Characteristics of hydrogen supersonic cluster beam generated by a Laval nozzle

Akiyoshi MURAKAMI, Junichi MIYAZAWA[1], Hayato TSUCHIYA[1], Takanori MURASE[1], Naoko ASHIKAWA[1], Tomohiro MORISAKI[1], Ryuichi SAKAMOTO[1] and Hiroshi YAMADA[1]

The Graduate University for Advanced Studies, 322-6 Oroshi-cho,Toki, 509-5292, Japan

[1]*National Institute for Fusion Science, 322-6 Oroshi-cho,Toki, 509-5292, Japan*

(Received: 20 November 2009 / Accepted: 23 February 2010)

Formation of a hydrogen cluster jet using a Laval nozzle has been investigated in the temperature range from 120 K to 300 K. Time-resolved 2-D images of Rayleigh scattering due to clusters have been measured by a fast charge coupled device camera. The scattering signal from hydrogen clusters is detected when the temperature is below 178 K, as expected from a calculation result of the condition to produce clusters. The scattering signal intensity is inversely proportional to the fifth power of the gas temperature and cubic dependence on the backing pressure as expected from an available cluster model.

Keywords: hydrogen cluster, Laval nozzle, fueling method, solenoid valve, Rayleigh scattering, Hagena parameter

1. Introduction

Physics of cluster formation by gas jet has been studied since 1956 [1]. A cluster beam for fusion research was studied firstly as the source of plasma heating in the 1970s [2]. Cluster jet injection (CJI) comes to the front again in recent study of fueling [3]. Fueling methods of gas puffing and pellet injection have been studied for a long time. Gas puffing has been used since early fusion plasma experiments. Especially in large plasmas, most of the particles supplied by gas puffing are ionized outside of the plasma confinement region. As a result, the fueling efficiency is as low as ~10 % [4]. On the other hand, pellet injection is able to supply fuel particles to the plasma core region [5]. However, a pellet injection device itself is complicated compared with a gas puff device and still has demanding technological issues for a fusion reactor. A new fueling method of supersonic cluster beam (SSCB) injection is being developed in the National Institute for Fusion Science. SSCB is an improved version of CJI developed for HL-2A, where liquid nitrogen of 77 K is used for gas cooling [3] and, the supersonic gas injector (SGI) developed for NSTX, where a Laval nozzle is used to generate supersonic gas jet [6]. Recently, the results of supersonic molecular beam injection (SMBI) on HL-2A are reported, where a conic nozzle is installed on the valve of CJI [7]. In SSCB, high-pressure hydrogen gas can be cooled to less than 100 K by a GM refrigerator and will be ejected through a fast solenoid valve with a Laval nozzle. Deeper penetration of the fuel particles injected by SSCB than ordinary gas puffing is expected to be beneficial for high fueling efficiency in large plasmas.

In this study, formation of the H_2 cluster jet using a Laval nozzle for SSCB has been investigated in the temperature range from 120 K to 300 K. Time-resolved 2-D images of Rayleigh scattering due to clusters have been measured by a fast charge coupled device (CCD) camera. Characteristics of cluster jet ejected from the Laval nozzle are discussed with regard to dependence on pressure and temperature.

author's e-mail:murakami.akiyoshi@LHD.nifs.ac.jp

2. Cluster Theory

2.1 Hagena Parameter

The condition to produce clusters can be described by an empirical scaling parameter Γ* that is proportional to a so-called "Hagena parameter", *k* [8, 9]

$$\Gamma^* = k\frac{(d/\tan\alpha)^{0.85}}{T_0^{2.29}}P_0\,, \qquad (1)$$

where d is the nozzle diameter in μm, α is the expansion half angle (α = 45° for the sonic case, α < 45° for the supersonic case), P_0 is the backing plenum pressure in 10^{-4} MPa, and T_0 is the pre-expansion temperature in Kelvin. Massive condensation, where the cluster size exceeds 100 atoms/cluster, is generally observed for Γ* > 1000[8, 9]. Figure 1 shows the parameter Γ* as a function of the gas temperature, where d = 300 μm, α = 12°, P_0 = 4 MPa are assumed, respectively. The nozzle diameter of d = 300 μm and α = 12° are equal to those of the Laval nozzle used in this experimental study. The curve line in the Laval nozzle hole has one inflection point. The angle of α = 12° corresponds to the slope angle of the tangent at the inflection point. It means that the angle of α = 12° is the maximum expansion half angle on the Laval curve line. In this calculation, species-dependent k of 184, 3.85, 2360, 528, 185, and 1650 are used for H_2, He, CH_4, N_2, Ne, and Ar, respectively. Previous study showed that clear scattering signals are observed at high valve

