

# The effects of the dilution gas for the properties of acceleration and combustion on the thermal choking ram accelerator

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## Abstract

Properties of methane-oxygen-nitrogen mixture for ram accelerator was investigated by comparing with the methane-oxygen-carbon dioxide mixture. The results indicate that the rate of reaction in combustion region of nitrogen dilution case is slower than carbon dioxide dilution. It was also found that the several factors strongly affect the stability of the ram acceleration. Projectile Mach number and thermal choking pressure can be thought as the effective factors.

## 1. Introduction

Ram accelerator is the hypervelocity mass launcher based on the ramjet-like cycle<sup>(1-2)</sup>. HURAMAC, which is the ram accelerator developed at Hiroshima University<sup>(3-4)</sup>, introduces the rectangular bore tube to enable the visualization inside the tube, and the thermal choking ram acceleration mode is confirmed by this device<sup>(5-7)</sup>. In this study, the methane-oxygen-carbon dioxide mixture used in the previous series of studies was changed to the methane-oxygen-nitrogen to simulate the pre-mixed combustion of methane-air mixture in the supersonic flow. The properties of acceleration and combustion were investigated to clarify the effects of the dilution gas.

## 2. Experimental Apparatus

HURAMAC shown in Figure1 consists of the initial launcher section and the ram acceleration section. The

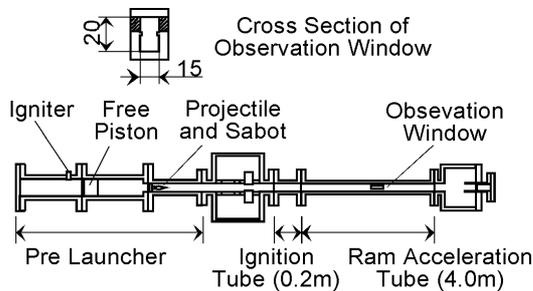


Fig.1 Experimental apparatus

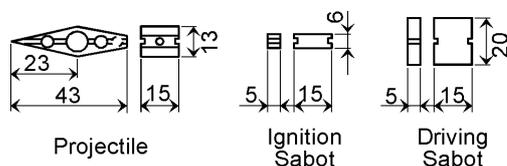


Fig.2 Projectile and sabots

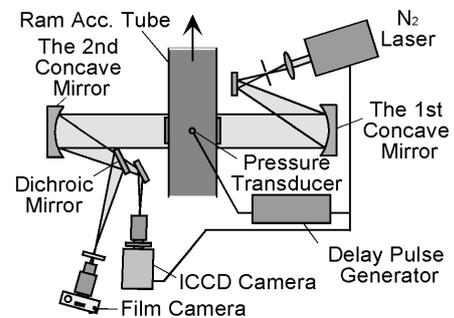


Fig.3 Optical system for simultaneous co-axial shadow/direct photography

launcher tube of light gas gun and ram acceleration tube has rectangular cross section. The ignition tube, which is 200mm long and filled with hotter gas diluted with relatively small amount of inert gas, is set just ahead of the ram acceleration tube. Therefore, reliable ignition for wide range of the projectile entry velocity is achieved. The projectile velocity and the pressure history are recorded during the projectile moving in the ram acceleration tube of 4000mm long. Projectile and ignition sabot, driving sabot are shown in Figure2.

The observation window is set at the 2300mm from the inlet of the ram acceleration tube. The upper half of the tube, which is 100.0 x 9.0mm, is visualized. The optical system for co-axial and simultaneous shadow/direct photography is shown in Figure3. Nitrogen laser with the wavelength of 331nm is used as a light source of shadowgraph photography. The dichroic mirror, which reflects the UV radiation from Nitrogen laser and transmits the visible radiation of combustion emission, realizes the co-axial shadow/direct photography.

### 3. Results and discussion

#### 3.1 Experimental conditions

Table1 shows the experimental conditions. Combustible mixture filled in the ram acceleration tube is stoichiometric methane-oxygen diluted with carbon dioxide or nitrogen. Initial pressure in ram acceleration tube is 0.4MPa, which is the factor of 1/5-1/10 lower than that of another facilities for protecting the observation window. Properties of the mixture, such as thrust and the conditions of burnt gas on the thermal choking mode, can be assumed by quasi-steady one-dimensional model proposed by Knowlen et al.<sup>(8)</sup> Non-dimensional heat release ( $q/c_p T_0$ ), and thermal choking pressure at Mach 4.0 are calculated by the model and shown in table1.

#### 3.2 Comparison of cold shot

The experiment of cold shot, which is the shot without igniting the mixture, was conducted to observe the flow field around the projectile, which is not affected by the flame. The results of the cold shot include the pressure history, shadowgraph image and the sketch are shown in Figure4. Passage time of pressure history is multiplied with the projectile velocity for easy comparison with the shadowgraph image. The flow pattern of two cases is similar each other, because the projectile Mach number is almost the same. The only difference between two cases is the flow pattern behind the projectile shoulder. In the case of carbon dioxide dilution, oblique shock wave from just behind the shoulder to the top wall, which is not seen in the nitrogen case, can be seen and makes pressure rise after the first pressure peak.

