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THE RESULTS OF EXPERIMENTAL STUDIES OF MOTOR OILS FOR QUARRY DUMP TRUCKS

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Abstract. Recently, much attention has been paid to the study of the influence of climatic conditions on the performance of mining transport equipment in quarries. Studies of motor oils operating in engines of heavily loaded mining transport equipment during operation in hot climates (air temperature in summer exceeds +50 C) and high dust levels show that motor oils are intensively contaminated with mechanical impurities. The Muruntau quarry is a unique mountain site. Its depth today is more than 620m. The width is more than 2.9 km and the length is more than 3.2 km. The length of quarry roads is 65-70 km. Due to rarefied air, the power of diesel engines is reduced by 20-25%; the insulation on the engines quickly ages and fails. The purpose of this work is operational research of the quality of motor oils of dump trucks operating mining transport equipment. For this purpose, the characteristics of working motor oils SAE15W-40, API CI-4/SL selected from the engine of CAT-789D dump trucks were determined.

Keywords: motor oil, oxidation, contamination, deposits, durability, dustiness

1. Introduction

The development of the global industrial complex and, in particular, the branches of mechanical engineering, constantly requires an increase in the production of metallurgical products, which, in turn, is accompanied by an increase in the production of relevant minerals. Special technological processes of extraction and processing of significant volumes of soils have been developed. Special equipment and techniques have been developed to implement these technologies. In particular, heavy-duty vehicles with a lifting capacity of over 120-150 tons or more are used to transport the extracted materials.

Recently, much attention has been paid to studying the influence of climatic conditions on the operation of mining equipment in quarries. Muruntau quarry is a unique mining facility. Its depth today is more than 620 meters. The width is more than 2.9 km and the length is more than 3.2 km. The length of the quarry roads is 65-70 km, the amount of dust increases to 10-50 g/m³. The experience of developing the Muruntau high-altitude quarry shows that rarefied air, low oxygen levels, low atmospheric pressure, air ionization and solar radiation negatively affect the performance of engine oils in dump trucks. Due to the thin air, the power of diesel engines is reduced by 20-25%, productivity is reduced by 20-25%, and engine insulation fails. When



directly exposed to low atmospheric pressure, the sealing conditions deteriorate and the sealing performance of bearings and other parts with liquid lubricants decreases.

Low and high air temperatures, together with the corresponding humidity, affect the resistance to the destruction of the air gap at a given air pressure. Studies of lubricating oils used in engines of highly loaded mining equipment, when operating in hot climates (summer air temperature exceeds $+50^{\circ}\text{C}$) and high dust levels show that lubricants are intensively contaminated with mechanical impurities, water, fuel and organic products, which leads to premature aging of the oil. The high thermal load on the parts of the forced engines, with which the engine oil has to come into contact, and the interaction with gases entering the crankcase from the combustion chambers dramatically worsen their operating conditions. Today, the analysis of operational lubricants is one of the most effective modern methods for diagnosing the condition of mining machinery components and aggregates and their degree of wear. The purpose of this work is to study changes in the performance of motor oils of dump trucks operating mining and transport equipment.

For this purpose, the characteristics of SAE15W-40 and API CI-4/SL working engine oils selected for CAT-789 D dump truck engines were determined. The Cat 789 mining dump trucks have the lowest cost of transporting a ton of equipment in their class. The dump truck is equipped with a powerful engine of its own design, the Cat 3500 series (3516C EUI). It has 16 cylinders and an increased piston stroke, which ensures more complete combustion of fuel.

The engine is designed for heavy loads and develops high power at low RPM. Taking into account the above features, the operating conditions of oils in dump truck engines are defined as more severe than in passenger car engines. This requires strict adherence to the oil and oil filter change intervals specified in the manufacturer's specifications. The engines of mining dump trucks operate in very difficult conditions - in places with extremely low or high temperatures. Therefore, the oils for this equipment must contain components that maintain the performance characteristics of the oil for a long time, despite difficult operating conditions. For this method, it is necessary to use special oils with high dispersing properties.

Materials and Methods

Laboratory physico-chemical and spectral analyses were carried out according to the established methodology to solve the given task. We conducted an experimental study of SAE15W-40, API CI-4/SL engine oils on CAT-789 dump trucks (series DVS-CAT 3516), which were operated in a quarry for the transportation of rock in the conditions of the "Navoiy MMC" activity.

For the purity of the tests, before filling the oil, the lubrication system of the internal combustion engine of the CAT-789 dump truck was flushed with the test oil according to the test



program. Before the start of testing, the central laboratory conducted an analysis of the incoming quality control of the motor oil received for testing. The results of the oil analysis showed the correspondence of the actual values of the physical and chemical parameters stated in the regulatory documentation.

To carry out the analysis, 150 ml of oil was regularly taken from the lubrication system of a heated engine of CAT -789D dump trucks when it reached a temperature of 500C after stopping. Sampling of oils for analysis in the central laboratory was carried out according to the test program. Laboratory physicochemical and spectral analyzes of oils were carried out according to established methods.

Table 1. Experimental data on quality indicators of used motor oil
SAE15W-40, API CI-4/SL.

Oil operating time, m/h	Kinematic viscosity at 100°C, cSt.	Total alkalinity, mg KOH/g	Flash point temperature, °C.
10	15,68	9,27	220
15	15,87	9,29	216
20	14,94	9,11	215
25	14,84	9,06	210
30	14,50	8,97	210
35	14,24	8,96	209
40	13,85	8,79	210
45	13,50	8,27	212
50	13,24	7,91	210
55	14,14	7,28	208
60	14,10	6,89	195
70	12,93	6,56	190
Oil change at operating time of 256 engine hours			
10	15,68	9,27	220
15	15,87	9,29	216
20	15,40	9,14	217
25	14,94	9,11	215
30	14,84	9,06	210



Oil change at operating time of 256 engine hours			
25	14,69	9,05	214
30	14,50	8,97	210
35	14,24	8,96	209
40	13,85	8,79	205
Oil change at operating time of 269 engine hours			
65	14,36	8,87	208
70	14,32	8,83	209
75	14,09	8,75	195
90	13,95	8,69	190
Oil change at operating time of 275 engine hours			
25	14,29	8,97	215
50	14,16	8,82	210
60	13,84	8,26	209
65	13,87	7,95	202
70	13,14	8,02	185
Oil change at operating time of 269 engine hours			
40	14,43	8,76	214
45	14,12	8,48	210
50	14,12	8,42	209
55	14,01	8,39	205
60	13,89	8,02	195
65	13,26	7,85	190
Oil change at operating time of 278 engine hours			
50	14,74	8,76	214
55	14,56	8,48	210
60	13,87	8,42	209
65	13,18	8,39	205
70	13,25	7,85	195

Tests were carried out on devices:

- analysis of kinematic viscosity was carried out according to GOST 31391-2009 on a VIS-T-08 liquid thermostat;



- flash point determination was carried out in accordance with GOST 4333-87 using a flash point analyzer in an open crucible,
- determination of the base number according to GOST 11362-96 on an I-160MI ionometer,
- spectral analysis of iron concentration was carried out according to GOST 20759-90 on an MFS-11 spectrometer.

Results and discussion

Based on the analysis of laboratory studies, deviations in quality indicators (viscosity, base number and flash point) became noticeable when the dump truck ran 200 m/h or more. During operation, the viscosity of the oil decreased to 12.93. This is due to changes in the structural-group composition and the ingress of fuel.

As follows from Table 1, the flash point of 190°C has approached the rejection value, which indicates the need for replacement and the impossibility of further use of this oil without reducing the operational reliability of the engine. The flash point changes when unburnt fuel gets into it and fuel leaks. For operating oils, the flash point limit is 170–180°C. Oil dilution with fuel causes a sharp deterioration in its anti-wear properties and accelerates the processes of carbon and varnish formation on the pistons.

