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Pulsed Thermoelectric Machine

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Abstract

A new type of thermoelectric transport is described, consisting of pulses of charge carriers that "fly" periodically through the external circuit from the hot end of the sample to the cold end, with a determined duration of the "on" and "off" times of the electric contacts, while maintaining continuously the thermal contacts. It is shown that such a non-equilibrium ideal thermal "machine" works cyclically with improved efficiency compared with efficiencies of the thermoelectric devices operated in an equilibrium transport regime, but the electric flow and power are increased, as a consequence of concentrating the charge carriers on pulses of a small spatial extent. The machine is reversible, in the sense that it can operate either as a thermoelectric generator or as an electro-thermal cooler. So, it is described special designing a new thermoelectric generator to fulfill the needs of pulse operating, and a setup able to measure the thermoelectric parameters of Non Steady-State (pulse) operated generators. Preliminary measurements show a minimum two times increase of delivered electrical power, using the same heat power input when we are working in the pulse operation. It is confirmed existence of a lower limit of frequency where the electrical power starts to increase comparing with the DC operation, and a superior limit of frequency where the increase is too low to be taken into consideration. All these results are strong confirmation of the theory of "pulsed thermoelectricity".

Keywords: Pulsed thermoelectricity, Improved thermoelectric efficiency, Thermoelectric generator

IMPULSOWA MASZYNA TERMOELEKTRYCZNA

Opisano nowy rodzaj transportu termoelektrycznego, złożonego z impulsów nośników ładunku, które przepływają okresowo przez zewnętrzny obwód z gorącego końca próbki do zimnego przy określonych czasach włączenia i wyłączenia kontaktów elektrycznych, utrzymując ciągle kontakty cieplne. Pokazuje się, że taka nierównowagowa, idealna „maszyna" cieplna pracuje cyklicznie ze zwiększoną wydajnością w porównaniu z wydajnością termoelektrycznych urządzeń, działających w równowagowych warunkach transportu, a przepływ i moc elektryczna są zwiększone jako skutek skoncentrowania nośników ładunku w impulsach o małym zasięgu przestrzennym. Maszyna jest odwracalna w takim sensie, że może ona działać albo jako generator termoelektryczny, albo jako chłodnica elektrotermiczna. Zatem, opisuje się specjalne projektowanie nowego termoelektrycznego generatora, spełniającego wymagania działania impulsowego, i układ pozwalający mierzyć parametry termoelektryczne generatorów (impulsowych) działających w stanie niestacjonarnym. Badania wstępne pokazują minimum dwukrotny wzrost dostarczanej mocy elektrycznej przy wykorzystaniu tej samej mocy wejściowej, wtedy gdy pracuje się w trybie impulsowym. Potwierdza się istnienie mniejszej granicznej wartości częstotliwości, przy której moc elektryczne zaczyna się zwiększać w porównaniu z trybem stałoprądowym, a także wyższej granicznej wartości częstotliwości, przy której wzrost jest zbyt mały, aby go uwzględniać. Wszystkie wyniki są mocnym potwierdzeniem teorii "impulsowej termoelektryczności".

Słowa kluczowe: impulsowa termoelektryczność, polepszona wydajność termoelektryczna, generator termoelektryczny

1. Introduction

If theoretical efficiency is not limited from the thermodynamic point of view (Carnot cycle) [1], the thermo-electric generators traditionally manufactured and steady-state operated (i.e., substantially continuous) have the maximum efficiency around 5% for a deltaT of ~ 200°C. Thus, a substantial increase of delivered electric power or efficiency cannot be expected from traditionally manufactured and steady-state operated thermo-electric devices except in circumstances wherein a particular thermo-electric material with a figure of merit ZT >> 1 will be developed. In the last two decades, several scientists proposed thermo-electric materials of dimensions smaller than their effective cooling lengths, as being capable of demonstrating enhanced thermo-electric properties [2-3]. Loginov and Gurevich [4-5] demonstrated that the interaction between electrons and phonons decreases, when the hot side of a sample is subject to heat pulses over a certain frequency range. Side interaction constitutes the extra source of heating in traditional bulk-dimensioned thermoelectric materials. As a result, the thermal lattice conductivity decreases. Connected with Gurevich's work, Ghoshal [6] claims a decrease in thermal conductivity by thermal contact switching, as by employing a MEMS device.

