 wt.%) and SnO_2 (10 wt.%) powders of semiconductor purity. The sputtering process occurred in an argon atmosphere at a pressure of 0.8 Pa, with a magnetron voltage of 500 V and a discharge current density of 12.6 mA/cm². The substrate temperature was maintained at T_p = 300–350 °C, allowing the production of ITO layers with optimal electrical and optical properties.

2. CdS films were then deposited on the ITO layers. The deposition took place at an argon pressure of 0.8 Pa and T_p = 270–280 °C. The electrical parameters of the plasma discharge during this process were a magnetron voltage of 550-600 V and a plasma discharge current density of 2.8 mA/cm².

3. Two methods were used to obtain the base layers of cadmium telluride (CdTe):

- In the first method, the CdTe layer was directly grown on the CdS/ITO films without intermediate cooling or vacuum disturbance. The substrate temperature was maintained at T_p = 280–320 °C.
- In the second method, the substrate with CdS/ITO layers was cooled to room temperature and exposed to air. After returning to the vacuum chamber, the CdS/ITO heterosystems were heated to T_p = 280–320 °C to form the base CdTe layer.

4. To deposit the cadmium telluride layers, direct current magnetron sputtering was employed. The plasma discharge parameters included a magnetron voltage of 650–700 V and a plasma discharge current density of 4.2 mA/cm².

5. The resulting ITO/CdS/CdTe heterosystems underwent chloride treatment. $CdCl_2$ films were deposited on the CdTe layers without heating the substrate using thermal evaporation at a pressure of 5.3×10^{-3} Pa. Subsequently, the ITO/CdS/CdTe/$CdCl_2$ heterosystems were annealed in air at a closed volume, reaching a temperature of 430 °C for 25 minutes.

6. After annealing, the heterosystems were etched in a bromomethanol solution, and two-layer Cu-Au electrical contacts were deposited on their surfaces using thermal evaporation.

7. The formed ITO/CdS/CdTe/Cu/Au solar cells underwent further annealing in air at a temperature of 200 °C for 20 minutes.

To examine the impact of "chloride" treatment on the structural and optical characteristics of the solar cells' base layers, ITO/CdTe heterosystems on polyimide substrates without a CdS "wide-bandgap" layer were obtained through DC magnetron sputtering, following the same physical and technological deposition conditions mentioned above.

Figure 1 illustrates the overall appearance of the thin-film samples obtained in this study.

Figure 1 – Depicts an overall representation of the thin-film PVC samples, which are based on the ITO/CdS/CdTe/Cu/Au heterostructure

The structure of the cadmium telluride films was analyzed using X-ray diffractometry techniques [8]. The X-ray spectra were automatically recorded by a DRONE-4 X-ray diffractometer, employing θ-2θ scanning with increments of 0.01–0.02 degrees in Kα radiation from a cobalt anode. To accurately determine the phase composition of the CdTe films, an "oblique" survey method was utilized. This method involves detecting diffraction reflections from specific planes of the sphalerite and wurtzite modifications of cadmium telluride during the θ-2θ scanning process. These reflections are not typically captured by the aforementioned registration method due to sample texturing.

The optical properties of the CdTe layers were investigated using an SF-2000 spectrophotometer [9–11]. The band gap of the thin films was determined by calculating the dependence of the absorption coefficient on the wavelength (α(λ)) using the Burger-Lambert formula [12, 13].

By extending a linear plot of the squared product $(\alpha\cdot h\nu)^2$ as a function of hν (where h represents Planck's constant and ν represents frequency) [14], the point of intersection with the energy axis hν can be used to determine the width of the band gap.

The light-voltage characteristics (LVC) of the ITO/CdS/CdTe/Cu/Au PVC samples were measured under AM1.5 illumination conditions using the compensation method. Through analytical analysis of the LVC data, various output parameters and characteristics of the PVC were determined, including the short-circuit current density (J_{SC}), open-circuit voltage (U_{OC}), fill factor (FF), and ultimately, the efficiency factor (η).

Investigation of parameters of flexible PVC based on the CdS/CdTe heterosystem.

Enhancing the performance of the cadmium telluride layer in ITO/CdS/CdTe/Cu/Au thin film PVC. When developing flexible PVC based on CdS/CdTe in a rear configuration, similar thermal vacuum deposition methods for CdS and CdTe layers [15], the "chloride" treatment process, and the formation of metal rear electrodes were used as in previous studies conducted on glass substrates. However, replacing the glass substrate with a flexible polyimide film significantly reduced the weight of the overall structure by 56 times.

Based on previous research findings [16], it was determined that the optimal thickness for the base layer in thin-film ITO/CdS/CdTe/Cu/Au PVC is 4 microns. Therefore, when producing experimental samples of flexible ITO/CdS/CdTe/Cu/Au PVC on polyimide substrates, the thickness of the cadmium telluride films was also set to 4 microns.

