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EXPERIMENTAL INVESTIGATION OF PERIODIC TRANSIENT MODE OF THERMOELECTRIC GENERATOR

This paper presents a measuring installation and proposes a new method for experimental investigation of periodic transient mode of thermoelectric generator. It is shown that the use of periodic transient mode of thermoelectric generator allows increasing considerably the generated power as compared to steady-state mode. The value of optimal frequency of changing the external thermal fluxes is determined and a qualitative explanation of the effect of generated power increase is given.

Key words: thermoelectricity, thermoelectric generator, direct energy conversion, transient mode, heat recovery.

Introduction

The advent of new materials, improvement of their fabrication techniques, ecological and energy problems in recent several years have lead to growing interest in problems of thermoelectricity. Thermoelectric devices (generators and coolers) allow converting thermal into electric energy and vice versa. The possibility of using these devices for "thermal waste" recovery, the absence of mechanical parts and poisonous coolants, low inertia and small dimensions indicate the viability of this development. However, low efficiency of thermoelectric devices restricts their wide application.

The efficiency of thermoelectric device can be temporarily improved in its unsteady-state modes. For instance, pulse cooling mode allows reaching at certain points a deeper cooling which is accounted for by a considerable difference in time constants of electrical and thermal processes occurring in thermoelectric cooler. Pulse cooling theory was developed in [1 – 3] where the authors point to the absence of opportunity to increase the efficiency for transient modes as compared to steady-state mode.

However, recent investigations of periodic steady-state modes of thermoelectric devices substantiate their appropriateness and promising outlook [4 – 6]. In [4], two modes of thermoelectric device are analyzed – periodic switching mode (*P*-mode) and continuous sinusoidal mode (*S*-mode). The specific feature of *P*-mode is periodic instantaneous reversing the temperature of the hot and cold ends of thermoelectric conductor, whereas in *S*-mode the temperature of junctions is continuously changed harmonically. In the course of theoretical treatment the authors prove the possibility of increasing parameter ZT (Z is thermoelectric figure of merit; T is absolute temperature) which determines the efficiency of thermoelectric device by 30 % for cooling in S-mode, whereas such ZT growth for electric energy generation modes is not expected. The last conclusion, most probably, results from the authors' assumptions in the framework of which the temperature of junctions and, accordingly, thermoEMF in P-mode are changed instantly, without regard to their thermal inertia.

In [6], a more universal model is proposed, wherein heat enters a TEG and leaves it through the plates. The numerical analysis made by the authors shows a maximum on the time dependence of generated thermoEMF the presence of which was later proved by them experimentally. Despite the fact that the mode in question was not periodic, the paper suggests its possible efficiency.

The *present paper* gives the results of experimental investigation of periodic transient modes of thermoelectric generators based on the module TEC112703. Later sections describe experimental installation, experimental procedure and the resulting data. The last section deals with discussion of the results and conclusions.

Measuring installation and experimental procedure

Experimental installation comprises three thermoelectric modules M1-M3 (Fig. 1). Modules M1 and M3 (TEC1-12708) are used as a heater and a cooler. Direct electric current is passed through these modules from the external source. If this current is positive, the surface of module M3 in contact with module M2 is heated. At the same time, the surface of module M1 in contact with module M2 is cooled. In this case module M3 can be regarded as a heater and module M1 is a cooler.

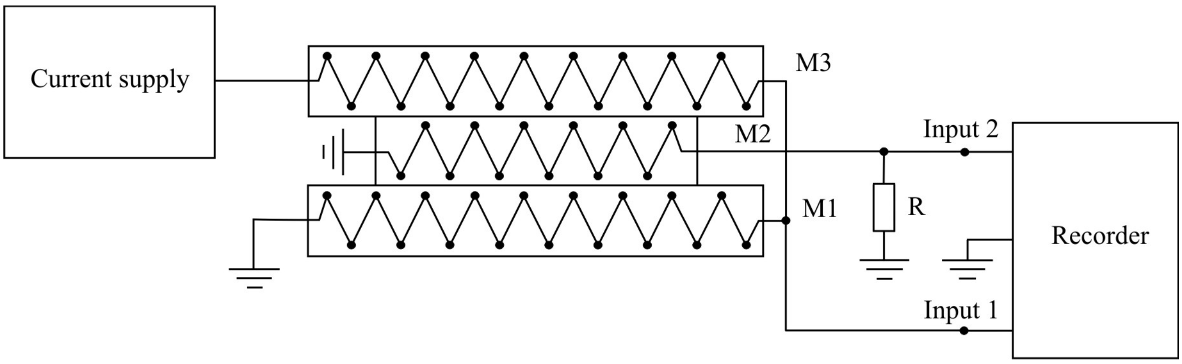

Fig. 1. Structural scheme of experimental installation.

