Chinese Journal of Aeronautics, (2016), 29(4): 855–862

Chinese Society of Aeronautics and Astronautics
& Beihang University

Chinese Journal of Aeronautics

cja@buaa.edu.cn
www.sciencedirect.com

Investigation of MHD power generation with supersonic non-equilibrium RF discharge

Yang Pengyu [a,b], Zhang Bailing [a], Li Yiwen [a,c,*], Wang Yutian [a], Duan Chengduo [a], Fan Hao [a], Gao Ling [a]

[a] *Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an 710038, China*
[b] *China Aerodynamics Research and Development Center, Mianyang 621000, China*
[c] *Science and Technology on Combustion, Internal Flow and Thermo-Structure Laboratory, Astronautics School, Northwestern Polytechnical University, Xi'an 710072, China*

Received 23 June 2015; revised 17 October 2015; accepted 15 March 2016
Available online 13 July 2016

KEYWORDS

Magnetohydrodynamic;
Non-equilibrium plasma;
Power generation;
Radio frequency discharge;
Supersonic flow

Abstract Magnetohydrodynamic (MHD) power generation with supersonic non-equilibrium plasma is demonstrated. Capacitively coupled radio frequency (RF) discharge (6 MHz, maximum continual power output of 200 W) was adopted to ionize the Mach number 3.5 (650 m/s), 0.023 kg/m^3 airflow. In a MHD channel of 16 mm × 10 mm × 20 mm, MHD open voltage of 10 V is realized in the magnetic field of 1.25 T, and power of 0.12 mW is extracted steadily and continuously in the magnetic field of 1 T. The reasons for limited power generation are proposed as: low conductivity of RF discharge; large touch resistance between MHD electrode and plasma; strong current eddies due to flow boundary layer. In addition, the cathode voltage fall is too low to have obvious effects on MHD power generation.

1. Introduction

The development of Magnetohydrodynamics (MHD) technology provides an innovative way to solve the important technical problems in hypersonic flight. The AJAX was presented by Russian scholar and caused that MHD technology applied to aircraft became a research hot spot.[1–6] The key of AJAX is that the temperature and velocity of flow entering into the engine are decreased by MHD power generation and reach the requirement of engine's stable work in hypersonic flight.[7–12]

The working medium of MHD power generation is conductive flow, so air needs to be ionized into plasma. There are two ionizing ways: equilibrium and non-equilibrium ionization. Equilibrium ionization requires a very high gas temperature, which is hard to realize in flight. Non-equilibrium ionization has no temperature requirement and is a more feasible. In general, it can be realized by strong electric filed or high energy electron beam.[13–16]

* Corresponding author at: Science and Technology on Plasma Dynamics Laboratory, Air Force Engineering University, Xi'an 710038, China.
E-mail addresses: xiaoyu182444840@126.com (P. Yang), zhangbailing2468@126.com (B. Zhang), lee_yiwen@163.com (Y. Li).

Peer review under responsibility of Editorial Committee of CJA.

ELSEVIER Production and hosting by Elsevier

http://dx.doi.org/10.1016/j.cja.2016.06.018
1000-9361 © 2016 Chinese Society of Aeronautics and Astronautics. Production and hosting by Elsevier Ltd.

Currently, the experimental study of MHD power generation with non-equilibrium plasma is in preliminary stage. Murray et al. realized the experimental observation of MHD power generation.[17] They ionized supersonic airflow with discharge driven by 2 ns, 100 kHz, 30 kV pulsed voltage, and achieved Mach number 3 supersonic non-equilibrium plasma. Faraday generator with continuous electrodes was adopted and the peak extraction power measured by optical isolation was about 4.2 mW. At the same time, Nishihara et al. also conducted similar experimental study.[18] They measured the MHD open voltage of 25-30 V, but extraction power could not be measured. In addition, producing supersonic non-equilibrium plasma for MHD applications was also experimentally studied. Bobashev et al. investigated the production of air (nitrogen) gas-discharge plasma in a supersonic MHD channel using a combined discharge consisting of a high-frequency discharge and a high-voltage pulse discharge.[19] McAndrew et al. designed and tested a supersonic plasma wind tunnel where the plasma was produced by a 50 kW, 1 ms pulse of microwave radiation at 2.45 GHz.[20]