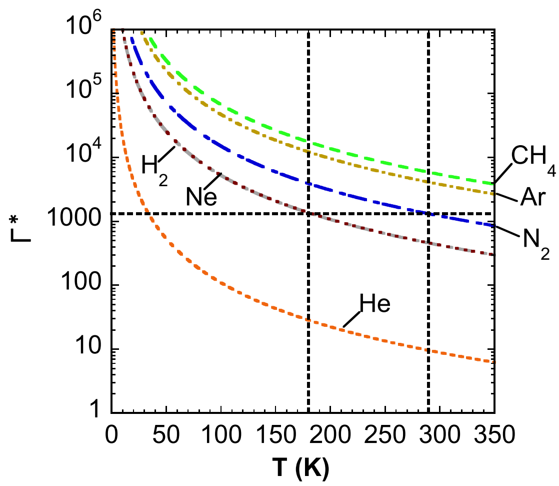

Fig. 1 Calculated results of the scaling parameter Γ*, where d = 300 μm, α = 12°, P_0 = 4 MPa. The parameter of hydrogen at the temperature region of ~180K corresponds to that of nitrogen at the room temperature.

backing pressure of more than 3-4 MPa at the room temperature in the case of CH_4, N_2, and Ar. Meanwhile, in the case of H_2, He, and Ne, no scattering signal has been detected up to 8.0 MPa at the room temperature [10]. This calculation result shows the parameter Γ* of H_2 at the temperature region of ~180 K corresponds to that of N_2 at the room temperature. In other words, it implies that H_2 will form clusters when the gas temperature is ~180 K from the room temperature.

2.2 Rayleigh Scattering

The total Rayleigh scattering signal S_{RS} is proportional to the product of the scattering cross section σ and the number density of clusters n_c. The cross section σ is proportional to the square of the averaged cluster size N_c defined by the averaged number of atoms per a cluster. n_c is approximately given by the monomer density before becoming cluster, n_0, divided by N_c, i.e., $n_c \approx n_0/N_c$. The scattering signal S_{RS} is proportional to P_0N_c since the monomer density is proportional to the backing plenum pressure P_0. Farges *et al.* showed that $N_c \propto P_0^{1.8\text{-}2.1}$, assuming a multilayer icosahedral model [11, 12]. This means that the scattered light signal S_{RS} should vary as below,

$$S_{RS} \propto P_0^{2.8-3.1} . \qquad (2)$$

3. Experimental Setup

The experimental setup is shown in Fig. 2. A solenoid valve of Parker-Hannifin Pulse Valve Series 99B07 is used. The available backing pressure is up to 8 MPa. This valve is equipped with the Laval nozzle of 300 μm throat diameter. The valve is installed in the vacuum chamber and cooled by a GM refrigerator via connection with copper

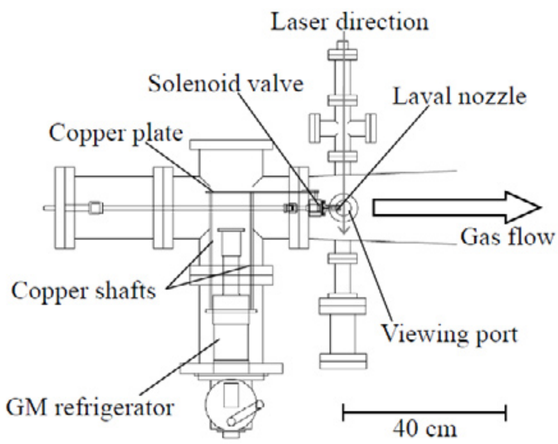

Fig. 2 Schematic of the experimental setup. A solenoid valve installed in the vacuum chamber is cooled by the GM refrigerator through copper plates.

Fig.3 Laval nozzle with 300 μm throat diameter. The nozzle was connected by the end of solenoid valve.

