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High efficiency inductive thermoelectric generator – illusion or reality

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Abstract

Direct current thermoelectric generators are well known. We present a thermal to electricity generator based on the Seebeck effect, connected to an inductive load operated at around 100 kHz. Jon Schroeder, in 1995, published a brochure on a similar device. In 2008, an efficiency was measured on his generator of 15%. Due to the design, no temperature measurements could be made, but estimating the temperature difference, this efficiency is about double the efficiency of a thermo-electric generator (DC). Two prototypes are designed with electrical and thermal measurements. This is a paradigm for thermoelectrics: A possible solution to "beat" the *ZT* materials barrier. We need to validate the prior measurements of 2008, and to try and understand the mechanisms, that produce such a high efficiency.
Keywords: Thermoelectricity, Electricity generation, Inductance

WYSOKOWYDAJNY INDUKCYJNY GENERATOR TERMOELEKTRYCZNY – ZŁUDZENIE ALBO RZECZYWISTOŚĆ

Generatory termoelektryczne prądu stałego są dobrze znane. Pokazano generator oparty na efekcie Seebecka podłączony do obciążenia impedancyjnego działającego przy około 100 kHz. Jon Schroeder opublikował w 1995 broszurę dotyczącą podobnego urządzenia. W roku 2008 zmierzono wydajność jego generatora, wynoszącą 15%. Powody konstrukcyjne uniemożliwiły pomiar temperatury, ale oszacowanie różnicy temperatury wskazuje, że wydajność ta jest dwukrotnie większa od wydajności typowego generatora termoelektrycznego (DC). Zaprojektowano dwa prototypy do pomiarów elektrycznych i temperaturowych. Odzwierciedlają one paradygmat termoelektryczności: dostarczyć takie prawdopodobne rozwiązanie, aby pokonana została bariera materiałowa współczynnika jakości *ZT*. Praca wychodzi naprzeciw istniejącej potrzebie potwierdzenia ważności wcześniejszych pomiarów z 2008 roku i chęci zrozumienia mechanizmów odpowiedzialnych za tak wysoką wydajność.
Słowa kluczowe: termoelektryczność, wytwarzanie elektryczności, indukcyjność

1. Introduction

Marin Nedelcu of the University of Bucharest, was able in 2008 to make an overall efficiency measurement on the inductive thermoelectric generator prototype built in 2004 by Jon Schroeder with bismuth telluride; the efficiency was 15%. Due to the design, no temperature measurements could be made, but estimating the temperature difference, this efficiency is about double the efficiency of a thermoelectric generator (DC). Apostol [1] describes pulses of charge carriers which "fly" periodically through the external circuit from the hot end of the sample to the cold end with high efficiency. Nevertheless this value is very hard for the thermoelectric community to believe. But as in all experimentation, such measurements, must imperatively be reproduced. Two prototypes are designed with electrical and thermal measurements.

Prototype I: The object is to "duplicate" intelligently the thermoelectric (TE) ring made by Jon Schroeder, which was soldered in one operation, a very difficult operation. Our TE ring D = 250 mm has 120 TE elements 4.5 cm^2, consisting of 8 segments that can be quality controlled before assembly into a ring. The ring design is complicated to manufacture. Heating the hot plates by hot gases is easy, but the thermal insulation at the level of the TE discs and between the hot and colds plate is difficult. All this is very costly, so a second unit as been designed.

Prototype II: It consists of 4 columns of 37 TE elements D = 24 mm and thickness = 1 mm. This design is easy to quality control and to assemble, and is much cheaper to build. If the measurements on this Prototype II do not show the results expected, we will have to consider building Prototype I.

The electronics packages, to chop the current and to increase the voltage, are the same for both prototypes. The inductive load is a winding on core of a transformer.

2. Traditional thermoelectricity

Thermoelectric electricity generation, using the Seebeck effect [2], Rayleigh [3], in 1885 considered the problem of the efficiency of a thermoelectric generator, but it was only in 1909 that Altenkirch [4] formulated the efficiency. It is only after the discovery of semiconductors and the research of A.F. Ioffe [5] in Saint Petersburg Russia that thermoelectric generators were developed. In 1956, H. J. Goldsmid [6] discovered bismuth telluride which is still today the best thermoelectric material for cooling and electricity generation at temperatures between -30°C and 250°C. Thermoelectric materials are characterized by a coefficient called the figure of merit Z:

$$Z = \frac{\alpha^2}{\rho \cdot \kappa}, \quad (1)$$

where: α – Seebeck coefficient [V/K], ρ - electrical resistivity [Ω·m], and κ – thermal conductivity [W/(m·K)].
Thermoelectric materials have a value of ZT ~1.

