

Observation and Modeling of DC Arcjet Flowfield in Stable Operation

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Abstract

It is one of the trends in DC arcjet researches to lower the operation power below 1kW. However the lower the operation power, more often the unstable mode appears. It is not suitable for stable and reliable operation. Therefore, stabilization of its operation is one of the urgent problems in low powered DC arcjet. So, internal observation of DC arcjet was carried out from arc ignition until stable operation via unstable mode that was every time appeared. It was found that local increase of ionization characteristic and electron density at the nozzle upstream region in unstable 'low mode', between ignition and stable 'high mode' was observed, and the mode transferred to high mode at just the end of the relaxation. In order to explain this phenomenon, a simple model was constructed and conditions to bring arc into existence were obtained. Applying them to DC arcjet, its operation modes were analyzed, and one method for stabilization of low power DC arcjet is proposed in this paper.

Introduction

In the Institute of Space and Astronautical Science (ISAS), a low power DC arcjet has been developed for a decade, and operation with 1kW was achieved by SAGAMI-I, with 600W by SAGAMI-II. In SAGAMI-III, the highest specific impulse, 400sec, was accomplished with 300W. As the input power is lowered, unstable discharge mode often appears during the operation. This is not suitable either for reliability or for endurance.

In this paper, the results by detailed internal observation in the flowfield of DC arcjet and a technique to stabilize its operation are presented.

Plasma Diagnostic

In order to understand the inner flowfield with plasma maintained by arc discharge, the concept of plasma phase is introduced, by which more information about ionizing and recombining plasma is obtained¹. To do this, electron temperature, electron density and population density ratio are necessary. In view of propellant which contains nitrogen and hydrogen (N_2+2H_2), hydrogen Balmer series are observed by means of emission spectroscopy. The electron density is deduced from Stark broadening of $H\beta$ line, that population density ratio is obtained by relative intensity of $H\beta$ and $H\gamma$ lines, and statistical weight, which is an important clue to understand plasma characteristic in detail. The electron temperature is deduced by Boltzmann plot, which is meaningful just when population density has some relation such as Boltzmann relation.

Experimental Setup

In ISAS, DC arcjet for internal observation (ISAS-VAJ) was designed and dedicated to the observations in the flowfield under operation to be possible. In Fig.1, the appearance of ISAS-VAJ and an example of observation are shown.

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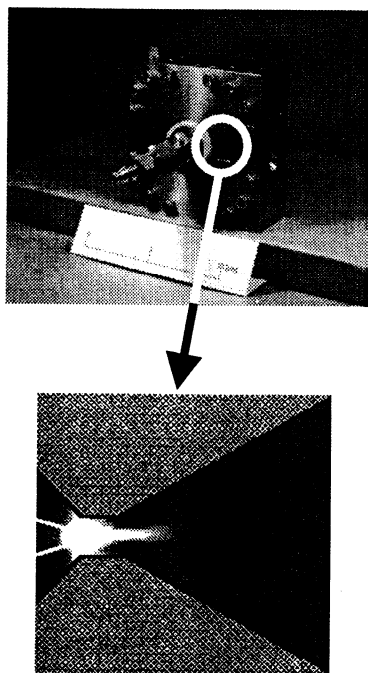


Fig.1: Appearance of ISAS-VAJ and an example of observation.

On one side, CCD camera system is placed to take arc column pictures expanded by a lens(300mm/f11). On the other side, Spectroscopic system is arranged. It consists of a lens(75-300mm/f4.5-5.6) to expand the image, a detector with 2-D CCD array(1024x256) attached to a spectrometer(f=150mm), which send the observed data to a personal computer. The CCD camera system is set to take pictures with 2Hz, and exposure time of spectroscopic system is set as 20msec and capable of getting spectroscopic images at 2Hz. Both systems are able to look into the flowfield in ISAS-VAJ simultaneously.

The entrance slit of spectrometer is aligned on center axis along the flowfield of ISAS-VAJ as in Fig.2. As the detector has 2-D CCD array, spatial distribution of spectroscopic data deduced to plasma parameters is acquired with resolution of several decades microns.