Taken into consideration all that progress in non conventional thermoelectricity

Nedelcu and Apostol [7-9] proposed the non steady-state operated thermoelectric generators based on original theoretical and experimental works. From a theoretical point of view, the pulse operation of thermoelectric devices is a potentially elegant way of obtaining the performance of super-lattices without having to manufacture them. The use of an ultra-fast process can supply an increased thermoelectric performances by minimizing the thermal dissipation.

2. Theoretical consideration

It is well known that the classical way of operating thermoelectric circuits consists of establishing small and continuous temperature and voltage gradients along a thermoelectric sample, while maintaining the local thermodynamic equilibrium. The sample is assumed to be homogeneous on the macroscopic scale, as for a stable thermodynamical phase. The physics and technology of classical thermoelectricity is described in great detail in reference treatises, textbooks, and handbooks, as those given in Refs.10-12. The electric flow *j* and heat flow *q*, i.e., the electric charge and, respectively, heat flowing across the unit area of the cross-section per unit time, are given by the basic equations of the thermoelectricity:

$$j = \sigma E - \sigma Q \,\mathrm{grad}\, T, \qquad (1)$$

$$q = \varphi j + QTj - \kappa \,\mathrm{grad}\, T, \qquad (2)$$

where σ is the electric conductivity, *E* is the external electric field, *Q* is the thermo-power, *T* is the temperature, φ is the electric potential ($E = -\mathrm{grad}\,\varphi$), and κ denotes the thermal conductivity.

The inherent limitations of the classical mode of operating thermoelectric devices originate in the small, continuous temperature gradient superimposed along the whole length of the sample. This circumstance brings about both small currents and heat flows, on one hand, and may increase appreciably the risk of heat loss through a spatially-extended

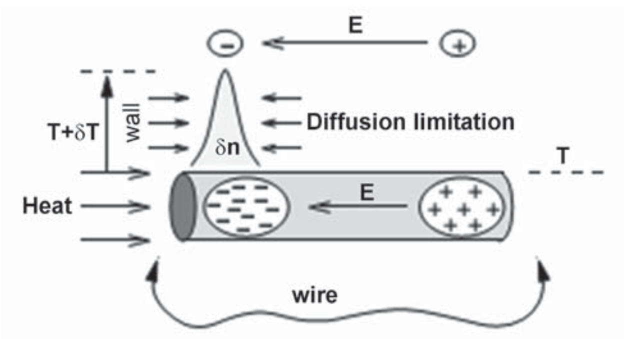

Fig. 1. Pulse and thermoelectric condenser.

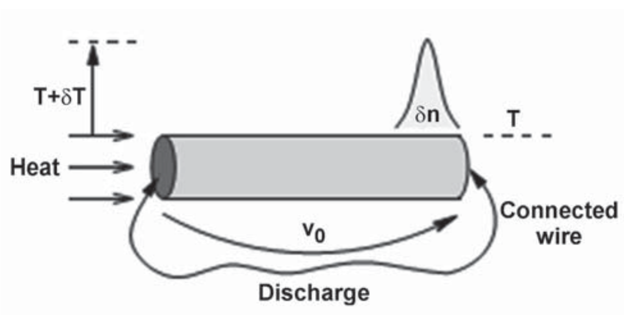

Fig. 2. Discharge of the "condenser."

dissipation, on the other. In particular, the undesired effects of a high thermal conductivity are enhanced by a continuous temperature gradient extending over the whole length of the sample. We put forward here a different mechanism of thermoelectric transport, based on pulses of heat and current, which may circumvent, to some extent, the aforementioned limitations. It leads to high electric pulses "flying" periodically through the external circuit of length l_e. The objectives of the pulse thermoelectric device are to increase the delivered electric flow and power, by concentrating the charge carriers on pulses of small spatial extent. A former, preliminary, description of this pulsed thermo-electric transport was given in Refs. [7, 13-14].

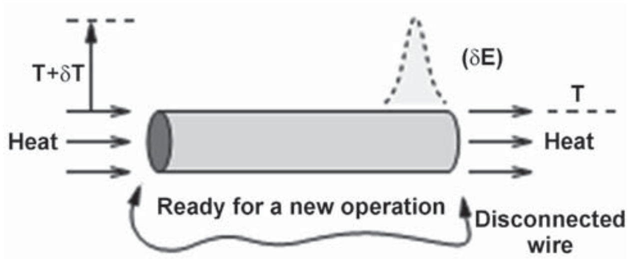

Fig. 3. Deflating the pulse, ready for another operation.

