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Inertial Thermoelectric Generator with Phase Change Thermal Modules

The purpose of the work is to calculate and create an inertial thermoelectric generator (ITEG) with integrated variable heat and cold modules on the hot and cold sides. The use of thermal modules (TM) on both sides of the ITEG will rigidly fix the temperature gradient in the generator. This will allow to build an autonomous thermoelectric generating system that will generate stable thermoelectric power throughout the entire operating time. The operating principle of the ITEG is based on the use of latent heat of crystallization and fusion of phase change materials. The use of replaceable thermal modules will ensure the rapid replacement of discharged TMs with charged ones, and will also allow to make a stock of preheated and cooled modules. Moreover, any heat and cold sources are suitable for heating and cooling. To increase the speed of charging and discharging, the TM has a network of internal radiators.

Keywords: Dual PCM, thermoelectric generator, thermal module, latent heat of fusion, phase change materials, enthalpy, exergy, thermal resistance.

Statement of the problem

In recent decades, much effort has been made to find new classes of thermoelectric materials with improved characteristics [1]. However, in addition to improving the characteristics, the appropriate arrangement of the thermoelectric generator, heater, and cooler can significantly increase the efficiency of the thermoelectric system.

In traditional thermoelectric generators (TEGs), heat is supplied and removed directly to (from) the junctions. For cooling TEGs, the most commonly used methods are air, liquid, thermoelectric cooling and cooling using phase change materials [2]. TEGs generate electricity as long as there is a temperature difference between the hot and cold sides. It is obvious that under unstable thermal boundary conditions, the thermoelectric power will also be unstable. The efficiency of a thermoelectric generator can be improved by combining it with phase

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change materials (PCMs). PCMs help maintain a constant temperature difference between the sides of the TEG for a long time. This leads to an increase in system efficiency, stabilization of the output voltage and power.

The purpose of the work is to calculate and create an inertial thermoelectric generator with integrated variable thermal modules based on PCMs on the hot and cold sides, which would generate a stable voltage independent of ambient thermal conditions.

Analysis of known research results

Currently, considerable attention is paid to heat storage using PCMs. Their advantages are high specific density of accumulation and storage of thermal energy (5–10 times higher compared to heat-storing liquids), constant phase change temperature, chemical stability, availability and low cost. The use of PCMs allows to stabilize the thermal operating mode and the temperature difference between the sides of the TEG, which is critically important for its effective operation.

In [4, 5, 6], the use of phase change materials (PCMs) to stabilize hot junction temperatures and improve the performance of thermoelectric systems subject to transient thermal loads was investigated. By absorbing and releasing latent phase change heat, PCMs prevent temperature fluctuations, maintain optimal thermal gradients, and continue power generation even after the heat source is switched off. Temperature management of thermoelectric generating systems has been studied by many authors, but they have not addressed the issue of design modularity.

In [7, 8], an integrated TEG system is presented, in which an internal temperature gradient is generated without a defined hot or cold side. Two PCMs with different melting points are located on opposite sides of the TEG, which allows the system to create periodic thermal hysteresis during heating and cooling cycles. The dual PCM-TEG energy harvester represents a new operational concept for passive energy harvesting, which allows the conversion of low-potential, non-directional ambient thermal fluctuations into electrical energy. This approach is well suited for low-power autonomous sensors and devices.

Unstable vehicle driving conditions and exhaust gas temperature fluctuations are crucial factors that hinder the development of automotive TEGs. In [9, 10], a new concept of joint operation of automotive TEG and PCM is presented. It is shown that PCM on the hot side of TEG reduces the influence of exhaust gas temperature fluctuations on the thermoelectric power (TEP) value and increases its efficiency. Studies have shown that stabilization of the thermoelectric power (TEP) leads to an increase in output power by 1.16 %.

