Investigation of the Clustering Condition for Various Gasses Ejected from a Fast Solenoid Valve for Supersonic Cluster Beam Injection

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The supersonic cluster beam (SSCB) injection method is being developed as a new fueling method for the Large Helical Devise (LHD) experiment. As a first step, cluster formation at a room temperature has been investigated for various gasses using a fast solenoid valve for SSCB. Rayleigh scattering of laser light by the cluster is measured by a fast charge coupled device camera. In the case of methane, nitrogen, and argon, clear scattering signals are observed at high valve backing pressure of more than 3-4 MPa. In the case of hydrogen, helium, and neon, on the other hand, no scattering signal is detected at < 8 MPa. The result that the expansion half angle is 22.5° suggests gas flow is supersonic. The scattering signals from argon and nitrogen clusters show approximately cubic dependence on the backing pressure as expected from a model. Meanwhile, stronger pressure dependence than this has been found in the case of methane, where the scattering signal increases with the fifth power of the backing pressure at 3.2 MPa-7 MPa, and it is further enhanced at > 7 MPa.

Keywords: fueling method, gas puffing, solenoid valve, cluster, Rayleigh scattering

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1. Introduction

In a future thermonuclear fusion reactor, fueling will be essential for the burning control and therefore development of effective fueling methods has been one of the key issues in the fusion study. Conventionally, 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 at outside of the plasma confinement region. As a result, the fueling particles efficiency is as low as ~10 % [1]. On the other hand, pellet injection is able to supply fuel particles to the plasma core region [2]. However, the pellet injection device itself is complicated compared with the gas puff device and still has unsolved issues in steady-state operation with variable control of the pellet size. A new fueling method of supersonic cluster beam (SSCB) injection is being developed for the Large Helical Device (LHD) experiment, which is the world-largest superconducting heliotron [3]. SSCB is an improved version of cluster jet injection (CJI) developed for HL-2A, where liquid nitrogen of 77 K is used for gas cooling [4], or the supersonic gas injector (SGI) developed for NSTX, where a Laval nozzle is used to generate supersonic gas jet [5]. In SSCB, high-pressure hydrogen gas cooled to less than 77 K by a GM refrigerator will be injected to vacuum through a fast solenoid valve with a Laval nozzle. Deeper penetration of the fuel particles expected in SSCB might be beneficial for achieving high fueling efficiency in large plasmas. SSCB has a possibility of steady-state operation as gas puffing while the required apparatus will be much simpler than that of pellet injection.

Although it is expected that SSCB will produce cluster beam as in CJI, there is no established theory to predict the cluster size in a free jet expansion. Nevertheless, it has been shown that the condition to produce clusters can be described by an empirical scaling parameter Γ^* that is proportional to a so-called "Hagena parameter", k [6,7],

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

where d is the nozzle diameter in μm, α is the expansion half angle ($\alpha = 45°$ for sonic nozzles, $\alpha < 45°$ for supersonic), 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 $\Gamma^* > 1000$ [6,7]. The parameter Γ^* as a function of the gas temperature is shown in Fig. 1, where $d = 500\,\mu$m, $\alpha = 45°$, and $P_0 = 4$ MPa are assumed, respectively. The nozzle diameter of $d = 500\,\mu$m is equal to that of the valve used in this study. 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 [6]. The result implies that the

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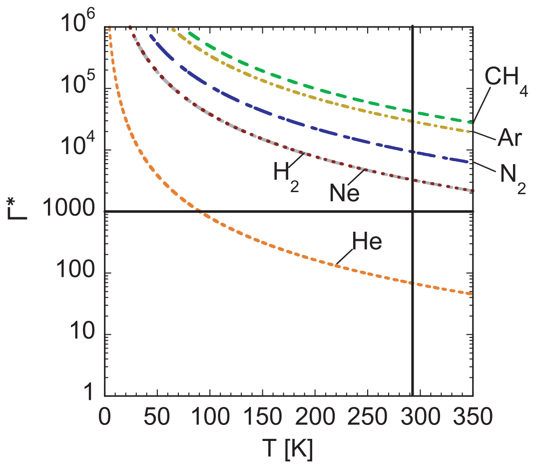

Fig. 1 Calculated results of the scaling parameter Γ^*, where d = 500 µm, α = 45°, P_0 = 4 MPa. The gasses except helium satisfy the condition for massive condensation of Γ^* > 1000 at room temperature (293 K).

gasses except He are expected to form clusters at a room temperature.