To identify the optimal technological parameters for the formation of flexible ITO/CdS/CdTe/Cu/Au PVC, the thickness of the cadmium sulfide and cadmium chloride films were varied within the range of 0.3–0.7 microns and 0.08–0.16 microns, respectively. Light-electromotive force (light-EMF) measurements were conducted on the manufactured flexible ITO/CdS/CdTe/Cu/Au PVC structures with different layer thicknesses under a luminous flux of 100 mW/cm^2.

Analytical processing of the experimental light volt-ampere characteristics data allowed for the determination of the efficiency, output parameters, and light diode characteristics of the laboratory samples of manufactured PVC. Based on the efficiency dependency on the light diode characteristics, several characteristic ranges of CdS thickness were identified. Table 1 presents the efficiency, output parameters, and light diode characteristics corresponding to these ranges (samples 1–3).

Table 1 – Output parameters and light diode characteristics of flexible ito/CdS/CdTe/Cu/Au PVC

Parameters	**Sample no.**				
	1	**2**	**3**	**4**	**5**
d_{CdCl2}, mkm	0.08	0.08	0.08	0.11	0.16
d_{CdS}, mkm	0.30	0.55	0.70	0.50	0.50
U_{OC}, mV	440	712	711	733	756
J_{SC}, mA/cm^2	16.9	17.1	15.7	19.3	19.4
FF, rel. un.	0.57	0.51	0.49	0.59	0.49
η, %	4.2	6.3	5.8	8.5	7.2
R_S, Ohm·cm^2	2.2	5.9	7.2	5.8	12.1
R_{SH}, Ohm·cm^2	180	218	328	2300	429
J_0, A/cm^2	$1.2 \cdot 10^{-5}$	$1.7 \cdot 10^{-6}$	$1.0 \cdot 10^{-6}$	$1.1 \cdot 10^{-7}$	$5.9 \cdot 10^{-9}$
A, rel. un.	3.5	2.9	2.7	2.2	1.8
$J_Φ$, mA/cm^2	17.8	17.6	16.0	19.6	19.9

By varying the thickness of the cadmium sulfide layers in the production of ITO/CdS/CdTe/Cu/Au PVC on polyimide films, it was observed that, with a constant thickness of cadmium chloride [17], increasing the cadmium sulfide layer thickness to 0.5 microns resulted in an increase in PVC efficiency due to an increase in the no-load voltage. However, the light current-voltage filling factor showed a slight decrease, while the short-circuit current density remained nearly unchanged.

Numerical modeling was used to investigate the impact of changes in light diode characteristics on the efficiency of PVC. The results showed that increasing the thickness of CdS to 0.5 microns led to an increase in PVC efficiency primarily due to a reduction in the density of the diode saturation current. The decrease in the light current-voltage filling factor observed experimentally was attributed to an increase in the serial electrical resistance of the PVC, which was caused by the increased resistance of the CdS layer with thickness [18]. However, when the CdS layer thickness exceeded 0.5 microns, the efficiency of PVC decreased due to a decrease in the short-circuit current density and the light current-voltage filling factor, while the no-load voltage (U_{OC}) remained relatively unaffected.

Furthermore, numerical modeling was performed to analyze the effect of changes in light diode characteristics on the efficiency of PVC when increasing the CdS thickness from 0.5 microns to 0.7 microns. The decrease in PVC efficiency in this case was attributed to a reduction in the photocurrent. Similar to PVC structures formed on glass substrates, the decrease in photocurrent density in flexible PVC was attributed to a decrease in the photon flux density entering the base layer, which naturally occurred due to a decrease in the average transmittance of the CdS layer in the visible range with increasing thickness [19]. The efficiency, output parameters, and light diode characteristics corresponding to different ranges of cadmium chloride layer thickness are presented in Table 1 (samples 2, 4, and 5).

Regarding the variation in the thickness of the cadmium chloride layer in the production of ITO/CdS/CdTe/Cu/Au PVC on polyimide films, it was observed that with a constant optimal thickness of the cadmium sulfide layer (d_{CdS} = 0.50 microns), an increase in the cadmium chloride layer thickness (d_{CdCl2} = 0.11 microns) resulted in improved efficiency due to increases in the no-load voltage, light current-voltage filling factor, and short-circuit current density. Numerical modeling revealed that the increase in PVC efficiency with the thicker cadmium chloride layer was attributed to a decrease in the density of the diode saturation current and an increase in the shunt electrical resistance. However, further increases in the cadmium chloride thickness led to a decrease in PVC efficiency, which was attributed to an increase in the series electrical resistance (R_S) and a decline in the shunt electrical resistance (R_{SH}).