3. Flying pulses

A thermoelectric sample with a charge pulse built up at the hot end evokes an electric "condenser," and, like any other condenser, such a "thermoelectric condenser" can be "discharged" by switching on the electric contacts to the external circuit. Under these circumstances the (ideal) sample end-wall does not block anymore the motion of the charge carriers, and the pulse "flies" through the external circuit as a whole, with a transport velocity $v_0 = v$. This is a macroscopic, non-stationary, fast, pulsed-like transport, taking place in the transient regime prior to establishing the extension of the pulse along the whole length of the sample. In order to make possible a smooth "fly," the cross-section of the external circuit must be equal to, or greater than, the cross-section of the sample (and, of course, the contacts are assumed to be perfect). The flying of the pulse through the external circuit of a length of l_e takes an "on" time $\tau_{on} = l_e/v$. On the other side, the time t' needed to build up a pulse at the hot end of the sample is an "off" time, $\tau_{off} = t'$. In addition, it is worth noting that such a flying pulse does not obey Ohm's law, as the transport is discontinuous. While flying through the external circuit the pulse dissipates therefore gradually the Joule–Lenz heat E_{el}, and gives away the Peltier heat (the Peltier heat is transported from the hot junction to the cold junction), until it reaches the cold end of the sample and compensates the positive ionic charges there. After completing its "flight" through the external circuit, the pulse is left with its internal heat $\delta E = cl'\delta T$, and it must be "deflated" of this internal energy in order to have a cyclic process. The time needed to extract this amount of heat is $\tau_{on} = \tau_{off}$, i.e., precisely the time during which an identical pulse is built up at the hot end of the sample, such that, after this duration, the thermoelectric sample is ready for another operation. It follows that the thermal contacts should be maintained continuously during the operation of such a pulsed-like transport, while the electric contacts must be switched off once the pulse arrived at the cold end of the sample; otherwise, the pulse would move continuously through the entire circuit and the stationary regime would set up. Therefore, the electric contacts must be switched on and off periodically, with a certain frequency $f = 1/(\tau_{off} + \tau_{on})$, where $\tau_{on} = l_e/v$, and a certain duration of the on- and off-times. The building of the pulse at the hot end is shown in Fig.1, the flying pulse is shown in Fig. 2 and the deflating of the pulse at the cold end is shown in Fig. 3.

The operating frequency is therefore $f=1/(\tau_{off}+\tau_{on})=v/(l_e+l'^2/\Lambda)$, and it ranges between $f_0 = v/(l_e + \Lambda)$, corresponding to δ-pulses, and $f_1 = v/(l_e+ l'^2/\Lambda)$, for pulses extending over the whole length l of the sample, where the stationary transport regime begins to set up. For reasonable values of l_e, the ratios $l^2/\Lambda l_e$, and $l'^2/\Lambda l_e$ acquire large values, so that one may write $f = v\Lambda/l'^2 = f_1 (l/l'^2)$, i.e., the operating frequency is quadratic in the ratio l/l' of the sample length l to the pulse extension l_e. This corresponds to very short on-times τ_{on} in comparison with the off-times $\tau_{off} = \tau_{on}$, and to pulses of large extension l'.

4. Power delivered into external circuit

The Joule–Lenz heat E_{el} is the total energy (per unit area of the cross-section) dissipated by a pulse during its flight. Consequently, the average power produced in such a pulsed transport operated cyclically is given by equation (3):

$$P^{Av} = (j^2/\sigma)(l'^3/v\Lambda \frac{1}{\tau_{on}+\tau_{off}} = P_s(l/l')\frac{1}{1+\Lambda l_e/l'^2} \quad (3)$$

