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The Preliminary Application of MHD Power Generation in Arc Heated Test

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Abstract

The high power electrical thruster system and energy supply system are needed necessarily on the high speed space detector. The space nuclear reactor power supply technology which is based on both high temperature gas cooling reactor and magnetohydrodynamic (MHD) power generation can solve the energy problem of high power thruster system. The domestic research of high temperature gas MHD power generation is infrequent. In this paper the MHD power generation experimental equipment which is based on high temperature inert gas has been built by using arc heater. The equipment has generated electricity successfully. The design of experiment and the composing of equipment are introduced detailedly, while the result is analyzed also. The experiment result shows that one side is the generated electricity power is decided by gas electrical conductivity, and the other side is $CsCO_3$ can improve the electrical conductivity of argon gas.

Keywords: *Magnetohydrodynamic, Power Generation, High Temperature Inert Gas, Arc Heated*

Nomenclature

P	=	*Output power of MHD power generation*
C	=	*Efficiency coefficient*
K	=	*Load coefficient*
σ	=	*Electrical conductivity*
u	=	*Flow velocity*
B	=	*Magnetic field strength*

1. Introduction

The high power electrical thruster system and energy supply system are needed necessarily on the high speed space detector. Especially the energy supply system with low mass power ratio and high output power is crucial technology. The nuclear MHD power generation can be used in high temperature environment comparing with the traditional energy conversion technology. Furthermore the MHD power generation can increase the radiator temperature, decrease the size and weight of space radiator. So that the mass power ratio of nuclear electrical source can be reduced obviously. In 1989, Italian scientist made the primary assumption of space nuclear power supply technology which is based on high temperature gas cooling reactor and MHD power generation[1]. In 2011, NASA consummated the space nuclear power supply technology to solve the energy problem of high power thruster system[2].

The basic theory of MHD power generation is Faraday Law of electromagnetic induction. The electric fluid flows across the magnetic field whose direction is vertical to the flow field direction, and the magnetic field will be incised to generate electric energy. Because of the high efficiency and low pollution of coal-fired MHD power generation, the USA has researched this technology in the world energy crisis from 1970. The other countries also developed the research of coal or natural gas MHD power generation. But due to the rubbish management problem and the business cost problem of coal-fired MHD power generation, this technology is always in the research stage in laboratory[3].

In experimental aspect, many countries laboratory started to develop the research of inert gas MHD power generation largely from 1970. The NASA Levis space center built the ground experiment equipment of MHD power generation, and made lots of experiment in inert gas MHD power generation. The experiment use the non-equilibrium ionization technology, and the electric power reached 2.2kW[4]. The USA Air Force Air Propulsion Laboratory and Avco-Everett Company had completed the research and experiment of 400kW ground theoretical generator by using MHD equipment which was drive by rocket engine and Aero engine[5].

Due to the application potential of high temperature gas MHD power generation, many countries started to make deep research in this technology from 1980. The Japanese Tokyo Industry University is one of them typically. Okuno's team made a theoretical analysis detailedly in space nuclear MHD power generation, and completed two types design of MHD power generation based on high temperature inert gas[6, 7]. The electric output power of Japanese equipment was 50kW, and the working duration can reach several days. The American researchers also made the design of pulsed MHD power generator which can work in helium gas and alkali metals. The electric output power of American equipment was 100kW, and the working duration can reach 500 seconds[8].

The high temperature inert gas MHD power generation research has been developed by several Chinese domestic academies and universities, but these researches are still at primary stage[9-12]. Our team has established the experiment equipment of MHD power generation based on high temperature inert gas by using arc heater as heat source, and makes electricity generation successful. In this paper the experiment design and equipment structure have been introduced detailedly, and the primary result and conclusion of experiment are shown.

2. Design of experiment

The output power of MHD power generation can be expressed as formula 1. The requirements of MHD power generation based on high temperature inert gas are shown as below. First the electrical conductivity and flow velocity of gas should be as high as possible. Second the magnetic field strength of the generator channel should be as strong as possible.

$$P = CK(1-K)\sigma u^2 B^2$$

The crucial technology of inert gas MHD power generation is the realization of inert gas ionization. There are three ionization modes:

(1) Thermal direct ionization. The inert gas is heated directly to increase the average kinetic energy and the non- elasticity collision of every kind of particle, so that the external electron could deviate from atomic nucleus to change to freedom electron. The gas temperature is higher, the particle average kinetic energy is greater, and the amount of freedom electron is more too.