By comparing the obtained results with the study on the influence of chloride and cadmium sulfide layer thickness on the efficiency of PVC with a rear configuration on glass substrates, it becomes evident that the qualitative effect of changes in light diode characteristics, resulting from variations in chloride and cadmium sulfide layer thickness, is the same for both flexible PVC and glass substrate-based instrument structures. Therefore, the underlying physical patterns that determine the observed changes in light diode characteristics also qualitatively coincide. However, there are several notable differences.

It has been shown that the optimal thickness of the CdS layer in the ITO/CdS/CdTe/Cu/Au PVC structure formed on polyimide substrates (d_{CdS} = 0.50 microns) is larger compared to the use of glass substrates (d_{CdS} = 0.40 microns), while the thickness of the CdCl2 layer is smaller (d_{CdCl2} = 0.11 microns and 0.35 microns, respectively). Despite this, the efficiency of flexible PVC (η = 8.5 %) noticeably lags behind the efficiency of PVC formed on glass substrates (η = 10.3 %). However, due to the significant reduction in substrate weight for flexible PVC, high values of specific power (2.0 kW/kg) were achieved. Comparing the specific powers of ITO/CdS/CdTe/Cu/Au PVC formed on polyimide film and glass substrate, it is evident that the specific power of flexible PVC instrument structures is 47 times higher.

According to simulation results, the higher efficiency of instrument structures formed on glass substrates can be attributed to the lower density of the diode saturation current. It should be noted that flexible PVC exhibits higher values of shunt electrical resistance, which, in our view, is due to the presence of sodium in glass substrates. The diffusion of sodium into the base heterosystem leads to a decrease in shunt resistance. This conclusion is supported by the results of a study on the effect of the cadmium chloride layer on the efficiency of ITO/CdS/CdTe/Cu/Au PVC with a frontal configuration. Thus, the conducted studies indicate that to achieve higher efficiency values for flexible ITO/CdS/CdTe/Cu/Au PVC with a rear configuration, it is necessary, first and foremost, to improve the quality of the separating barrier in order to reduce the diode saturation current [20].

Optical properties of ITO/CdS/CdTe/Cu/Au film PVC. The visible radiation range properties of PVC were evaluated by measuring the transmission and reflection coefficients using an SF-2000 spectrophotometer connected to a personal computer. The spectrophotometer operates based on a ratio measurement between two light rays: one passing through the test sample and the other through the control sample. It covers a wavelength range of 190 nm to 1100 nm, employing a Hamamatsu deuterium lamp for measurements between 190 nm and 345 nm, and a Philips halogen lamp for measurements between 345 nm and 1100 nm.

In this study, the visible transmittance was measured incrementally in 3 nm steps within the range of 400 nm to 1100 nm. The reflection coefficient of the cadmium sulfide layers was determined using the SFO-2000 attachment, following the same method as the transmittance measurements, and within the same wavelength range. The dependencies of the transmittance (T) and reflection (R) of the PVC film based on cadmium telluride on the radiation wavelength are depicted in Figures 2 and 3, respectively [21, 22].

The calculation enables the determination of the absorption coefficient of solar energy for flexible PVC based on cadmium telluride in the visible range, which is found to be approximately 94–96 %.

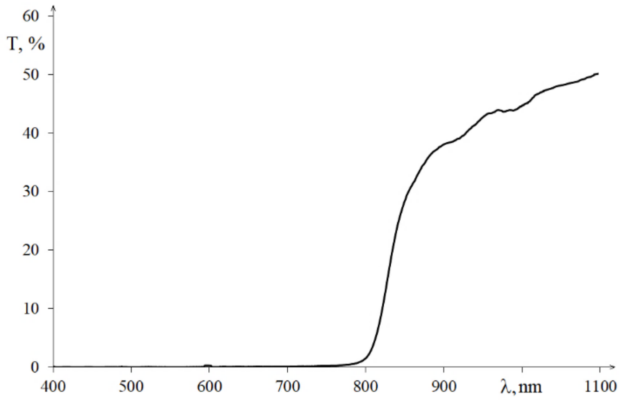

Figure 2 – Wavelength dependence of the transmission coefficient for cadmium telluride-based PVC in the wavelength range 400–1100 nm

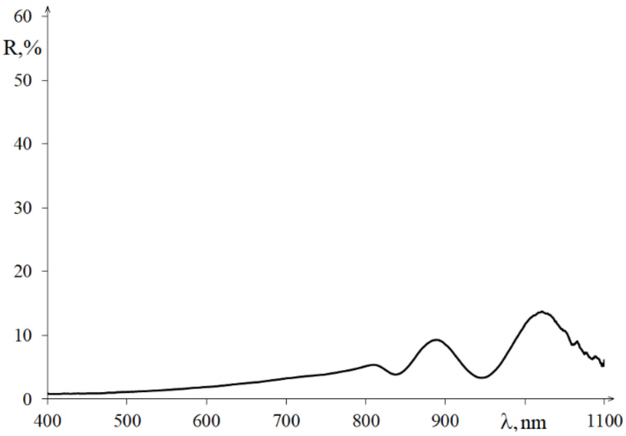

Figure 3 – Wavelength dependence of the reflection coefficient for cadmium telluride-based PVC in the wavelength range 400–1100 nm

In addition to examining transmittance within the absolute absorption range of 400–800 nm, which is relevant to light absorption and electrical energy generation, it was necessary to investigate transmittance and reflection in the infrared radiation range of 1000–15000 nm.