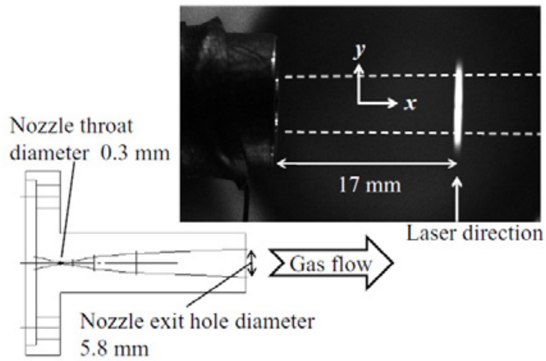

Fig. 4 Typical CCD image in the case of H_2 at 125 K and the cross section of the Laval nozzle. The backing pressure is 8.0 MPa, and the exposure time is 10 ms. The laser beam direction (y) is perpendicular to the gas flow (x). The broken lines denote extension of the exit hole with a diameter of Laval nozzle (5.8 mm)

plate and shafts. The temperature of copper valve jacket is measured by a thermocouple. The picture of the Laval nozzle is shown in Fig. 3. A semiconductor laser of NEOARK LDP2-6535A with 650 nm standard wavelength and 35 mW power is guided in the chamber to perpendicularly intersect the gas flow. A beam dump is set at the opposite side of the laser inlet and the Laval nozzle is rolled by black tape in such a way that the stray light is lowered. The distance between the nozzle exit and the laser chord is 17 mm. A fast CCD camera of 1280 × 1024 pixels is arranged in the direction perpendicular to both the gas flow (x-direction) and the laser beam (y-direction). A typical CCD image of 8.0 MPa H_2 cluster jet at 125 K and the cross section of the Laval nozzle are shown in Fig. 4. A straight emission line that is scattered by clusters is observed along the laser beam.

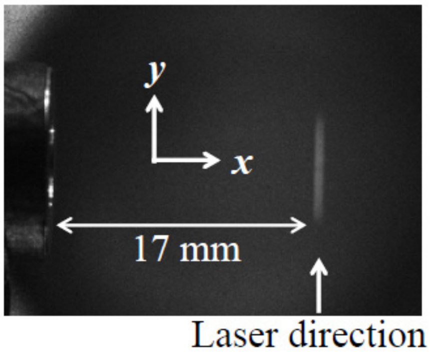

Fig.5 The image of scattering signal emission line in the case of H_2 at 178K. The backing pressure is 5.0 MPa, and the exposure time is 10 ms.

4. Results and Discussion

4.1 Temperature dependence of scattering signal

The scattering signals are detected when the temperature is below ~180 K as expected from the calculation. The image of scattering signal emission line of H_2 at 178 K is shown in Fig. 5. The empirical scaling parameter $\Gamma^*$of H_2 at ~180 K nearly corresponds to that of N_2 at the room temperature. Figure 6 shows scattering signal profiles along the laser light direction (y), where the temperature is varied from 119 K to 143 K. The exposure time of the CCD camera is fixed to 10 ms and the backing pressure is fixed to 5 MPa for this scan. The width of 5.8 mm in Fig. 6 denotes the exit hole diameter of the Laval nozzle. These profiles are axisymmetric. The full-width of half-maximum (FWHM) is 6.2 ± 0.2 mm. The FWHM does not depend on temperature. Two peaks observed in the profiles indicate that the center of cluster flow has hole. Similar hollow profile was observed in the study on plasma produced by laser pulses irradiating a cluster target generated by a Laval nozzle [13]. The points on three y-coordinate (y = 2.9 for □, 0.7 for ○, 0 mm for △) of the scattering profile are plotted in Fig. 7. The signal points of y = 2.9 mm is the radial of nozzle exit hole diameter (5.8 mm). The signal points of y = 0.7 mm indicate the peak signals in the profiles. The signal points of y = 0 mm show the center of hollow profiles. The points on three y-coordinate of scattering signal increase with $\sim T_0^{-5}$. This result is similar to the results in Ref. [8].

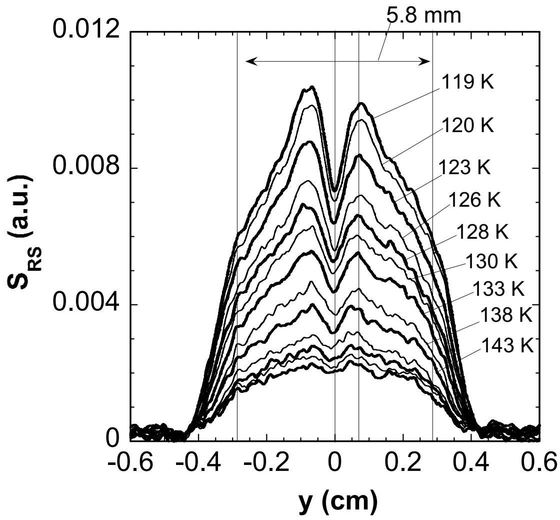

Fig. 6 Scatter signal profiles normalized by the exposure time (μs), where the temperature is varied from 119K to 143K.

