DOI: 10.63527/1607-8829-2025-4-82-92

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Combined Source of Thermal and Electrical Energy Based on a Pyrolysis Burner and a Universal Thermoelectric Generator

The results of tests of a combined heat and power generation system consisting of a PP-8 pyrolysis burner and a universal thermoelectric generator are presented. The thermophysical characteristics of the system in different burner operating modes are investigated, and the conditions for matching the thermal parameters of the burner and the thermoelectric module are determined. The effect of heat exchange intensification on the operating temperature difference and the output electrical power of the TEG is analyzed. It is shown that by optimizing the combustion modes and design conditions for supplying heat flow, it is possible to ensure stable operation of the generator with an electric power of up to 200 W. Brief technical characteristics of the universal thermoelectric generator and pyrolysis burner PP-8 are given.

Keywords: thermoelectric converter, thermoelectric module, energy efficiency, optimal control methods, contact resistance, thermal resistance, interconnect and isolating plates.

Introduction

The use of thermoelectric generators (TEG) as part of micro-systems for combined heat and power generation (μCHP) is considered promising for use at autonomous facilities, in field conditions, and in case of emergencies. Known developments of experimental and commercial

Citation: Yu.M. Lobunets, V.P. Klius, G.O. Chetveryk, Yu.Yu. Rozver, M.V. Havryliuk, I.A. Konstantynovych (2025). Combined Source of Thermal and Electrical Energy Based on a Pyrolysis Burner and a Universal Thermoelectric Generator. *Journal of Thermoelectricity*, (4), 82–92. https://doi.org/10.63527/1607-8829-2025-4-82-92

μCNR samples can be divided into two groups – these are systems with TEG integrated into the burner design and systems with universal generators that can use various heat sources. In the latter case, there is a need to coordinate the thermal modes of the source and the energy converter in order to achieve acceptable technical and economic indicators of the system. The main task in this case is to ensure optimal heat flows in the heat source – TEG – cooling system with regard to the design features of the generator and the heat energy source. Most known μCHP systems use direct combustion devices of solid biofuels (firewood, wood chips, pellets and briquettes) as a source of thermal energy [1–5]. The main disadvantages of such sources are the instability of thermal regimes, the complexity of their regulation and large emissions of soot and carbon monoxide into the atmosphere. These shortcomings can be eliminated by using gas generator burners that implement the pyrolysis combustion mode of solid fuel. This paper presents the results of research on the μSNR system, which includes a universal thermoelectric generator developed at the Institute of Thermoelectricity and a PP-8 pyrolysis burner developed at the Institute of Renewable Energy.

Universal thermoelectric generator

The universal thermoelectric generator [6] is made in the form of a water heating tank, to the bottom of which a thermoelectric unit is attached from the outside. The unit consists of two heat exchange units – “hot” and “cold”, between which thermoelectric modules are placed. The heat flow coming from the source passes through the thermoelectric unit and is dissipated in the volume of the tank due to heating and evaporation of the coolant. This creates a temperature difference across the unit's thermocouples, causing the unit to generate a thermal emf whose magnitude is proportional to the temperature difference and the number of thermoelements connected in series. The generator is equipped with a voltage stabilizer, ensuring a constant output voltage for powering the loads. A universal thermoelectric generator, designed for mounting on water tanks with a volume of 2–5 liters, has the appearance shown in Fig. 1.

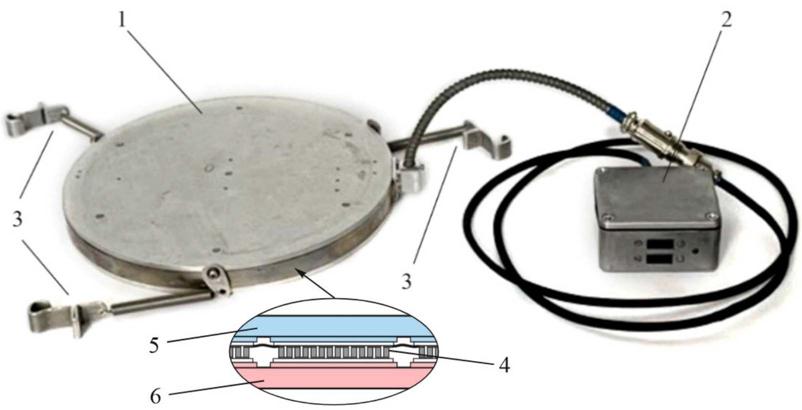

*Fig. 1. Appearance of a universal thermoelectric generator:
1 – thermoelectric generator; 2 –electronic output voltage stabilization unit,
3 – hooks on springs for attaching the generator to a water tank, 4 – thermoelectric generator modules; 5 – “cold” heat exchanger; 6 – “hot” heat exchanger*