(2) Non-equilibrium ionization by adding seed. The alkali metals whose ionization potential energy is lower can promote the ionization of inert gas. The higher electron density can be realized in 2000K temperature when the alkali metals mixed with inert gas.

(3) Non-equilibrium ionization by injecting external energy. The electron could be injected energy to increase the temperature and average velocity of electron, so the collision between electron and neutral particles can be increased. At last the ionization of inert gas can be realized.

The experiment design briefly includes the selection of gas, the application of arc heater, the design of channel and magnet, and the design of acceleration nozzle.

Selection of gas

The electron density of argon gas and helium gas which is added cesium particle or xenon gas has been analyzed. The environment condition is 2500K temperature, 0.6MPa pressure, and 0.01% seed percents. The analysis result is shown in figure 1. If the electron density should reach 1×1019 without seed addition, the electron temperature of helium gas is 8000K~9000K, but which of argon gas is 5000K~6000K. This result shows that the direct ionization of helium gas is much more difficult than argon gas, so argon gas is selected as the experiment gas. The result also shows that the cesium particle is the most effective to make argon gas ionize at the same electron temperature, so the cesium particle will be added to improve argon gas electrical conductivity.

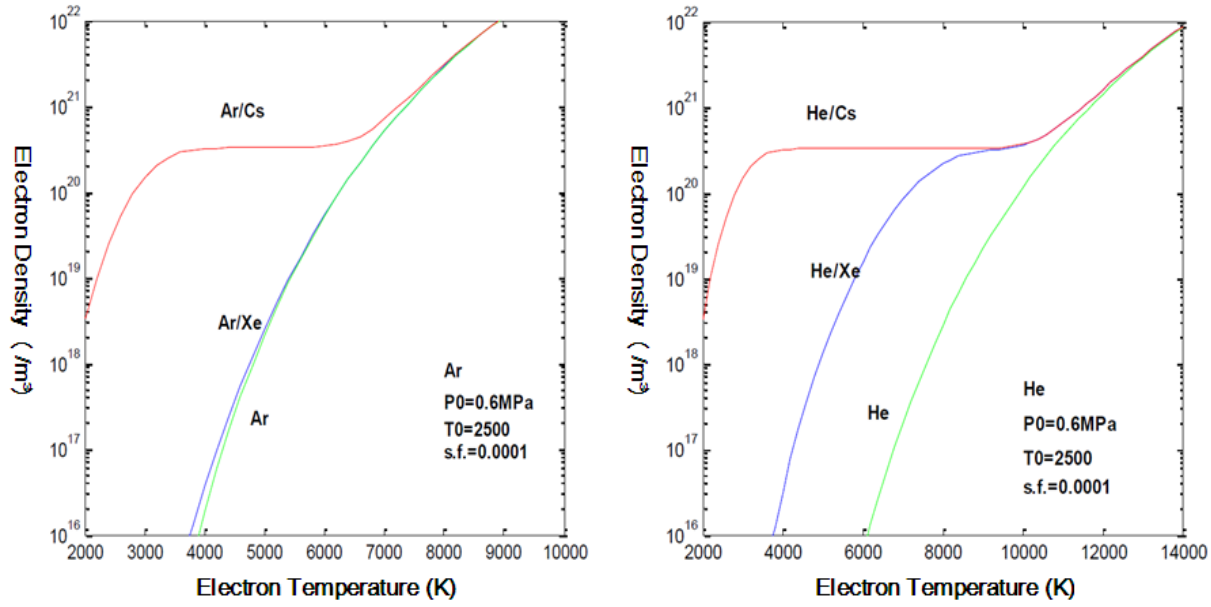

Fig. 1 The relativity of electron density and temperature for argon gas and helium gas

Application of arc heater

The argon gas must be in plasma condition to realize generating electricity, so the arc heater is applied to heat argon gas in experiment. The huel type arc heater is a proper option to complete the heating mission. The characters of huel type arc heater are middle enthalpy, high pressure, and high power, which can heat gas to 3000K~6000K temperature and maintain the total pressure at least 5atm. The front and rear electrodes of huel type arc heater are tubular, and the arc length is free. Gas is tangentially injected into the heater chamber with a high rotation speed. The forward direction of airflow movement is consistent with the arc axial direction and substantially parallel to each other. The gas stream can control the arc in the vicinity of the heater center axis, and the arc can be stretched too[13].