Before applying SSCB to LHD, a solenoid valve for SSCB has been tested at a room temperature in a test vacuum chamber. Various gasses shown in Fig. 1 were used in the experiment to investigate the clustering condition.

2. Experimental Setup

The experimental setup is shown in Fig. 2. A solenoid valve of Parker-Hannifin Pulse Valve Series 99B07 with a 500 µm diameter orifice is used. This valve is equipped with a tapered nozzle. The available backing pressure is up to 8 MPa. This valve is set inside the vacuum chamber. The pressure in the vacuum chamber is measured by a pressure gauge of MKS Baratron capacitance manometer (MODEL#617A) set at the opposite side of the valve. When the valve is open, the gas flows from left to right in Fig. 2. Various gasses of H_2, He, CH_4, N_2, Ne, and Ar are used in the experiment. A semiconductor laser of NEOARK LDP2-6535A with 650 nm standard wavelength and 35 mW power is set inside the chamber to perpendicularly intersect the gas flow. A beam dump is set at the opposite side of the laser and the valve is rolled by black tape in such a way that the stray light is lowered. The distance between the valve exit and the laser chord is variable from 3.5 mm to 4.0 mm. A fast charge coupled device (CCD) camera of 1280 × 1024 pixels is arranged in the direction perpendicular to both the gas flow and the laser beam. An example CCD image is shown in Fig. 3.

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 be-

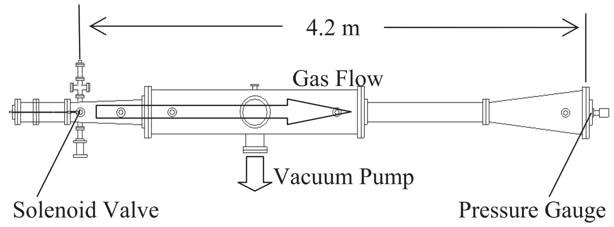

Fig. 2 Schematic of the experimental setup. The distance from the solenoid valve to the baratron pressure gauge is 4.2 m. Inside the chamber is pumped to less than 10^{-4} Pa. The laser is set inside the chamber.

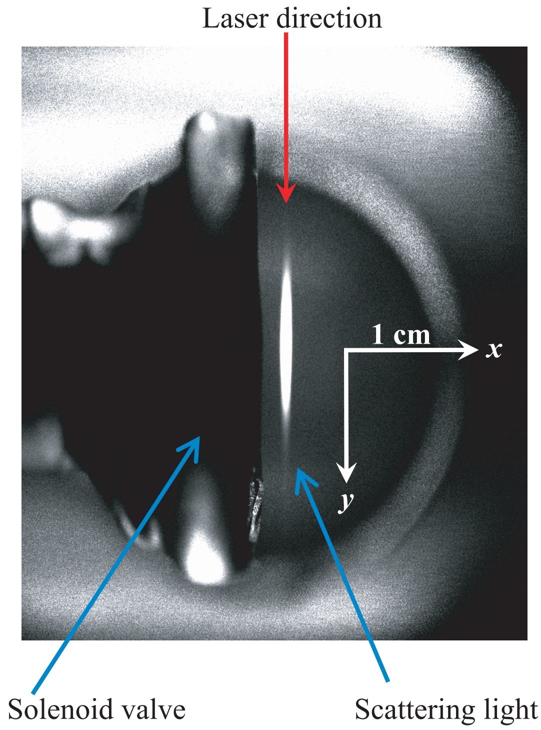

Fig. 3 The scattering light image detected by the CCD camera in the case of CH_4. The backing pressure is 8.0 MPa, and the exposure time is 10 ms. The laser beam direction (y) is perpendicular to the gas flow (x).

fore 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 $P_0 N_c$ 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 [8, 9]. This means that the scattered light signal S_{RS} should vary as below,

$$S_{RS} \propto {P_0}^{2.8\text{-}3.1} \,. \tag{2}$$

3. Results

Figure 4 shows the temporal behavior of the scattering signal intensity in the case of Ar. The valve is opened from 0-120 ms. The camera exposure time is fixed to 1 ms. The scattered light signal intensity is approximately constant during the valve open. This means that the cluster is