In order to maintain cleaning properties, motor oils must have a certain alkalinity. The ability to wash away contaminants inside the engine is one of the most important characteristics of modern oil. The higher the alkaline number, the greater the amount of acids formed during oil oxidation and fuel combustion that can be converted into neutral compounds. Having reacted with an acid, the alkali is consumed irrevocably, therefore, at a certain point in time, the reserve of the alkaline number decreases so much that the additives are no longer enough to neutralize all the acids that enter the oil. High sulfur content in fuel causes the oil base number to decrease rapidly. The operating conditions of mining equipment should also be taken into account. It works in highly dusty conditions.

When using fuel with a low sulfur content, alkaline additives in the oil are spent to a lesser extent on neutralizing fuel combustion products and, to a greater extent, on neutralizing oil oxidation products and protecting it from oxidation in general.

The service life of motor oil in our experiment was assessed by the balance of acid and base numbers in samples of used oil. These indicators were determined using a titrator in mg KOH/g. It is generally accepted that when the acid and alkaline numbers reach equivalent values, the oil reaches a limiting state and its further use is unacceptable. Oil samples were taken from

engines with an average frequency of 2000 km. Based on the data obtained, the average daily operating time of vehicles ranged from 50 to 140 km/day.

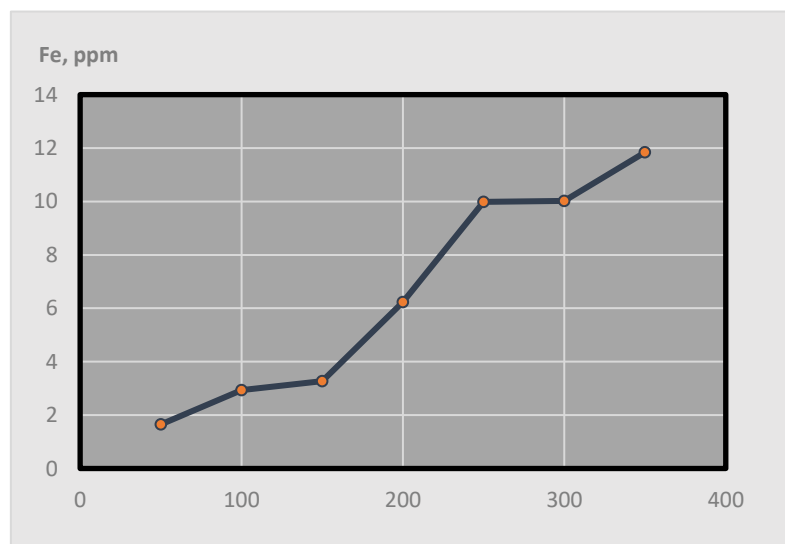
The table also shows that the alkaline number during operation decreased from 9.27 to 6.56. Operating the engine on oil with an alkaline number below the limit leads to accelerated wear of engine parts, which also shows an increase in iron concentration. The main lubricated components and parts of a piston engine are main and connecting rod bearings, camshaft bearings and gears, piston rings, valve rods and lifters, piston-cylinder interfaces, piston-piston rings.

In a diesel engine, engine oil components are exposed to the following factors: high surface temperatures of parts and the gas mixture, the catalytic effect of wear products of parts during oil oxidation, the presence of atmospheric oxygen, nitrogen and carbon oxides, sulfur oxides, products of incomplete combustion of the fuel mixture, which leads to the formation high-temperature deposits - carbon deposits, varnish and sludge.

When engines operate, significantly more large metal wear particles accumulate in the engine oil, indicating increased wear of rubbing parts. The wear of engine parts can be monitored by the concentration of wear products in the oil.

Analysis of the research results shows that during the research the average value of iron content increases. The iron content characterizes the anti-wear properties of the oil and their changes during operation, the wear resistance of engine parts and the effectiveness of cleaning agents included in the lubrication system.

The most dangerous component from the point of view of engine durability is the component of mechanical impurities, which includes wear products (Fe) and other solid particles. Increased iron content indicates intensified wear processes of iron-containing engine parts.





With an increase in the iron content in the oil, the frictional, anti-wear, antioxidant and detergent properties of the oil change. This influence leads to the following negative phenomena:

- coking of piston rings, which leads to increased friction losses, increased emissions of harmful substances, increased fuel and oil consumption, scuffing of the rubbing surfaces of cylinder-piston parts;
- significant “bulging” of the piston rings, especially the upper ones, due to the formation of deposits of solid carbon particles on the inner walls of the grooves and, as a result, increased wear, scoring of rings and cylinders;
- carbon formation on the side surface of the pistons, which causes cylinder polishing, increased oil consumption, deterioration of environmental characteristics, and surface scuffing;
- corrosion - mechanical wear of parts of the cylinder - piston group, crank - connecting rod mechanism, especially those made of non-ferrous metal alloys;
- abrasive wear of parts caused by solid particles of contaminants.

These reasons reduce the reliability of diesel engines, increase the cost of their maintenance, and in some cases cause emergency situations and premature failure..

In this regard, we offer a new alkylsalicylic additive, which has high-temperature detergent, dispersant, anti-oxidative and neutralizing properties. The additive Detersol is a colloidal dispersion of calcium carbonate in a diluent oil, stabilized with calcium alkyl salicylate based on ethylene oligomers.

This additive, compared to other additives, is quite effective and stable at relatively high temperatures. The additive is completely soluble in oil and is applicable as not only an anti-wear, but also an antioxidant additive in motor oils operating in hot climates and high dust levels.

Conclusion

For advanced diesel engines, lubricant developers offer a large selection of motor oils with multifunctional additives, the use of which should significantly reduce the level of contamination by mechanical impurities formed and circulating in the lubrication system and, as a result, increase the reliability of equipment.

Taking into account all the experimental data we have received on changes in quality indicators (base number), we recommend additionally introducing alkyl salicylate additives into the engine oil.

When choosing an additive, it is assumed that it dissolves well in the oil and actively exhibits a detergent effect for a long time.

Additives Detersol (D-50, D-140, D-180, D-300) impart detergent, neutralizing and antioxidant properties to motor oils. We suggest adding additive D-180 for motor oils in heavily

loaded quarry transport engines. The effect of their action is that the engine pistons, after operating in oil with such a detergent additive, remain clean and the piston rings do not burn as a result. These additives also have the ability to improve other quality indicators of oils (anti-corrosion, anti-wear).

Table 2. Characteristics of alkyl salicylate additives.

<i>Indicators m/h</i>	<i>D-50</i>	<i>D-140</i>	<i>D-180</i>	<i>D-300</i>
<i>Alkalinity number, mg</i>	<i>50-70</i>	<i>135-170</i>	<i>155-200</i>	<i>280-320</i>
<i>KOH/g</i>				
<i>Flash point in open</i>	<i>195</i>	<i>195</i>	<i>190</i>	<i>185</i>
<i>crucible, °C,</i>				
<i>Kinematic viscosity at</i>	<i>35</i>	<i>35</i>	<i>60</i>	<i>100</i>
<i>100°C, mm²/s.</i>				

Thus, due to the content of more active additives in the oil, its physical and chemical properties are improved, the wear of diesel parts is reduced, which has a positive effect on both the service life of the oil and the durability of engines.

Currently, research continues on the effectiveness of the influence of the nature and concentration of additives on the performance indicators of motor oils operating in engines of heavily loaded mining and transport equipment and high dust content in the air.

