25G07

Measurement of the Specific Heat Ratio of Ions in Plasma with Various Rare Gases

各希ガス種におけるプラズマ中のイオン比熱比の測定

Yuko Hashima, Naohiro Takahashi, Kohei Okawa, Hiroshi Watanabe, Yuki Izawa, Nozomi Tanaka and Akira Ando

橋間裕子, 高橋直大, 大川耕平, 渡部　博, 伊澤裕紀, 田中のぞみ, 安藤　晃

Department of Electrical Engineering, Graduate School of Engineering, Tohoku University
6-6-05, Aramakiji, Aoba-ku, Sendai 980-8579, Japan
東北大学大学院工学研究科　〒980-8579　仙台市青葉区荒巻字 6-6-05

We have experimentally evaluated the specific heat ratio of ions γ_i in plasmas by comparing the behavior in a magnetic nozzle with the isentropic flow model. Axial profiles of ion Mach number M_i were measured in a fast-flowing plasma passing through a Laval type magnetic nozzle. The γ_i was derived from M_i at the nozzle throat and behavior of M_i in the nozzle. The γ_i in He, Ne and Ar plasmas were evaluated.

1. Introduction

The specific heat ratio γ is one of the important parameters specifying thermodynamic behavior of media. In processes of gas compression or expansion, the pressure p and the volume V obey the polytropic relation, $pV^{\gamma} = const.$. Generally, γ is derived as $\gamma = (f + 2)/f$, where f is the degree of freedom. The specific heat ratio with γ = 5/3 is frequently postulated in energetic relations of mono-atomic plasmas. In plasmas many processes of ionization and electron excitation make the derivation of γ difficult.

We have experimentally determined the specific heat ratio of ions γ_i by using isentropic relations. When the nozzle cross section gradually changes, physical quantities of passing plasma flow vary according to the isentropic relations [1]. The γ_i was evaluated by comparing the ion Mach number M_i with the relations.

2. Experimental Apparatus and Procedure

Figure 1 shows a schematic of the HITOP (HIgh density TOhoku Plasma) device. We use a MPDA (MagnetoPlasmaDynamic Arcjet) as a plasma source. Plasma is exhausted from the MPDA with Mach number of nearly unity [2,3]. In this study, divergent and convergent magnetic nozzle configurations were used as shown in Fig.2. The maximum magnetic field was 0.065 T and magnetic throat was formed at Z = 2.2 m, where the Laval type nozzle was formed. Various gases of He, Ne, Ar and Kr were used in the experiments.

The plasma parameters were measured by a Mach probe (a three direction probe) and a three-grid energy analyzer (Faraday cup) for the measurements of ion energy distribution. All diagnostic tools were set on a two dimensional movable stage in the chamber. The parameters were measured from Z = 0.8 m to 2.6 m.

The plasma passes through the divergent region (Z = 1-1.5 m), where Mach number M_i increases [4]. When it comes into converging cross section region at Z = 1.5 m to 2.2m, collisional shock wave occurs and Mach number of plasma flow suddenly

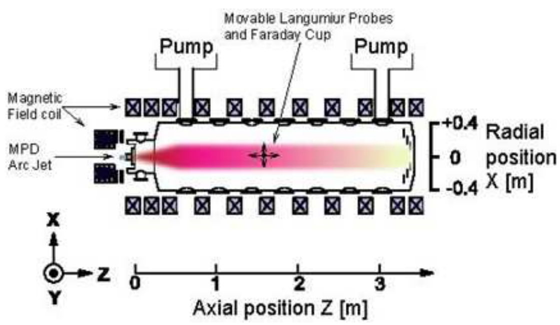

Fig.1. Schematic of HITOP device. The position of Z = 0 corresponds to the cathode tip position of the MPDA.

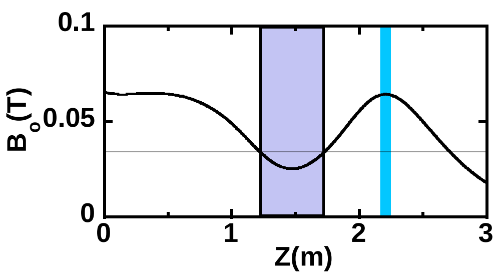

Fig.2 The axial magnetic field configuration used in the experiment. Purple area corresponds to the occurrence of shock wave, and light blue line corresponds to nozzle throat of the Laval nozzle.

decreased. The subsonic flow passes through a Laval nozzle near Z = 2.2 m, and Mach number increases from subsonic to supersonic according to the isentropic flow model as expressed in Eq.(1).

$$\frac{dM_i}{M} = \frac{2+(\gamma_i-1)M_i^{\,2}}{2(M_i^{\,2}-1)}\frac{dS}{S} \quad , \qquad (1)$$

Here, S is the cross section of the magnetic nozzle.