The maximum efficiency of thermoelectric generator, when the load electrical resistance is equal to the electrical resistance of the generator, is given by the formula [4]:

$$\eta = \frac{T_{hot} - T_{cold}}{T_{hot}} \cdot \frac{M-1}{M + T_{cold}/T_{hot}}, \quad (2)$$

where

$$M = \left[1 + \frac{1}{2} Z\left(T_{hot} + T_{cold}\right)\right]^{\frac{1}{2}}. \quad (3)$$

With T_{hot} = 523 K (250°C), T_{cold} = 323 K (50°C), and the $Z = 3.3 \cdot 10^{-3}$ K^{-1} at 300 K (ZT = 1) for the best bismuth telluride material available today, the Carnot efficiency is 0.38, the second term is 0.25, and overall efficiency is = 9.5%.

3. Inductive generator

An "inductive" thermoelectric generator is a completely different type of generator from a resistive load direct current generator.

In 1990 in Edinburgh Scotland, Strachan studied a generator [6] that operated in the MHz frequency range. It was a very complicated design. The frequency was determined by a piezoelectric component PZT. The voltage was produced by a stack of 600 sheets of metalized PVDF with: on one side Ni+Al, on the other side Fe and Mylar. The load was inductive [7-8]. The generator of several cm^3 powered a small fan; the heat sources were ambient air temperature and ice. No measurements were published on the electrical power or the efficiency (electrical power/ thermal power).

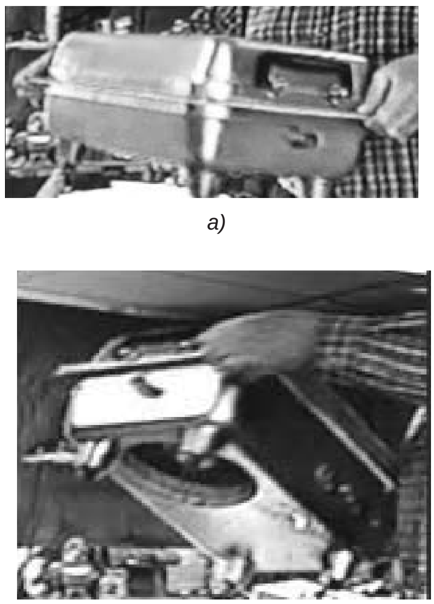
In 1995 in Leander Texas USA, Jon Schroeder distributed a brochure on a thermo-electric generator called "Trymer 5000"; it claimed an electrical power output of 5 KW, and the thermal power was never indicated. The author of this paper visited Jon Schroeder that same year, what he saw was a very rudimentary unit, that did not produce much electricity, but he considered the concept very interesting, and that if well designed might, produce electricity. Jon Schroeder [9] continued to develop his generator, and in 2004, he showed people that a unit, weighing about 15 kg and 20 cm × 30 cm × 60 cm in size, operated by propane combustion, that produced 5 kW of electricity. But he never communicated the thermal power input.

In 2008, Marin Nedelcu from Bucharest in Romania visited Jon Schroeder in Texas. He took with him at the request of the author a bottle of propane gas that had been weighed. The generator was operated with propane from this bottle. The electrical output was on a resistive load consisting of electric filament type electric light bulbs. An output electrical power of 4 kW was measured. The propane bottle was reweighed afterwards so as to calculate the amount of propane used. It was possible to calculate the overall system efficiency. It included the power to the fan, and to the electronics, (chopping and up-converter). A value of 15% was found. This value, which is a system-efficiency, means that the generator has an efficiency double the thermoelectric efficiency. We calculated previously with temperatures similar to those of this generator that the maximum thermoelectric (DC) efficiency to be 9.5% without auxiliaries.

