Behavior of Gas Injected Fast Ignition Targets*)

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Gas target injection system is newly fabricated to observe behaviors of injected fast ignition targets. It can eject a mimic fast ignition target by pressured nitrogen gas and magnetic separator. The flight attitude of injected target is observed by high-speed cameras. Analysis of high-speed camera images indicates that the target velocity is increased with the injection gas pressure up to around 100 m/s which meets the demanded specification of a reactor and the target flight angle is varied in wide range shot by shot. The technical problem how to control flight angle is recognized for a fast ignition reactor.

Keywords: fusion reactor, fast ignition, target injection, high-speed camera, image analysis

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1. Introduction

A lot of researches on implosion core plasmas have been reported. A fusion experiment with high repetition rate is essential to develop a commercial fusion reactor. However, most of the experiments for physics study have been done on a single shot basis using high power lasers [1–4]. As technical study, an experiment of repetitive fuel target supply by free fall is reported [5]. Conceptual design of the fast ignition laser fusion power plant, KOYO-Fast, demands 2 Hz repetation rate for injection system [6]. Because the solid deuterium fuel target should reach the center of the reactor as not to be melted, target injection system with acceleration mechanism is essential. The accelerated flight speed should be approximately 100 m/s in the condition that the center of the reactor is 10 m away from the injection point. In addition to the injection rate and flight speed issue, targets are expected to be injected with high accuracy in flight attitude for fast ignition scheme, in which the laser alignment is asymmetry [7]. At the laser irradiation point, the position accuracy should be within laser spot whose size is around 150 micrometre, and the inclination of the symmetry axis of the target should be within ±2 degrees. There are only a few research works on how to supply targets at such a high speed and high repetition rate. Sakae *et al.* developed a simple gas gun device and carried out a projectile-shooting experiment [8]. In their experiment, the flight speed was about 65 ~ 150 m/s and the flight deviation was within 1.5 mrad at flight distance of 2085 mm. Since, they used simple cylindrical projectiles made of DURACON®, the result should be different for fast ignition targets with complex structures. Therefore, we have developed an injection system to accelerate fast ignition targets by high pressured gas. In this paper, we report the behavior of the injected fast ignition target with various injection gas pressure as a first step of controlling the target injection.

2. Experimental Setup

Figure 1 shows the schematic diagram of our target injection system. The experimental apparatus mainly consists of a gas storage tank, a solenoid valve, an acceleration tube, a sabot separator, and an observation chamber. The gas storage tank has a volume of 0.0196 m^3 and is filled with room temperature nitrogen gas. The inner diameter of acceleration tube is 10.21 mm. Three observation windows with a nominal diameter of 200 mm are installed in the observation chamber. Figure 2 shows a schematic diagram of the target assembly. The aluminum target mimics the shape of fast ignition target which has a fuel shell with a corn [2–4]. As shown in Fig. 2, a holder made of DURACON® is screwed into an aluminum sabot, and a target is mounted into the holder. The weight of a target and sabot with the holder are 0.356 g and 3.963 g, respectively. The assembled target is placed at the entrance of the acceleration tube, and injected by nitrogen gas with opening the solenoid valve. The assembled target runs in the acceleration tube and reaches the sabot separator. Ring shaped permanent magnets are placed as the sabot separator. When the assembled target passes through the sabot separator, eddy currents are induced on the surface of the sabot. A Lorentz force induced by the magnetic field of permanent magnets and eddy currents acts on the sabot and decelerate it (Fig. 3) [9]. As a result, the target flies out from the target holder due to inertia. We use high speed cameras SA-Z (made by Photron Ltd.) at 1st window and

