論 文
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내화금속 다이오드에서 전자기에너지 발전에 관한 연구

Generation of Electromagnetic Energy in a Refractory Metal Thermionic Diode

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Abstract - A thermionic energy converter test station is constructed for the study of electromagnetic energy generation. Of particular interest is the frequency variations due to changes in the interelectrode gap, the electrode temperature, and the cesium vapor pressure. It is found experimentally that the most intense ratio-frequency(rf) oscillations occur at two non-overlapping regions.

Key Words : Knudsen-Arc-Mode(누슨아크모드), Knudsen-Operating-Mode(누슨동작모드), Coulomb Collision(콜롱충돌), Volume Ionization(대량이온화현상), Oscillation(변환)

1. Introduction

Thermionic energy converter (TEC) is coupled with space nuclear reactors in most considerations of high power generation for future space missions. Continous studies of TEC have been conducted in the Soviet Union since the 1960's for space applications as the continuous and reliable source of electricity and in information-based space systems(communication satellites, Earth surveillance for studying the atmosphere, crops, resources, transportation control, etc). TEC is a compact, light weight, modular static generator. Furthermore, power producing thermionic diode oscillators have excellent prospects for research exploitation. Since TEC's are operated in low voltage region (less than 3 volts), power conditioning is necessary to convert low voltage direct current (dc) output to higher voltages and alternating current (ac). Morris [1] pointed out that "for improved TEC with the same efficiency but hotter collectors, somewhat above $1200K$, power conditioning requires about tiwice the waste-heat-radiator area necessary for TEC". The indirect conversion of relatively low voltage dc output into

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ac requires a large additional heat rejection weight and imposes a major problem for TEC in space nuclear power applications. Therefore, electromagnetic energy outputs from TEC offer important advantages over its traditional *dc* power output. The direct internal generation of *ac* outputs can render power conitioning obsolete in certain regimes.

The observed oscillation modes[1, 2] are divided into two. One is the Kundsen-Arc-Mode (KAM). The experimental conditions include low emitter temperatures and high cesium vapor pressures. The volume ionization is a key collision process of the KAM. The Knudsen-Operating-Mode(KOM) requires high emitter temperatures and low cesium vapor pressures. Higher emitter temperatures produce high electron emission from the emitter that results in higher current density. The coulomb collision, which is the dominant mechanism in the KOM, involves a long-range force that does not contribute to scattering. Therefore, two modes are possible for producing oscillation behavior.

Most oscillation experiments have been done with tungsten, tantalum, and molybdenum electrode materials. However, the oscillation behavior of polycrystalline rhenium electrode material has not been evaluated previously. Polycrystalline rhenium exhibits a work function maxima over a broad temperature range[3]. It has a very high bare work function of 5.0eV. Therefore, it should require less cesium vapor pressure than other metallic emitters because the high bare work function can produce the surface ionization more easily than other materials(*W*, *Ta*, *Mo*). The composition of polycrystalline rhenium is 99.96% and the surface has a smoothness of less than 2×10^{-4}mm.

In a low cesium pressure diode the frequency is theoretically inversely proportional to the distance between the electrodes, and to the square of that distance at high cesium pressure[4]. Therefore, high frequency plasma oscillation will be produced when the electrodes are closely spaced. The study of *ac* output is accomplished with a spectrum analyzer(Hewelett-Packard, 140T/8553B/8552A). The intent of this present effort is to examine the frequency dependency for given conditions at interelectrode gaps in the range of 1 to 0.13mm.

2. Experimental procedure

TEC is one of direct energy conversion methods from heat into electrical energy. The electrons and ions are produced by thermionic emission and surface ionization respectively from the hotemitter surface. The emission of plasma from heated refractory electrode metal is the driving reaction in the direct conversion of heat to electricity. Then, if two electrodes are electrically connected, current will flow. The current oscillation (electromagnetic energy) occurs due to the electron and ion interaction that results in plasma instability inside the diode gap under certain conditions. But the stable plasma produces power output.

A variable spacing diode for this work was built by Electro-Optical Systems, Inc. (EOS) for a wide range of operation necessary to characterize electrode material performance for application to TEC. The experimental conditions of the present work are met by varying parameters. The interelectrode gap is to vary from 0.13mm to 1mm with an accuray of $\pm$0.015mm. Emitter temperatures range from 1300K to 2200K, collector temperatures from 300K to 1000K, and liquid cesium reservoir temperature from 300K to 600K. The corresponding cesium vapor pressures are from 1.8×10^{-6} torr to 4 torr. The configuration of the present test vehicle is similar to the vehicle described in Campbell's work[5]. A TEC test station is shown in Fig. 1.