Design of channel and magnet

The straight channel can realize the magnetic field more easily than discal channel, and the design of straight channel is simpler too. So the straight channel is chosen to make the theoretic experiment. In order to make the channel has the performances of high temperature applicability and electrical insulation, the channel is designed as a structure of many separate parts. The electrode is placed on the sidewall of channel which is made of the tungsten- copper alloy. The insulation material of channel is boron nitride. The permanent magnet whose magnetic field strength is higher than 1T is selected to ensure the channel has a higher thermal efficiency.

Design of acceleration nozzle

The electrical conductivity of gas is lower than which of metal as usual, so the velocity of gas must be increased to make up the inferior position of its low electrical conductivity. But it is not advantaged to make the gas velocity faster and faster, because the temperature and electrical conductivity of gas will decrease obviously with the velocity increase. So the Mach number of gas is controlled from 0.8 to 2.0. In this experiment one acceleration nozzle whose Mach number is 1.6 is used to increase the gas velocity. The Nozzle has inside part and outside part which looks like the sandwich structure. The material of inside part is copper, and outside part is stainless steel. In order to cooling the inside part of the nozzle, the high-pressure cooling water flow between the two parts.

3. Experiment equipment

The whole experiment system is consist of many equipments such as gas storage, arc heater, mixing chamber, seed injection system, acceleration nozzle, electricity generation channel, permanent magnet, smoke outlet, electrical load, measurement system and so on. The experiment sketch is shown in figure 2.