4.2 Pressure dependence of scattering signal

Figure 8 shows scattering signal profiles along the laser light direction (y), where the backing pressure is increased from 3.0 to 8.0 MPa at ~125 K. The FWHM of these profiles is 5.83 ± 0.3 mm and roughly corresponds to the exit hole diameter of the Laval nozzle. The points on three y-coordinate (y = 2.9 for □, 0.7 for ○, 0 mm for △) scattering profiles in Fig. 8 as a function of the backing pressure are plotted in Fig. 9. The peak scattering

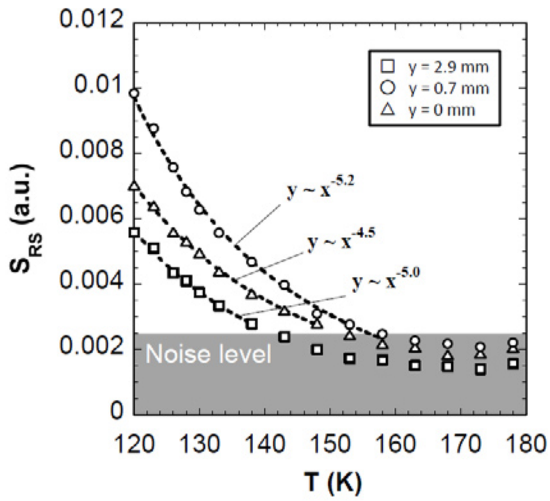

Fig.7 The points on three y-coordinate (y = 2.9 for □, 0.7 for ○, 0 mm for △) of the scattering profiles in fig.5 are plotted.

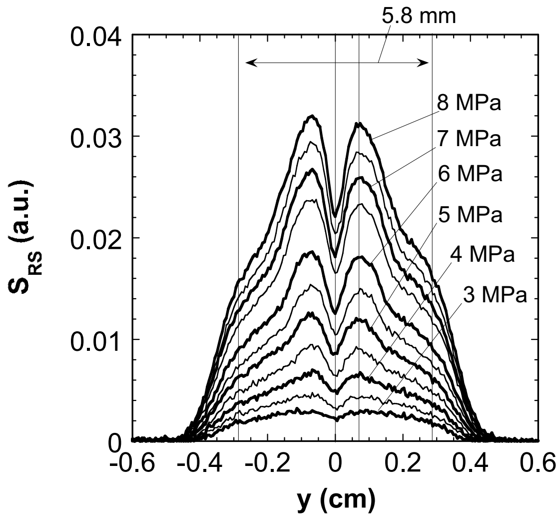

Fig.8 Scatter signal profiles normalized by the exposure time (μs), where the backing pressure is varied from 3.0 MPa to 8.0MPa

signal (y = 0.7 mm) increases with ~P_0^3. The result is

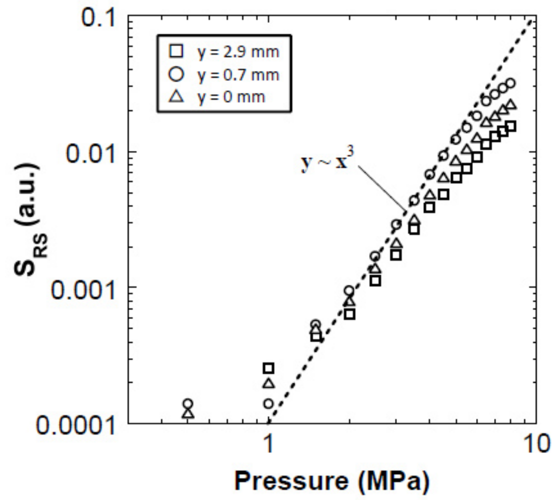

Fig.9 The points on three y-coordinate (y = 2.9 for □, 0.7 for ○, 0 mm for △) of the scattering profiles in fig.7 are plotted.

similar to the expectation of Eq. (2) and the results in Ref. [8, 10]. Farges et al. estimated this relation assuming a multilayer model for Ar cluster. This suggests that the structure of hydrogen cluster also has the multilayer model for Ar cluster. The other signal points of y = 2.9 and 0 mm are smaller than the cubic dependence on the backing pressure.