The interelectrode gap calibration is performed before each experiment. With an ohm-meter (Omega, 881C) and three linear motion flanges (Hungtingtion, VF-165-1) with precision micrometers(Mitutoyo, 0-25mm), the electrode continuity is checked at the terminal outputs (emitter and collector) after the emitter is heated to evaporated the liquid cesium within the interelectrode gap. Three separate aluminum (2024-T4) spur gears are attached on the linear motion flanges. A center spur gear is mounted on the center of the top stainless steel plate to control the three outside gears simultaneously. This procedure provides

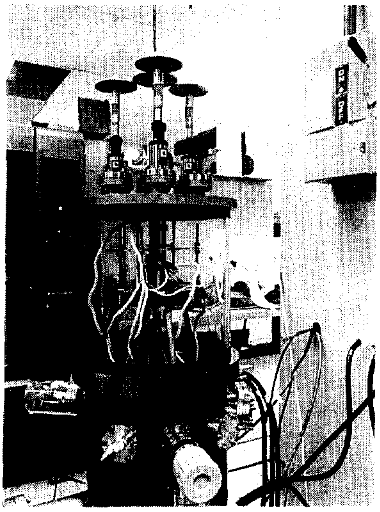

Fig. 1 A TEC test vehicle.

electrode parallelism. Then, the in-situ interelectrode gap adjustment is accomplished at testing environment. Vacuum inside a pyrex bell jar better than 10^{-8} torr is obtained with a turbomolecular pump and an ion pump. A pancake shape counterwound tungsten filament (1.9cm diameter) is employed as a heat source of the emitter. The custom-made tungsten filament is heated and bombarded by 0-30 volts ac and 0-5000 volts dc power supply (The Superior Electric Co.). The emitter is intentionally grounded to get the reference level with respect to the collector. The collector is cooled by the mechanical attachment of a copper radiator (3.3cm×15.7cm). A nichrome cable heater is brazed on the copper radiator for maintaining the collector temperature at the desired levels. The cesium reservoir is heated by a shielded resistance heater which is brazed on the cesium reservoir wall.

The dc current-voltage (I-V) characteristics are obtained using a differential oscilloscope (Tektronics, Inc., type 564). The interelectrode current is determined by measuring the voltage drop across a precision shunt (0.01Ω) and is displayed on the y-axis of an x-y oscilloscope. The applied voltage is measured directly across the diode and is displayed on the x-axis of the oscilloscope. The *ac* components are detected across a 30Ω resistor with a spectrum analyzer. An oscilloscope camera (Beattie, FP-K5) is used to take pictures of the graphic portion of the display on the spectrum analyzer. On the CRT of spectrum analyzer, the x-axis represents the frequency. The y-axis is the log scale amplitude. Before each experiment, a calibration is performed to check for proper instrument operation using a function generator (Hewlett-Packard, 3312A). The maximum peak signal is considered as zero and the x-axis scale is counted to determine the frequency. The maximum signal peak is called as "the zero frequency" throughout this work. The emitter temperature is determined through hohlraum by means of an optical pyrometer. The temperature is determined by monitoring a hohlraum (10 : 1, length to diameter ratio) on the side of the emitter which acts as a source of blackbody radiation[6]. The emitter temperature accuracy is $\pm 7K$. The collector and the cesium reservoir temperature are measured using alumel-chromel (type K) thermocouples. The thermocouples are routed from the temperature measuring point through the vacuum system's wall to the digital temperature meter (Omega Engineering Inc., CN310-K-C). The temperature error accuracy is $\pm 5K$.

3. Results and Discussion

Experimental result of a typical I-V characteristic of the cesium plasma diode is illustrated in Fig. 2. The *dc* output is taken from a differential oscilloscope. The x-axis is the voltage with a scale of 2 volts per division. The y-axis represents the current with a scale of 2 amperes per division. The oscillation oscillogram is obtained at an interelectrode gap of 0.09mm, an emitter temperature of 2008K, a collector temperature of 489K, and a cesium reservoir temperature of 498K. The current oscillations appear only in the saturation mode, positive voltage range of 0 to 3 volts. The observed value of the contact potential difference is 3 volts. These experimental observations are consistent with the theoretical model reported by Johnson[7].