Discharge current is set up at 7A, and mass flow rate of propellant, 176mg/sec, results in the plenum pressure up to 3atm.

Experimental Result

The experimental result is shown in Fig.2. The top figure is time-development of discharge voltage and plenum pressure. According to

discharge voltage, it shows unstable mode for about 1 second after ignition, low voltage mode from 1 to 3.5 second. After them, it achieves high voltage mode at 3.5 second and maintains the same mode. The obtained data, electron temperature, electron density, population density ratio, are also shown in Fig.2. The vertical axis is spatial, corresponding position in the flowfield is presented next to each figure, and the horizontal axis is time-development. In view of population density ratio, electron temperature deduced by Boltzmann plot has no meaning at almost all the part and time but in constrictor where it is about 5000K under low voltage mode and 10000K under high voltage mode. Concerned with electron density and population density ratio, interesting phenomenon was observed, that is, the local and sudden alteration at the upper-most region in nozzle divergent part comes up just before transition from low voltage mode to high voltage mode. Electron density has the maximal that increases higher than 10^{15} cm^{-3} and ionization-dominant characteristic comes up in the location of 0.8-1.0mm at 2.5-3.0 second. Just when they disappear completely, the discharge mode transfers to high voltage mode. During this alteration, plenum pressure sustains to be constant. To take them into consideration, it may be suspected that these change in electron density and ionization characteristic affect significantly to transition of operation mode. As no information, however, was extracted from this phenomenon, a simple model² was considered as the following.

Condition To Form Arc

A simple model was constructed by Kuriki², which takes slip caused by collision between charged and neutral particles into consideration. It leads to the following differential equation. Now

$$\frac{D_e \mu_i + D_i \mu_e (1 - \gamma M^2)}{(\mu_e + \mu_i)(v_p - v_r n)} \frac{d^2 n}{dx^2} - \frac{U}{\mu_e + \mu_i} \left(\frac{\mu_e + \mu_i}{v_p - v_r n} - \frac{\mu_e}{v_i} - \frac{\mu_i}{v_e} \right) \frac{dn}{dx} + n = 0 \quad (1)$$

the point where electron density has a maximum is to be discussed. Equation 1 is simplified to the following.

$$\frac{D_e \mu_i + D_i \mu_e (1 - \gamma M^2)}{(\mu_e + \mu_i)(v_p - v_r n)} \frac{d^2 n}{dx^2} = -n < 0 \quad (2)$$

Here, the necessary condition such that Eq.2 has solution is acquired as Eq.4 with a boundary

Mach number M_c ,

$$M_c \equiv \sqrt{\frac{1}{\gamma} \left(1 + \frac{D_e \mu_i}{D_i \mu_e} \right)} = \sqrt{\frac{1}{\gamma} \left(1 + \frac{T_e}{T_i} \right)} \approx \sqrt{\frac{1}{\gamma} \frac{D_a}{D_i}} \quad (3)$$

and,

$$M < M_c, \quad v_p - v_r n > 0, \quad \frac{d^2 n}{dx^2} < 0 \quad (4-i)$$

$$M < M_c, \quad v_p - v_r n < 0, \quad \frac{d^2 n}{dx^2} > 0 \quad (4-ii)$$

$$M > M_c, \quad v_p - v_r n > 0, \quad \frac{d^2 n}{dx^2} > 0 \quad (4-iii)$$

$$M > M_c, \quad v_p - v_r n < 0, \quad \frac{d^2 n}{dx^2} < 0 \quad (4-iv)$$

For example, let the condition apply to the point stated above. Under low voltage mode, electron density distribution has a maximum ($d^2 n/dx^2 < 0$) and ionization characteristic is dominant, that is, $v_p - v_r n > 0$, then, Mach number here is smaller than M_c because of the condition (i). On the other hand, electron distribution can be regarded as $dn/dx = 0$, $d^2 n/dx^2 < 0$ and ionization characteristic is dominant, that is, $v_p - v_r n > 0$, then $M_c < M$ because of the condition (iii) under high voltage mode. Here, a technical possibility rises, that is, the discharge mode of DC arcjet can be altered intentionally if these conditions can be broken and another one can be formed.

