Buildings Facade Photovoltaic-Thermal Collectors based on Aluminum Heat Pipes

Sergii Khairnasov, Boris Rassamakin, Dmytro Kozak and Alyona Naumova

Heat Pipes Laboratory, Heat and Power Department, National Technical University of Ukraine “KPI”, 709, Polytechnichna str. 6, Kiev, 03056, Ukraine

Corresponding author: Sergii Khairnasov (sergey.khairnasov@gmail.com)

Abstract: An advance of the energy efficiency and the ecological level of the housing sector is general task at energy supply new and old buildings. Apply renewable energy sources, in particular, solar energy is very perspective for it. Meanwhile, with allowance for the constructive properties of using solar heat and electric systems, it is urgent to simplify their integration and the use of these systems as elements of roofs and building facades. Good prospects are opened by using heat pipes as autonomic elements of solar collectors. Given article considers new approach to the design of photovoltaic-thermal collectors on the basis of aluminum heat pipes for use in building facades. In this case, aluminum heat pipes perform a complex role: they simultaneously serve as an absorbing surface, as highly thermal conductive device and as a cooling system for photovoltaic cells. The possibility to use such collectors is confirmed by experimental data which showed that the efficiency of photovoltaic-thermal collector with parameter $X = (0.02...0.06)$ K·m²/W is 0.35...0.60. Besides, the photovoltaic-thermal collector can further produce electricity up to 135 W/m² and maximum heat output up to 457 W/m² at the incident solar radiation of 900 W/m². Experimental test was carrying out on the mock-up of facade photovoltaic-thermal collector with dimension 1,340 × 500 mm. Such design of the photovoltaic solar collector could be easily integrated into building constructions.

Key words: Photovoltaic-thermal collector, heat pipes, buildings facade.

1. Introduction

Today, energy consumption of residential and industrial buildings in most European countries is estimated at 35-40% of total energy costs. The situation is similar for Eastern Europe, including Ukraine and Russia. For example, in Ukraine, the part of energy, consumed on buildings supplying, is about 40% of total energy consumption. At that up to 75% of the thermal energy is consumed in the residential sector. In order to improve energy efficiency in buildings, the use of new elements of facades, insulation materials and windows is widespread today. In this case, additional renewable and alternative sources of heat and electricity should be considered at designing of new buildings. This exact direction of additional solar energy use can be helpful, as it is closely represented in the book of U. Eicker [1].

Solar energy systems for use as building elements develop rapidly to date [2, 3]. Technology of photovoltaic-thermal collectors (PVT), presented in the review of the authors Xingxing Zhang, Xudong Zhao, Stefan Smith et al. [4], which allows to convert solar energy simultaneously into electricity and heat, is promising. Additionally, this technology makes it possible to improve the electrical performance of photovoltaic panel (PV) due to the solar cells (SC) cooling during their operation. Many international companies have already reached the market with such products. Also, there is a Europe program, which developed by the authors Pascal Affolter, Wolfgang Eisenmann, Hubert Fechner et al. [5], includes objectives and areas of the PVT implementation in production and operation during the coming years. However, one of the main tasks that
remain open is simplifying of the PVT integration into the facades and roofs of buildings [5].

Practically no solutions of this problem are offered today. A number of experimental studies by the authors Sleiman Farah, Wasim Saman, Martin Belusko [6] are fulfilled with the purpose of the performance optimizing of the PVT integrated into buildings. The researches are made for the Australian climate.

According to the author many existing problems can be solved due to the use of heat pipes (HPs) [7] as elements of PVT absorbers. Application of heat pipes as absorbers of solar collectors is not an original solution. This approach was used by L.L. Vasiliev [8] in the late eighties. But the construction of solar power systems based on the HP as elements of the buildings is a new trend. For example, the possibility of the evacuated tubular solar collector [9] using as a stationary window blinds was considered by R. Alexander [10]. The system solves the dual task of direct room shading and at the same time of further thermal energy generation for hot water supply.

The design of such solar systems can be greatly simplified by using aluminum HPs. This investigation line is developed by Rassamakin B.M. research team [11]. In this case, HP can be used both as the PVT elements [12] and as the building ones [13]. In this article, the authors present the results of the PVT thermal and electrical characteristics studies. The PVT model is based on aluminum heat pipes. The experiments were conducted at the National Technical University of Ukraine “KPI”.

2. Laboratory Investigation

2.1 Experimental Samples

The PVT mock-up was designed and manufactured in the National Technical University of Ukraine “KPI”. When designing it was considered that the construction of such PVT should ensure its easy installation in the facades of buildings (Fig. 1). In this case, each heat pipe with SC can be regarded as a single unit. When integrating this construction into building façade the solar system can be composed of a various number of such units having different lengths.