The functionality of monolithic structures of TEG-PCM systems can be significantly improved. In particular, some modern studies introduce the concept of interchangeable cassette modules [11, 12]. Such an engineering approach allows, by quickly replacing cassettes with phase change materials on the hot and cold sides (for example, the transition from high-temperature salt hydrates to low-temperature eutectics), to expand or shift the thermal range of TEG operation in the desired direction. The modular design of the thermal accumulator with PCM is described in detail in [11]. The PCM absorbs excess heat and prevents overheating of

the LED elements and their degradation. The simultaneous use of replaceable modules with PCM on the hot and cold sides of the TEG for active heating and passive cooling is an innovative combination.

The purpose of the work is to create an inertial thermoelectric generator with integrated thermal accumulators on the hot and cold sides, which would generate a stable voltage independent of variable ambient temperature conditions.

Design and calculation of a thermoelectric generator

As follows from the second law of thermodynamics, not all the heat supplied to a heat engine can be converted into useful work. Only a certain part of it is suitable for this. The efficiency of thermal energy is assessed by calculating its exergy [3].

$$E_x \leq Q_h \left(1 - \frac{T_c}{T_h} \right) \quad (1)$$

where Q_h is the amount of heat supplied to the heat engine from the heater, T_h is the temperature of the heater, T_c is the temperature of the cooler. The equal sign is valid only for an equilibrium thermodynamic process.

A thermoelectric generator is a solid-state heat engine in which the role of the working medium is performed by an electron gas. If the heat source has a temperature T_h and the cooler has a temperature T_c , then the only possibility to obtain the maximum electric power, having received heat Q_h from the source, is for the electron gas to carry out a direct thermoelectric Carnot cycle. Using the second law of thermodynamics, it can be shown that in a thermoelectric process, exergy can be described by the relation

$$E_x = (Q_h - Q_c) = Q_h \cdot \left(1 - \frac{T_c}{T_h} \right) \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_c/T_h} \quad (2)$$

where T_h is the heater temperature, T_c is the cooler temperature, ZT is the dimensionless thermoelectric figure of merit of the semiconductor material [1], Q_c is the amount of heat transferred to the cooler, $T = (T_h + T_c)/2$ is the average temperature.

Exergy characterizes the efficiency of thermal energy, determining the fraction of energy that can be converted into electricity. The greater the exergy, the greater the efficiency of thermoelectric energy conversion. Structurally, the TEG is made in the form of a sandwich, in which hot and cold modules with PCM are tightly pressed to its hot and cold sides through heat-conducting gaskets.

In the first stage, the PCM of the hot module absorbs the supplied heat, heats up and melts at the temperature T_{jh} . The enthalpy change during heating and fusion occurs in two stages:

- heating the solid phase of the PCM from the initial temperature T_{min} to the fusion temperature T_{jh} ;
- phase change at fusion temperature T_{jh}

$$\Delta H_h = m_h \cdot \left[\int_{T_{\min}}^{T_{fh}} c_{sh}(T) \cdot dT + \lambda_h(T) \right], \quad (3)$$

where m_h is the mass, $c_{sh}(T)$ is the specific heat capacity of the solid phase, $\lambda_h(T)$ is the specific heat of fusion of the PCM of the hot module. The process of charging the hot module with heat continues until the phase change material in it is completely melted. Since the specific heat capacities and specific heats of fusion of the PCM depend weakly on temperature, in further calculations we will consider them constant.

In the second stage, the process of heating and melting of the PCM in the cold module and the process of crystallization of the PCM in the hot module begin.

The change in enthalpy during heating and melting occurs in three stages:

- heating of the solid phase of the PCM from the initial temperature $T_{\min}$ to the fusion temperature T_{fc} ;
- phase change at the fusion temperature T_{fc} ;
- heating of the liquid phase (PCM) from the fusion temperature T_{fc} to the maximum temperature $T_{\max}$.

$$\Delta H_c = m_c \cdot \left[\int_{T_{\min}}^{T_{sc}} c_{sc}(T) \cdot dT + \lambda_c(T) + \int_{T_{fc}}^{T_{\max}} c_{fc}(T) \cdot dT \right], \quad (4)$$

where m_c is the mass, $c_{sc}(T)$ and $c_{fc}(T)$ is the specific heat capacity of the solid and liquid phases, $\lambda_c(T)$ is the specific heat of fusion of the PCM of the cold module.