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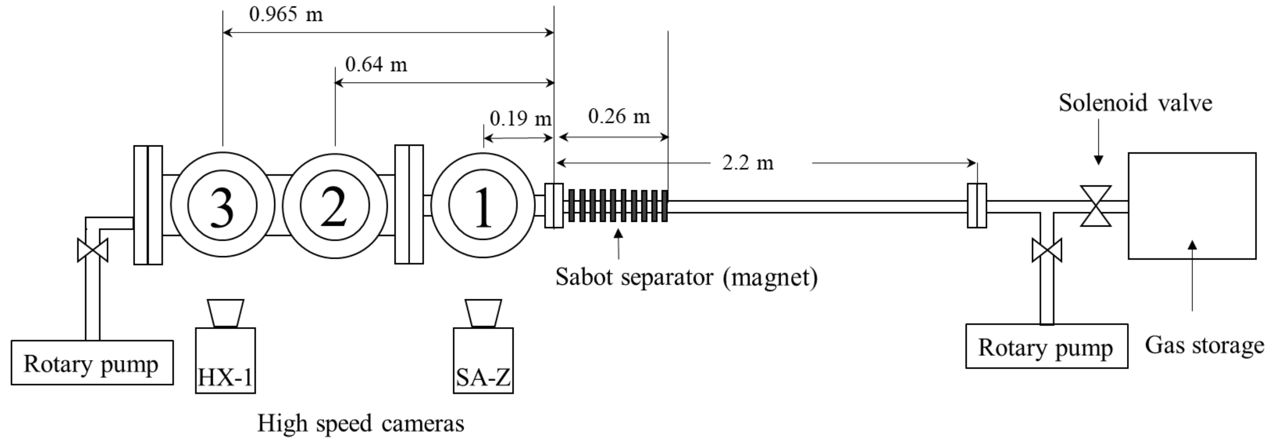

Fig. 1 Schematic diagram of the target injection system.

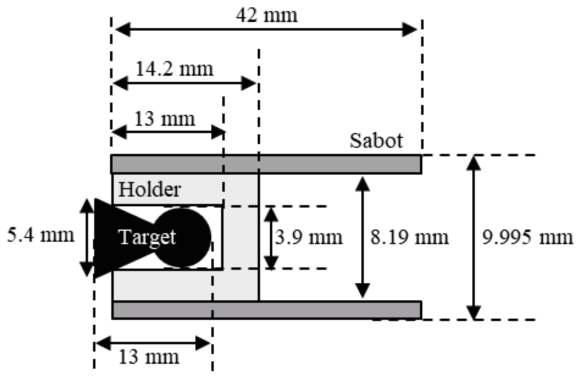

Fig. 2 Schematic diagram of the target assembly.

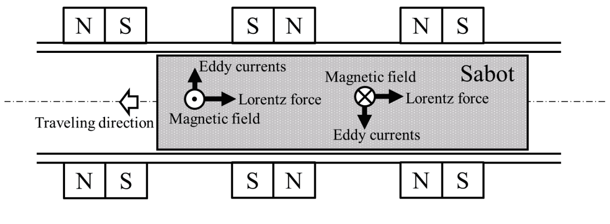

Fig. 3 Image of sabot separation mechanism.

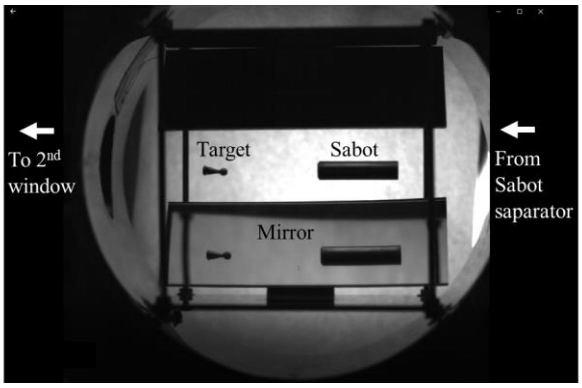

Fig. 4 Example of high-speed camera image at 1st window.

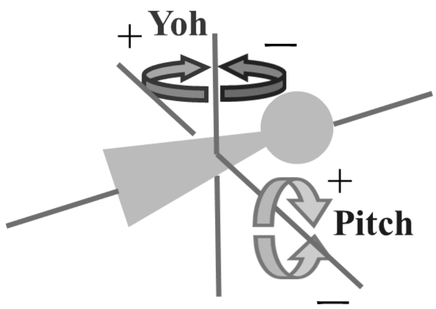

Fig. 5 Definition of flight angle axis.

HX-1 (made by nac Image Technology Inc.) at 3rd window to observe injected targets. Figure 4 shows an example of high-speed camera images at 1st window. The frame rate is 10000 fps. Mirrors are used to observe the flight attitude of targets in the yoh direction. Figure 5 shows the definition of flight angle axis. The pitch direction is the rotation around the left-right axis and the yoh direction is the rotation around the upper-lower axis.