One can see that for macroscopic pulses, corresponding to short on-times, i.e., for $\Lambda l_e/l'^2 << 1$, the average power is practically identical with the pulse power given by $P^+ = P = P_s(l/l')$, i.e., it is increased by the factor l/l'. In this case, the operating frequency $f = f_1(l/l')^2$ given above is proportional to the square of the electric power, i.e., $f \sim P^2$. In the opposite limit however, corresponding to microscopic pulses of extension Λ, the increase factor is controlled by the ratio l/l_e of the sample length to the length of the external circuit (which may be higher than unity very well). In both cases the average power is increased in comparison with the equilibrium-operated thermo-elements. The maximum value of the average power is obtained for $l = \sqrt{\Lambda l_e}$, i.e., just for the border between microscopic and macroscopic pulses, as defined before. It is perhaps more convenient to refer the power to the maximal power $P_{dc} = U^2/4r = P_s/4$, corresponding to a load electric resistance equal to the internal resistance in a stationary operating regime (drift current). One obtains therefore $P^{Av}_{max} = 2(l/\sqrt{\Lambda l_e})P_d$. The optimal power in the pulsed-operating regime is much higher than the stationary power. A maximum value at the optimal frequency $f = ½\ \tau_{on}$ given before, and a characteristic frequency dependence. Making use of $\tau_{on} = l_e/v$, gives also a characteristic dependence of the external power on the load resistance l_e. The pulsed-operating mode of the thermoelectric transport is shown in Figs. 4–6.

The theoretical efficiency, η, of a thermo-electric device designed in agreement with the parameters of our pulse operating regime can be very close with Carnot efficiency. This increase in efficiency accompanies the decrease of thermal conduction and heat dissipation produced in pulse operation. Technical barriers of decreased conversion efficiency met in traditional thermo-electric generators will be lifted by ultra-fast "electric pulses" transfer in a magnetic field, this idea representing a new and revolutionary concept on thermoelectric devices manufacturing and customized operating regime. A thermoelectric sample with a charge pulse built up at the hot end evokes an electric "condenser," and, like any other condenser, such a "thermoelectric condenser" can be "discharged" by switching on the electric contacts to the external circuit.

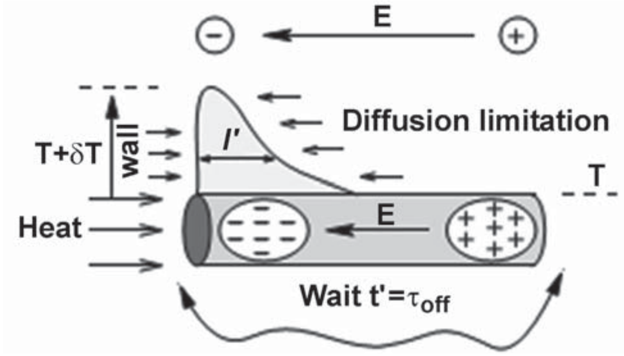

Fig. 4. Building up a Gaussian pulse in a thermoelectric condenser.

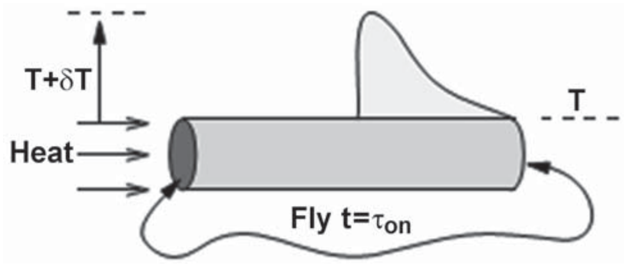

Fig. 5. Discharging a Gaussian pulse in a thermoelectric condenser.

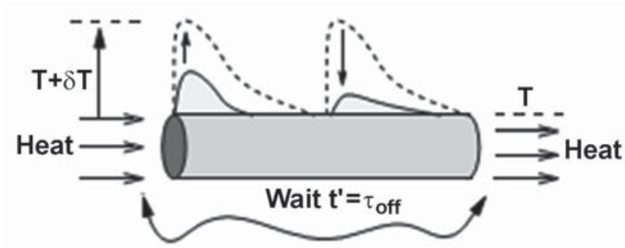

Fig. 6. Deflating the pulse while building up another.

5. Experimental attempts on non-stationary (pulse) operation

In this work we experimentally investigate the possibilities of pulse operation of thermoelectric devices by establishing the equivalent electrical circuit of a thermoelectric generator. A special potentiostat-galvanostat AUTOLAB EcoChemie with impedance-meter facilities used in electrochemical measurements was applied to measure impedance-frequency dependencies. From these measurements, the equivalent RLC electrical circuit has been found. The results are shown in Fig. 7 and Table 1. Using both a special program and the data used to obtain the graph in Fig. 7, we found experimentally the equivalent RLC circuit from Fig. 8. The electrical circuit shown in Fig. 9 was used to measure the internal resistance of the TE generators in DC operation and the variation of internal resistance with frequency operation. This circuit allows us to measure the internal resistance used in DC operation using AC current (Hartman method) and on the other hand to measure the variation of internal resistance with frequency when the pulse operation is used.