Table1 Experimental Conditions

	690	818
Mixture in Ram Tube ( $\text{CH}_4+2\text{O}_2+\text{X}$ )	4.7 $\text{CO}_2$	10.7 $\text{N}_2$
Initial Pressure in Ram Tube MPa	0.4	
Initial Temperature K	300	287
Acoustic Velocity m/s	296	346
CJ Detonation Velocity m/s	1495	1707
Non-dimensional Heat Release ( $M=4.0$ )	9.22	6.77
Thermal Choking Pressure MPa ( $M=4.0$ )	4.85	4.73
Mixture in Ign. Tube ( $\text{CH}_4+2\text{O}_2+\text{X}$ )	3.5 $\text{CO}_2$	7.4 $\text{N}_2$
Initial Pressure in Ign. Tube MPa	0.3	
Mass of Projectile g	4.2	3.9
$M_p(V_p \text{ m/s})$ at ST2	3.52 (1044)	3.50 (1211)
$M_p(V_p \text{ m/s})$ at ST4	4.26 (1263)	4.11 (1424)

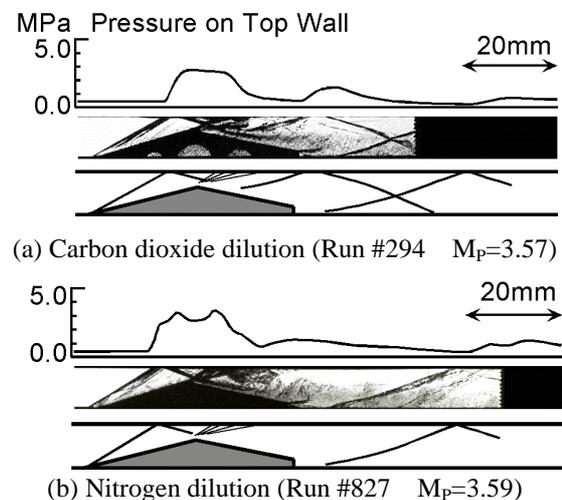
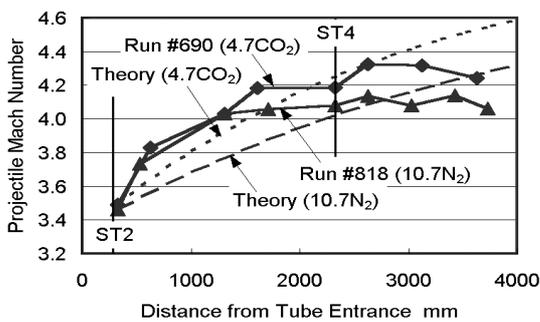


Fig.4 Flow field around the projectile in cold shot case [Pressure history, shadowgraph image, sketch]

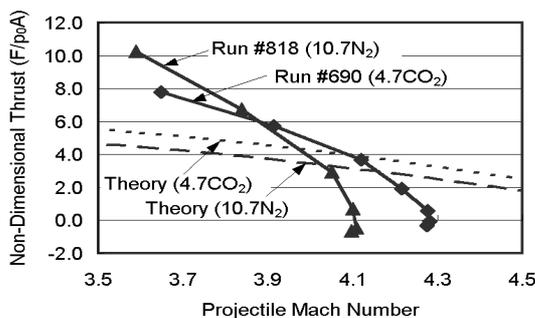
### 3.3 Properties of acceleration and combustion in hot shot

Figure 5(a) shows the variation of projectile Mach number along the ram acceleration tube. Mach number change calculated by quasi-steady one-dimensional theory is also plotted as a dotted line. The projectile is injected into the tube at about Mach 3.5 in both cases, and then projectile is accelerated in the similar Mach number profile. Acceleration is very large in the first half of the tube, however it is peaked in the latter half section. Although increase of Mach number from entry to peak is larger in the case of carbon dioxide than nitrogen case, increase of the projectile velocity is about 200m/s in both cases. Figure 5(b) shows the projectile Mach number vs. non-dimensional thrust profile. Non-dimensional thrust is the thrust divided by initial pressure and the area of tube cross section. Theoretical value is also shown in the figure. Initial thrust is much larger than that of theory, especially that is twice of the theoretical value in the nitrogen case. However, thrust gets lower than theoretical value as projectile moves in the tube and projectile Mach number increase. This tendency is the character of HURAMAC and assumed that the large acceleration immediately after the entry indicates that the acceleration itself is strongly affected by the ignition process.