Validity of Model

Validity of the model related to the previous section is examined. The flow velocity at the point where the electron density distribution and ionization characteristic has maximum under low voltage mode must be measured. In the previous section, it is represented as $M < M_c$ under low voltage mode, as $M_c < M$ under high voltage mode, so velocity measurement was done by means of absorption spectroscopy. The system used is shown in Fig.3. The one of the light emitted from LASER transmits the half mirror HM2 to ETALON and the other reflects on it to ISAS-VAJ simultaneously. The latter transmits ISAS-VAJ aligned to be inclined some degree against the laser, and reflects on M to transmit ISAS-VAJ again. In this time it transmits HM2 to the detector PD. Thus, the detected data has two absorbed spectral profiles by atomic absorption with Doppler shift. From these profiles, the flow

velocity measured is 0.911 ± 0.362 m/s under low voltage mode, 1.14 ± 0.105 m/s under high voltage mode, respectively. This result is just as the model expected that it is smaller than M_c under low voltage mode and greater than M_c under high voltage mode. According to this fact, it is concluded that the model is valid to apply to operation of DC arcjet.

Controlling Discharge Mode

As mentioned above, the condition (i) for low voltage mode or (iii) for high voltage mode at the nozzle upstream region expresses the operating mode of DC arcjet. In this section, a possibility to control the discharge mode of DC arcjet intentionally by forming or breaking the condition (i) or (iii) is discussed. It is expected that a) transition from low to high voltage mode is occurred with the trigger by forming the condition (i) at upper region of nozzle under low voltage mode, b) transition from high to low voltage mode is occurred by breaking the condition (iii) at the same region under high voltage mode. One of the concrete methods to make them actual may be the external perturbation by pulse discharge at the region. Based on these expectations, another cathode C_2 is added to ISAS-VAJ as shown in Fig.4 to make pulse discharge.

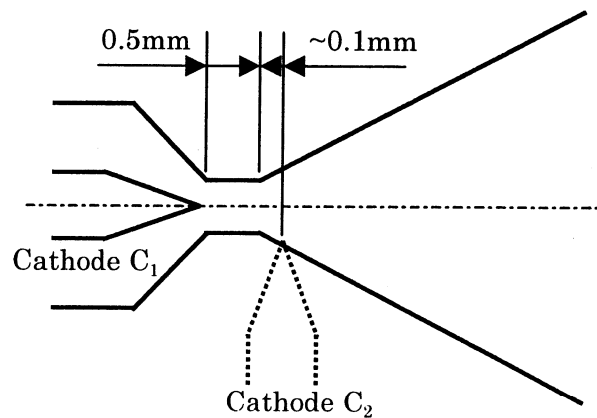


Fig.4 : Electrodes placement

C_2 is the additional cathode.

It has the same electric potential as C_1 , and the input power and energy of pulse discharge is about 22kW peak and 22J per pulse, respectively. The results of a) and b) are shown in Fig.5(a) and (b).