4. Motivation to study this generator

Thermoelectric generators (operating in the direct current mode) have an efficiency limited by the ZT of the thermoelectric materials available. The author considers that we need a paradigm to break the ZT limit estimated at about 2. A generator, operating in a non-stationary state, is a new concept and could be: The Paradigm.

It is absolutely necessary to duplicate the measurements made by Marin Nedelcu in 2008. It is difficult because, the unit of Jon Schroeder (Fig. 1) has no temperature measurements at the hot side and cold side of the thermoelectric material. So we need to design a unit where such temperature measurements are possible. The original characteristic of the Schroeder generator is that the load is inductive. The generator has a major flaw, all the elements are all soldered in one operation, so quality control is quasi-impossible, and Jon Schroder has great difficulties to make other units.



a)

b)

Fig. 1. Jon Schroeder holding the generator: a) side view, b) underside.

5. Design considerations for an "inductive" generator

5.1. Description of the Schroeder generator

We have two sources of information: (i) patent [9] filed in 2002 (Figs. 2-4 are taken from the patent), (ii) photographs and videos that he communicated to visitors. We have extracted photos from the videos to make Fig. 1.

Fig. 2 shows the ring of 250 mm in diameter, with 124 pieces of bismuth telluride 20 mm × 20 mm × 1mm, alternately N and P. This ring is very, very difficult to make as the TE elements are soldered in one operation.

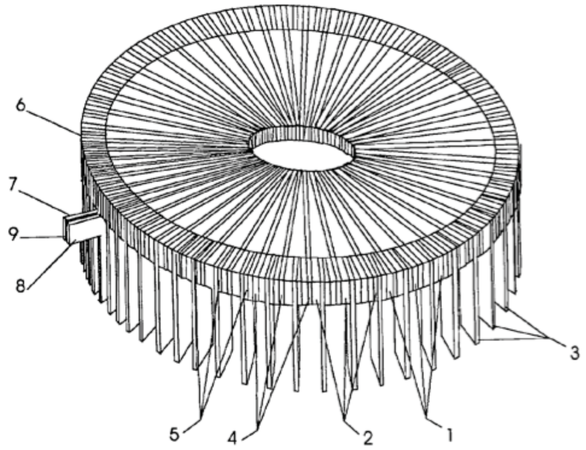


Fig. 2. The ring of 250 mm in diameter in the Schroeder generator.

Fig. 3 shows the central burner, the hot plates connected to the hot side of the pieces of TE are marked 4, the cold plates are marked 3. They are called paddles in the patent.

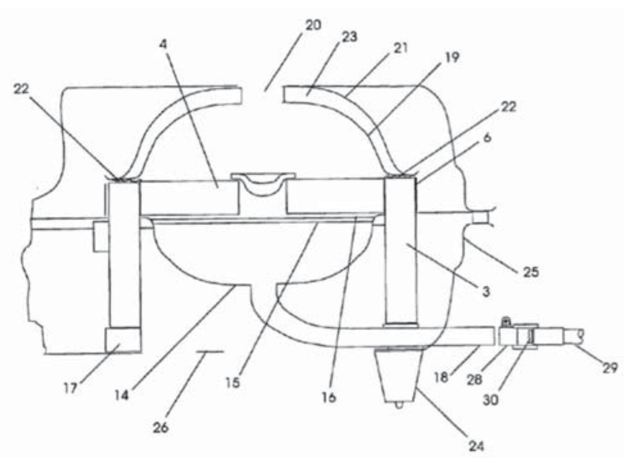


Fig. 3. A cross section of the unit (patent [9] Fig. 6).

The propane is burned in volume 4, the hot combustion gases exit through the central hole 20.

The electrical circuit, shown in Fig. 4, consists of "TE" generating ring, ref. 6; the outlet connectors are 121 and 126. The switching is done by MOSFETs (IRL2203N-ND) at 127 and 128. Ref. 125 is the core of a transformer. There is a 2 turn primary winding: ref. 123 and 124.