The device can operate from various heat sources: heated flat surfaces of stoves, gas or multi-fuel camping stoves, and open flames. The container (pot) is used to heat water or cook food. The heat from the combustion of fuel passes through the thermoelectric modules and is transferred to the volume of the pot, heating the water. As a result, a temperature difference is formed between the heat exchangers, and accordingly between the hot and cold sides of the modules, which causes the appearance of an electric voltage proportional to this difference. The power that can be obtained from the modules is determined by the power of the heat source. The technical characteristics are given in Table 1 [7].

Table 1

Technical characteristics of the universal thermoelectric generator

DC output voltage	5 ± 0.2 V, 12 ± 0.2 V
Rated output power	15 W
Thermoelectric modules type Altec 1061	3 pcs.
Maximum operating temperature	300 °C (short-term up to 400 °C)
Maximum coolant volume	2.5 l
Time to enter mode	5 min
Continuous operation time (with coolant)	unlimited
Weight, not over	1.8 kg
Dimensions	220 × 200 × 160 mm

Most consumers need a stable standard voltage, most often 5 V DC, which is used in chargers and power banks. Stabilization is provided by an electronic unit based on a boost-down converter, which operates only within a given range of input voltages. At the start of TEG operation, the temperature difference between the hot and cold heat exchangers is small, so the module voltage is insufficient to initiate the stabilization circuit. Operating mode is reached only after warm-up, and the warm-up time depends on the power of the heat source. Stabilized voltage is supplied to two USB connectors; its presence is indicated by a green LED next to the connector. The delivery package also includes a cable with a 5 V to 12 V converter, which can be used with both the generator electronic unit and the power bank.

Pyrolysis burner PP-8

The PP-8 pyrolysis burner was created as a mobile solid fuel furnace for heating rooms, dugouts and generating electricity using a thermoelectric generator [6]. Its main features are high specific power (about 1 kW/kg), high efficiency (up to 85 %), no harmful emissions, and stable combustion on one fuel charge for 3–5 hours. To achieve these indicators, the design is based on a vertical gas generator burner with an upper fuel combustion zone (Fig. 2). The furnace is made of thin-sheet stainless steel, its diameter is 320 mm, height is 700 mm. The weight of the furnace is 12.5 kg. The volume of the furnace retort is 32 l, which is enough to accommodate 10…12 kg of hardwood firewood. The furnace is equipped with a chimney with a diameter of 100 mm and a height of 4 m.