The PVT mock-up (Fig. 2) has the following characteristics:
- dimensions of absorption surface with SC is 1,340 \times 500 \text{ mm};
- number of SC is 36;
- total surface area of SC is 0.56 \text{ m}^2
- maximum electric power is 75 \text{ W};
- dimensions of polycrystalline SC is 125 \times 125 \text{ mm};
- SC efficiency is 15%;
- a glass with light transmitting ability of 0.91 and 0.004 \text{ m} thickness;
- protective coating for the SC is silicone coating PC-68 with light transmitting ability of 0.96.
The PVT mock-up is a basic design with maximum output power of 75 W. The design includes four heat pipes (2) with nine SC (1) on each one. The design is constructed so that each heat pipe represents a separate photovoltaic unit. This makes possible to create a system with different numbers of photovoltaic units, varying their length. Such construction is primarily designed for its integration into building facades. The heat exchanger (6) (Fig. 3), which is mounted on the heat pipes surface using only conductive layer (thermal paste SPTC-8 in our case) and screws, was specially designed for this purpose. It provides easy and fast system installation.

The unit also has some additional design elements which are commonly used in thermal solar collectors such as: case (8), which is made of 6060 aluminum alloy with anodized protective coating; insulation (4)-ISOVER 50 mm; cover (5) which is a galvanized metal sheet of 0.5 mm thickness; glass (7) with low iron content; corner (8) made of aluminum alloy 6060 with silicone sealant, inlet and outlet tubes for the heat carrier (9) made of 6060 aluminum alloy.

2.2 Laboratory Tests

To investigate the efficiency of the PVT mock-up a special experimental stand with the sun simulator was created (Fig. 4). The halogen lamps with a colour temperature of 4,000 K, which corresponds to the emission spectrum of the Sun, were used as the simulator of solar flow. The simulator was created in accordance with the normative document [14].

Test procedure for the PVT mock-up was developed on the basis of regulations defining test methods of PVT [15] and SC [16]. This procedure allowed to investigating the PVT thermal and electrical efficiency.

The PVT thermal efficiency \( \eta \) was calculated as the ratio of the effective heat flux \( Q_{\text{ef}} \) to the total one \( Q_{\text{tot}} \).

The effective heat flux can be obtained by formula:

\[
Q_{\text{ef}} = G_w \cdot C_p \cdot (t_{\text{out}} - t_{\text{in}}) \quad (1)
\]

where \( G_w \) and \( C_p \) are accordingly the heat carrier flow rate and thermal capacity; \( t_{\text{out}} \) and \( t_{\text{in}} \) are outlet and inlet temperatures of the heat carrier passing through the PVT heat exchanger.

The total heat flux incident on the heat absorption surface having area \( F_{\text{hs}} \) is:

\[
Q_{\text{tot}} = (1 - A) \cdot E \cdot F_{\text{hs}}, \quad (2)
\]

where \( E \) is the incident solar radiation, W/m\(^2\); \( A \) is coefficient of efficiency of SC.

To assess the PVT electrical efficiency its current-voltage characteristic was fixed. In this case, the PVT maximum electrical power output \( P_m \) (W) was defined as the product of current \( I \) (A) and voltage \( V \) (V). Then the PVT unit electrical efficiency was calculated by the formula:

\[
\eta = P_m / (E \cdot A) \quad (3)
\]

Experiments were conducted at three flow rates (0.35-1 L/min) of cooling fluid (water) and then recorded using flow meter integrated into the hydraulic circuit. For each value of flow rate the heat flux density varied within the range 400-1,000 W/m\(^2\) and was measured by pyranometer CMP3. Furthermore, the average temperature of the cooling fluid varied and was equal to 30 °C; 45 °C; 60 °C; 75 °C.
The copper-constantan thermocouples were used as the temperature sensors. Temperature values were recorded using an analog-digital device MBA8, and then these digital signals were received by the personal computer.

During the experiments, the hydraulic resistance of the heat exchanger was also measured using digital pressure gauges installed on the inlet and outlet of the collector.

The maximum error of the temperature measuring by thermocouple is 0.4 °C. Maximum measured error of \( C_p, G_w, F_{hs} \) was ± 0.5%, ± 2.5%, ± 0.5% respectively. Error caused by the incident solar radiation is ± 3.0%. Thus, the maximum error of thermal efficiency for the parameter \( X = 0.02 \text{ K·m}^2/\text{W} \) was ± 0.8% for thermal efficiency. Maximum measured error of current I (A) and voltage V (V) was ± 0.8% and ± 1.5% respectively. So, the maximum error of the electrical efficiency was ± 1.7%.

3. Results and Discussion

As a result of experimental studies the PVT thermal efficiency curve was obtained. Comparison of PVT and standard flat plate solar collector (FPC) operation (Fig. 5) shows that the thermal efficiency of PVT is about 10-15% less. First of all it is the result of the fact that the part of the energy is converted into electrical energy by SC.