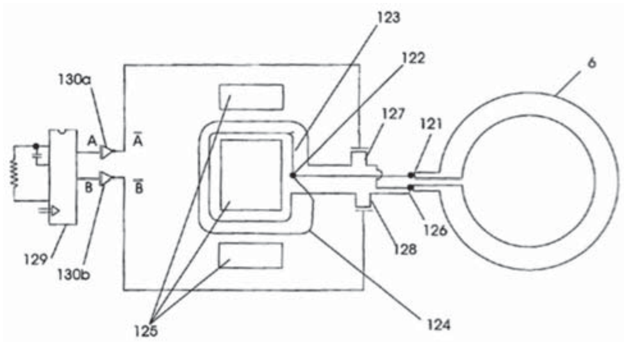


Fig. 4. The electrical circuit of the unit (patent [9] Fig. 25).

5.2. Remarks on patent [9]

This patent is in public domain. It is extremely detailed with a lot of information that will help us to make a unit to validate the measurements. Claims from 1 to 37 are essentially mechanical. It is only at claim 38 that the electrical circuit outside the ring is presented. We note in claims 38 and 39: The device comprises bidirectional primary windings around a ferrite core, a means to rapidly switch current flow of the primary windings, and means to switch current direction in primary windings is a plurality of semiconductor gates controlled by a high frequency circuit. In the disclosure of the invention, we note in [0063] Fig. 25 of the patent. There is a description of the operation of the circuit shown in Fig. 4, which allows alternating current to be obtained from the low direct current voltage of ring 6. 121 is the positive lead of thermoelectric ring 6, and connects to the centre tap 122 of a 2 turn primary winding 123 and 124 around a ferrite core,125. In the preferred embodiment, the centre tap of the 2 turn primary winding is unbroken. Each end of the winding connects to negative terminal 126 of ring 6 with MOSFET switches 127 and 128. A controller pulse width modulator chip, 129, controls the opening and closing of the MOSFET switches through MOSFET drives 130a and 130b to make before break current paths back to the negative terminal 126. To work properly the MOSFET drives 130a and 130b have inverted outputs, so as to allow the make before break feature. When the primary circuit is in alternate make-before-break mode, there is no stopping of current in the thermoelectric ring and therefore no inductive spike of loss of power output from the ring .The switching frequency is between 50,000 Hz and 100,000 Hz.

6. Operation of the "Trymer 5000" generator

The unit operates without any connection to a power supply. It generates its own electricity to operate the electronics. The operator must start the flow of propane, light it with piezoelectric spark, and wait a few minutes until the DC voltage builds up in the ring. At a given time, which is critical, the operator turns a switch, which allows the electronics to be powered by this generator. This sequence is very important when one wants an autonomous generator. This situation does not interest us to build a unit to validate the concept. We will power the electronics from another source of power, and we will measure the amount of power used to operate the generator, as it must be included in the overall efficiency of the generator.

6.1. Principle of operation – general description

The hot paddles (hot side flat plate heat exchangers) go inwards towards the centre of the ring 6; they are heated by the hot propane combustion gases. The cold paddles are oriented downwards, and cooled by ambient air blown onto them. A temperature difference is established between the 2 sides of the bismuth telluride discs (20 mm × 20 mm × 1 mm), therefore creating due to the Seebeck effect a voltage, and hence an electrical current goes around the ring. The 2 output copper wires are connected to the primary of a transformer, which is an inductive load via an electrical switch, which allows the current to flow alternatively one way then the other way around the ring.

The secondary winding is connected to a full wave bridge to produce direct current. The DC current can be easily transformed into AV 110 V or 220 V.

6.2. Electrical resistance

Bismuth telluride elements (20 mm × 20 mm × 1 mm) are sandwiched between hot (25 mm × 3 mm × 115 mm) and cold (about 25 mm × 3 mm × 200 mm) copper paddles. The electrical resistance R of one element (type N or P, the values are similar) associated with a copper paddle is: $\rho = 10 \cdot 12^{-6}\ \Omega \cdot m$ with cross section S = 20 mm × 20 mm = 4 cm^2, L = 1 mm thick, and $R = \rho \cdot L/S$ = 25 μΩ.

For the copper parts, assuming that their effective cross section is the same as that of the TE element and is S = 4 cm^2, at a thickness of 3 mm and $\rho = 1.68 \cdot 10^{-8}\ \Omega \cdot m$, $R = \rho \cdot L/S$ = 0.13 μΩ. The electrical resistance per element is 25 + 1 = 26 μΩ.