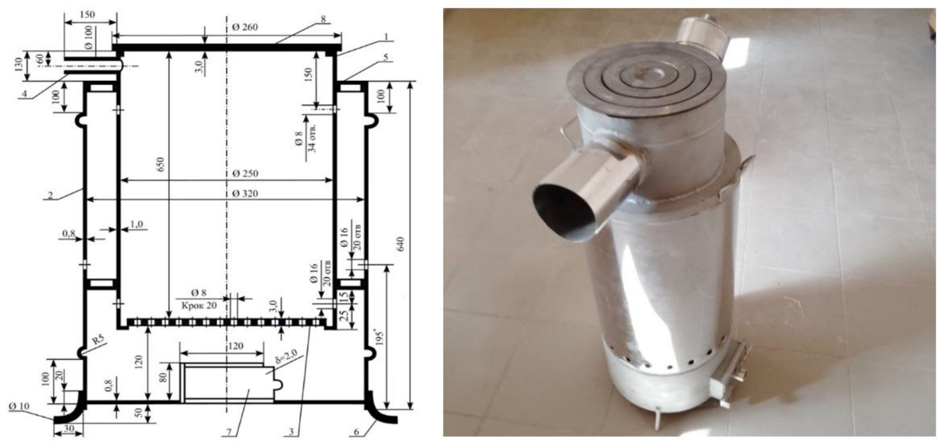

Fig. 2. Schematic and appearance of the PP-8 burner

The gas generator is a vertical, batch-type reactor containing a dense bed of fuel. Fuel ignition occurs from the top, and air is supplied from the bottom. After ignition, the high-temperature region begins to move towards the blast at a constant speed. This phenomenon resembles a front of thermal and chemical conversion of the fuel or a gasification zone. The gasification zone is the part of the layer that separates the zones of raw biofuel and formed biochar. The movement of the gasification zone occurs due to the high thermal conductivity of the fuel. The biofuel layer is gradually heated and pyrolysis occurs. In the pyrolysis zone, volatile substances are oxidized by oxygen from the primary air. Then, part of the biochar is oxidized and the oxygen is completely consumed. Next, carbon oxidation reactions with water vapor and carbon dioxide occur. Behind the combustion front, a layer of red-hot biochar remains, in which thermal decomposition (cracking) of resins occurs. Due to the supply of secondary air, biochar is burned to ash.

To increase the efficiency of the burner, the secondary air is heated by passing through the gap between the combustion chamber wall and the outer casing of the furnace.

The furnace's power is regulated by controlling the air flow using a gate valve and dampers. The excess air ratio for complete gasification does not exceed 0.30–0.50. By reducing the volume of flue gases, the burner's efficiency as a heat source is significantly increased. The transfer of heat flow from the burner to the thermoelectric generator can be carried out by thermal conduction from the heating surface consisting of cast iron rings, or by convection from combustion products by placing the TEG heating surface directly in the combustion chamber or at the entrance to the chimney.

Conditions for matching TEG and burner parameters

To ensure maximum electrical power of the μSNR, it is necessary to create conditions under which the temperature difference across the thermoelectric modules will reach the maximum possible value. The theoretically permissible temperature difference is determined by the difference between the maximum permissible operating temperature of the hot side of thermoelectric modules T_p = 300 °C and the boiling point of the coolant t_w = 100 °C:

$$\Delta T_t = T_p - t_w = 200°\text{C} \tag{1}$$

The heat flow density required to create such a difference can be estimated to a first approximation using the Fourier law of thermal conductivity:

$$q_0 = \frac{\lambda \cdot \Delta T}{h}, \tag{2}$$

where λ is the thermal conductivity coefficient of the thermoelectric material; h is the height (thickness) of the thermoelements.

Based on the characteristics of the ALTEC-1061 type modules, the nominal heat flow density can be estimated as $q_0 \approx 9 \ldots 10$ W/cm^2. This corresponds to a total heat flow through the module of about $Q \approx 250$ W. When this heat flow passes through the system, temperature differences occur on its components, proportional to the corresponding thermal resistances. Therefore, the μCNR thermal model can be considered as a series connection of three resistances: the thermal resistance of the heating section R_{th}, the thermal resistance of the thermoelectric modules R_{tm}, and the thermal resistance of the cooling system R_{tx}. That is, the total thermal resistance of the system:

$$R_t = R_{th} + R_{tm} + R_{tx}, \tag{3}$$

where $R_t = (t_h - t_w)/Q$.

The latter expression imposes restrictions on the thermal resistances of the heating and cooling systems, since the other components are known from the problem statement. Given that the temperature of the combustion products significantly exceeds the operating temperature of the TEG ($t_h > T_p$), this excess must be compensated for by the thermal resistance of the heating section R_{th}. The temperature difference across the thermal resistance of the cooling system R_{tx} must be minimized, as it reduces the useful "temperature head" $\Delta T_0 = T_h - T_c$.

The task of optimizing TEG parameters under similar conditions was considered in [8–12], and to specify the operating modes requires determining the thermophysical parameters of the system. For this purpose, an experimental study of the characteristics of μSNR was carried out as part of a universal thermoelectric generator and a PP-8 pyrolysis furnace.

Program and methodology for testing

The test program involves monitoring the parameters of the μSNR prototype during the full operating cycle of the burner, which makes it possible to determine the dependence of its electrical and thermal power on the thermal operating mode of the burner.