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DEVELOPMENT OF A DUAL-AXIS SOLAR TRACKING SYSTEM BASED ON ARDUINO AND LDR SENSORS

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Abstract: Currently, the efficient use of solar energy is one of the global priorities. The efficiency of solar panels largely depends on their orientation to the sun. Stationary panels can receive maximum sunlight only during certain periods, which leads to a significant decrease in energy production. In order to solve this problem, a two-axis automatic sun-tracking system was developed and tested in this project. The system is based on the Arduino Uno microcontroller and consists of four LDRs (light-sensitive resistors), two MG90 servo motors, two 80x80 mm solar panels, a breadboard, and other electronic components. And device automatically moves throughout the day depending on the angle of incidence of sunlight and keeps the panel in the optimal position. The body of the device is made using 3D printing technology. As a result of the tests, it was noted that the energy production efficiency of the solar panel using the system significantly increased compared to traditional stationary systems. The project is important not only for increasing the efficiency of sustainable energy production but also for ensuring maximum utilization of solar panels in regions with variable climatic conditions. This system can serve as a basis for the creation of affordable and efficient solar energy systems adapted to local conditions in the future.

Keywords: solar energy, solar tracking system, dual-axis tracker, Arduino Uno, servo motor, LDR sensor, energy efficiency, renewable energy.

Introduction.

In recent years, the energy problem has become one of the most pressing issues on a global scale. As a result of population growth, industrial expansion, and the increase in the number of vehicles, energy demand is increasing. At the same time, traditional energy sources – fossil fuels such as oil, gas, and coal – are causing environmental problems, and their reserves are limited. In such conditions, the issue of effective utilization of renewable energy sources, especially solar energy, is gaining urgent importance.

The total amount of solar energy that falls on the earth in a year is thousands of times higher than humanity's annual needs. However, the full and optimal utilization of this energy is still one of the issues that must be solved through technological solutions. From this point of



view, systems that automatically track the sun's rays – solar tracking technologies – play an important role.

Solar tracking systems have been developed to use solar energy as efficiently as possible. Stationary photovoltaic panels operate at maximum efficiency only when they are directly exposed to the sun. Systems that do not take into account the movement of the sun receive less light during the day, and therefore, the level of energy production decreases. Solar tracking systems, on the other hand, rotate the panel towards the sun during the day, thereby maximising the intensity of the rays falling through it. Various studies show that by using such systems, the efficiency of solar panels can be increased by 20% to 40%. Special attention is paid to modern components and equipment so that these devices are relatively compact and convenient to operate and control occurs easily [1].

From a scientific point of view, such devices are located at the intersection of the fields of physical optics, automation, microelectronics, and programming and are also of great importance in developing students' practical skills. Such convenient, inexpensive, and compact systems allow for practical use in many areas, especially in developing countries, to reduce energy shortages.

Dual-Axis Solar Tracking Systems

Dual-axis solar tracking systems offer higher efficiency compared to single-axis systems because they track both directions of the sun. These systems are particularly capable of handling the variability of solar radiation. This technology is widely used to improve the efficiency of dual-axis systems. For example, a study by Hussain et al. (2019) developed low-cost and efficient variants of dual-axis tracking systems. In this study, systems were developed using digital logic circuits, which are ideal for small and off-grid systems (Hussain, Baloch, & Chachar, 2019) [2]. Also, a study by Ibrahim et al. (2020) compared the efficiency of different control strategies. In this study, PID control and fuzzy logic techniques were compared, and it was shown that the fuzzy control strategy is the most adaptive to environmental changes. PID control, on the other hand, shows high efficiency under steady-state conditions, which means that it is an important factor in choosing a control strategy for system development (Ibrahim, Qamar, Ali, & Sadiq, 2020) [3].

Energy Maximisation Approaches

One of the most important issues in optimising solar energy is to maximise the energy yield of solar panel systems. A guide developed by Chowdhury et al. (2021) emphasizes that dual-axis systems show the highest results in terms of energy production when evaluating different tracking systems and their operating mechanisms. According to their recommendations,

dual-axis systems can achieve a large amount of energy with intelligent control systems (Chowdhury et al., 2021) [4]. Srinivasan et al. (2019) studied maximum power point tracking (MPPT) algorithms in solar PV systems. MPPT algorithms allow for maximum energy yield depending on the variability of solar radiation and temperature conditions. Integrating MPPT systems with dual-axis tracking systems maximises the electrical efficiency of the system, which should be considered as an important factor in the design of future systems (Srinivasan, Xu, & Wang, 2019) [5].

Practical Studies and Real-World Results

The results of theoretical studies have been confirmed by real-world experiments. A comparative study by Zhang et al. (2020) showed the difference between two-axis systems and static systems. According to their analysis, two-axis systems offer up to 35% higher efficiency in daily energy production, depending on geographical location and weather conditions (Zhang, Chen, & Lee, 2020) [6]. An environmental assessment study by Liu et al. (2021) also discusses the long-term economic benefits of PV systems using two-axis systems. They argue that two-axis systems may require higher initial investments, but their efficiency and energy production advantages make them economically viable in the long run. Their study also showed that two-axis systems are also beneficial from an environmental perspective, as they provide higher efficiency in energy production and consume fewer resources (Liu, Wang, & Zhang, 2021) [7].

Future Approaches and Technological Innovations

New technologies and approaches for solar tracking systems are emerging in the future. Bansal et al. (2021) study the use of artificial intelligence-based forecasting systems, Internet of Things (IoT) integration, and a mix of passive and active systems. These approaches can enable the next generation of tracking systems to be smarter, more efficient, and more flexible, which can play a major role in sustainably meeting global energy needs (Bansal, Kumar, & Singh, 2021) [8]. This article aims to create a model of an inexpensive and user-friendly device that automatically tracks sunlight and studies its operating principle. The device uses an Arduino UNO microcontroller, two servo motors, and four light sensors (LDR — Light Dependent Resistor). The device algorithm is designed to determine which side receives the strongest light and rotates the solar panel in that direction. The model is designed on a small scale, which can be used for educational laboratory work or testing in small-scale households. This article analyses the principle of operation of the device, its design, the reasons for choosing technical parameters, and the results, and it discusses future directions for improvement.

Materials and methods.

This section provides a detailed step-by-step analysis of the practical stages of the project, namely the creation of the device, the selection of components, their assembly, programming, testing, and the principle of operation. The main goal of the device is to maximise energy production by facing the sun's rays at an optimal angle.

Design and preparation of 3D printed parts

The device's outer casing and mechanical support parts were printed using a 3D printer in PLA material. The casing includes unique slots for mounting servo motors, a platform for placing solar panels, and mounting points for LDR sensors. These parts were previously designed in a 3D modeling program and modeled according to the dimensions. Then, they were printed using a 3D printer, and the necessary holes for assembly were also made in each part. These parts ensure the mechanical stability of the device and allow for a firm placement of components Fig.1.

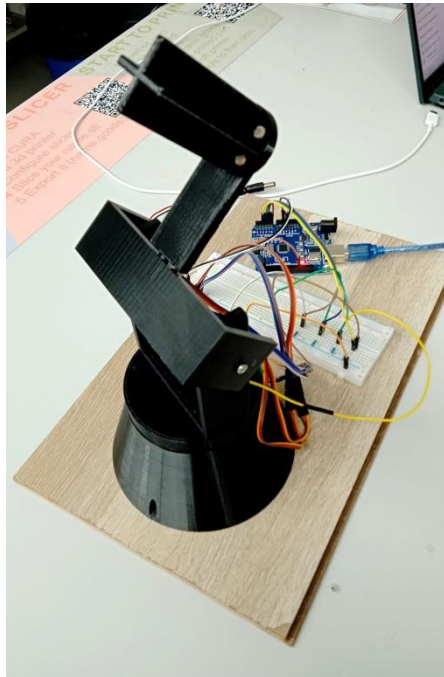


Fig. 1. Device

Electronic components and their functions.



Fig. 2. Arduino Uno

This microcontroller is the heart of the project. It receives signals from all sensors, analyses them, and drives the necessary servo motors. The code was written based on the Arduino C/C++ programming environment.

