Cold-Source-Free Thermoelectronic Energy Converter Based on Self-Organization of Thermal Energy into Electrical Energy

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Abstract

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Full Text

Thermionic Energy Converter without Cold Reservoir Based on Self-Organization of Thermal Energy into Electrical Energy

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Abstract

Both heat engines and thermoelectric direct conversion devices require a cold reservoir. If thermal energy could self-organize into electrical energy, this conventional limitation could be overcome. Research reveals that the surface barrier of a solid emitter generates a negative entropy flow by dissipating the kinetic energy of emitted electrons, making thermionic emission from the solid emitter a dissipative structure. As the solid emitter loses electrons and becomes positively charged while the surroundings gain electrons and become negatively charged, a macroscopically ordered electric double layer self-organizes. To release the electric field energy of this double layer into a circuit, this study employs a solid emitter as the thermionic cathode and a non-emitting molten metal liquid without surface potential barriers as the collector, constructing an experimental thermionic energy conversion device where emitter and collector maintain the same temperature. Experimental results demonstrate stable voltage and current output, realizing a novel cold-reservoir-free direct thermoelectric conversion method based on self-organization phenomena. This device holds promising prospects for efficient, compact, and safe implementation of direct thermoelectric conversion.

Keywords: Thermionic emission; Self-organization; Cold reservoir; Thermionic energy converter

Classification: TM915

2.1 Thermionic Emission from Solid Emitters and Dissipative Structures

[Figure 1: see original paper] Comparison of electron and molecular thermal motion: (A) Schematic of thermionic emission from a solid emitter in an isolated system, (B) Molecular evaporation from a solid emitter in an isolated system

As shown in Figure 1, comparing electron and molecular thermal motion facilitates understanding of how electron thermal motion differs from molecular thermal motion. Since the net Coulomb force on electrons within a solid emitter is zero, electron thermal motion is equivalent to that of ideal gas molecules. Electrons at the solid emitter surface experience asymmetric Coulomb forces, constituting the surface potential barrier of the solid emitter, with ϕ representing the surface work function.

Figure 1(A) illustrates that in an isolated system at sufficiently high temperature, some electrons within the solid emitter possess sufficient kinetic energy to overcome the surface work function and emit into the surroundings, making the electrons in the solid emitter an open system. The entropy change of an open system can be divided into two parts: one caused by interaction between the solid emitter and surroundings (i.e., the thermionic emission process), called the entropy flow term, denoted as dSe; the other produced by irreversible processes

of electron thermal motion within the solid emitter system, called the entropy production term, denoted as dSi.

During thermionic emission, consider an electron in solid emitter A that absorbs an infinitesimal amount of heat dQ and is transferred to surroundings B through emission. Since dQ is infinitesimal, the temperatures of solid emitter A and surroundings B can be considered constant at temperature T.

According to the entropy increase principle, the entropy flow of solid emitter A is:

$$dS_e^A = -\frac{dQ}{T}$$

The entropy flow of surroundings B is:

$$dS_e^B = \frac{dQ}{T}$$

The total entropy flow of the electron system is:

$$dS_e^{total} = dS_e^A + dS_e^B < 0$$

The total entropy of the electron system is:

$$dS = dS_i + dS_e^{total}$$

Therefore, from equations (6) and (7), for an open electron system, as long as a sufficiently large negative entropy flow is maintained, the system can sustain some ordered state. The negative entropy flow of -ϕ/T plays a crucial role in the spontaneous process from disorder to order. Only electrons with kinetic energy greater than the solid emitter' s surface work function can be selectively emitted by the surface potential barrier. The surface potential barrier of the solid emitter acts similarly to a "Maxwell' s demon," dissipating energy equal to the surface work function ϕ for each emitted electron. In contrast, the Maxwell's demon in Figure 1(B) cannot consume molecular kinetic energy and thus cannot form a dissipative structure. Therefore, thermionic emission from solid emitters satisfies one condition for dissipative structures.