The thermal power of the burner is determined using the following method:

- The total amount of thermal energy Q_o released during the operating cycle, is determined by the mass of fuel G and its lower calorific value Q_n. For the case under consideration: $G = 10$ kg, $Q_n = 4$ kWh/kg; $Q_o = 40$ kWh;
- The instantaneous thermal power of the burner is estimated by the product of the instantaneous temperature of the combustion products t_a by the temperature coefficient K_τ, which is defined as

$$K_\tau = \frac{Q_o}{t_a \cdot \tau_o} \left(\frac{\text{kW×h.}}{\text{K}}\right); \tag{4}$$

- The burner eficiency η_t is defined as the ratio of useful heat Q_u to total heat output:

$$\eta_t = \frac{Q_u}{Q_o} = \frac{\left(Q_o - Q_d\right)}{Q_o}, \tag{5}$$

where $Q_d = K_\tau \cdot t_d$ are heat losses with flue gases.

$$\eta_t = 1 - \frac{t_d}{t_h}. \tag{6}$$

The thermal efficiency of the burner can be written through the measured temperatures in the form:

$$\eta_t = 1 - \frac{t_d}{t_h}. \tag{6}$$

The electric power of the generator is defined as:

$$N = E^2 \frac{m}{\left(m+1\right)^2}, \tag{7}$$

where E is the generator EMF; $m = R_L/R$ is the load factor; R is the internal resistance of the TEG; R_L is the electrical resistance of the payload.

The optimal value of m depends on the heat exchange conditions. As a first approximation, $m_{opt} \approx 1.2$. can be used. The EMF, in turn, is determined by the temperature difference across the thermoelements.

$$E = e\left(T_h - T_c\right)n_i, \tag{8}$$

where e is the Seebeck coefficient; T_h and T_c are the junction temperatures of the thermoelements; and n_i is the number of thermoelements connected in series. The properties of thermoelectric materials are significantly dependent on temperature. Therefore, their average values over the given temperature range were used in the calculations. The temperature dependences of the properties of thermoelectric materials required for the calculations were determined as:

Thermal conductivity coefficient $\lambda = 0.0035\exp\left(0.01t\right)$;

Electrical conductivity coefficient $\sigma = 12.5\exp(0.0254t)$;

Seebeck coefficient $e = 4.5\cdot10^{-4} - 13.5\cdot10^{-7}t$;

where t is the absolute operating temperature, which is defined as the average between the measured temperatures of the heat exchange surfaces: $t = (t_1 + t_2)/2 + 273$. Due to the presence of additional thermal resistances between the heat exchange surfaces and the junctions of the thermoelements, thermal head losses occur, which can be estimated by calculating the operating temperature difference $\Delta T = T_h - T_c$ through the EMF of the converter and its properties:

$$\Delta T = \frac{E}{e \cdot n_i} \tag{9}$$

This temperature difference value allows us to estimate the actual heat flow density through the converter as

$$q = \frac{\lambda \cdot \Delta T}{h}\left(\frac{\text{W}}{\text{cm}^2}\right). \tag{10}$$

The total heat flow through the converter is equal to

$$Q = q \cdot s \cdot n_i \,, \quad (11)$$

where s is the cross-sectional area of the thermoelement. This data allows estimating the thermal resistance between the heat source and sink and the thermoelectric converter.

Results of experimental studies

During the research, the following parameters were measured during the burner operating cycle:

- temperature of gases in the combustion chamber t_h;
- temperature of flue gases t_d;
- temperature of the hot heat exchange plate t_1;
- temperature of the cold heat exchange plate t_2;
- water temperature t_w;
- EMF of the thermoelectric converter E

Measurement data were recorded by a computer with a time interval of 5 seconds.

As a result, data arrays of temperature distribution in μSNR and the corresponding values of EMF and generator power were obtained (Fig. 3, Fig. 4). During the experiment, the combustion mode was adjusted by changing the hydraulic resistance of the gas path using a gate valve on the chimney and valves in the primary air supply fitting. The adjustment moments correspond to the peak values on the temperature graphs. At the final stage of the cycle (after 95 and 110 minutes), the contact heat supply was replaced by heating the TEG with an open flow of combustion products by removing the central rings on the burner cover. Due to more intensive heat exchange, this led to an increase in heat flow and a noticeable increase in the operating temperature of the thermoelectric converter.