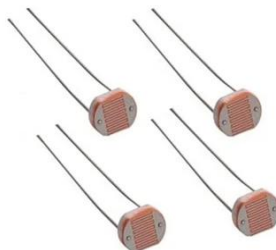


Fig. 3. LDR sensors

Four light-sensing sensors are installed in the four directions of the device: north, south, east, and west. Each is connected via a voltage divider circuit with a 10 kΩ resistor. The sensors determine in which direction the light is stronger.



Fig. 4. Servomotor

Fig. 4. 2 servo motors control the movement, depending on the signal from the sensors, the servo motors moves the panel to the most optimal position with 1-2 degrees of movement; 1 for horizontal (azimuth) movement, 1 for vertical (zenith) movement.

Each motor can move within 180°. In the initial position, the solar panel is placed at an angle of 45°, which provides approximately maximum coverage of natural light. The movement is changed depending on the signal from the sensor.

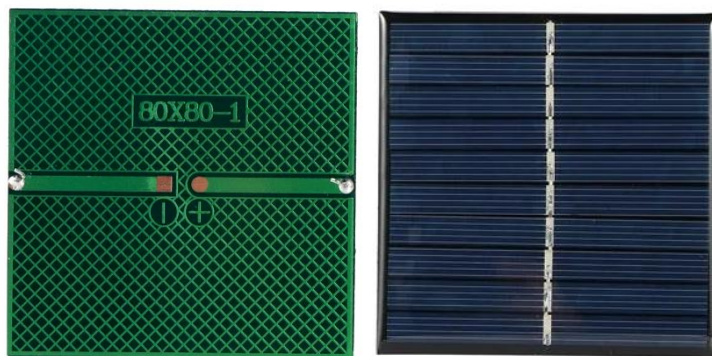


Fig. 5. Solar panels

2 80x80 mm polycrystalline silicon solar panels were used in series. They power the Arduino, sensors, and servo motors. The efficiency of this solar panel was calculated by the formula below:

$$\eta = \frac{P}{a \cdot b \cdot 1000} \cdot 100\% = \frac{0,8}{0,08 \cdot 0,08 \cdot 1000} \cdot 100\% = 12,5\%$$



Fig. 6. Jumper wires

Fig. 6. all components were connected to the Arduino via a breadboard using 22 coloured jumper cables. They serve to correctly route the appropriate voltages and signals.

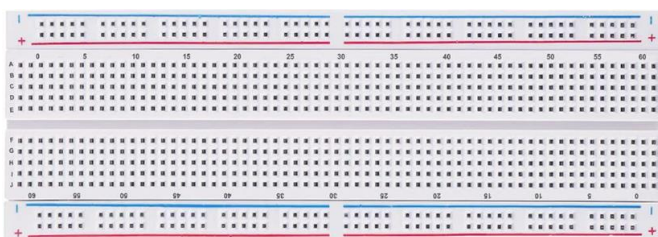


Fig. 7. Breadboard

Fig. 7. a circuit board designed for temporary assembly that does not require soldering. Through it, LDR sensors, servo motors, and resistors are connected to the Arduino.



Fig. 8. 10kΩ resistors

Fig. 8. resistors were connected in series with each LDR (light-dependent resistor). This is necessary to increase their signal accuracy and ensure that a stable analog value is sent to the Arduino. One for each LDR - a total of 4 10k Ω resistors were used. They acted as a voltage divider for the sensor and helped control the output signal depending on the resistance of the photoresistor.



Fig. 9. Battery (Li-Ion)

Fig. 9. an external power source – a 9V/12800 mAh DC battery (or portable power supply) – was connected to operate all the electronic components. The system was powered by an Arduino Uno, which also activated the servo motors and sensors. The battery was a reliable power source and ensured uninterrupted operation during the testing. Below are all the necessary materials and their quantities:

List of components. Table 1

Component name	Quantity
Arduino uno	1
MG90 servo motor	2
LDR sensor	4
Solar panel (80x80mm)	2
Breadboard	1
Jumper wires	22
10k Ω resistor	4
3D printed parts	4

Device assembly.

First, the 3D-printed parts were assembled, and the sensors and servo motors were fixed in the appropriate places. After connecting the components to the breadboard via jumper wires, the sensors and motors were configured correctly. The LDR sensors were connected in series with 10 k Ω resistors via the breadboard and connected to the Arduino analogue pins. The servo motors should be connected to the Arduino's PWM pins (usually pins 9 and 10).

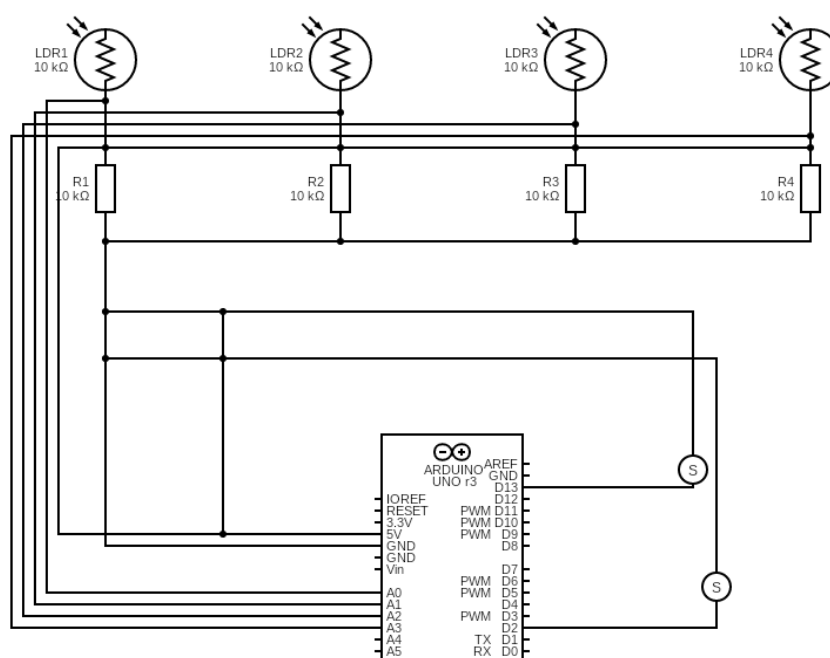


Fig. 10. The scheme of electronic connections

The algorithm for detecting sunlight and turning the motor was written using the Arduino IDE and uploaded to the microcontroller. After powering up the device, the system started automatically. A program written in C/C++ was uploaded to the Arduino Uno board. The program continuously reads the data coming from the LDR sensors, calculates the difference between them, and sends a PWM signal to the servomotors, which drives them. The program performs the following functions:

- Detects the difference in light between the sensors;
- If the difference is significant, the servo motors rotate the panels in the direction of stronger sunlight;
- All actions are rechecked once every 1 second;
- The panel always starts at an angle of 45° and turns to the appropriate direction after the sensors detect a change. This design allows it to move in the direction where the sunlight falls most optimally.

Principle of operation

The values from each LDR sensor are compared. The direction from which the strongest light is coming is determined. Arduino rotates the servo motor corresponding to this direction by 1–2 degrees. The system takes a new measurement every 1–2 seconds and updates the position



of the panel. With this mechanism, the solar panel is always in the most efficient position, which allows it to produce 20–30% more energy than ordinary stationary panels.

Results and discussions.

Several important results were achieved during the project by developing a system that moves according to the movement of sunlight. The device was successfully assembled, programmed, and tested. The following is an analysis of the system's performance, advantages, limitations, and future improvement directions.

The device controlled all components via an Arduino Uno microcontroller. The ambient light level was detected using four LDR sensors, and the servo motors were driven according to the strongest light source. The panel initially started working at a 45° angle. Depending on the signal from the sensors, the servo motors moved the panel to the most optimal position with 1-2 degrees of movement. This system continuously monitored the solar radiation and remained in an adjusted position throughout the day. Compared to conventional stationary panels, the energy production efficiency increased.