Since the crystallization and melting processes are isothermal, the temperature difference between the hot and cold modules remains constant throughout the entire charge-discharge cycle.

$$\Delta T = (T_h - T_c). \quad (5)$$

In TEG, work is performed due to the generation of thermoelectric current. Moreover, as follows from the first law of thermodynamics, the work of the current

$$W = (Q_h - Q_c) = \Delta H_h - \Delta H_c, \quad (6)$$

where Q_h is the amount of heat supplied to the TEG from the heater, Q_c is the amount of heat transferred to the cooler.

On the other hand

$$W = P \cdot \Delta t, \quad (7)$$

where P and Δt are the power and operating time of the TEG, respectively.

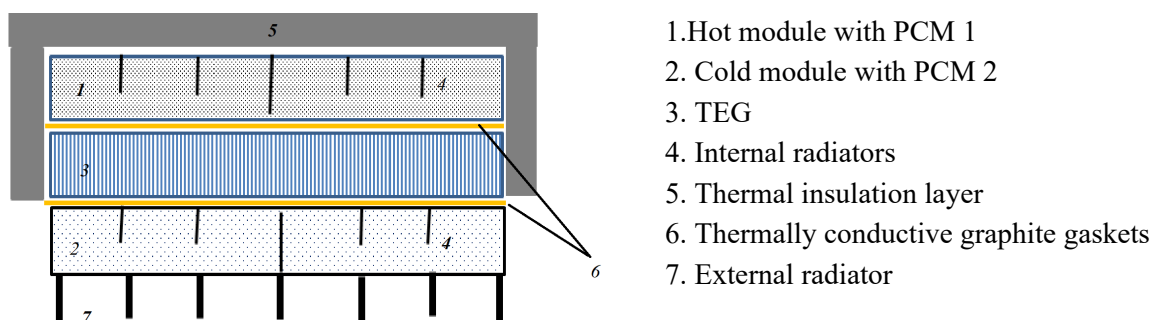


Fig. 1. Schematic structure of an inertial thermoelectric generator

Using PCM on both sides of the TEG will allow creating a thermoelectric generating system with high inertia, which is capable of generating stable thermoelectric power even with unstable heat flux from the heater. Making thermal accumulators replaceable (for quick replacement) will allow making a stock of preheated and cooled thermal modules. Moreover, any heat and cold sources are suitable for heating and cooling. The use of replaceable thermal modules will allow the replacement of salt hydrates with PCMs with a higher fusion temperature without replacing the TEG, thereby increasing the ΔT and generating power.

Table 1

Phase change materials with high enthalpy

	Phase change material	Chemical formula	T_{fc} °C	c_s (kJ/kg K)	c_f (kJ/kg K)	λ (kJ/kg)	ρ (lg/m ³)
1.	Erythrol	C ₄ H ₁₀ O ₄	118–121	1.38–1.42	2.76–2.85	300–340	1450
2.	Magnesium nitrate hydrate	Mg(NO ₃) ₂ ·2H ₂ O	89	1.85	2.30	147–167	–
3.	Barium hydroxide octahydrate	Ba(OH) ₂ ·8H ₂ O	78	1.2–1.4	2.1–3.3	265.7	–
4.	Stearic acid	C ₁₈ H ₃₆ O ₂	69.6	1.76	2.30	198.9	–
5.	Myristic acid	C ₁₄ H ₂₈ O ₂	54.0–58.8	1.89	2.00	198.7	–
6.	Paraffin wax	C ₂₅ H ₅₂	55	2.14	2.90	200–220	–
7.	Sodium acetate trihydrate	NaC ₂ H ₃ O ₂ ·3H ₂ O	58	2.57	4.88	264–280	–
8.	Glauber's salt	Na ₂ SO ₄ ·10H ₂ O	32.4	2.09	4.88	267	–
9.	Lithium nitrate trihydrate	LiNO ₃ ·3H ₂ O	30	1.6–1.8	2.7–2.9	280–296	1550
10.	Water (for comparison)	H ₂ O	0	4.18	4.20	333.5	1000

