Visualization of Burning Flow Around the Projectile in Ram Accelerator by Coaxial Simultaneous Shadow/Direct Photograph

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1. Introduction

Ram accelerator is a device to accelerate a projectile with a sharp nose. When the projectile is injected at supersonic speed into the ram tube filled with combustible gas, the projectile is accelerated by high pressure caused by combustion. Ram accelerator is proposed by Herzberg et al. (1) in 1980's, after that, it has been studied by many researchers.(2)~(5) In Hiroshima University, the ram accelerator which we call HURAMAC, has been developed to study not only on the ram acceleration itself but also on the supersonic combustion.(6)~(8) Therefore, HURAMAC is designed to enable to visualize the inside of the ram tube, the cross section of which is rectangular to install the flat observation windows. The movement of the projectile is restricted by the rail attached on the wall of ram tube and the grooves on both side of the projectile. The projectile has the two-dimensional shape for fitting the rectangular bore tube, accordingly the flow field around the projectile is relatively simple and favorable for CFD.

In our experiments, the ram tube is filled with the methane-oxygen-carbon dioxide mixture. We observed the projectile traveling with the velocity slower than that of the C-J detonation of the mixture using instantaneous shadow photograph and the direct photographing. The measurements of the pressure history at the observing point are also very useful to understand the flow field. In the present paper, we show the experimental results on the flow fields around the projectile, such as shock wave, rarefaction waves, boundary layers and the flames.

2. Experimental Apparatus

HURAMAC consists of the pre-launcher, the helium evacuation tank, the ram acceleration part, and the deceleration part as shown in Fig.1. The projectile and the ignition/driving sabots shown in Fig.2 are accelerated up to more than 1.0km/s by two stage light gas gun in the pre-launcher section. The ram acceleration section consists of 0.2m length of the ignition tube and 4.0m length of the ram acceleration tube. In the ignition tube, hotter mixture gas that is diluted with relatively small amount of CO_2 is filled, so as to ignite easily by normal shock wave caused by ignition sabot. On the other hand, relatively colder gas diluted with larger amount of CO_2 is filled in the ram tube, not to detonate easily.

The projectile shown in Fig.2 is designed so that the reflected shock wave of leading oblique shock wave reaches to the top of the projectile shoulder, when the projectile velocity is about 1000m/s. Velocity range of HURAMAC to sustain the ram acceleration is larger than 1050m/s in our experiments. Therefore reflected shock wave attacks behind the shoulder of the projectile in the working range, and the flow patterns around the projectile are not affected so much by projectile velocity if the shot is executed without combustion.

The passage time of the projectile is recorded by 19 magnetic sensors installed along the ram tube and Sm-Co magnet attached in the projectile. The projectile velocity is measured by these recorded data. There are 6 measuring stations (ST1~ST6) where the pressure transducer and light sensor, magnetic sensor are installed in a same cross section. The first measuring station (ST1) is in the ignition tube.

3. Photographing method

Fig.3 shows the schematic diagram of the optical system for photographing. Observation windows made of quartz are installed at the 4th measuring station (ST4). The size of the window is 100.0x9.0mm^2. The light source of the shadow-graph optical system is a Nitrogen laser, the wave length of which is 337.1nm. Parallel beam of laser light made by condensing lens and the 1st concave mirror passes through the observation part, the 2nd concave mirror condenses the beam. The beam is reflected by the dichroic mirror, and lead into the film camera. The interference filter set in front of the camera cuts all of the light such as light from combustion, except the UV laser light. Camera lens is also made of quartz that is transparent for UV light. The camera shutter is left to open, and film is exposed by 5ns width of laser pulse. Used film is a black and white of ISO 400. On the