With a change in external current direction, the heater and the cooler swap places. In this case the surface of module M3 in contact with module M2 is cooled, whereas the surface of module M1 in contact with module M2 is heated. Module M2 (TEC112703) works in the mode of generation of electric power which is released on load resistance *R*.

The voltage on module M1 is a sum of the voltage on the internal resistance of module R_{M1} denoted by U_{M1} and thermoEMF ε_{M1} developed by the module. The value $(U_{M1} + \varepsilon_{M1})$ is measured on input 1 of the recorder.

The voltage on load resistance R denoted by U_R is recorded on input 2. This voltage is the difference between thermoEMF ε_{M2} on module M2 and the voltage due to thermal current flow:

$$U_R = \varepsilon_{M2} - I_{TH2} R_{M2},$$

where I_{TH2} is thermal current of thermoelectric generator;

R_{M2} is internal resistance of module M2.

External current through modules M1 and M2 is periodic with a period T. During time $\frac{T}{2}$ there is direct current flow of one direction, then current is reversed, but its value remains the same.

This periodically reversing current, flowing through modules M1 and M3, causes the appearance on device inputs 1 and 2 of alternating periodic voltages recorded by the device.

The device operates as follows.

The signal on input 1 is recorded during 0.04 s. Then during the same time interval signal recording takes place on input 2, and so on. Thus, on each of device inputs signal recording takes place every 0.08 s, so signals on inputs 1 and 2 are shifted in time by 0.04 s.

Discussion of results

Fig. 2 shows one period of signal $(U_{M1}+\varepsilon_{M1})$ for different values of load resistance R ($R = 20$ Ω, 10 Ω, 5 Ω, 2.2 Ω and 1 Ω). The value of external current through modules M1 and M3 was 0.8 A, and the period T – 327.68 s.

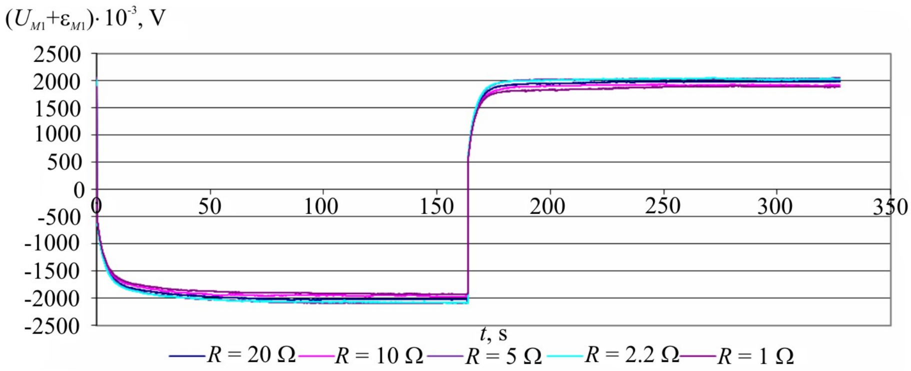

Fig. 2. Signals $(U_{M1}+\varepsilon_{M1})$ for 5 values of load resistance.

From Fig. 2 it follows that a change in the load resistance in the range of 1 ÷ 20 Ω produces a minimum effect on the signal $(U_{M1}+\varepsilon_{M1})$. The latter fact points to a marginal impact of change in the heater and cooler's thermal load in the capacity of which acts thermal generator M2.

Fig. 3 represents one period of signal U_R for the same values of load resistance, current through modules M1 and M3 and period.

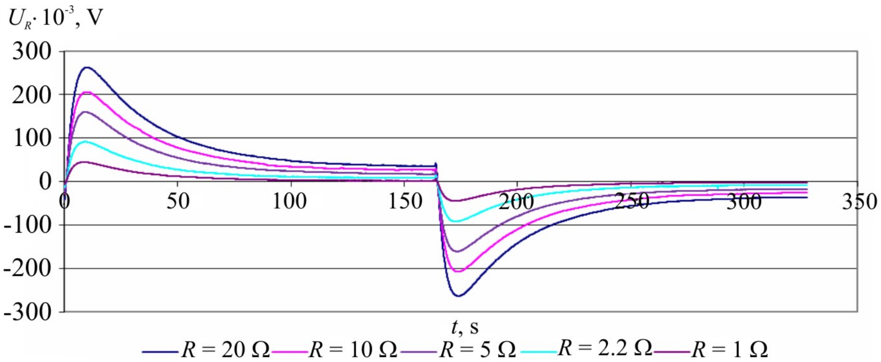

Fig. 3 Signals U_R for 5 values of resistance.