As shown in Figure 1, the emission rates of both electrons and evaporated molecules from the solid emitter surface follow Maxwell' s velocity distribution. Because Coulomb force is long-range while molecular force is short-range, the effect of Coulomb force far exceeds that of molecular force. In Figure 1(B), vapor molecules in the surroundings undergo random thermal motion, distributing uniformly throughout the surroundings in equilibrium state. In Figure 1(A), electron density in the surroundings increases with proximity to the solid emitter, forming an electron cloud state where electron thermal motion is far from equilibrium. Thus, thermionic emission from solid emitters satisfies another condition for dissipative structures.

In Figure 1(B), the gravitational force from the solid emitter on vapor molecules is negligible, and no interaction exists between vapor molecules and the solid emitter. In Figure 1(A), electrons are continuously emitted from the solid emitter due to thermal motion, while simultaneously returning from the surroundings to the solid emitter under Coulomb force. This nonlinear Coulomb force feedback drives electron thermal motion toward complexity and order. Therefore, thermionic emission from solid emitters satisfies the third condition for dissipative structures.

In summary, thermionic emission from solid emitters conforms to dissipative structure theory and represents a self-organization phenomenon in nature.

2.2 Macroscopic Ordered Structure

As shown in Figure 1(A), during thermionic emission, the net charge of electrons lost by the solid emitter is +q, while the net charge gained by the surroundings is -q, forming a macroscopic electric double layer similar to that at the positive electrode in chemical batteries. The electric field direction of this double layer points from the solid emitter to the surroundings. Therefore, the macroscopic ordered structure spontaneously formed by thermionic emission from solid emitters is an electric double layer, and the thermionic emission process is one that self-organizes disordered thermal energy into ordered electric field energy. As long as a certain critical temperature is exceeded, the solid emitter will emit electrons, enabling self-organization of thermal energy into electric energy without requiring a cold reservoir.

2.3 Efficiency of Thermal Energy Self-Organization into Electrical Energy

Electrons within the solid emitter obey kinetic gas theory. The thermal energy Q absorbed by an electron manifests as translational kinetic energy Ek, where is the Boltzmann constant, and the average translational kinetic energy of electron thermal motion is:

$$E_k = \frac{3}{2}\kappa T$$

Taking a coefficient α ($\alpha > 3/2$), the kinetic energy of an emitted electron can be assumed as:

$$E_{emitted} = \alpha\kappa T$$

The electric field energy of the electric dipole is We, and the efficiency of thermal energy self-organization into electric field energy for one emitted electron is:

$$\eta = \frac{W_e}{E_{emitted}} = \frac{\varphi}{\alpha\kappa T}$$

From equation (10), since infinite temperature T or zero ϕ is impossible, and effective requires sufficiently large T, the solid emitter cannot self-organize all

thermal energy into electric energy, nor can all thermal energy at any temperature be self-organized into electric energy. Therefore, the cold-reservoir-free solid emitter converting thermal energy into electric energy through thermionic emission is not a second-kind perpetual motion machine, but rather an application and development of the second law of thermodynamics in non-equilibrium thermodynamics.

The solid emitter can be regarded as a cold-reservoir-free thermionic energy generator. To release the electric field energy from this double layer into a circuit, a collector that does not emit electrons at the same high temperature must connect to the surroundings, and molten metal liquid satisfies this condition. These considerations provide the theoretical foundation for developing cold-reservoir-free direct thermoelectric conversion experimental devices.

3. Experiment

3.1 Experimental Apparatus

[Figure 2: see original paper] Experimental apparatus: (A) Photograph of the experimental setup, (B) Schematic diagram of the apparatus structure

The experimental apparatus consists of a tungsten electrode (5.8 mm diameter × 20 mm height) inserted into a closed-bottom ceramic tube (6 mm inner diameter × 0.5 mm wall thickness × 40 mm height), placed in a corundum crucible and filled with copper particles. Molybdenum wire sheathed with insulating ceramic tube serves as the conductor.

In the experimental apparatus, the electron emitter is tungsten (W > 99.5%) with a surface work function of 4.55 eV; the electron collector is molten copper liquid (Cu > 99.95%); the conductor is molybdenum wire (Mo > 99.5%). Possible electromotive forces from alloying reactions between copper, tungsten, and molybdenum are excluded. The wires connecting the high-temperature emitter and collector to the room-temperature ammeter and voltmeter are made of the same molybdenum material to exclude possible thermoelectric electromotive forces from the Seebeck effect [3].