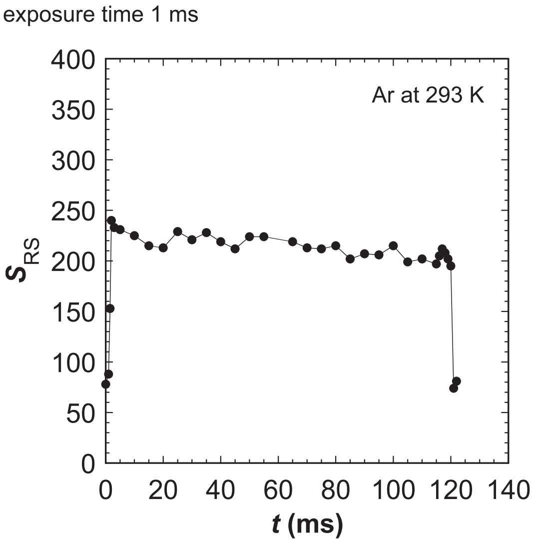

Fig. 4 Typical temporal behavior of the scattering signal intensity. The working gas is Ar and the backing pressure is 7.1 MPa.

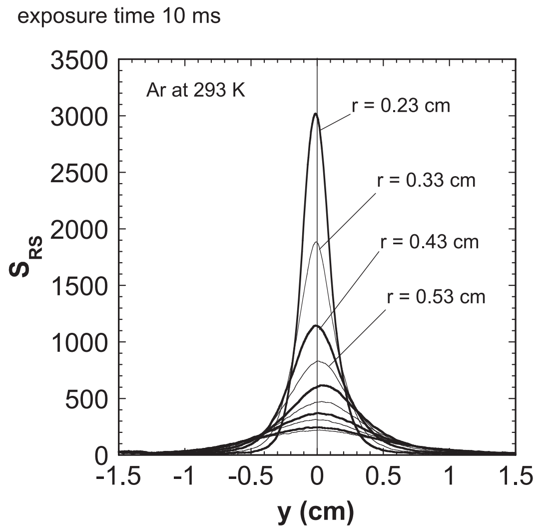

Fig. 6 Scatter signal profiles in the case of Ar, where the distance from valves to laser light is varied from 0.23 cm to 1.0 cm. The direction y is parallel to the laser beam.

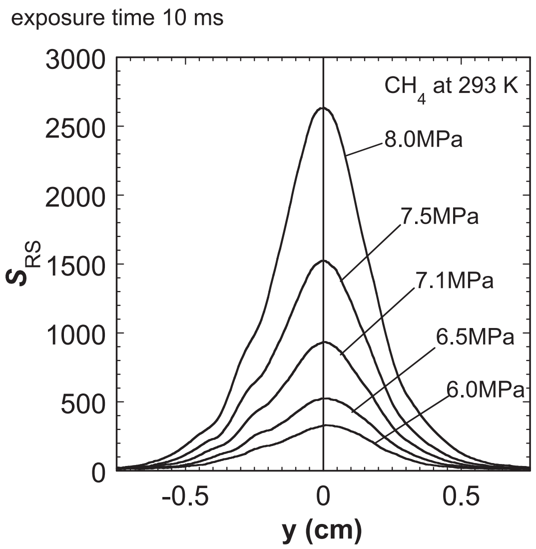

Fig. 5 Typical scatter signal profiles in the case of CH_4. The direction y is parallel to the laser light. The backing pressure P_0 is scanned from 6.0 MPa to 8.0 MPa, while the gas puff pulse length of 40 ms, the CCD camera trigger timing of 35 ms, and the exposure time of 10 ms are fixed.