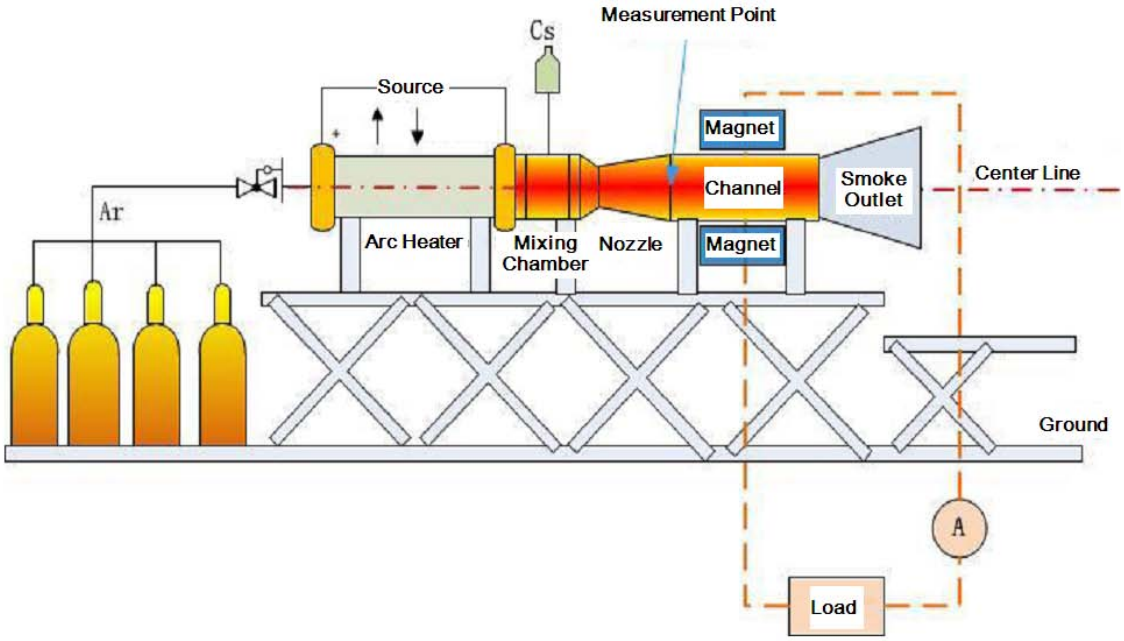

Fig. 2 The experiment sketch

- The gas storage is used to save pure argon gas.
- The temperature of argon gas will be heated to 4000K by using arc heater.
- The temperature of gas flowing out of arc heater is thousands of degrees. In order to satisfy different test conditions and eliminate the influence of airflow pulsating, the hot gas will flow into a mixing chamber usually. At the entrance of mixing chamber, cold gas and seed are injected to mix with hot gas fully, thus the temperature of gas is adjustable.
- The seed injection system is used to inject cesium particle into mixing chamber, and the seed mass rate is 0.0002~0.002. The cesium carbonate is used instead of pure cesium because of the pure cesium is unstable and dangerous in air.
- The acceleration nozzle has a supersonic Laval shape which can increase the gas velocity higher than 1000m/s.
- The electricity generation channel is a straight Faraday channel which effective size is 250mm length, 64mm width, and 14mm height.
- The permanent magnet covers the outside of channel to provide a 1T strength vertical magnetic field.
- The smoke outlet could ensure the gas flow in a right direction.

4. Experiment result

The experiment condition is shown as below. The research lasted three months, and twenty-nine experiments have been carried out in total. The first part is measurement calibration experiment which includes nineteen times, and the second part is power generation experiment which includes ten times. Fortunately, every time of second part can generate electricity successfully.

Gas	Total Pressure atm	Total Tem K	Mass Flux g/s	Flow Velocity m/s	Time s
Ar	5.2	3700	330	1350	5~10

In the first power generation experiment two bulbs were lighted, which means the experiment equipment design of MHD power generation based on high temperature inert gas is feasible. The lighten bulbs are shown in figure 3. The typical emission spectrum of cesium has been measured by

spectrograph, and the relative strength trend curves of two sensitive spectrums in high temperature were obtained. The center wave length of D1 is 894.35nm, and center wave length of D2 is 852.12nm.

Fig. 3 Two bulbs have been lighted in experiment

The experiment result shows that the electricity generation power of inert gas MHD is correlative with gas electrical conductivity nearly. The gas electrical conductivity is higher so that the electricity generation power is higher. At the same experiment condition the gas electrical conductivity is correlative with the injection mass flux of cesium carbonate seed nearly. The peak outlet power is 28W when the electrical load is two ohm resistance in experiment. One phenomenon can be concluded through the relative strength curves of cesium atom spectrums and the curve of electricity generation output power, which is the time point of maximum output power and maximum spectrum strength is coincident totally. The two parameters reach maximum themselves at the 2nd second all, so the output power is correlative with cesium atom quantity nearly.

In the succedent research the seed injection equipment has been improved to ensure more cesium carbonate can be injected into mixing chamber evenly during experiment. By the improved equipment the electrical conductivity of argon gas was increased and the time stability of electrical conductivity was improved also. At last ten bulbs were lighted in experiment which is shown in figure 4. The outlet electrical parameters can not be measured accurately when the electrical load are bulbs because the bulbs resistance is variable with the outlet voltage. The peak outlet power of the last experiment is nearly 100W through the calculation of other parameters.

Fig. 4 Ten bulbs have been lighted in the last time experiment

5. Conclusion

In this experiment the theory of MHD power generation based on high temperature inert gas is feasible which has been validated by the system designed ourselves. During the experiment the gas electrical conductivity has been increased by improving the seed injection equipment so that the peak output power can be increased from 20W to 100W. The experiment result shows that first the critical factor of high temperature gas MHD power generation is the value of electrical conductivity because the electrical conductivity is higher the output power is higher, and second the electrical conductivity of argon gas can be increased by adding cesium carbonate particle effectively meanwhile the output

power and working stability of MHD generator can be improved also. In the future research many necessary work should be developed such as non-equilibrium ionization test, stability of seed injection, precise plasma diagnosis and so on.

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