Figure 10 shows the images of cluster scattering signals in the case of H_2 at ~130 K without the Laval nozzle (a) and with the Laval nozzle (b). In the case of N_2, Ar and CH_4, a rapid increase of the signal intensity has been observed and similar results are also shown in Ref. [8]. The scattering signals of this region are much stronger than that of clusters. This might presumably be due to the phase transition to the liquid state. In this regime, the particle flow is visible by eye and it is possible to take the image of shadow graph by the CCD camera. Figure 10 (c) shows a shadow graph image of the particle flow in the case of CH_4 at 180 K with the Laval nozzle. The backing pressure is 7.0 MPa, and the exposure time is 1 ms. Fig. 10 (b) and (c) imply that the width of clusters during 17 mm is similar to the exit hole diameter and the width of the liquid particle flow is slightly broader than that of clusters. Previous study shows the expansion half angle of the solenoid valve without a Laval nozzle is 22.5°[10]. The divergence of cluster jet has been decreased after installation of the Laval nozzle.

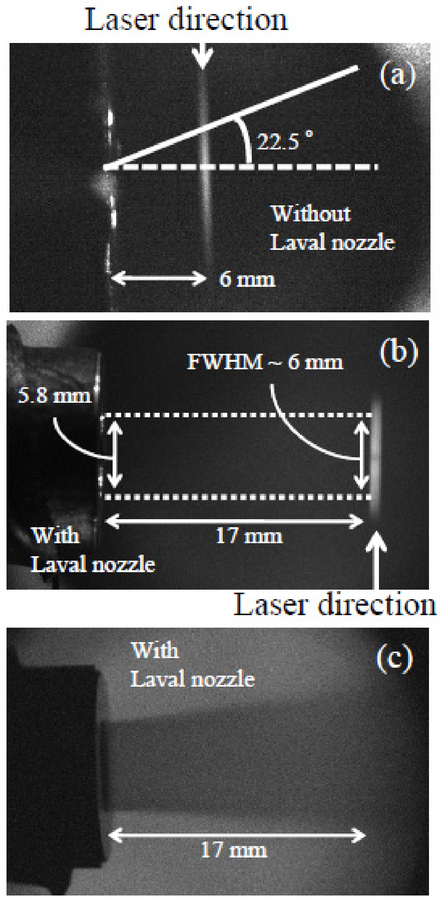

Fig.10 The images of cluster scattering signals in the case of H_2 at ~130 K without the Laval nozzle (a) and with Laval nozzle (b). The backing pressure is 5.0 MPa, and the exposure time is 10 ms. A shadow graph image of the particle flow in the case of CH_4 at 180 K with the Laval nozzle (c). The backing pressure is 7.0 MPa, and the exposure time is 1 ms.

5. Summary

Clustering condition for hydrogen has been investigated in the temperature range from 120 K to 300 K. The Rayleigh scattering signal is detected by the CCD camera when the hydrogen gas temperature is below 178 K as expected from available model. The scattering signals increases with $\sim T_0^{-5}$ and $\sim P_0^3$ as expected from a cluster model. The divergence of cluster jet has been decreased after installation of the Laval nozzle. Based on the knowledge obtained here, a supersonic cluster beam (SSCB) injection is planned as a new fueling scheme in LHD.

Acknowledgments

This work has been financially supported by NIFS09ULPP517.

[1] E.W. Becker, K. Bier, and W. Henkes, Zeitschrift für Physik, **Bd. 146**, (1956) S333.
[2] B. J. C. Burrows *et al*., Paper **51**, Fifth Symposium on Fusion Technology (1968).
[3] L. Yao *et al*., Nucl. Fusion **47**, 1339 (2007)
[4] J. Miyazawa *et al*., Nucl. Fusion **44**, 154 (2004)
[5] R. Sakamoto. *et al*., Nucl. Fusion **41**, 381 (2001)
[6] V. A. Soukhanovskii *et al.*, Rev.Sci. Instrum.**75**, (2004) 4320
[7] C. Y. Chen *et al*., Presentation for APFA2009 A29a-3
[8] R. A. Smith *et al* Rev Sci Instrum. **69**, 3798 (1988).
[9] O. F. Hagena Z. Phys. D **4**, 291 (1987)
[10] A. Murakami *et al*., to be published in Plasma Fusion Reserch
[11] O. F. Hagena and W. Obert, J. Chem. Phys. **56**,1793 (1972)
[12] J. Farges, M. F. de Feraudy, B. Raoult, and G. Torchet, J. Chem. Phys. **84**, 3491 (1986)
[13] I. Yu. Skobelev *et al*., JETP **94**, 966 (2002)