The Schroeder ring has 62 couples plus one element so that the output circuit is connected to the cold side of an element; we will consider 124 + 1 = 125 elements. The electrical resistance of the ring is 125·26 μΩ = 3.25 mΩ.

6.3. Principle of operation

We are not aware, if any temperature measurements were ever made on copper hot or cold the paddles of the generator. So, we can only estimate these temperatures. Some simple thermal calculations lead us to believe that the temperatures at the interface with the bismuth telluride wafers are cold side: 100°C and hot side 250°C

The solder used by Jon Schroeder, from what we know, melts between 250°C and 300°C, so assuming a hot side temperature of 250°C is realistic. The cold side is cooled by ambient air blown onto the cold paddles, so assuming 100°C is realistic; it may be higher, but we have a maximum value of the temperature difference = 150 K.

6.4. Operation of the generator in DC

With an estimated Seebeck of 200 μV/K , $V_{opencircuit}$ = 124·200·150 = 3.72 V

The electrical resistance R of the generator is, as we found earlier, 3 mΩ, so maximum power is obtained when connected to a resistive load of 3 mΩ: $P = (V_{opencircuit})^2/4R$ = 1153 W.

6.5. Pulsed operation

The electrical current when the output is short circuited is: I = 3.72/0.003 = 1240 A

Such a generator operated in the DC mode would have a load resistance = generator electrical resistance = 3 mΩ, so the electrical current would be 620 A.

The patent indicated a frequency of around 100 kHz. Apostol [1, 10-11] and Nedelcu [14] have published on the operation in the pulsed mode. They show how a pulse flies through a thermoelectric sample with a charge pulse built up at the hot end, and evokes an electric “condenser,” and, like any other condenser, such a “thermo-electric condenser” can be “discharged” by switching on the electric contacts to the external circuit. Under these circumstances the motion of the charge carriers proceeds, and the pulse “flies” through the external circuit as a whole, with the transport velocity. This is a macroscopic, non-stationary, fast, pulsed-like transport that takes place in the transient regime prior to establishing the extension of the pulse along the whole length of the sample.

Another theory, very simplistic, is that the thermo-elements of bismuth telluride act as thermal capacitors that are charged by heat (Seebeck effect) and discharged alternatively in one direction and then in the other direction. If this is correct then the heat, that goes from the hot side to the cold side, does not have time to reach the other side before the current is inversed (or shut off); this would explain why the measured efficiency is greater than the efficiency when operated in the DC mode.

7. Validation

The ideal solution is to duplicate, as well as we can, the Schroeder ring unit that used combustion gases as the source of heat and forced ambient air for cooling.

7.1. Ring generator

We design and build a ring generator with temperature sensors for thermal measurements. It is not possible to measure accurately the heat fluxes, but we can know the power of the burner from the amount of propane burnt.

The soldering of a complete ring with 120 thermoelectric discs in one operation, as Jon Schroder has done once, is very, very difficult, and it seems that he is incapable of repeating this operation. A logical solution is to divide the ring into segments, for example 6, to quality control each segment, and to retain segments that are well soldered. Each segment, then can be individually checked by measuring its electrical resistance. This modification increases the electrical resistance of the ring, but is negligible. Drawings have been made.

Nevertheless, the manufacturing of this ring, with a propane burner, a fan to cool the cold side, and in particular the delicate assembly with all the thermal insulation, is expensive.

We don't know the importance of the geometrical ring on the operation of the generator, as it generates a magnetic field.

7.2. Column generator

There is an alternative design: a column generator, which consists of a stack of bismuth telluride slices between heated and cooled plates. We have designed a unit consisting of 4 columns of 37 TE slices = 148 TE slices. This generator also generates a magnetic field, but of a different shape. This design has many techno-logical and thermal advantages.

The assembly of such a unit has been studied; to facilitate the assembly, discs of bismuth telluride have been soldered by the thermoelectric company manufacturer of discs 24 mm diameter and 0.8 mm thick, to copper caps at 350°C. In this way we only have to solder copper to copper which is a well know procedure. We solder the "hot side" of the copper capped disc to a hot plate one at a time with a paste solder alloy; melting temperature 287–296°C, composition Pb 92.5% – Sn 5% – Ag 2.5%.