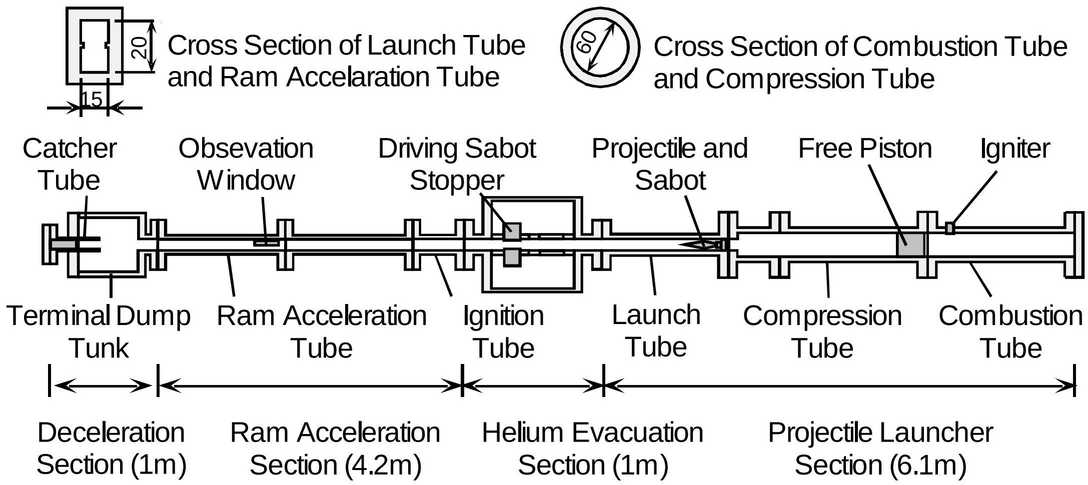

Fig.1 Experimental Apparatus

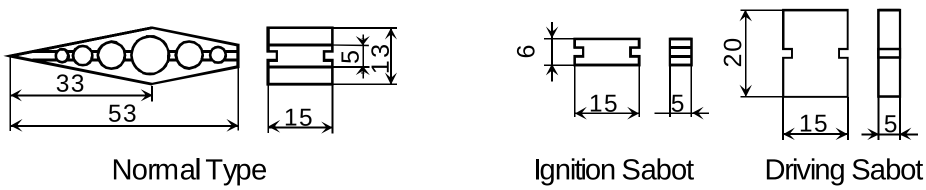

Fig.2 Projectile and Sabots

other hand, for the direct picture, some parts of the optical system of shadow-graph are utilized, so that the direct picture has the same optical axis with shadow-graph. In such optical system, the light emitted from flame is condensed by the 2nd concave mirror. Visible light from the flame, the wave length of which is longer than 450nm transmits the dichroic mirror. Selected visible light is reflected by mirror just behind the dichroic mirror, and lead into the high speed camera. The high speed CCD camera used in a direct photographing can take a black and white image of 640x480 pixels. The exposure time is 1.0 micro sec. Because of very short exposure time, the built-in image intensifier is used. When the projectile arrives at ST4, the pressure transducer set there detects the pressure jump from the shock waves generated by the leading wedge of the projectile. After some suitable delayed time from the pressure signal, the N_2 laser and the high speed camera are triggered.

4. Experimental results and discussion

Fig.4 shows an example of the the images obtained by simultaneous photographing. The image of (b) is the direct photographing image, and the image (c) is shadow-graph image. The pressure history is also shown in (a), where the abscissa is taken as the distance instead of the time by multiplying the velocity of projectile at the observation part, in order to compare with the pictures. The pressure sensor is set on the upper wall of the tube at the observation part. Fig.4 (d) is the sketch of the assumed image of the waves on the bases of the Fig.4 (a)-(c). Table 1 shows the experimental conditions. Ram tube is filled with the stoichiometric mixture of methane and oxygen diluted with the carbon dioxide of 5.1 times to methane in mole. C-J detonation velocity of the mixture is 1465m/s.

The case of Run No.377 shown in Fig.4 has relatively low projectile velocity. In such case, flame front

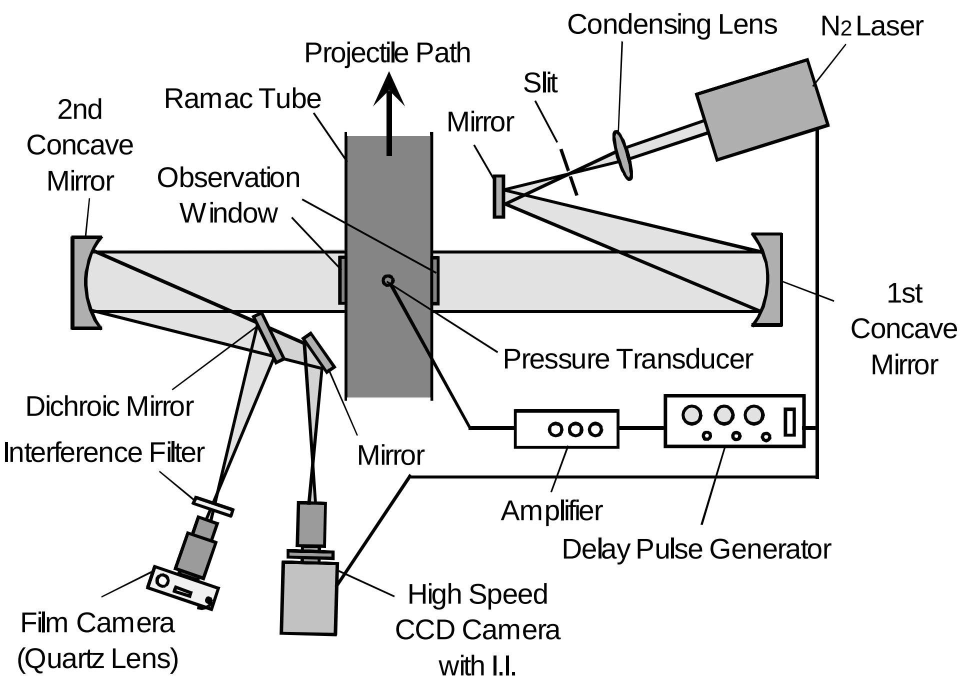

Fig.3 Schematic diagram of photographing system

frequently exists at the leading wedge part of the projectile. When the projectile comes into the ignition tube, where easily ignitable gas mixture is filled, the flame propagates quickly forward up to the front of the projectile. If the projectile velocity is enough high, the remained flame in boundary layer on the leading wedge of the projectile will be blew out and goes back to the rear part of the projectile. If the velocity is not so high as in the case shown in Fig.4, the flame front remains at the leading wedge [8].