3. Image Analysis of Injected Targets

We automatically cut out the area of injected target from a high-speed camera image by an image recognition program. Figure 6 shows an example of cut-out image set at 1st window. The cut-out images show that the injected target (frame number 5 to 20) and then the separated sabot (frame number 26 to 50) flies. In other frames, the target is not detected correctly or does not exist in the high-speed camera image. Figure 7 shows the time variation of the cut-out image position, which corresponds to the position of target. The vertical axis shows the position along flying direction in the high-speed camera image and the horizontal axis shows the frame number of the high-speed camera image which corresponds to time. As the target position (frame number 5 to 20) is changing linearly with time, target velocity is simply calculated from the gradient.

To get a flight angle, the cut-out target image is compared to the horizontal reference target image by changing

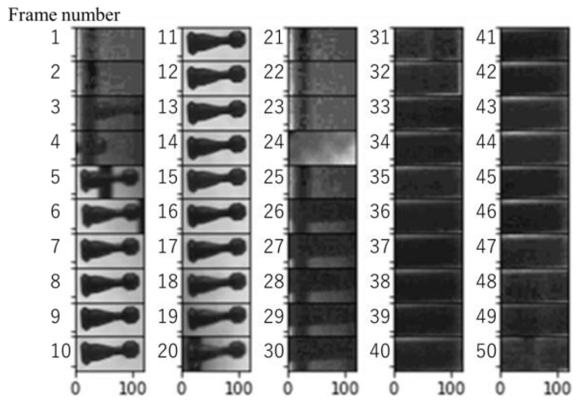

Fig. 6 Example of cut-out image set at 1st window.

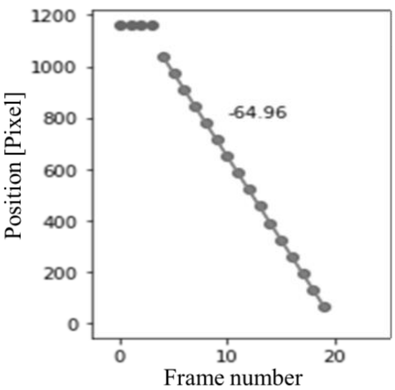

Fig. 7 Time variation of the target position.

its angle by 0.01 degree. The angle that matched the reference image the most was defined as the flight angle.

4. Results of Target Velocity Analysis

Figure 8 shows the result of target velocity analysis. The circle markers show data points measured in the air. One square marker shows data point measured in vacuum. It is seen that the target velocity is increased with the injection gas pressure. Here, the injection gas pressure is defined as difference between the pressure in the observation chamber and the pressure in the gas storage tank. Dotted line shows the value calculated by using the theoretical equation of flying pellet injection [10].

$$U(t) = \frac{2C_0}{\gamma - 1}\left[1 - \left\{1 + \frac{(\gamma+1)A_p}{2MC_0}P_0 t\right\}^{-(\gamma-1)/(\gamma+1)}\right]. \tag{1}$$

Here, $U(t)$ is target velocity at a time t after the application of the gas at pressure P_0. C_0 is the gas sound speed, γ is the ratio of specific heats. M and A_p are the assembled target mass and cross section, respectively. In our case, C_0 is 334 [m/s], γ is 1.4, M is 4.319 g and A_p is 78.46 mm^2. We calculated the target velocity at 1st window. As shown Fig. 5, the measured target velocity is about 70% of calculated velocity in the air and 80% of calculated velocity

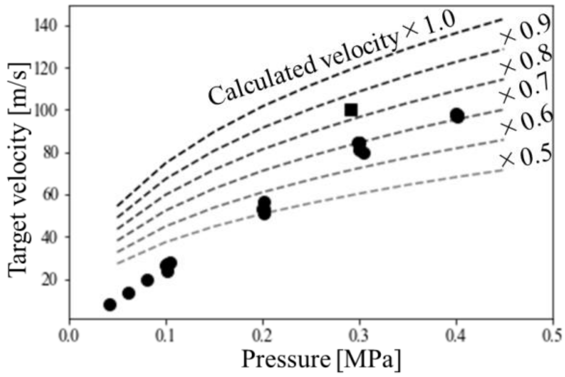

Fig. 8 Injection gas pressure dependence of the target velocity.