Moreover, SC with adhesive layer serves as thermal insulation element and reduces the PVT thermal efficiency at low solar heat fluxes and at large temperature difference between the absorption surface and the environment.

Fig. 6 shows the results of water heating rate in accumulator tank of 95 L during the day, i.e. at solar flux changing. Data were recorded at the time of zero consumption of hot water.

The following tendency was observed: lower initial temperature of the water in the tank causes more intensive water temperature growth. Thus, the obtained data confirmed that optimal performance of PVT unit takes place at temperatures of its absorption surface no more than 60 °C, which corresponds to the temperature of SC.

Rising of the cooling water temperature at the system outlet up to the temperature used in hot water supply leads to increase in temperature of SC up to 50-55 °C, which will reduce the power output by 20%. This allows us to consider cooling water recycling only as an additional source of hot water supply that can be used with other heating systems (such as solar collector, heat pump or industrial heat source).

Current-voltage characteristic describes the electrical efficiency of the PVT. The results showed increasing of the battery voltage up to 17.8% and
rising of the current strength up to 60.7% with temperature decreasing of the SC from 90 °C to 44 °C (results obtained in the “idling”).

Studies have shown that due to the SC cooling of the PVT can improve the efficiency of electrical energy producing up to 28%, with the PVT maximum electric power of 135 W/m². In addition to the electricity, one can simultaneously obtain heat flux up to 457 W (Table I) from the heat absorption surface of 1 m² (for water heating).

Analysis of the PVT thermal and electrical efficiency shows that absorption surface temperature below 60 °C is the most productive for the PVT functioning. Rising of the cooling water temperature at the system outlet up to the temperature used in hot water supply leads to increasing of the SC temperature up to 70 °C, and so it reduces the electric power output by 20%. On the other hand, even when temperature of the PVT absorption surface comes up to 60 °C, water temperature in the accumulation boiler will be no more than 45 °C. This value is too small for heat water supply and even more so for the heating system. On the one hand increasing of water temperature in the boiler is good for the heat water supply system and on the other hand it results in performance decreasing for the system combined with the PVT. Therefore, the most effective is using of the PVT to preheat water for heat water supply systems with maximum additional power generation. This was also confirmed by the PVT sample experimental research.

Analyzing the results it can be argued that PVT saves surface on the facade or roof of the building. In the real-life environment, we can set 1 m² PVT on a given surface area of 1 m², but we can not install SC and FPC with an area of 1 m² each, but we can distribute this area between them, for example, 0.5 m² for each one. In this case we can increase efficiency by design features such as, for example, length of the heat pipes. Thus, when the length of the heat pipes is 1,340 mm the PVT provides 26% more energy than separate PV cell and FPC, and at heat pipes length of 2,340 mm up to 30% more energy.

Another important feature of the PVT is the hydraulic resistance of its heat exchanger, which affects the efficiency of the PVT functioning as a part of the solar thermal system. The results showed that considered design of the PVT has a low value of hydraulic resistance. Thus, when the water flow is 2.2 L/min the hydraulic resistance of the standard FPC is 460 Pa, while the hydraulic resistance of the PVT with the heat pipes is 2.4 times less. Hence, the PVT on basis of profile aluminum heat pipes has lower hydraulic resistance. This fact is very important when using the PVT with area more than 10 m² in the façade Solar system, which requires installation of more powerful pump that increases energy consumption during use.

### Table 1  Dependence of thermal and electric power PVT at E = 900 W/m².

<table>
<thead>
<tr>
<th>t_{out}</th>
<th>Q_{th}, W/m²</th>
<th>P_{el}, W/m²</th>
</tr>
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<tbody>
<tr>
<td>25</td>
<td>457</td>
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<tr>
<td>50</td>
<td>323</td>
<td>121</td>
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<tr>
<td>75</td>
<td>243</td>
<td>106</td>
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4. Conclusion

Technology of photovoltaic-thermal collector (PVT) that allows to convert solar energy simultaneously into electricity and heat is promising. Additionally, this technology makes it possible to improve the electrical performance of solar cells (SC) due to the cooling of during their operation. However, one of the main tasks is the quick integration into facades and roofs of buildings and it remains open. Therefore, the proposed design of the PVT based on aluminum heat pipes has great potential.

The developed PVT design can further be used as a part of the facade having large solar system over 10 m². At that one should ensure optimal operation mode of the PVT, defined by absorption surface temperature below 60 °C. The PVT can be considered both as a system for water pre-heating throughout Ukraine and as the heating source for the main heat
water supply system in the southern regions of Ukraine where they can be installed as southern side of the building roof. Also the PVT can be used as secondary system providing electricity throughout Ukraine.

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