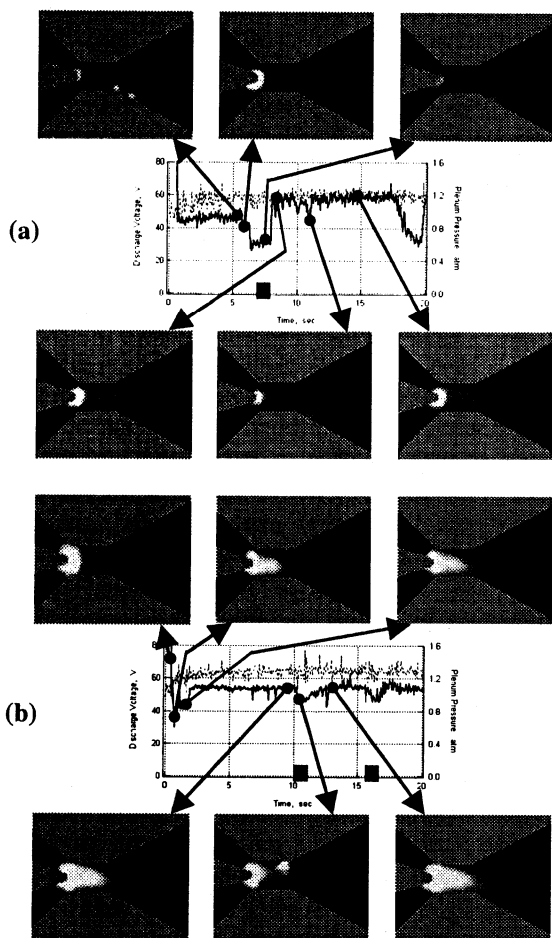


Fig.5 : a)Low→High, b)High→Low

The timing with pulse discharge is shown by closed rectangle in the figure. Thus, pulse discharge between anode and cathode C₂ under operation is effective to transfer the discharge mode. The technical possibility of controlling

intentionally was found to stabilize low-powered DC arcjet.

Conclusion

The internal observation under operation from ignition to stable mode in low-powered DC arcjet has done in detail using ISAS-VAJ to find the local and sudden increase of electron density and ionization characteristic in nozzle upstream region. It took place just before transition from low voltage mode to high voltage mode.

A simple model was constructed to explain the inner flow characteristics under low and high voltage mode to find the conditions to form arc in the flowfield. It is resulted that the Mach number at nozzle upstream region was smaller than M_c under low voltage mode, and greater than M_c under high voltage mode. The model validity was confirmed by measuring the flow velocity at the point.

Extra cathode pin was added to give pulse discharge in nozzle upstream region to satisfy arc-formation conditions intentionally. Owing to this technique, the operation mode was changeable to another one. This implies that there is possibility to operate and stabilize the discharge modes of DC arcjets.

References

[1] T. Fujimoto, *BUNKO-KENKYU*, 34, 6, pp.347 (1985).
 [2] K. Kuriki, "Arcjet Flow Condition Compatible with High Voltage Mode," *UCHU-YUSO Symposium* (1999)

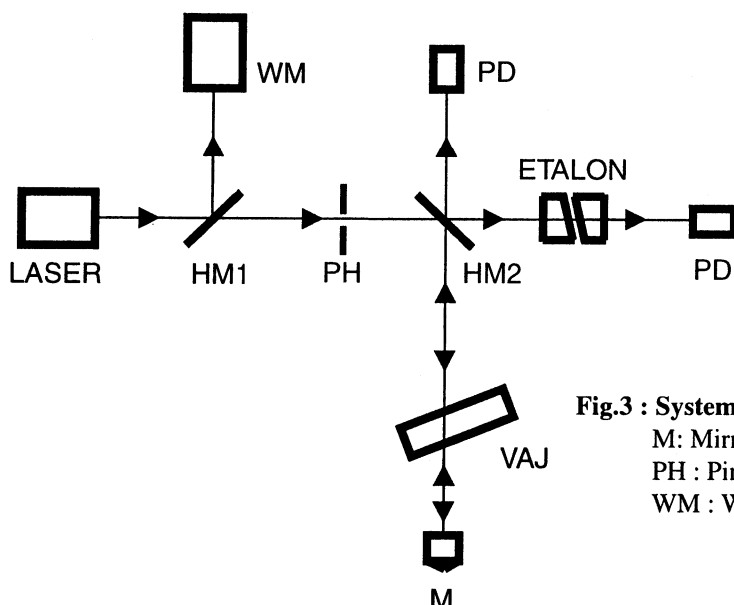


Fig.3 : System for Absorption Spectroscopy
 M: Mirror, HM : Half Mirror,
 PH : Pinhole, PD : Photodiode Detector,
 WM : Wavemeter