T_{fc} is the fusion temperature, c_s is the specific heat capacity of the solid phase, c_f is the specific heat capacity of the liquid phase, λ is the specific heat of fusion, ρ is the density.

A significant disadvantage of PCMs, compared to metals, is their low thermal conductivity, which prevents rapid charging and discharging of thermal modules. To reduce the overall thermal resistance in TMs, internal radiators or a cellular structure are used. The use of metal foam or cellular inserts radically changes the heat transfer mechanism. The metal will occupy about 5–10% of the total volume of the TM. This will slightly reduce the mass of the PCM, but will increase the thermal conductivity of the PCM by an order of magnitude.

The hot and cold modules contain erythrol and lithium nitrate hydrate as the phase change materials, respectively. Erythrol is one of the most effective phase change materials for storing thermal energy at low temperatures. It has a high latent heat of fusion density in the range of 0–120 °C. Its favorable phase change temperature and stable fusion temperature of approximately 120 °C make it ideal for bismuth telluride-based thermoelectric systems. Its high thermal conductivity, compared to organic PCMs, ensures rapid heat absorption and release. In turn, lithium nitrate trihydrate is capable of absorbing a large amount of energy during its transition from a solid to a liquid state. This means that a relatively small TM can absorb the heat passing through the TEG for an extended period without heating above 30 °C. It acts as a "thermal sponge." The speed of replacing the TM with the PCM in the TEG depends on the design of the fastening system and the method of ensuring thermal contact. To minimize downtime and maintain efficiency, it is necessary:

- use guide rails along which the module with the used PCM is pulled out, and a new one (cold, hot) is inserted in its place;
- to fix the modules, use spring-loaded clamps or eccentric clamps instead of screws, which will allow you to quickly replace the required module;
- instead of thermal paste that needs to be cleaned and reapplied, use flexible graphite sheets. They do not dry out, do not require cleaning when replacing the container, and provide excellent thermal conductivity;
- to prevent complete cessation of thermal generation when replacing modules, the cold and hot modules are separated into parts.

Let us find the amount of heat that must be stored in the hot module for the battery to operate with an electric power P for a time Δt . From (2) we obtain

$$Q_h = \frac{P \cdot \Delta t}{\left(1 - \frac{T_c}{T_h}\right) \cdot \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + T_c/T_h}}. \quad (8)$$

In turn, the amount of heat that the cold module must absorb

$$Q_c = Q_h - P \cdot \Delta t. \quad (9)$$

The required mass of hot and cold PCM can be found from the relationships

$$m_h = \frac{Q_h}{\lambda_h}, \quad (10)$$

$$m_c = \frac{Q_c}{\lambda_c}, \quad (11)$$

Numerical analysis of results

Heat in the modules accumulates mainly due to phase transitions, so we will not take into account the heat capacity of the liquid and solid phases. Let us find the amount of heat that erythrol will release and lithium nitrate will absorb. As follows from relations (8) and (9), to ensure autonomous operation of the ITEG with a power of $P = 30$ W for $\Delta t = 1$ hour = 3600 s, the hot thermal module must emit $Q_h \approx 2915$ kJ, and the cold one must absorb $Q_c \approx 2808$ kJ of heat. For the thermoelectric figure of merit of modules based on bismuth telluride, we take a realistic value $ZT = 0.8$. In this case, $T_h = 393$ K, $T_c = 303$ K, $\Delta T = 90$ K.