The effect of frequency on the interelectrode gap and the cesium pressure at two non-

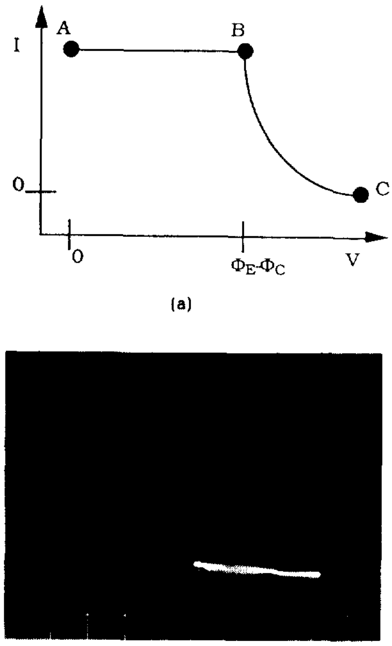

Fig. 2 Typical I - V characteristic of cesium plasma diode : (a) schematic diagram (Ref. [7]) and (b) oscillation oscillogram at spacing 0.09mm, emitter temperature 2008K, collector temperature 489K, and cesium reservoir temperature 498K. (Vertical scale : 2amperes/division, Horizontal scale : 2volts/division)

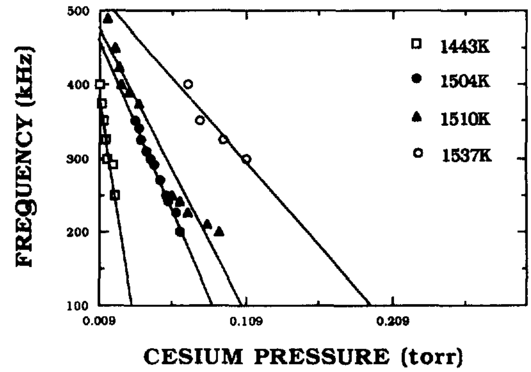

Fig. 3 The variation of frequency with cesium vapor pressures at a spacing of 1mm and indicated emitter temperature.

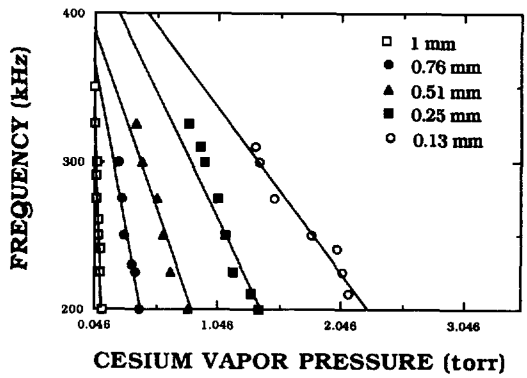

Fig. 4 The variation of frequency with cesium vapor pressures at emitter temperature 1521K and indicated spacings.

overlapping regimes are evaluated with a spectrum analyzer. The variations of the minimum frequency of signals with decreasing interelectrode gap at emitter temperatures of 1300 to 1550K are observed. The minimum frequency of the spectrum moves to zero frequency with increasing cesium vapor pressures and then sinks into zero frequency at a certain cesium pressure. The luminous band of signals indicates qualitatively that intense volume ionization occurs[8]. The variation of frequency with cesium vapor pressures are shown in Fig. 3. The frequency decreases linearly with increasing cesium pressures at a fixed gap and emitter temperature. As the gap is greater, the slope is steeper.

Above results are compared as a function of gap at different emitter temperatures as seen in Fig. 4. A lower emitter temperature results in a lower cesium vapor pressure. This may be explained by low electron emission due to the effect of temperature.

The maximum frequency over the interelectrode gap at an emitter temperature of 1500K and a cesium vapor pressure of 0.14 torr is shown in Fig. 5. The solid line is a theoretical curve and the dotted line corresponds to the experimental results. The frequency is inversely proportional to the square of the interelectrode gap. The maximum frequency of signal is 13MHz.