When the system was tested, the solar panel's generated voltage increased by 23% (in a comparative test). During the experiment, the panel automatically changed its position relative to the sun. The results showed the stability of the system and its suitability for practical use [9].

Semi-automatic energy monitoring systems are important for energy efficiency and maximum power utilization. Although this project was implemented on a small scale, its basic principles can be applied on an industrial scale. The device can work with low-cost components. Ease of expansion and customization through an Arduino-based program is also one advantage. However, there is a possibility of false readings of the sensors due to the temperature or dust. In the future, it can be improved by implementing MPPT technology, developing its algorithm that can predict the optimal position in any weather conditions, or by monitoring the system online.

Conclusions and Recommendation.

The dual-axis solar tracking system developed within the framework of this project was tested and proved to be suitable for practical use. During the tests, an increase of up to 23 percent in the voltage generated by the solar panels was observed, which indicates the potential of the tracking system to increase energy efficiency. The device's algorithm, based on the Arduino platform worked stably and allowed automatic adaptation to solar radiation.

During the project, the integration of the Arduino platform, servo motors, light sensors (LDRs), and other electronic components was studied in depth. The device was assembled from 3D printed parts, providing durability and aesthetics suitable for outdoor environments. Initial tests showed stable operation of the device and positive changes in energy production. The mobility of the panel, real-time response to light sources make the device useful in various weather and location conditions.

The studied area — namely, solar tracking systems — is one of the most relevant directions today in the transition to alternative energy sources, achieving environmental cleanliness and ensuring energy independence. The relative unlimited and free availability of solar energy requires the search for ways to use it as efficiently as possible. Tracking systems are one of the most promising and useful approaches in this regard.

In the future, these technologies will have such development paths as artificial intelligence, automatic optimization based on weather forecasts, and integration with large-scale photovoltaic farms. Also, further development of sensor technologies, energy-saving servo motors, and self-adjusting software can further increase efficiency. This will be important for sustainable energy supply on an industrial scale, in the residential sector, and in remote areas. In general, the system developed within the framework of this article is a small but highly practical prototype that can be considered an excellent example of a technology that can be used not only for educational purposes, but also in real life.

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DEVELOPMENT AND TESTING OF VARIOUS HEAT COLLECTOR METHODS FOR COOLING PHOTOVOLTAIC-THERMAL BATTERIES

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Abstract This article analyzes the results of research aimed at improving the efficiency of renewable energy sources, in particular the utilization of solar energy, by enhancing the performance of photovoltaic (PV) modules through the application of new types of cooling systems. A comparative study was conducted on two photovoltaic–thermal (PV/T) modules, each based on identical 180 W photovoltaic panels but equipped with different types of thermal collectors.

The research examined the problem of reduced PV efficiency under elevated temperatures and explored methods of mitigating this effect. The findings demonstrated that, by integrating specially designed PV/T modules developed at the Institute of Physics and Technology, the electrical performance of the photovoltaic panels was significantly improved through effective thermal regulation.

According to the results, PV/T systems not only increase the efficiency of photovoltaic modules but also provide hot water for household needs. Furthermore, two types of thermal collectors—based on cellular polycarbonate and polyethylene tubing—were developed, and their technical and economic performance was comparatively analyzed.

Keywords: photovoltaic–thermal battery (PV/T), photovoltaic battery (PV), collector, open-circuit voltage (Voc), short-circuit current (Isc), thermal collector.

Introduction.

In the present era, ensuring environmental sustainability and the efficient use of energy resources has become a pressing global issue. The limitations of conventional energy sources and the necessity of protecting the environment are increasing the significance of renewable energy sources, particularly solar energy, in power generation.

Photovoltaic (PV) modules and photovoltaic–thermal (PV/T) systems represent the primary directions in the utilization of solar energy. While PV technologies enable the direct conversion of solar radiation into electricity, PV/T systems play a crucial role in simultaneously producing electrical power and capturing thermal energy. With the application of modern technologies, the efficiency of these systems has been enhanced, allowing their wider implementation in both industrial and household sectors [1–2].



Recent studies have further demonstrated the economic efficiency and environmental benefits of integrated solar energy utilization. In particular, the combined operation of PV and PT technologies has been shown to increase overall energy production while reducing energy losses [3].

Research methods.

Extensive research is being carried out at the Institute of Physics and Technology to enhance the efficiency of photovoltaic (PV) systems and adapt them to the climatic conditions of our republic. An increase in the operating temperature of PV modules significantly reduces their efficiency. This effect is mainly associated with the reduction of the band gap energy of semiconductor materials. On average, with every 1°C rise in temperature, the efficiency decreases by approximately 0.4–0.5%. Therefore, PV systems require cooling or thermal management to maintain maximum efficiency [4]. As temperature increases, the open-circuit voltage decreases, leading to a reduction in power output at the maximum power point. High operating temperatures also negatively affect the long-term durability of PV panels [5–6].

To improve the performance of PV modules, a technology was developed to attach a thermal collector to the rear surface of the PV module. Experimental tests based on the newly developed photovoltaic-thermal (PVT) modules are currently being conducted at the Heliopolygon of the Institute of Physics and Technology. The advantage of such PVT systems lies not only in improving the electrical characteristics of PV modules but also in providing hot water for domestic needs [7]. In these systems, cold water is circulated through the thermal collector, which removes the accumulated heat from the rear side of the PV module via water flow.

In the development of PVT modules, two different variants of thermal collectors were employed:

Cellular polycarbonate collector: The polycarbonate sheet was cut to match the dimensions of the PV module. To allow water circulation through the rectangular channels of the polycarbonate, slits were cut at the opposite ends, where polyethylene pipes were inserted for water inlet and outlet. These joints were sealed with a special adhesive to prevent leakage. To install the polycarbonate collector on the rear side of the PV module, a part of the supporting aluminum profile was removed. The collector was then mounted onto the PV module, followed by the placement of a protective thermal insulation layer, polystyrene foam, and a pressed wooden or plywood back cover, all tightly fixed [8].

Polyethylene tube collector: In this method, the total surface area of the thermal collector was made identical to that of the PV module. A polyethylene flexible tube (diameter 1 cm,

length 50 m) was arranged in a rectangular pattern and adhered to the rear surface of the PV module. The collector was then enclosed with a cover. Heat accumulated on the rear surface of the PV module was removed via water flowing through the tube [9].

The advantages and drawbacks of both collector designs were analyzed experimentally. The first method, using cellular polycarbonate, provided uniform contact across the rear surface of the PV module, thereby ensuring efficient heat transfer from the PV module to the collector. In contrast, the second method, which utilized polyethylene tubing, did not ensure full contact with the PV rear surface, resulting in relatively poor heat transfer. To mitigate this drawback, thermal paste (a chemical compound designed to improve thermal conductivity) was applied between the tubing and the PV module surface.

An economic analysis of both collectors demonstrated that the second method required 20–30% lower material costs. Furthermore, one of its notable advantages was higher resistance to mechanical deformation caused by external factors



a)

b)

Fig 1. Front view of PVTs with heat collectors made of cellular polycarbonate and polyethylene soft tubing.

Figure 1a shows a photovoltaic-thermal (PVT) module equipped with a thermal collector made of cellular polycarbonate. As can be seen in the figure, cold water enters the thermal collector through the blue pipe, and the accumulated heat at the rear surface of the PVT module is removed through the red pipe.

Figure 1b illustrates a PVT module equipped with a thermal collector made of flexible polyethylene tubing. As noted earlier, this second design of the thermal collector demonstrates higher resistance to external mechanical deformations, since its technical components are fully embedded within the structure and do not extend beyond the PVT module surface.