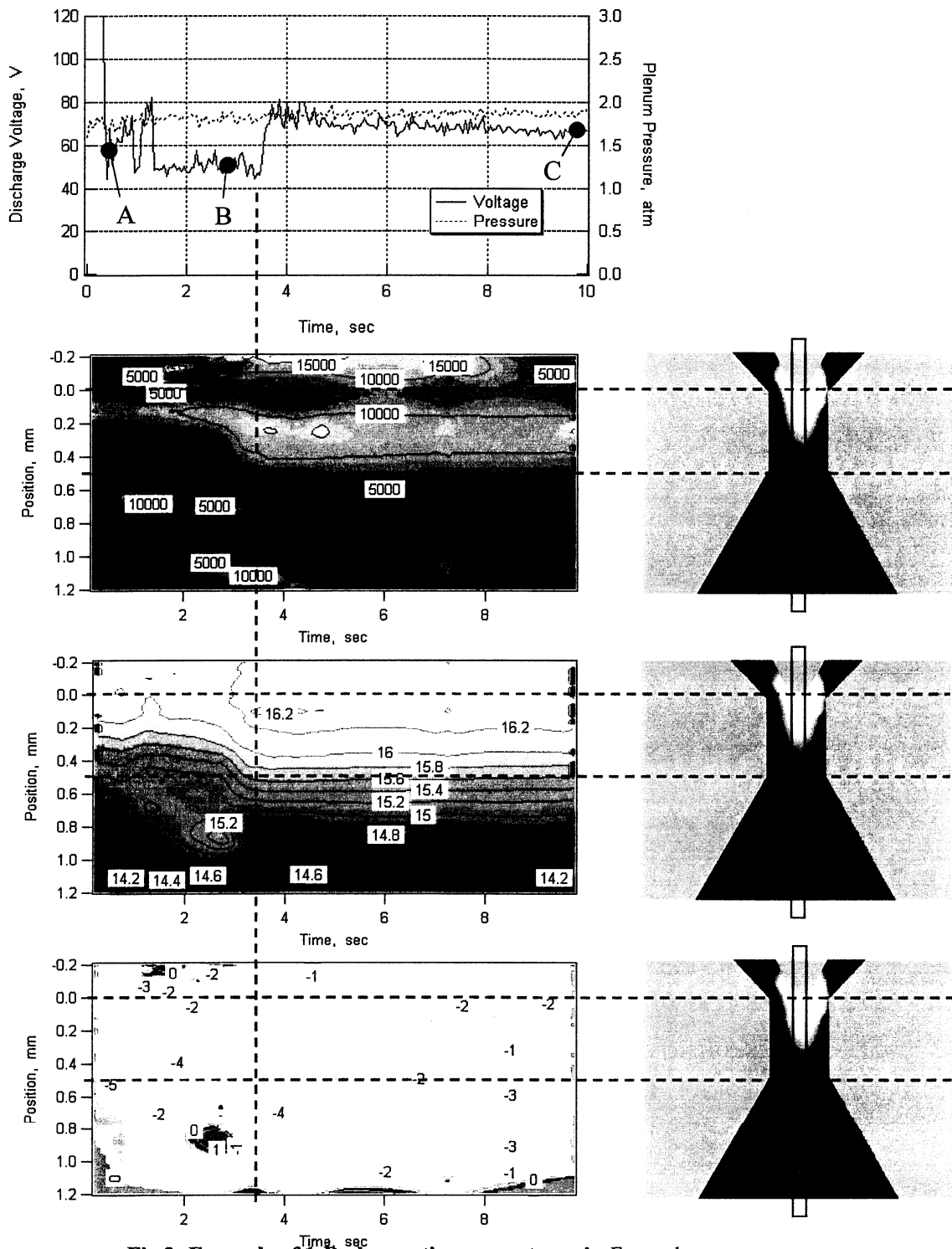


Fig.2: Example of 1-D observation on center axis. From above, Discharge voltage and plenum pressure, electron temperature, common logarithm of electron density multiplier of population density ratio, corresponding to the position in the right figure.