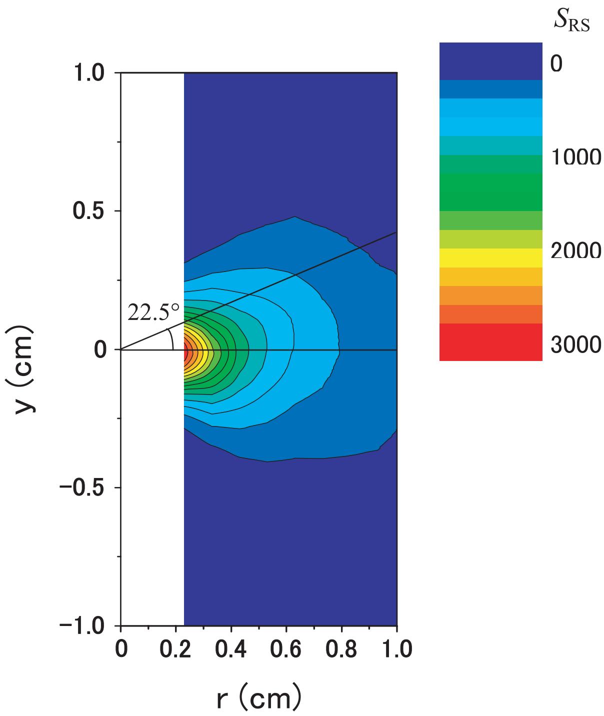

Fig. 7 Contour plot of scatter signal profiles shown in Fig. 6.

formed as long as the valve is open. Hereinafter, the valve opening time of 40 ms and the CCD camera trigger timing of 35 ms are fixed.

Typical scattering signal profiles in the case of CH_4 are shown in Fig. 5. The direction y in Fig. 5 is parallel to the laser light (see Fig. 3). The backing plenum pressure P_0 is varied from 6.0 MPa to 8.0 MPa. While the exposure time of the CCD camera is fixed to 10 ms. These profiles are axisymmetric and the full-width of half-maximum (FWHM) does not depend on the backing pressure. Similar characteristics are also observed for N_2 and Ar.

Figure 6 shows that scattering signal profiles of Ar measured at different position, where the distance from the valve to laser light is varied from 0.23 cm to 1.0 cm. A contour plot of these profiles is shown in Fig. 7. The FWHM increases with the distance from the valve. The expansion half angle of 22.5° suggests that this gas flow is supersonic.

The maximum of the scattering signal as a function of the backing pressure is plotted in Fig. 8. The scattering signal increases with $\sim P_0^{2.8}$ for Ar (Fig. 8 (a)) and $\sim P_0^{3.2}$ for N_2 (Fig. 8 (b)). These results are similar to the expectation