Results and discussion. In the development of the photovoltaic-thermal (PVT) modules, identical photovoltaic panels (180 W each) were employed. To compare their physical parameters, experimental tests were conducted on November 10 at the Heliopolygon of the Institute of Physics and Technology. Two PVT modules equipped with different types of thermal collectors were placed side by side, and cold water.

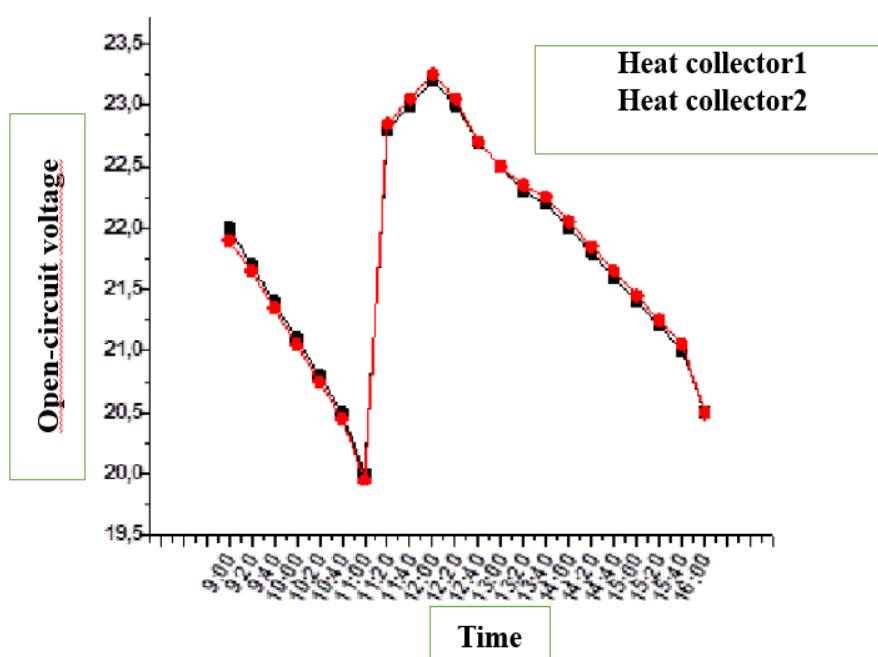


Fig 2. Variation of the salt-flow voltage over time of PVTs equipped with two different heat collectors

As observed from Figure 2, the cooling capacity of the two different types of thermal collectors integrated into the PVT modules is almost identical. This indicates that both collector designs can be reliably employed for the continuous cooling of PVT systems. In addition to enhancing the physical parameters of the PVT modules through the integration of thermal collectors, these systems also provide the practical advantage of supplying hot water for domestic applications. The measured temperature values of the hot water obtained from the thermal collectors are presented in Figure 3.

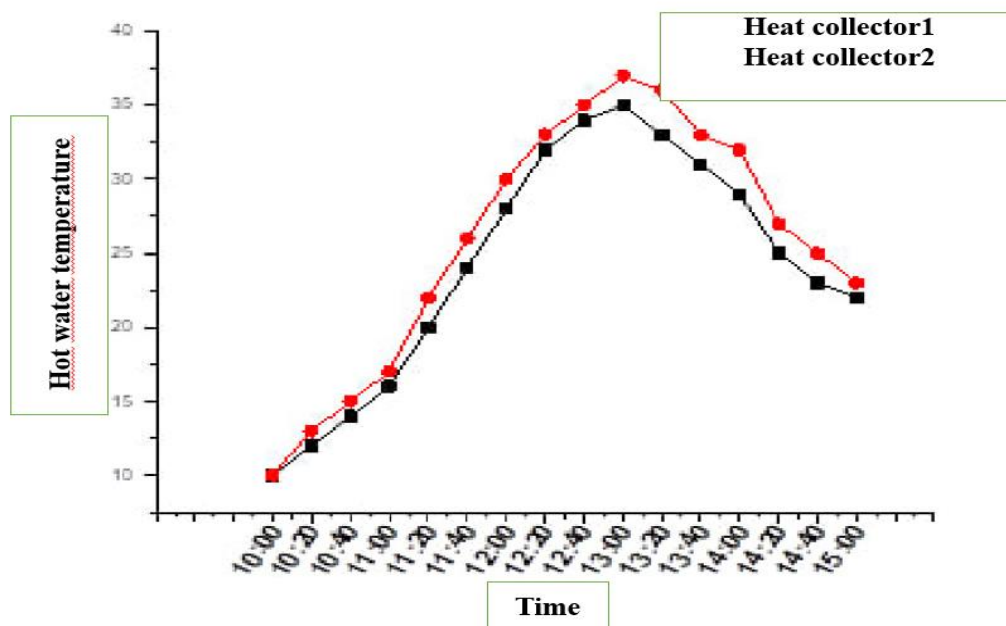


Fig 3. Time variation of hot water temperatures obtained through two different heat collectors

In Figure 3, the values of the water temperature represented by the black curve correspond to the results obtained from the thermal collector made of cellular polycarbonate. The values shown by the red curve indicate the water temperature measured from the thermal collector constructed using polyethylene flexible tubing. As seen from Figure 3, the second method (polyethylene tube collector) resulted in higher water temperatures.

The reason for this is that the polyethylene flexible tube, with a total length of 50 m, was arranged in a rectangular shape on the backside of the PVT module. Thus, after entering the thermal collector, the cold water must travel the entire 50 m distance before exiting, which leads to greater heating of the water.

During the month of November, the maximum hot water temperature obtained from the thermal collector was 35 °C. In spring, the maximum hot water temperature reached 35 °C, while in the summer months, the maximum hot water temperature achieved was 48 °C [10]. It is well known that the global demand for electrical energy is increasing day by day. Over the past five years alone, the worldwide demand for electricity has risen by almost 50% annually. This growing trend necessitates the expansion and development of alternative energy sources. According to the International Energy Agency, if the current rate of solar energy utilization continues, by 2050 solar power will be able to supply up to 25% of the world's electricity needs. Moreover, this transition is expected to reduce annual carbon dioxide emissions by approximately 6 billion tons, thereby contributing significantly to global environmental sustainability.

Conclusion.

In summary, the findings of this research demonstrate that the utilization of photovoltaic–thermal (PVT) systems offers significant advantages over conventional photovoltaic (PV) modules. While PV modules are only capable of generating electrical energy, PVT systems ensure dual functionality: they improve the electrical parameters of PV modules through thermal management and simultaneously provide a sustainable source of hot water for domestic applications. This dual-purpose efficiency makes PVT systems more suitable for energy diversification, particularly in regions with high solar radiation.

In this study, two different types of thermal collectors were developed and experimentally tested under identical environmental conditions. The first design was based on a hollow polycarbonate structure, while the second design employed a polyethylene flexible tube integrated into the rear surface of the PV module. Comparative analysis revealed that both types of collectors exhibited nearly similar cooling capacity, with a positive impact on the short-circuit current (I_{sc}) and open-circuit voltage (V_{oc}) of the PV modules.

However, it was also observed that the polyethylene flexible tube–based collector showed slightly higher efficiency in terms of thermal energy utilization. This is attributed to its longer water flow path (50 meters), which allowed the water to absorb more heat before exiting the system. As a result, the maximum hot water temperature obtained during the autumn season reached approximately 35°C, while in summer conditions, it increased up to 48°C.

The results of this study highlight the potential of PVT systems as a practical solution for both improving PV efficiency and addressing domestic hot water demands. Furthermore, the economic evaluation indicates that the polyethylene flexible tube collector is more cost-effective, requiring 20–30% less investment compared to the polycarbonate-based collector, while also offering greater resistance to external deformations.

Based on these findings, it can be concluded that the development and large-scale implementation of PVT systems in Uzbekistan and other regions with similar climatic conditions could contribute significantly to increasing energy efficiency, reducing fossil fuel dependency, and enhancing environmental sustainability.