It can be seen in the shadow-graph image of Fig.4(c) that the leading oblique shock wave has

Table 1 Experimental conditions

Run No.	#377
Gas mixture in ram tube :	
Composition	$CH_4+2O_2+5.1CO_2$
Pressure	0.4 MPa
Temperature	281 K
C-J velocity (V_{CJ})	1465 m/s
Gas mixture in ignition tube :	
Composition	$CH_4+2O_2+3.0CO_2$
Pressure	0.3 MPa
Velocity of projectile (V_P) at;	
-2nd measuring station [ST2]	1177 m/s
-4th measuring station [ST4]	1217 m/s
Mach number (V_P/a_0)	4.24
Ratio to C-J velocity (V_P/V_{CJ})	0.831
Projectile : Mass	4.8 g

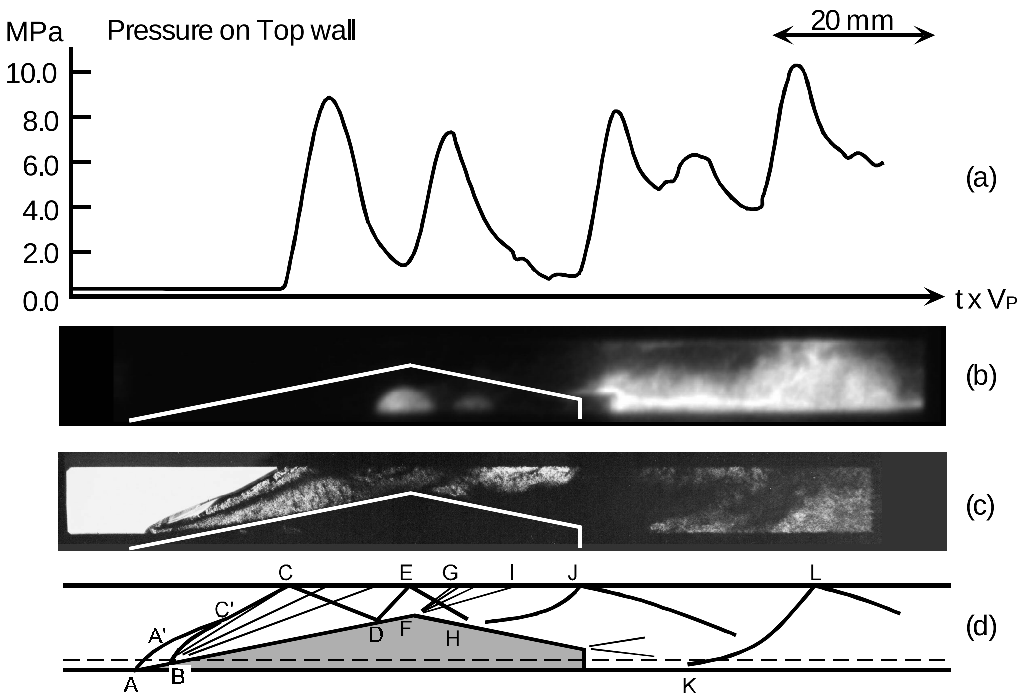

Fig.4 Images at the 4th measuring station for Run No.377. (a) The pressure history at the top wall, (b) the instantaneous direct photographing image, (c) the instantaneous shadow graph image, and (d) the sketch of the assumed image of the flame.

somewhat complicated shape. It is assumed that the tip of the wedge of the projectile is slightly damaged in this case. Moreover, a small piece of flame is expected to exist around the point B in Fig.4(d), because it can be seen that the shock wave is formed at this point. Two shock wave merge at point C' into one shock wave C'C. This leading oblique shock wave reflects at the top wall, then the pressure jump up to 9MPa as shown in Fig.4(a), which is much higher than 2.6MPa estimated by the leading wedge of the half angle 11.1 degree of the projectile. This peak pressure is reduced by the expansion wave from the point B, and the reflected shock wave makes pressure jump from point E. After the pressure oscillation like this, the strong combustion looks like occurring behind the point J in the shadowgraph image. On the other hand, in the direct photographing image, luminous flame can be seen behind the tail of projectile and spread to the whole tube area behind the reflected shock wave KL.

In the instantaneous direct photograph shown in Fig.4(b), we cannot see any luminous fragment of the flame in the boundary layer at the leading wedge. Therefore, it is assumed that the reaction of the combustion around there is very weak, but the flame front at the tail part of the projectile is not so clear. In the shadow photograph in Fig.4(c), the flame front at the tail part looks around the shock-boundary layer interacting point H.

5. Conclusion

Visualization of the supersonic combustion flow field around the projectile in the ram accelerator using the coaxial simultaneous shadow/direct photographing is conducted successfully. The luminous flame is observed behind the tail of the projectile. On the other hand, the luminosity of the flame at the leading wedge of the projectile is so weak that we cannot detect the visible light in the present experiments.

Reference

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