To conduct these investigations, an infrared spectrophotometer IKS-29 was employed. This instrument operates within the wavelength range of 2.5–25 microns and utilizes a heated silite rod (globar) with a temperature of 1400 ℃ as the light source. The obtained results, along with the dependence of the reflection coefficient, are presented in Figures 4 and 5, respectively, with extrapolated data indicated by dotted lines.

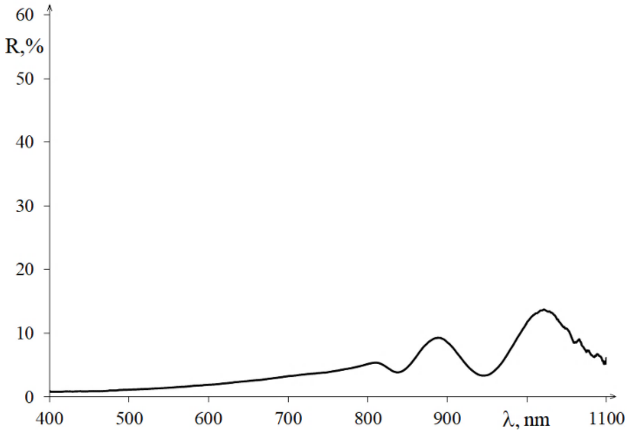

Figure 4 – Dependence of the transmission coefficient on the wavelength for PVC based on cadmium telluride in the wavelength range of 2.5–15 microns

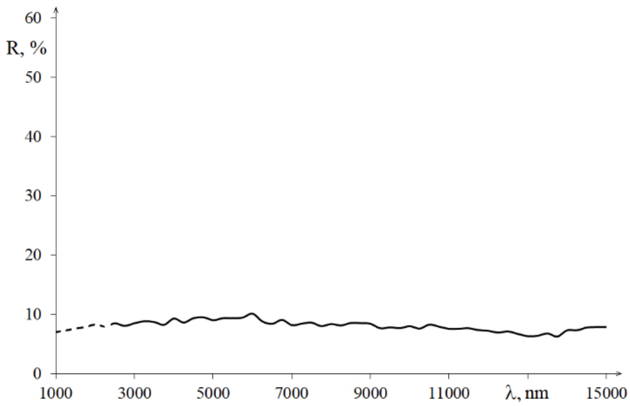

Figure 5 – Dependence of the reflection coefficient on the wavelength for PVC based on cadmium telluride in the wavelength range of 2.5–15 microns

Conclusion. These findings have significant implications for the design and performance of flexible PVC-based solar energy systems. The high absorption coefficient of solar energy in the visible range indicates that flexible PVC films can effectively capture a large portion of the incident sunlight, maximizing energy conversion. Additionally, the low reflection coefficient in the infrared region suggests that the PVC films exhibit good thermal properties, minimizing heat loss through reflection.

The absence of a need for an absorber with a selective coating in the collector design simplifies the construction of the system and reduces manufacturing costs. By utilizing the film photoelectric converter as the absorber, the efficiency of the collector can be maintained without the added complexity of additional coating layers.

Moreover, the calculated thermal conductivity values demonstrate that the polyimide-based flexible PVC films have a moderate ability to conduct heat [23]. This property allows for a relatively small temperature difference within the thin film PVC, which is important for maintaining thermal stability and reducing energy losses. The utilization of copper in the collector ensures efficient heat transfer and limits the transverse temperature gradient across the collector plate, thereby minimizing thermal stresses.

By optimizing the thermal resistance of the system, it becomes possible to achieve an excess temperature of the film PVC above the coolant temperature. This temperature differential of approximately 2.5 ℃ enhances the energy conversion efficiency of the PVC-based solar energy system, as a higher temperature can lead to increased power output.

In conclusion, the research findings support the viability of flexible PVC-based solar energy systems using cadmium telluride. The high absorption coefficient, low reflection coefficient, and favorable thermal properties make flexible PVC films an attractive option for efficient and cost-effective solar energy conversion. Further optimization and development of such systems have the potential to contribute significantly to the renewable energy landscape.

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