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**TECHNOLOGY FOR EFFECTIVELY SOLVING THE SUPPLY OF
ELECTRICAL AND THERMAL ENERGY IN THE WINTER SEASON USING
PORTABLE PHOTOELECTRIC-THERMAL DEVICES**

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Abstract. In this article, the experimental results of the photovoltaic-thermal device (PVTd) are presented, aimed at increasing efficiency in the production of electrical and thermal energy during the winter season. In the device, a polycarbonate thermal collector and light-reflecting reflectors were used, and the possibility of obtaining stable energy even on cloudy days was studied by increasing the intensity of solar radiation.

According to the obtained results, with the help of reflectors, the light radiation on the frontal surface of the PVTd was increased up to two times, and the short-circuit current also increased proportionally to the radiation.

When the cooling system was applied, the stability of the electrical parameters of the PVTd was ensured. The experiments showed that the PVTd produced on average 1.65 times more electrical power compared to the conventional photovoltaic (PV) battery. In addition, by passing cold water through the collector at the back of the device, it became possible to obtain usable hot water up to 50 °C.

Keywords: electric power, radiation, reflector, short-circuit current, open-circuit voltage, temperature.

Introduction. In the winter season, the demand for electrical and thermal energy increases significantly. Traditional energy sources, however, are limited, environmentally harmful, and often unable to provide sufficient efficiency. Therefore, portable photovoltaic–thermal devices are of great importance as an energy source. These systems not only generate electrical energy but also serve as a source of heat, which ensures high efficiency in the winter season. One of the main issues in solar photovoltaics is the efficient conversion of solar optical radiation energy into electrical energy and the continuous supply of consumers with energy at the required power. It is known that the efficiency of a PV module decreases sharply as its temperature increases [1,2].

In PVT systems, thermal collectors of different materials and shapes have been tested [3]. The effect of reflectors on the parameters of PVT devices has also been widely covered in many studies, with their main function being to increase the solar radiation reaching the PV module and to protect it from dust accumulation [4].

As temperature increases, the open-circuit voltage decreases, leading to a reduction in power output at the maximum power point. High operating temperatures also negatively affect the long-term durability of PV panels [5–6].

Research methods. In the winter months, due to the short duration of the day, the low density of solar radiation flow, the frequent cloudy weather, the low air temperature, and the high diffuse scattering, attempts to obtain sufficient electrical energy and hot water have been ineffective. Therefore, with the proposed technology, opportunities are opening up to solve a number of problems. A photovoltaic-thermal device (PVT) that guarantees the production of electrical energy and hot water throughout the year, both in winter and summer, by creating the required solar radiation intensity in extreme mountain and foothill areas, was developed and experimental test results were obtained. In this experiment, by creating additional light intensity through reflectors, the goal was to provide sufficient electrical and thermal energy even on cloudy days in winter. In order to reduce energy losses caused by the increase in the surface temperature of the PVT through cooling and at the same time to obtain additional thermal energy, a photovoltaic-thermal device was developed and equipped with a polycarbonate thermal collector and reflectors. The PV used in the device with a white protective coating has a power of 200 W. The experiment was carried out in real conditions at the Physics-Technical Institute, Heliopolygon, on 18.02.2025 from 10:00 to 15:00 in solar tracking mode. Since cloudy days are common in the winter months, the experiment was conducted on a cloudy day. A special support structure was developed for the PVT, designed for rotation around one axis and for vertical movement attached to a trailer. Accordingly, the same conditions were created for the PV, and experimental test results were obtained at 20-minute intervals and electrical parameters were measured. The experiment was carried out in solar tracking mode at a horizontal angle of 55° using the special construction developed in the device (Figure 1).



a)

b)

Figure 1. a) Photovoltaic-thermal device b) Photovoltaic battery.

The PVTD is equipped with a total of 4 light-reflecting planes. On the sides of the PVTD, there are 2 light-reflecting planes, each with a surface equal to that of the PV, and the combined surface area of the 3rd and 4th light-reflecting planes is also equal to the PV surface. The experiment was conducted under conditions where the ambient air temperature ranged from 12 °C to 16 °C during the day, comparing the differences between the PVTD and the PV (Figure 1). The effect of reflectors on the parameters of the PVTD has also been widely covered in many studies, with their main function being to increase the solar radiation energy reaching the PV and to protect the PV from dust accumulation [7].



Figure 2. Appearance of the sun behind the clouds.

In Figure 2, various appearances of the sun behind the clouds are shown. Observations carried out during the day showed that the degree of the sun's open visibility varied in the range of approximately 22% to 30%. In such conditions, the solar radiation flow significantly weakens when passing through the cloud layer. As a result, the density of the light flow decreases, and the efficiency of photovoltaic batteries (PV) sharply decreases. During the experiment, it can be observed that when the clouds thicken and their amount exceeds 30%, the amount of electrical energy generated in the PV decreases even more sharply. In such a situation, in order to maintain the efficiency of the PV, it is possible to use light-reflecting planes. They collect the rays coming from the sun, create the required light flow density, and thus support the operation of the PV. However, it should also be noted that when the cloud cover increases greatly and exceeds 30%, the efficiency of the light-reflecting planes also decreases considerably. Because in such

conditions the sunlight almost cannot pass sufficiently. Nevertheless, as shown in Figure 2, in cases where the sun is partially visible through the clouds, this device can still operate effectively and supply the PV with a certain amount of stable energy.

Photovoltaic batteries (PV) receive power directly from sunlight. If the density of the light flow decreases, the amount of electrical energy generated by the PV also sharply decreases. The experimental results showed that when the cloud cover exceeds 30%, the efficiency of the PV decreases significantly. In such situations, it is possible to use light-reflecting planes as an auxiliary tool. Simply put, they can be likened to a “large mirror reflecting the rays of the sun.” These planes collect the rays coming from the sun and direct them to the PV panels, and in this way create the required light flow density. As a result, even if the light falls dimly through the clouds, the panels still continue to operate to some extent.

Results and discussion. Of course, such a solution cannot always provide full benefit. For example, if the sky becomes completely covered with dark clouds, the reflecting planes cannot help either. Because in order to reflect rays, there must first be rays themselves. But, as shown in Figure 2, when the sun is partially visible through the clouds, this method gives very good results. In the conditions of Uzbekistan, such technology can be especially useful. Because in our country, the number of sunny days per year reaches 280–300, but in winter and spring cloudy days also increase. Therefore, with the help of light-reflecting planes, it is possible to use PV more efficiently. In this way, stability in energy production can be ensured and losses can be reduced even on cloudy days.

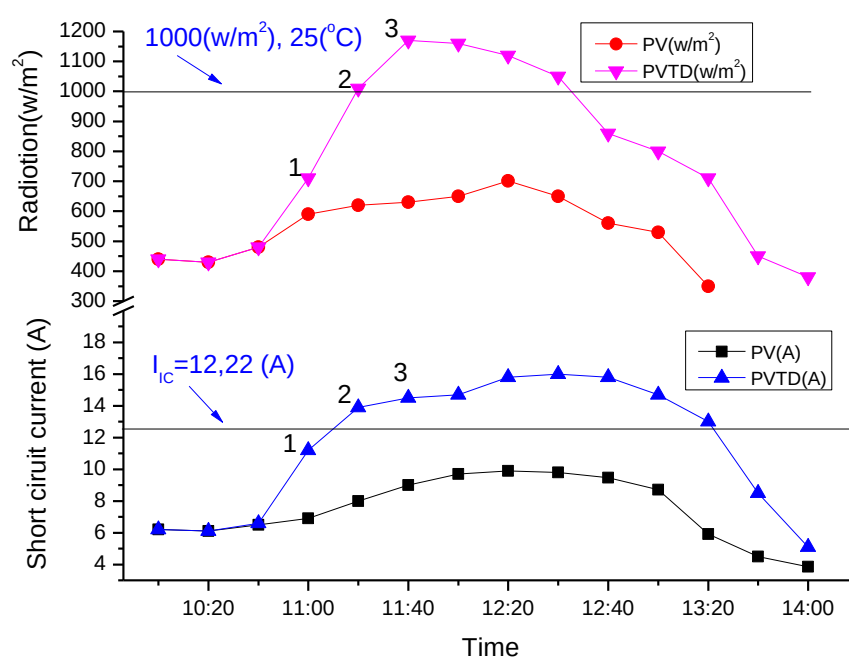


Figure 3. Dependence of short-circuit current and radiation on daytime.