At emitter temperatures in the range of 1900K to 2200K, oscillations first appear and then gradually disappear into the background with increasing cesium vapor pressure. The sequence of spectrum

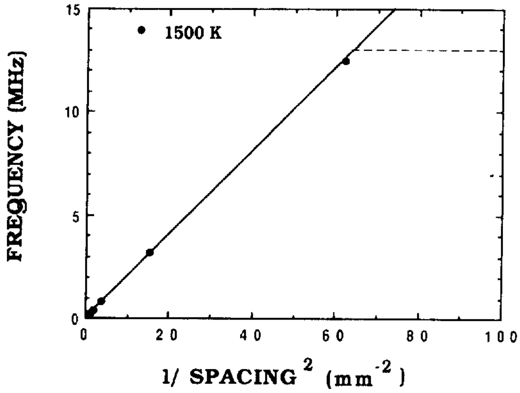

Fig. 5 The dependence of frequency on spacing at an emitter temperature of 1500K and a cesium vapor pressure of 0.14torr. (solid line : theory, dotted line : experimental data)

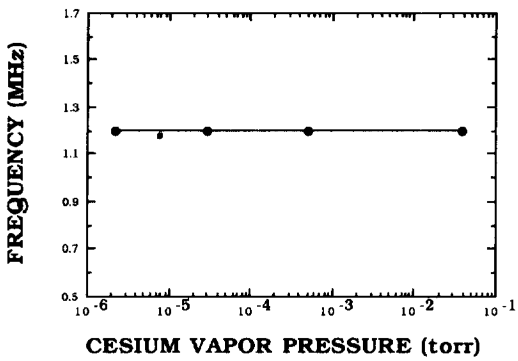

Fig. 6 The dependence of frequency on the cesium vapor pressure at a spacing of 0.76mm and an emitter temperature of 1949K.

damping indicates that Coulomb collisions are a key collision process[9]. The cesium vapor pressure does not cause the appreciable change of the oscillating frequency. Fig. 6 shows the variations of frequency with increasing cesium vapor pressure at an interelectrode gap of 0.76mm and an emitter temperature of 1949K A 1.2 MHz signal remains with increasing cesium vapor pressures (10^{-6} to 0.1 torr) and then disappears into the original frequency background. The same trends are observed at different gaps. The emitter temperature (above 1900K) also has the same trend

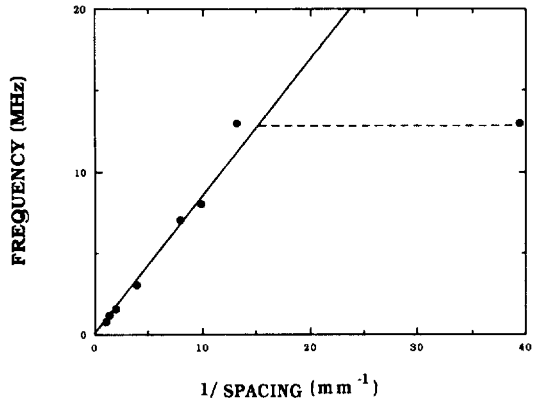

Fig. 7 The dependence of frequency on the spacing. (solid line : theory, dotted line : experimental data)

as that of the cesium vapor pressure. Therefore, it is clear that the cesium vapor pressure (10^{-6} to 0.1 torr) and the emitter temperature (above 1900K) are independent of the oscillating frequency. The effect of the interelectrode gap on frequency is also observed wherein the frequency is found to be inversely proportional to the interelectrode gap. It is illustrated in Fig. 7.

The above experimental observations were evaluated with the theory reported by Stakhanov and Stepanov[4]. They established the relationship of frequency with parameters at two different cesium pressures. At high cesium pressures (above 10^{-2} torr) and low emitter temperatures (1300 to 1550K), the frequency was inveresely proportional to the cesium vapor pressure and to the square of the gap. At low cesium vapor pressures (below 10^{-2} torr) and high emitter temperatures (above 1900K), the frequency was only a function of interelectrode gap. The frequency was inversely proportional to the interelectrode gap. These theoretial relationships are in good agreement with the experimental results. The obserevd frequencies were compared with the theoretical frequencies[10]. It was found that these were the plasma-ion frequencies.

4. Conclusion

At high cesium vapor pressures (above 10^{-2} torr) and low emitter temperatures (1300 to

1550K), the observed frequency was inversely proportional to the cesium vapor pressure and to the square of the interelectrode gap. The intense volume ionization appeared to be the primary reason of the low emitter temperature oscillations. The lumious bands and continous spectra were experimentally observed. The strong exitation of oscillations in the region of the intense ionization was a characteristic of the KAM because the spectrum was damped to the zero frequency with increasing cesium vapor pressure.

At low cesium vapor pressures (below 10^{-2} torr) and high emitter temperatures (above 1900K), the frequency was inveresely proportional to the interelectrode gap. The broad spectra were experimentally observed and damped to the background without moving. The long-range coulombic collision played a significant role in the high emitter temperature oscillations. Coulomb collision was a characteristic of the KOM. The virtual emitter formation due to the Pierce instability [11, 12] may be the main reason for oscillations in this regime.

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