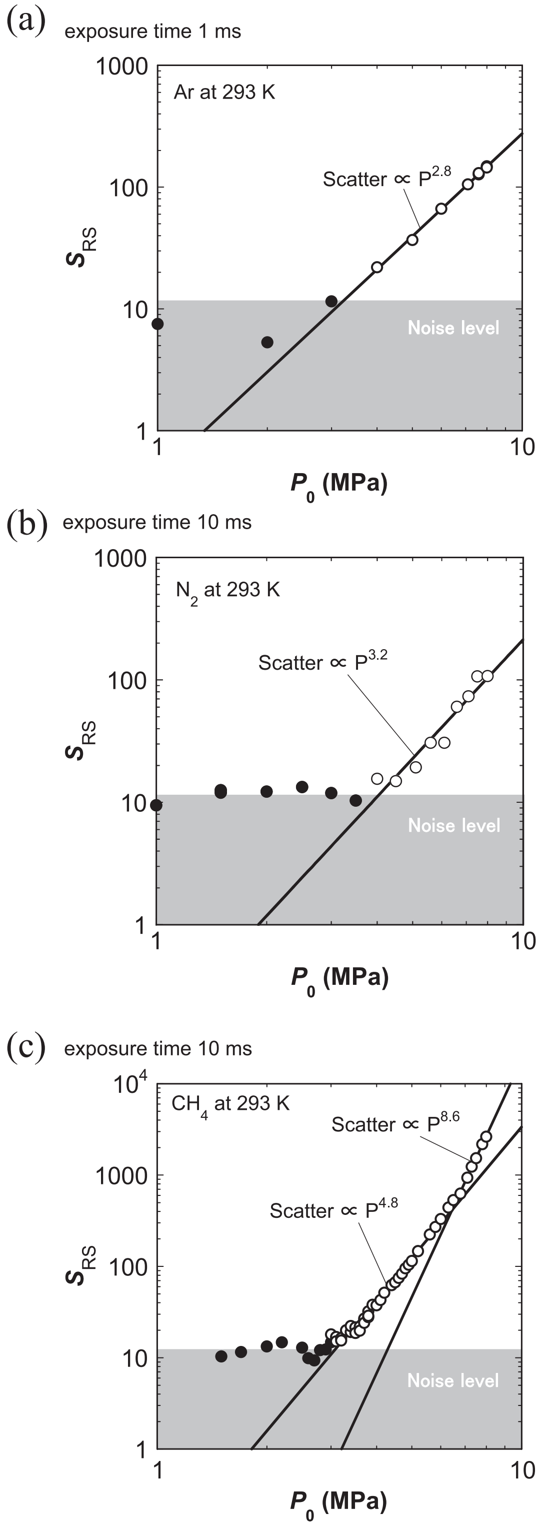

Fig. 8 Peak scattered signal as a function of the backing pressure in the cases of (a) Ar, (b) N_2 and (c) CH_4. Closed circles denote the signals under the noise level. Regression analysis has been done using the data points denoted by open circles.

of Eq. (2) and the results in Ref. [6]. However, in the case of CH_4 (Fig. 8 (c)), it is found that the backing pressure dependence is stronger than expected, i.e., $S_{RS} \propto P_0^{4.8}$ at $P_0 < 7$ MPa and $S_{RS} \propto P_0^{8.6}$ at $P_0 > 7$ MPa. This result is different from $S_{RS} \propto P_0^{2.8\text{-}3.1}$ (Eq. (2)). Farges *et al.* estimated this relation assuming a multilayer icosahedral model for an Ar cluster. This model seems to be reasonable also for N_2, which shows similar pressure dependence as Ar. However, a new structure model would be necessary to determine the cluster size of CH_4, which shows stronger backing pressure dependence than Ar or N_2.

The scattering signal is detected when the backing plenum pressure is above 3.2 MPa, 3.0 MPa, and 4.0 MPa for CH_4, Ar, and N_2, respectively. In the case of H_2, He, and Ne, no scattering signal has been detected up to 8.0 MPa. Especially, even though the massive condensation condition of $\Gamma^* > 1000$ is satisfied for H_2 and Ne, no cluster has been detected. Even for CH_4, Ar, and N_2 the scattering signals appear at high Γ^* of 31000, 22000, and 9000, respectively. These are much higher than 1000. Possible causes of this might be; the noise level was larger than the scattering signal, or the laser power was too low. In order to detect scattering signals of hydrogen and neon clusters, it would be necessary to improve the experimental setup.

4. Summary

Clustering condition for various gasses at a room temperature has been investigated using a fast solenoid valve for SSCB. The Rayleigh scattering signal is detected by a fast CCD camera when the backing plenum pressure is above 3.2 MPa, 3.0 MPa, and 4.0 MPa for CH_4, Ar, and N_2, which correspond to 31000, 22000, and 9000 of Γ^*, respectively. In the case of H_2, He, and Ne, no scattering signal is detected. Nearly symmetric shapes of the scattering signal profile in CH_4, Ar, and N_2 are observed by the CCD camera. It has been found that the scattering signal intensity dependence on the backing pressure is similar to the expectation of Eq. (2) and the results in Ref. [6] for N_2 and Ar. In the case of CH_4, stronger backing pressure dependence is observed, i.e., $S_{RS} \propto P_0^{4.8}$ below 7 MPa and $S_{RS} \propto P_0^{8.6}$ at $P_0 > 7$ MPa. These are different from $S_{RS} \propto P_0^{2.8\text{-}3.1}$ (Eq. (2)) expected from the result of Farges *et al.* [8, 9].

In SSCB, high-pressure gas cooled to less than 77 K will be injected to the fusion plasma through a fast solenoid valve with a Laval nozzle. At a low temperature below 77 K, Γ^* for H_2 increases to the similar level as those of Ar and CH_4 at a room temperature (see Fig. 1) where clear Rayleigh scattering signals are observed in this study. Therefore, it is expected that hydrogen cluster beam will be easily formed below 77 K.

Acknowledgments

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