Figure 3. Dependence of short-circuit current and solar radiation intensity on daytime. In the graph presented in Figure 3, special light-reflecting reflectors were used in order to increase the intensity of solar radiation. In the experiment, the reflectors were installed at separate time intervals, and the results obtained in 3 stages were recorded separately. Through this, it was observed under which conditions the reflectors work more effectively and to what extent they increase the light flux. The results showed that by using reflectors, the light radiation on the front surface of the PVT D was increased up to two times.

It can also be seen from this graph that the short-circuit current is directly proportional to the light radiation. As the reflecting planes were installed in 3 stages, the values of the short-circuit current also increased in 3 stages. In Figure 3, the passport data of the PV are also given, and it is shown that through the reflecting planes, both the light flux density and the short-circuit current exceeded the passport data. At the time when the light radiation reached 1150 W/m^2 , the short-circuit current achieved 16 A (Figure 3).

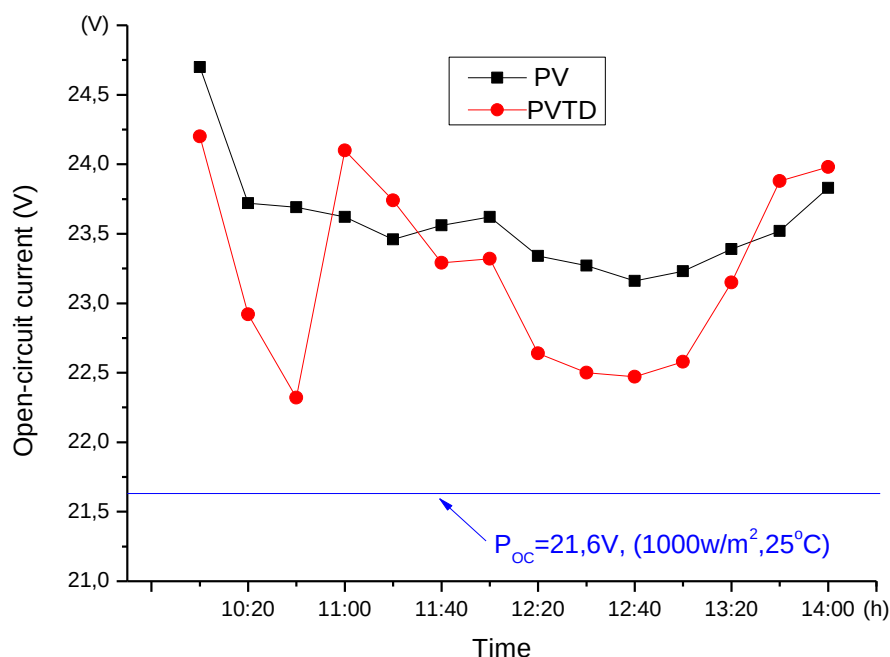


Figure 4. Dependence of open-circuit voltages of PVT D and PV on daytime.

In this figure, the graphs of the dependence of the open-circuit voltages of the PVT D and PV on daytime are presented. The value of the open-circuit voltage of the PVT D decreased until 10:40, then after the PVT was cooled with water, it rose again. Due to the density of the solar radiation flow collected by the reflecting planes, the front surface of the PVT D heated up

sufficiently, as a result of which the open-circuit voltage began to decrease again. After the sun passed through the zenith point, the open-circuit voltage started to rise again. Since the air temperature during the day was in the range of 12 °C to 16 °C, the front surface of the PV did not heat up enough, therefore the open-circuit voltage of the PV did not decrease significantly (Figure 4). The irregular variation of the values of PV and PVTd during the day can be explained by the changes in the cloud masses forming the weather.

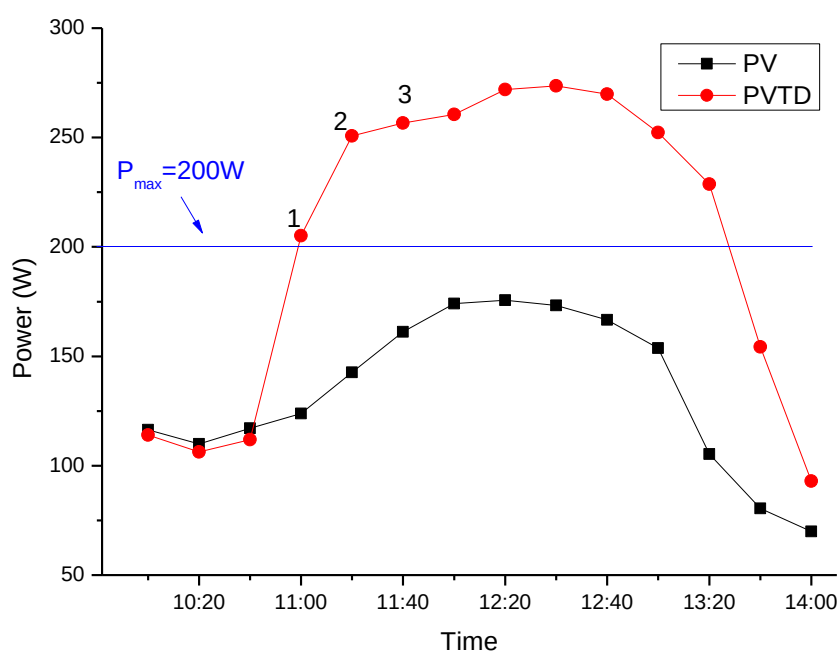


Figure 5. Dependence of the electrical powers of PVTd and PV on daytime.

In the following graph, the general differences of the electrical powers of PV and PVTd are clearly shown. The initial results indicate that during the time until 10:40, the PVTd showed less power compared to the PV. In particular, calculation results show that the PVTd produced less power than the PV. The reason for this is that until 11:00, no water was passed through the cooling system of the PVTd, therefore it heated more compared to the PV. As a result, the open-circuit voltage of the PVTd decreased compared to the PV. From 11:00, due to the cooling system, the front surface of the PVTd was cooled, and its open-circuit voltage increased compared to the PV. In addition, as a result of the light radiation obtained through the reflecting planes, additional power was achieved. The total average power of PV and PVTd was respectively 138.7 W and 228.7 W. The average values of the electrical powers produced by the PVTd during the day differ by 1.65 times compared to the PV.

Conclusion. The research results show that the use of a portable photovoltaic-thermal device makes it possible to obtain sufficient amounts of electrical and thermal energy even in the winter season. The light-reflecting planes enhance the light flux on cloudy days, significantly increasing the short-circuit current and electrical power. At the same time, with the help of the cooling system, the temperature of the device is kept within normal limits, preventing a decrease in efficiency. Based on the experimental results, it was confirmed that the PVT technology provides higher performance compared to conventional PV under winter conditions and can be widely applied in practice as a renewable energy source in the future.

The average power generated by the PVT was 65% higher compared to the average power generated by the PV. In addition to electrical energy, under conditions where the air temperature during the day was 4–12 °C, it was possible to obtain hot water at 50 °C with a flow rate of 20 l/hour.

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