Table 2

Technical characteristics of TEG at $T_c = 30^\circ\text{C}$ and $T_h = 120^\circ\text{C}$ in maximum power mode

TEG type	U_{oc} V	U_{opt} V	I_{sc} A	I_{opt} A	P_{max} W	R_{opt} Ohm	R_t , °C/W	n	$Eff.$ %
MTG2-1,15-199DT2S	6.12	3.06	2.70	1.26	3.89	2.3	0.9	199	3.04

U_{oc} – open circuit voltage, I_{sc} – short circuit current, R_{opt} – optimal load resistance, R_t – thermal resistance, n – number of p-n – pairs

To obtain maximum power at a temperature difference between the heater and the cooler $\Delta T = 90^\circ\text{C}$, thermoelectric modules must have low internal electrical and thermal resistance and an optimal number of internal thermocouples. Given this, we will take as a basis the standard thermoelectric module MTG2-1,15-199DT2S, the main parameters of which are given in Table 2. In maximum power mode, it will generate about $P_{max} = 3.9$ W, at a voltage $U_{opt} = 3.1$ V. Let us find the required number of modules. $N = P/P_{max} \approx 8$ pcs. With such a temperature difference, most standard TEG modules work at the limit of their capabilities, since they are optimized for much larger differences ($\Delta T \approx 150\text{--}200^\circ\text{C}$). To improve reliability, we will form two legs of 4 TEGs each and connect them in parallel. At optimal load, the maximum power of the ITEG will be $P_{max} = 31.2$ W, at optimal voltage, $U_{opt} = 12.4$ V. Calculating the mass and volume of the hot and cold PCM yields: $m_h = 9.1$ kg, $m_c = 9.5$ kg, $V_h \approx 6.3$ l, $V_c \approx 6.1$ l. The described ITEG is significantly more efficient than simple TEGs on traditional radiators, as it has "thermal inertia."

Conclusions

The use of thermal modules integrated into the TEG will allow creating a generator with high inertia, capable of generating stable thermoelectric power. The use of replaceable thermal modules will allow creating a reserve of preheated and cooled modules, with any heat and cold sources suitable for heating and cooling. The TEG with a set of backup thermal modules can be used to power electronics in blackout conditions, as well as in a fully autonomous mode, since it will be possible to "stretch" the energy of a relatively small amount of fuel for a long time.

An important advantage of ITEG is the stability of the output voltage. This is critical when powering communications systems, where a sudden power outage can lead to configuration failure. It is obvious that by scaling it will be possible to create ITEGs of much higher power.

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Інерційний термоелектричний генератор із фазоперехідними тепловими модулями

Метою роботи є розрахунок та створення інерційного термоелектричного генератора (ІТЕГ) з інтегрованими в нього змінними модулями тепла і холоду на гарячій і холодній стороні. Застосування теплових модулів (ТМ) з обох сторін ІТЕГ жорстко зафіксує величину градієнта температури в генераторі. Це дасть змогу побудувати автономну термоелектричну генеруючу систему, яка буде генерувати стабільну термоЕРС протягом всього часу роботи. Принцип роботи ІТЕГ базується на використанні прихованої теплоти кристалізації і плавлення фазоперехідних матеріалів. Використання змінних теплових модулів забезпечить швидку заміну розряджених ТМ зарядженими, а також дасть змогу зробити запас попередньо нагрітих і охолоджених модулів. Причому, для нагрівання і охолодження придатні будь-які джерела тепла і холоду. Для збільшення швидкості заряджання і розряджання в ТМ передбачена мережа внутрішніх радіаторів.

Ключові слова: Дуальний ФПМ, термоелектричний генератор, тепловий модуль, прихована теплота плавлення, фазоперехідні матеріали, ентальпія, ексергія, тепловий опір.