3. Experimental Results

We have evaluated γ_i by the following two methods. The first method is comparison between experimental value and isentropic flow model (Eq.(1)). Figure 3 shows axial profiles of M_i in helium plasma assuming as (a) γ_i = 1.0, (b) γ_i = 5/3 and (c) γ_i = 2.0. The M_i is obtained from Mach probe measurements [5-7]. Experimental results were compared with the theoretical curves, and the specific heat ratio was close to 1.0 rather than 5/3.

The second method is based on the assumption that M_i becomes unity at the throat of the Laval nozzle. The specific heat ratio is expressed by the following equation,

$$\gamma_i = \frac{T_e}{T_i}\left(v_f^2 - \gamma_e\right) \quad . \qquad (2)$$

Here, γ_i and γ_e are ion and electron specific heat ratio and T_i and T_e are ion and electron temperature, respectively. The v_f is expressed as

$$v_f = U/\sqrt{\gamma_e T_e / m_i} \quad . \qquad (3)$$

Here, U is flow velocity and m_i is ion mass of the plasma. We obtained the ion specific heat ratio of helium plasma as 1.1 by assuming electron specific heat ratio as unity. The obtained specific heat ratios were consistent with each other, and much smaller than 5/3.

We have evaluated γ_i in other rare gases and obtained different values from that of helium plasma. The γ_i of neon and argon plasmas were around 1.6 and 2.0, respectively. There are some processes to make the γ_i lower in plasmas, such as electron-ion collisions, charge-exchange collisions, ionization and excitation processes. We have measured the specific heat ratio in different density of plasmas and evaluated mean free paths in these reactions in plasma.

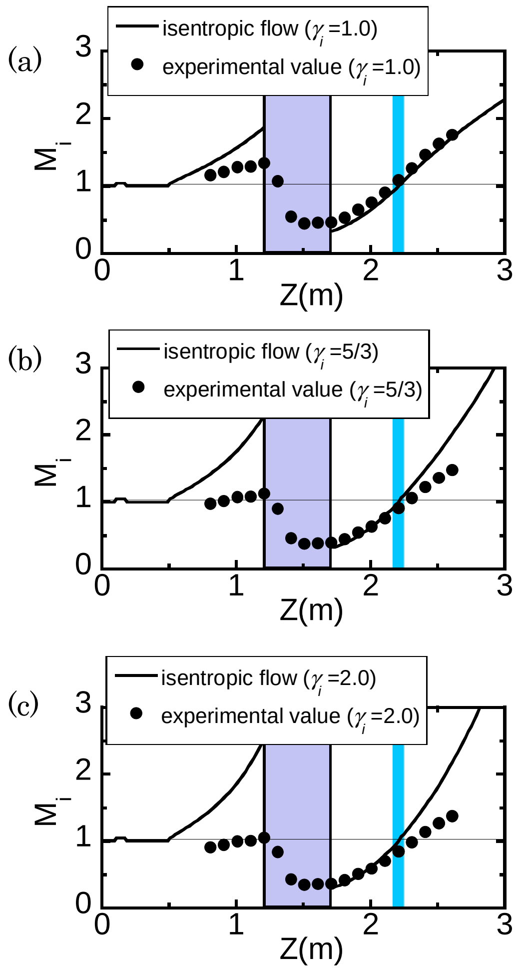

Fig.3 Axial profile of M_i in helium gas (closed circles). Solid line represents theoretical curve calculated from Eq.(1) by assuming (a) γ_i = 1.0 (b) γ_i = 5/3 (c) γ_i = 2.0.

4. Summary

The ion specific heat ratios of plasmas were evaluated by comparing with the isentropic flow model by using two methods. The obtained values showed good agreement to each other, and they were smaller than 5/3 in helium plasma. The γ_i is different in other rare gas plasmas. The effects of collisions on the specific heat ratio were investigated and detail discussions are necessary further.

References

[1] M. Inutake, A. Ando, K. Hattori, H. Tobari and T. Yagai: J. Plasma Fusion Res. **78** (2002) 1352.

[2] M. Inutake and A. Ando: Plasma Phys. Control. Fusion **49**, (2007) A121.

[3] H. Tobari, A. Ando, M. Inutake, and K. Hattori: Physics of Plasmas, **14** (2007) 093507.

[4] A. Ando, T. Hagiwara, T. Komagome, K. Hattori and M. Inutake: Plasma and Fusion Research. **3**, (2008) S1018

[5] A. Ando, T. K. Watanabe, T. Makita, H. Tobari and K. Hattori: Contributions to Plasma Phys., **46** (2006) 335.

[6] A. Ando, T. S. Watanabe, T. K. Watanabe, H. Tobari, K. Hattori and M. Inutake: J. Plasma and Fusion Res., **81** (2005) 451.

[7] A. Ando, H. Tobari, M. Shibata, H. Isobe, K. Hattori, H. Higaki and M. Inutake: Trans. of Fusion Science and Tech., **51** (2007) 217.