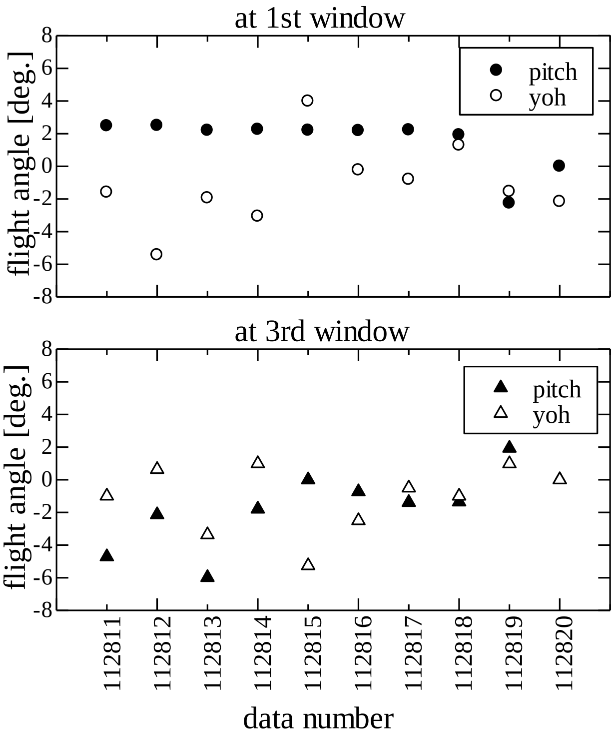

Fig. 9 Flight angle of the injected target.

in the vacuum. We think that the air resistance causes the lower target velocity in the air. In the theoretical equation, non-ideal effects such as friction is not considered. Thus, we think the difference between theoretical value and experimental data comes from these non-ideal effects. Note that our device achieved around 100 m/s target speed in vacuum, which meet the demanded target speed.

5. Results of Target Flight Angle Analysis

Figure 9 shows the results of target flight angle analysis. The horizontal axis shows the shot number. Closed symbols represent angles in the pitch direction. Open symbols represent angles in the yoh direction. It is seen that the target flight angle varies widely shot by shot. The max-

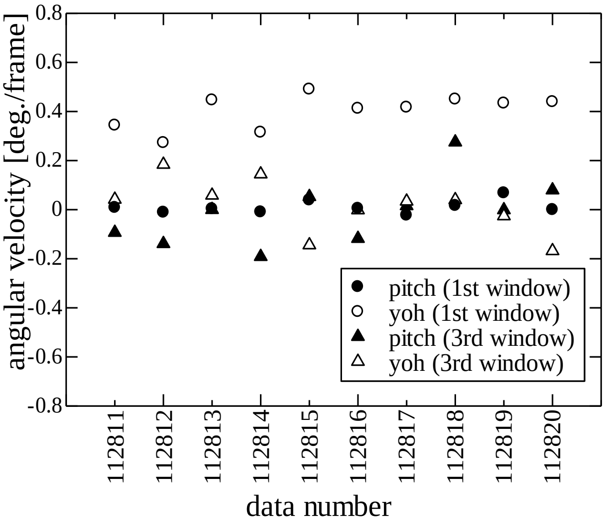

Fig. 10 Angular velocity of the injected target.

imum flight angle is about 5 degrees. This is far from the demanded specification. Figure 10 shows the change of the target flight angle, the angular velocity of the target, in 1st window and 3rd window. Note that the angular velocity is calculated in one window, not from 1st window to 3rd window, since the coordinate axes of the two cameras are not aligned. It is seen that the angular velocity is very small. The target flight angle may have been determined at the moment when the sabot is separated. Gas flow and the impact of the separation may disrupt the flight attitude.

6. Summary

We have assembled the target injection device. Mimic fast ignition targets are injected by nitrogen gas and its flight attitudes are observed by high-speed cameras. It is found that the injected target velocity depends on the injection gas pressure and it is about 80% of the calculated velocity in vacuum. The important thing is that our device can meet the demanded target velocity. It is also found that the flight angle varies shot by shot, up to about 5 degrees and it is not changed very much in chamber. This is far from the demanded value for a fusion reactor. To stabilize the flight attitude of the target, we plan to improve the form of target holder and injection system.

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