Note that with a rather large time of flow of direct current of the same direction (not less than 5 min) a steady-state value of voltage is set on the load resistance *R*. The results of measuring steady-state values of voltage U_R with different load values for the positive $\left(U_{ST(+)}\right)$ and negative $\left(U_{ST(-)}\right)$ direction of external current are represented in Table 1. Also, Table 1 represents the results of calculation of power P_{ST} generated by thermoelectric generator in the steady-state mode by the formula:

$$P_{ST} = \frac{<U_{ST}>^2}{R}$$

where $<U_{ST}>$ are average values of steady-state voltages calculated by the values $U_{ST(+)}$ and $U_{ST(-)}$.

Table 1

Operating characteristics of thermoelectric generator (steady-state mode)

R, Ω	20	10	5	2.2	1
$U_{ST(+)}$, mV	32.545	24.875	17.055	7.351	1.454
$U_{ST(-)}$, mV	-32.526	-24.884	-17.073	-7.363	-1.465
$<U_{ST}>$, mV	32.54	24.88	17.06	7.36	1.46
P_{ST}, μW	52.93	61.90	58.24	24.60	2.13

The specific feature of thermoelectric generator transient mode is the presence of a maximum on the time dependence of output voltage. For signals represented in Fig. 3 the average power in the period T which is generated by thermoelectric generator can be calculated by the formula

$$P_{TR} = \frac{\int_0^T \frac{U_R^2}{R} dt}{T}.$$

The results of such calculation are presented in Table 2 and correspond to current through modules M1 and M3 equal to 0.8 A and the period of 327.68 s.

Table 2

Operating characteristics of thermoelectricgenerator (periodic transient mode)

R, Ω	20	10	5	2.2	1
P_{TR}, μW	630.16	755.54	838.38	567.44	269.47

The data given in Tables 1 and 2 testify to the presence of maximum useful electric power both for the steady-state and periodic transient modes with a well-defined load resistance close to 5 Ω.

A dependence of average in the period useful power P_{TR} on the period value was experimentally studied for T = 20.48 s, 40.96 s, 81.92 s, 163.84 s, 327.68 s. Fig. 4 represents a dependence of useful power on the period for load resistance R equal to 5 Ω and external current 0.8 A.

Analysis of the resulting experimental dependence of power generated by thermoelectric generator proves the availability of optimal value of generator operation period. In our case maximum power P_{TR} (P_{TR} = 1704.43·10^{-6} W) corresponds to period T = 81.92 s. Note that in the steady-state mode with the same temperature conditions on the heater and the cooler the value of generated power P_{ST} is 58.24·10^{-6} W.

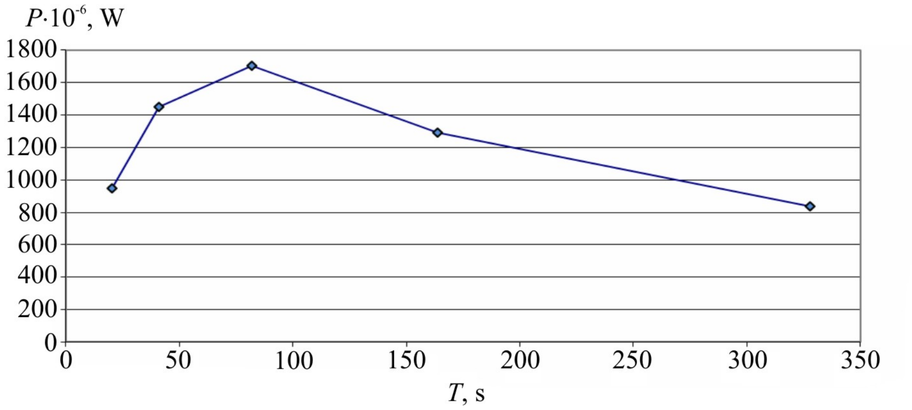

Fig. 4. Average power versus period.

Fig. 5 represents time dependence of signal U_R in maximum power generation mode. The value of external current through modules M1 and M3 was 0.8 A, period T – 82.92 s, load resistance R – 5 Ω. Also, this figure shows the values of steady-state voltages U_R for the negative $\left(U_{ST(-)}\right)$ and positive $\left(U_{ST(+)}\right)$ current directions through modules M1 and M3.

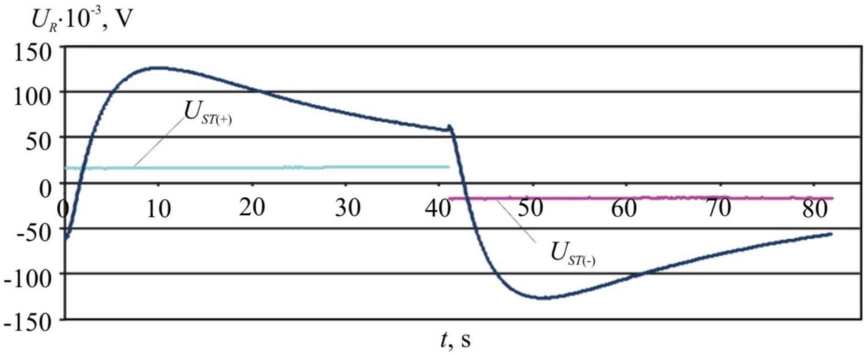

Fig. 5. Signals U_R in periodic transient and steady-state modes.