The experiment employs α-Al_2O_3 transparent ceramic tubes (α-$Al_2O_3 > 99.7\%$) used in high-pressure sodium lamps as the ceramic separator. Intergranular pores (< 0.1 nm) are smaller than tungsten and copper atomic diameters but larger than electron diameter. At high temperatures, this separator electrically isolates the emitter and collector while maintaining a small gap and allowing emitted electrons to diffuse through, similar to separators in chemical batteries. The crucible is a corundum crucible (α-$Al_2O_3 > 97\%$), excluding possible electromotive forces from chemical reactions between copper, tungsten, and α-Al_2O_3.

A gap of approximately 0.2 mm exists between the tungsten electrode and ceramic tube. While filling this gap with alkali metal vapor could significantly reduce the emitter work function and eliminate space charge accumulation [4],

sealing is difficult. Considering the large difference in saturated vapor pressure between copper and tungsten, this study adopts copper vapor evaporated from the collector to naturally fill the gap, simplifying the experiment.

3.2 Experimental Method

The vacuum tube furnace has a maximum heating temperature of 1973 K with temperature control precision of $\pm 0.5 K and a constant temperature zone length of 20 mm. The corundum tube ($-A$ > 97%) has a diameter of 60 mm. The vacuum pump' s ultimate pressure is 4$\times$10^{-4}$ Pa. At 1773 K, the leak rate of the furnace tube sealing system is < 0.15\times$10^{-5}$ Pa $\cdot$ L/s, excluding electromotive forces from chemical reactions due to air leakage.

The thermionic energy conversion experimental device is placed in the constant temperature zone of the vacuum tube furnace to ensure uniform temperature distribution. During heating, the vacuum pump continuously evacuates gases from the furnace tube. When heated to copper' s melting point of 1357 K, the vacuum level in the furnace tube reaches 4$\times$10^{-4}$ Pa. The vacuum pump is then turned off, allowing copper vapor from the molten copper liquid to fill the gap between the tungsten rod and ceramic tube. At this point, the pressure in the room-temperature section of the furnace tube is approximately 2$\times$10^{3}$ Pa until heating to 1773 K. The ammeter has an internal resistance of 10 Ω with measurement precision of $\pm$0.1 A. The voltmeter has an internal resistance of 10 MΩ with measurement precision of $\pm$0.1 mV.

4. Experimental Results and Discussion

4.1 Relationship Between Voltage, Current, and Temperature

[Figure 3: see original paper] Relationship between current, voltage, and temperature

Current is measured directly under short-circuit conditions, and voltage is measured directly under open-circuit conditions. In the temperature range from 1573 K to 1773 K, current and voltage values are recorded every 10 K, with each measurement point held for 5 minutes to ensure uniform temperature and stable voltage/current. Figure 3 shows the experimentally measured relationship between current, voltage, and temperature. Each temperature point yields corresponding voltage and current values, both increasing with temperature. Voltage increases from 91 mV to 227 mV, while current increases from 14 A to 115 A. Possible electromotive forces from crystallographic structural changes in experimental materials are excluded. The experimental device produces stable DC voltage and current output, with the tungsten rod as the positive electrode and molten copper liquid as the negative electrode. When power to the vacuum tube furnace is cut off, voltage and current persist in the circuit, excluding possible induced electromotive forces in the thermionic energy converter within the vacuum tube furnace. Therefore, the experiment proves that thermal energy can be directly converted into electrical energy without a cold reservoir.

4.2 Relationship Between Voltage, Current, and Time

[Figure 4: see original paper] Relationship between current, voltage, and time at 1773 K

Figure 4 shows the relationship between current, voltage, and time for the thermionic energy converter at constant temperature 1773 K. Current rapidly decreases from 155 A to a smaller stable value of 115 A, similar to a capacitor discharge process. Voltage rapidly increases from 180 mV to a larger stable value of 227 mV, similar to a capacitor charging process. This pattern resembles an RC series circuit in DC circuits [5]. Here, the insulating property of the transparent ceramic tube functions as the dielectric in a capacitor, consistent with the experimental apparatus' s capacitive structural characteristics. Meanwhile, the transparent ceramic tube allows electron diffusion, creating large resistance that results in relatively small output voltage and current.