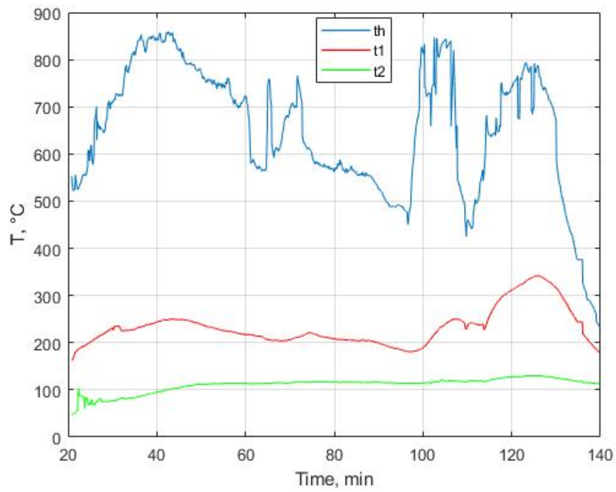

Fig.3. Distribution of parameters during the burner operating cycle

The corresponding correlation between the data is visible in the graphs of temperature, EMF and generator power distribution.

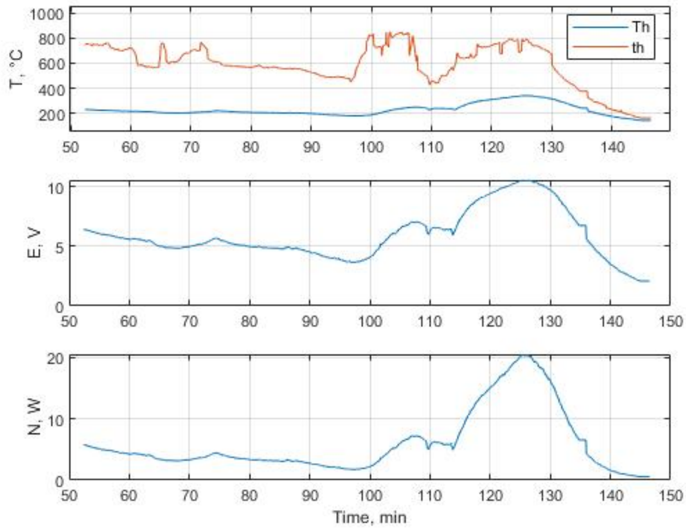

Fig. 4. Distribution of temperatures t_h, T_h, EMF E and power generator N

The generator power increases monotonously with a rise in the hot side converter temperature and at $T_h > 300°C$ reaches 20 W (Fig. 4).

The determining factor for the TEG power is the operating temperature difference across the thermoelements. However, the measured temperature difference is somewhat overestimated: there are additional thermal resistances between the heat exchange surfaces and the junctions. The actual value of the difference can be determined by formula (9). The error in this case is determined only by the accuracy of the temperature dependences of the material properties used.

The analysis shows that the ratio of the calculated and measured temperature differences is approximately $\frac{\Delta T}{\Delta t} \approx 0.75$, i.e. about 25 % of the difference is lost at the contact thermal resistances.

The distribution of heat flow during the experiment is shown in Fig. 5, and the distribution of thermal resistances and temperature differences between the components of the system is shown in Fig. 6.