Thus, comparing powers generated by thermoelectric generator in the steady-state and periodic transient modes, it can be argued that the use of periodic transient mode leads to increase in power ($\frac{P_{TR}}{P_{ST}}$) by a factor of ~ 29.

When thermoelectric generator operates in the steady-state mode, its thermal resistance is low. It is due to considerable heat losses inside the generator, namely the heat from the hot module side passes to the cold side.

With a drastic change in the direction of heat fluxes, the thermal resistance of module is considerably increased for some time. Physically, it means that heat losses are reduced, and the heat that comes to the junctions of semiconductor thermocouples from the heater, heats the junctions to much higher temperature compared to the steady-state mode.

Similarly, a reduction of thermal energy losses due to thermal conductivity inside the module leads to the fact that cold junctions are cooled to considerably lower temperature compared to the steady-state mode. The appearance of additional temperature difference between the hot and cold junctions determines the appearance of a maximum in the output voltage of thermoelectric generator.

The average in the period thermoEMF value in transient mode is $85.26 \cdot 10^{-3}$ V, whereas in the steady-state mode thermoEMF does not exceed $17.06 \cdot 10^{-3}$ V. Comparing these thermoEMF values it can be supposed that in transient mode the effective value of thermal conductivity is reduced by a factor of about 5, thus assuring a proportional reduction of thermal losses due to thermal conductivity inside the module.

This qualitative explanation gives an insight to the appearance of a maximum in the output signal of thermoelectric generator and possible increase of its generated power.

Conclusions

Experimental investigation of transient mode of thermoelectric generator has proved the possibility of considerable improvement of thermal into electric energy conversion as compared to steady-state conversion method. Transition to periodic transient mode of thermoelectric generator will make possible the increase of generated power by a factor of 20 and more.

The increase in the operating efficiency of thermoelectric generator when passing to the unsteady-state mode is based on the appearance of a maximum in its output voltage, which is accounted for by short-term, about 20 s, increase in generator thermal resistance. On expiry of this time, thermal resistance is reduced and steady-state generation mode is restored. The appearance in transient mode of the time dependence of generator thermal resistance indicates the need for determination of optimal generator period in terms of maximum power generation. The task of determination of optimal velocity of change in the external thermal fluxes requires separate consideration. In the course of preliminary investigation it was established that with decreasing velocity of current buildup through modules M1 and M3 with its reversal, the effect of maximum appearance in the output voltage of generator is reduced and eventually disappears.

Our investigation testifies to reduction of thermal losses due to thermal conductivity inside the module. Thus, one can expect certain efficiency increase of generators working in transient mode.

The obtained results point to promising outlook for further research and the necessity of transition to a real heater and cooler. In such systems, one will be able to change mechanically the direction of thermal fluxes in thermoelectric generator, for instance, the generator will be cylinder-shaped and periodically rotate by 180 degrees between the heater and cooler having semi-cylindrical cavities. One possible variant of such TEG is represented in Fig. 6.

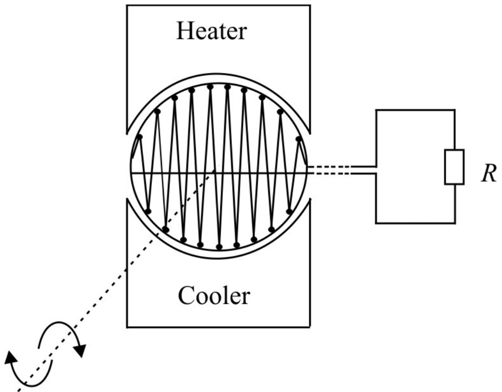

Fig. 6. Schematic of TEG working in pulse transient mode.

It should be noted that the experiment considered in this paper was performed with a slight temperature difference of the order of unit degrees. Assuming that when performing the experiment on a real and sufficiently powerful TEG the above peculiarity (the availability of a maximum on time dependence of thermoEMF) is retained, in this case one can expect considerable increase of power produced. Naturally, in this case we are not talking about a real reduction of TEG thermal conductivity. One can only say that as a result of periodic reversal of thermal fluxes inside TEG due to thermal inertia the amount of heat passing from the hot to cold junctions is considerably reduced.

Formally, it can be said that periodic transient mode of TEG proposed here can essentially improve TEG performance, therefore one can expect the increase of both efficiency and the useful power produced.

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