The column is assembled with a system to compress and all "cold sides" are soldered in one operation with a preform of solder 42-58 Bi Sn solder melting at 138°C.

Then it is placed in an oven, with an inert gas at 150°C. After cooling down and when the column is at room temperature after one night, the column is visually examined and electrical resistance of the column is measured with an AC micro-ohmmeter that compensates for any residual Seebeck effect to see, if it has a normal value.

7.3. Switching device

The switching device is the same for the ring design as for the column design. The transformer is described in Fig 5 of the patent [9] (Fig. 4).

A 2 turn winding consisted of sheet copper so as to have a very low electrical resistance. In the load circuit the main electrical resistance if from the MOSFETs. MOSFETs typically have electrical resistances of around 10 mΩ; to reduce this, several MOSFETs are installed in parallel for example 10. The 2 ends of the 2 turn winding are connected to the negative terminal of ring 6. The centre point is connected to the positive terminal of ring 6. The entrance from the first winding contains a MOSFET; the exit from the second winding also contains a MOSFET. The centre point is always connected to the positive terminal of ring 6. The operation make before break is described in [0063] of patent [9]. The ferrite core is 20 mm × 20 mm. The primary and secondary windings are around the centre core. The control system of the MOSFETs is very important, and is described in [0063] of patent [9].

The generator must be operated at an optimum frequency, a sort of resonant frequency, which depends on the design. The patent indicates a frequency between 50 kHz and 200 kHz. We have noted that only one half cycle is used by Jon Schroeder.

7.4. Validation testing

The first prototype should be a column design because it is much easier and cheaper to build. It can be relatively easily quality controlled and can incorporate thermocouples or thermistors. It can be designed for measurements of thermal powers to be able to calculate thermal energy balances. The electrical power output must be carefully measured depending on the design of the electronics package DC output or low frequency 50 Hz output. As we are dealing with high frequencies, we must measure the parasitic magnetic fields and the cosφ, besides voltmeter and ammeters a wattmeter must be used.

Should the efficiencies not correspond to those measured on Jon Schroeder's unit; we must examine what are the reasons.

We know that the reason might be the ring? Its magnetic field may be an important factor! We have used bismuth telluride discs, which have no Ni on the sides, perhaps the reason!

8. Conclusions

This thermal to electric generator with a pulsed output may be the design of the future if the performances are much better than those of a thermoelectric generator operated in the DC mode. When interesting performances have been measured then the generator must be thoroughly studied.

A mathematical model of the operation of the generator must be written. There are very few books written on the transient operation of a thermoelectric generator; one is by Paul E. Gray [12] 1960, another by E. K. Iordanshvili [13]: more general.

When the performances have been validated endurance testing must de done because there may be pyro-electric effects that are known to be unstable. The characteristics of the interfaces must be examined: carrier concentration, micro-structure, X ray diffraction etc.

The generator uses bismuth telluride (Bi_2Te_3); we don't know if Bi_2Te_3 is the best material until a mathematical model has been validated experimentally. It seems from the analysis of Apostol that the thermal conductivity of the material is not a pre-dominant parameter, so then it is the power factor *PF* = Seebeck^2/electrical resistivity that will be the most important material parameter.

Should the model confirm the importance of the power factor, then high temperature thermoelectric materials with a power factor greater than the PF of Bi_2Te_3) can be used. Materials such as SiGe can be operated at elevated temperatures so will have efficiencies that might be suitable for the MW power range.

The positive aspects are as follows:

- efficiency measurements made in 2008 on the Schroeder ring,
- flying pulse theory of Marian Apostol [1],
- recent experiments by Marin Nedelcu on a thermoelectric module as a function of frequency [14].

All this leads to say: not an illusion - but the reality needs to be verified scientifically, we hope that this will materialize in the near future.

Acknowledgments

The author is indebted, to Jon Schroeder for the efficiency measurements made for the first time, with video and photos by Marin Nedelcu on his generator, to Marin Nedelcu for many years of useful discussions, for his perseverance in building and testing non steady state thermoelectric devices, to show their potential; For having made and communicated the efficiency measurements, the video, photos. Also indebted to Marian Apostol for his contributions to the theory of operation and many useful discussions and to Christophe Goupil for many discussions and for his support in designing a column unit.

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