From the measurements made with the AUTOLABEcoChemie on the variation of impedance and its RLC components with frequency it has been found that the equivalent circuit of the TE generators is not a power source having an internal resistance, R_{in}, but the equivalent circuit is more complex as shown in Fig. 8, having an important capacitive component in parallel with a resistive one. The inductive component is not so important if the connection wires are not so long.

One can see that for frequencies larger than 400–500 kHz, the capacitive components become major and the real part of resistance becomes negative. So, it can be seen from Fig. 7 that the inductive component starts to count over 900 kHz for the studied TE generators.

From Table 1 we can see the values of internal resistance, R_{in} and the parallel capacitance for two frequencies:

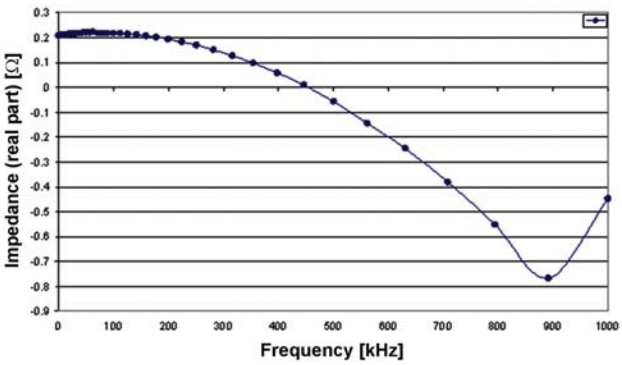

Fig. 7. Impedance (real part) vs. frequency for a traditionally manufactured HiZ-20 thermoelectric module.

Table 1. Resistance and capacitance vs. applied potential and frequency for a high power TE generator traditionally manufactured (HZ-20).

No.	Potential V [V]	Parallel R [Ω]	Parallel C [F]
f = 10 kHz			
1.	0.000	$2.216 \cdot 10^{-01}$	$1.813 \cdot 10^{-05}$
2.	0.100	$2.215 \cdot 10^{-01}$	$1.812 \cdot 10^{-05}$
3.	0.200	$2.217 \cdot 10^{-01}$	$1.813 \cdot 10^{-05}$
f = 100 kHz			
1.	0.000	$7.971 \cdot 10^{-01}$	$3.252 \cdot 10^{-06}$
2.	0.100	$7.974 \cdot 10^{-01}$	$3.256 \cdot 10^{-06}$
3.	0.200	$7.577 \cdot 10^{-01}$	$3.234 \cdot 10^{-06}$
4.	0.300	$7.571 \cdot 10^{-01}$	$3.238 \cdot 10^{-06}$

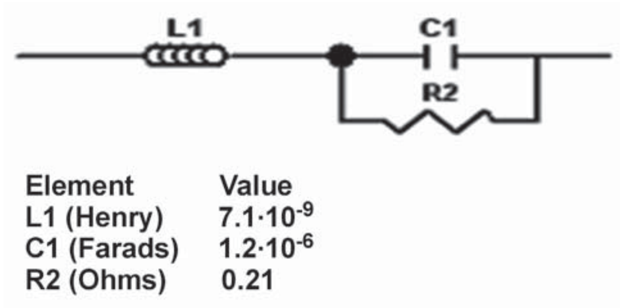

Fig. 8. Equivalent RLC electric circuit of a TE generator traditionally made.

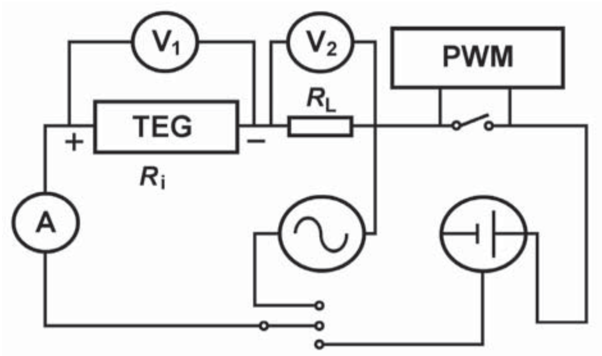

Fig. 9. Electrical circuit for R_i (internal resistance) and P_{el} (delivered power) measurements in pulse operation.