Current cannot rely on electron transport through the ceramic separator alone; charges must cross the ceramic diaphragm. Based on the circuit' s current direction, either electrons emitted from the tungsten rod cross the ceramic diaphragm to reach the molten copper liquid, or copper ions cross the ceramic diaphragm to reach the tungsten electrode. Molten copper liquid cannot ionize at this temperature, and copper atoms cannot pass through high-purity aluminum oxide ceramic to become copper ions. Therefore, the current in the circuit is inferred to originate from electrons thermionically emitted from the tungsten electrode.

With experimental electromotive force interference excluded, the experimental device maintained stable voltage and current output for 2 hours in the constant temperature zone of the tube furnace, ensuring uniform temperature distribution. The experiment again proves that thermal energy can be directly converted into electrical energy without a cold reservoir.

4.3 Comparative Analysis of Three Energy Conversion Devices

In this experiment' s thermionic energy converter, the emitter at high temperature source emits electrons, while the collector at the same high temperature source does not emit electrons because it is molten metal liquid.

Phototubes can directly convert light energy into electrical energy, where the emitter under illumination emits electrons while the collector with larger work function does not emit electrons [7]. Traditional practical thermionic energy converters have emitters at high temperature source emitting electrons and solid emitters as collectors at low temperature source that do not emit electrons due to low temperature [8].

Comparing these three devices, the collector is prevented from emitting electrons by different methods, and the collector's role is merely to release electrical energy into the circuit. Therefore, cold-reservoir-free thermionic energy conversion is feasible.

4.4 Inferences and Speculation

[Figure 5: see original paper] Comparison of electron circulation and current circulation: (A) Schematic of electron circulation between solid and surroundings, (B) Current circulation between solid and molten metal

As shown in Figure 5(A), during solid thermionic emission, electrons continuously absorb heat and emit from the solid emitter to the surroundings, while continuously returning from the surroundings to the solid emitter under Coulomb force. Random thermal motion and ordered electrical motion cyclically coexist between the solid and surroundings. As shown in Figure 5(B): If the molybdenum wire and ceramic separator are removed from the experimental device, electrons emitted from the solid possess initial kinetic energy and move toward the non-emitting molten metal collector, generating corresponding current in the circuit. This reveals a possible physical effect of current circulation between solid and molten liquid under high-temperature conditions.

Speculation: Can this cold-reservoir-free thermionic energy conversion device directly convert the inexhaustible thermal energy from Earth' s volcanic lava into electrical energy? Earth, composed of solid emitters and lava, resembles the structure shown in Figure 5(B). Can the physical effect of current circulation between solid and molten liquid explain the formation mechanism of Earth' s magnetic field?

Studying thermionic emission from solid emitters using non-equilibrium thermodynamics reveals that thermionic emission is a dissipative structure through which solid emitters self-organize thermal energy into electrical energy. This experiment, using a tungsten electrode as the thermionic emitter and molten copper liquid as the collector, realizes a novel cold-reservoir-free direct thermoelectric conversion method based on self-organization phenomena.

References

[1] Ma Wenwei (Editor-in-Chief). Physics Course, Higher Education Press, 2002.7.-193
[2] Li Rusheng (Author), Non-equilibrium Thermodynamics and Dissipative Structures, Tsinghua University Press, 1986.4-45
[3] Wang Guodong (Editor-in-Chief). University Physics, Higher Education Press, 2007.12.-189
[4] Jiang Zhongliang, Chen Xiuyun (Authors), Temperature Measurement and Control, Tsinghua University Press, 2005.8-63
[5] J. B. Cui, J. Ristein, and L. Ley, Phys. Rev. Lett. 81, 429 (1998)
[6] Jiang Heqian (Editor-in-Chief), Electrical Engineering, Higher Education Press, 1986.10 -37
[7] Xi Gang (Editor-in-Chief), College Physics Fundamentals, Higher Education Press, 2008.7.-141
[8] Ned S. Rasor, Thermionic Energy Conversion Plasmas, IEEE transaction on plasma science vol. 19, no. 6, december1991

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Note: Figure translations are in progress. See original paper for figures.