These studies have employed pulse discharge to ionize airflow, but their results present some unsolved problems. First, the cathode voltage fall is significant, and Faraday current is seriously limited when MHD voltage is lower than the cathode voltage fall. Second, the pulse discharge plasma leads to a discontinuous power generation and low time-average extraction power due to the fast delay of plasma. Third, the pulse discharge voltage and current coupling into MHD circuit lead to very strong interference, and the weak signal of extraction power is hard to capture. Thus the extraction power was not measured directly in Munetake Nishihara's experiment. And in Murray's experiment, the extraction power was measured by adding a bias voltage into MHD circuit and adopting optical isolation between MHD and measurement circuit.

Pulse discharge seriously limits MHD power extracting according to above studies, and to our best knowledge, the continuous MHD power generation from supersonic non-equilibrium plasma has not been realized till now. Thus it is very necessary to investigate MHD power generation with continuous discharge. This paper tries to produce volume-filling, steady, and continuous non-equilibrium plasma in supersonic airflow employing capacitively coupled radio frequency (CCRF) discharge, and conducts continuous MHD power generation. In addition, the factors limiting the performance of MHD power generation are analyzed by experimental and numerical methods.

2. Experimental system

The supersonic non-equilibrium plasma was produced by CCRF discharge in the supersonic airflow realized within a small-scale, in-draft wind tunnel facility. The image of discharge was monitored by two cameras. Faraday MHD channel with continuous electrodes was designed to extract power. The room of MHD channel was full of uniform magnetic field produced by an electromagnet. The value of extraction power was obtained through measured load voltage.

2.1. Wind tunnel

Mach number 3.5 airflow was achieved through a converging/diverging nozzle. Test cross section was 10 mm × 20 mm. Wind tunnel worked in an in-draft setup using a vacuum system to realize the low backpressure. Employed reducing valve adjusted the pressure of nozzle's inlet down to 40 kPa resulting in the airflow of the Mach number 3.5 (650 m/s), 0.023 kg/m^3 through the test section, and the stable running time was 15 s.

2.2. Plasma production

Continuous and steady non-equilibrium plasma was produced by CCRF discharge. The power supply is an AG1017L radio frequency (RF) voltage generator with a maximum continual power output of 200 W and a range of frequency from 10 kHz to 10 MHz. The discharge electrode was made of Al_2O_3 ceramic and its surface was placed on a 10 μm thick palladium (Fig. 1). The Palladium metal was separated from the plasma by the ceramic piece. There was a match circuit between RF power and discharge electrodes. The match circuit was composed of two 35 mH inductances which connected with each electrode, respectively. The optimal match was realized at the radio frequency of 6 MHz. As the variation of load characters could change the original optimal match, the radio frequency has to be slightly adjusted to recover the optimal match.

2.3. MHD electrode

MHD electrode was made of copper. Some problems were considered to design MHD electrodes. Firstly, MHD electrodes need to touch the plasma. The images of RF discharge in static air gas and supersonic airflow are shown in Fig. 2. It can be seen that the bright region does not move forward following supersonic air. In other word, stronger ionization region, where the plasma is dense, is still located in the room covered by the discharge electrodes. In addition, the non-equilibrium plasma life time is at the order of 1 μs in weak electric field,[21–23] making the plasma sparse in other region. Thus MHD electrodes were deposed at the room covered by the discharge electrodes to touch plasma.

Secondly, MHD electrodes could affect the distribution of discharge electric field, and result in a sharp local ionization between MHD electrode and discharge electrode. The local ionization is hard to control especially under higher pressure, but we can take effort to decrease the possibility of its production. One of the means is to increase the distance between

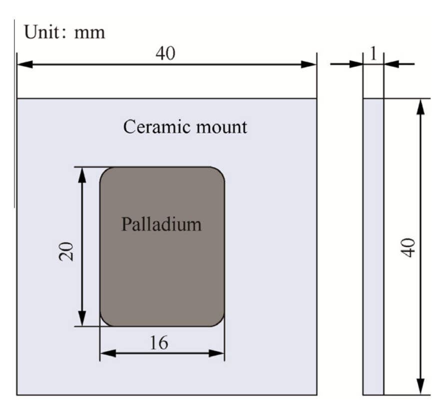

Fig. 1 Schematic of discharge electrode.