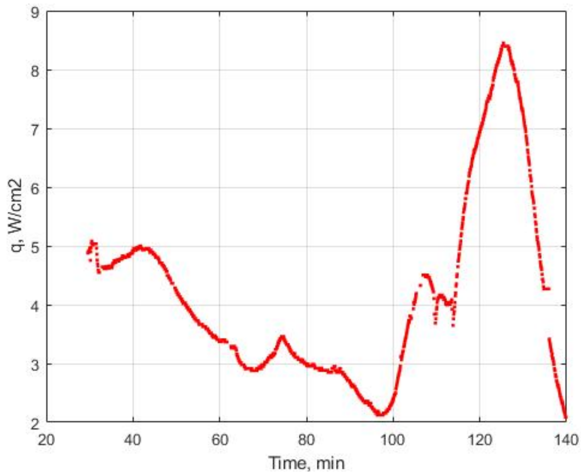

Fig. 5. Specific heat flow density through TEG

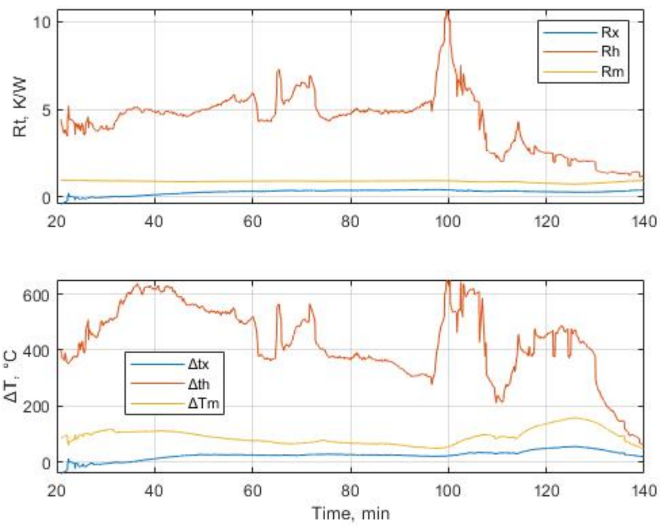

Fig. 6. Distribution of thermal resistances and temperature differences on the components of μSNR
R_x – cooling system; R_h – heating system; R_m – thermoelectric converter

From the data presented, it can be seen that in the μSNR thermal scheme, the thermal resistance of the heating system R_h dominates, which compensates for most of the temperature head Δt_h and limits the heat flow Q. After intensification of heat exchange, R_h significantly decreases, which ensures an increase in the heat flow and the generator reaches a temperature mode close to the design one: the operating temperature difference across the thermoelements is about 160°C (about 80% of the maximum).

The cycle duration was 2.44 h, which is half the standard for the PP-8 burner due to temperature control. Accordingly, the burner power has increased significantly. From Fig. 3 it is clear that the average temperature of the combustion products is $t_a \approx 550$°C. In accordance with (4), the temperature coefficient of the burner power is:

$$K_\tau = \frac{40}{2.44 \cdot 550} = 0.0298\ \frac{\text{kW}}{°\text{C}}. \quad (12)$$

The average instantaneous burner power per cycle was $Q\tau = 16.4$ kW.

Conclusions

1. Experimental tests of the μSNR, consisting of a pyrolysis burner PP-8 and a universal thermoelectric generator, were conducted. The thermophysical characteristics of the system in different burner operating modes were investigated.
2. The conditions for matching the burner and TEG parameters are determined. It is shown that regulating the air flow rate provides the optimal thermal mode of operation of the thermoelectric generator, in particular, increasing the operating temperature difference across the thermoelements to ~160°C.
3. The efficiency of heat exchange intensification by changing the design conditions for heat flow supply has been confirmed, which makes it possible to reduce the thermal resistance of the heating system and increase the heat flow through the TEG.
4. Based on the experimental data obtained, it was established that the PP-8 burner can ensure the operation of the TEG of the studied type with an electric power of up to 200 W.

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Submitted: 05.12.25

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Комбіноване джерело теплової та електричної енергії на базі піролізного пальника та універсального термоелектричного генератора

Наведено результати випробувань комбінованої системи виробництва теплоти та електроенергії, що складається з піролізного пальника ПП-8 та універсального термоелектричного генератора. Досліджено теплофізичні характеристики системи в різних режимах роботи пальника, визначено умови узгодження теплових параметрів пальника та термоелектричного модуля. Проаналізовано вплив інтенсифікації теплообміну на робочий перепад температур і вихідну електричну потужність ТЕГ. Показано, що за рахунок оптимізації режимів горіння та конструктивних умов підведення теплового потоку можливо забезпечити стабільну роботу генератора з електричною потужністю до 200 Вт. Наведено короткі технічні характеристики універсального термоелектричного генератора та піролізного пальника ПП-8.

Ключові слова: Термоелектричний перетворювач, термоелектричний модуль, енергоефективність, методи оптимального керування, контактний опір, термічний опір, комутаційні та ізоляційні пластини.

Надійшла до редакції 05.12.25