10 kHz and 100 kHz. These values suggest us more information about the future design of pulse operated TE generators. Fig. 10 shows the variation of electrical power E_{el} with frequency for a TE generator traditionally manufactured. The measurement of voltage (V) and current (I) was made using an oscilloscope, and a very important remark is that the voltage and current are in phase. The experimental results are an important confirmation of our theory in all its components.

The left-most point on the graph in Fig. 10 corresponds to the maximum delivered electrical power in DC operation, with RL = Ri. The other points are the maximum delivered electrical power, using the best duty factor for marked frequencies (Ri = 0.2 Ω, duty cycle τ = 0.1, deltaT = 70°C, RL = 0.02 Ω).

6. Preliminary results on pulse operation experiments

When continuously operated the given TE generator using a resistance load R_L = 0.02 Ω, the delivered electrical power was very low (some miliwatts).

To obtain more electrical power delivered, we need to change the resistance load, R_L, to a value as close as with internal resistance, or we must change the duty factor to be as close as with ratio R_L/R_i.

Using the tuning method, we tuned the duty factor around 2%, and the results are described in Fig. 10.

At pulse frequencies between 1 Hz and almost 5 kHz (f_0), the delivered electrical power was almost the same as the maximum electrical power for the DC operation.

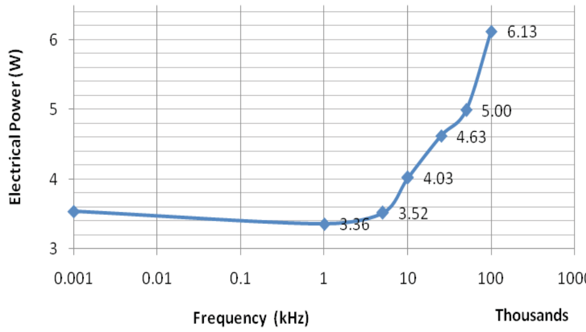

Fig. 10. Maximum electrical power (P_{el}^{max}) vs. frequency (f) for a pulse-operated TE source.

For frequencies higher than a minimum (f_0), the interaction between the electron and phonon subsystems starts to diminish, and the electric power becomes greater than the maximum electric power delivered by the same thermoelectric device in the DC (continuous) operation.

At much higher frequencies, f_1, the incremental increase in electric power with frequency declines as near-completion of electron-phonon decoupling is approached.

7. Conclusions

In conclusion, a mechanism of thermoelectric transport has been described, which proceeds by pulses of charge carriers. It is a macroscopic, cyclic, non-stationary, fast, transient regime transport, which may diminish the effects of a spatially-extended thermal diffusion. This pulsed-like transport regime operates by periodically switching on and off the electric contacts, while maintaining continuously the thermal contacts. The operating frequency is determined, as well as the on- and off-times, as functions of the nature of the sample, the extension of the pulses and the length of the external circuit. The electric flow and power are higher for the pulsed-like transport than for the stationary, classical one, as a consequence of concentrating the charge carriers on pulses of a small spatial extent. Such a pulsed-like transport may be operated cyclically, with an ideal efficiency quotient equal with the ideal efficiency quotient of the stationary transport. It may open the possibility of a practical realization of a thermoelectric converter of high electrical power. High values of thermopower Q and electrical conductivity σ are desirable, but low values of thermal conductivity κ are not critical. Of course, the pulsed transport described here is an ideal process, intended to illustrate the physical principles of another type of thermoelectric transport.

From an experimental point of view, the new operating technique that we developed allows us to overcome the intrinsic limitations of conventional thermoelectric devices as applied in series or parallel to obtain higher output voltages or currents. The benefit lies in our ability to obtain maximum electrical power, even when the load resistance is less than the internal resistance of a device (such as a DC motor) connected in series. The duty cycle $\tau = \tau_{on}/T$ yields the maximum electric power at a specified frequency less than f_0 is $D \sim R_L//R_i$. By tuning the duty cycle and pulse frequency, we are able to obtain power at the same level as the maximum available from the same thermoelectric assembly when normally operated in the steady state with the external load resistance equal to the internal resistance, $R_L = R_{in}$.

It is concluded that the experimental observations herein reported demonstrate excellent agreement with our theoretical conclusions. Taken together, they form the basis of our designing process for new thermoelectric generators expected to yield higher power and higher thermal conversion efficiency than conventional generators or those in a steady state operating regime.

Acknowledgement

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