Results of the visualization include the pressure history, shadowgraph image, direct photograph and sketch are shown in Figure 6. The flow pattern ahead of the projectile shoulder in the shadowgraph image is similar to that of cold shot shown in fig.4. This indicates that the flame does not affect this region. Pressure rise caused by the shock wave in front of the combustion region can be seen behind the pressure peak made by the leading oblique shock wave from the wedge. Pressure gradually increases up to thermal choking pressure. The region behind the projectile is dark shadow, which is not shown in the cold shot case. Here is the region affected by the flame. The region in nitrogen case is pitch dark as compared to the carbon dioxide case, which has bright part around the tube axis. In the shadowgraph photography, the region with large refraction factor becomes dark. If the density becomes small by combustion, refraction factor must become small as well. Therefore, the degree of the completion of combustion affects strongly to the refraction factor. Additionally, emission from combustion region in direct photograph in nitrogen dilution can be

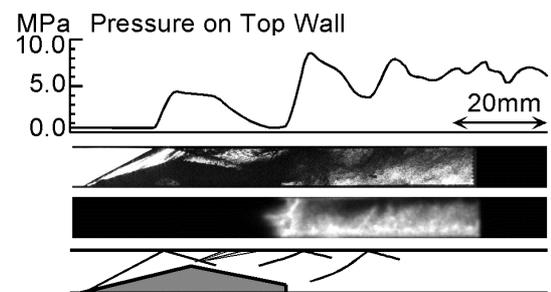


(a) Variation of projectile Mach number

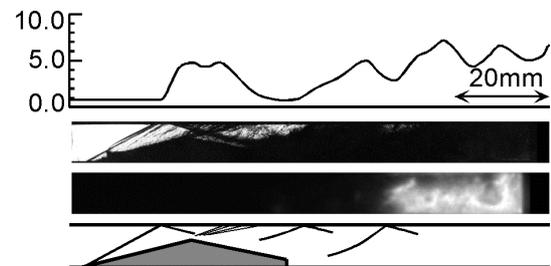


(b) Variation of non-dimensional thrust

Fig.5 Relation between thrust and projectile Mach number



(a) Carbon dioxide dilution (Run #690  $M_p=4.26$ )



(b) Nitrogen dilution (Run #818  $M_p=4.11$ )

Fig.6 Flow field around the projectile in hot shot case [Pressure history, shadowgraph image, direct photograph sketch]

seen far from the projectile compared to the carbon dioxide dilution. Accordingly, it can be assumed that reaction rate of the combustion region of carbon dioxide is larger than that of nitrogen dilution.

#### 3.4 Stabilization of ram acceleration phenomena

In the previous series of study, the successful start of ram acceleration has obtained at Mach number of 3.5-4.5 in the condition of carbon dioxide dilution. In the nitrogen case, the stable ram acceleration could not be obtained at the condition of less than Mach 3.5. Therefore, Mach number must be one of important factors on stability. Quasi-steady one-dimensional theory says that the non-dimensional heat release might be also a factor for ram acceleration phenomena. As shown in table1, non-dimensional heat release for successful ram acceleration in carbon dioxide dilution is 36% larger than that of nitrogen dilution. This large difference indicates that non-dimensional heat release is not the factor for the stabilization. On the other hand, it can be speculated that thermal choking pressure might be the factor, because the stabilized ram acceleration exists on the delicate balance of combustion region sustained by the thermal choking pressure. The difference of thermal choking pressure between two cases is 3% as shown in table1. Consequently, thermal choking pressure is more important than non-dimensional heat release on the consideration of the stabilization of ram acceleration.

#### 4. Conclusion

Successful ram acceleration with methane-oxygen-nitrogen mixture as well as methane-oxygen-carbon dioxide was obtained. The following results were clarified by comparison of two different mixtures.

- 1) Flow pattern just behind the projectile shoulder in cold shot case is different.
- 2) The thrust immediately after the entry of projectile is larger than theory, and peaked in the latter half of acceleration tube. This is the result of the strong effect of the ignition process.
- 3) Rate of reaction in combustion region is smaller in the nitrogen dilution case than that of carbon dioxide dilution case.
- 4) The minimum projectile Mach number for the stable ram acceleration is 3.5 in both cases.
- 5) Thermal choking pressure is more important than non-dimensional heat release on the consideration of the stability of ram acceleration. In case of the HURAMAC at the condition of 0.4MPa in initial pressure, 4.8MPa of thermal choking pressure at Mach 4.0 realizes the stable ram acceleration.

#### Reference

- [1] Hertzberg A., Bruckner A.P., Bogdanoff D.W., AIAA J 26:195-203 (1988)
- [2] Bruckner A.P., Proc of the 3rd Int Workshop on Ram Accelerators, pp3-23 (1997)
- [3] Chang X., Kanemoto H., Shiro Taki, ISTS Paper 94-a-05 (1994)
- [3] Chang X., Kanemoto H., Taki S., AIAA Paper 95-2496 (1995)
- [4] Taki S., Yatsufusa T., Zhang C., The 3rd Asian-Pacific Conference on Technology and Science, pp363-368 (2000)
- [5] Yatsufusa T., Chang X., Shiro Taki, AIAA Paper 2001-1765 (2001)
- [6] Yatsufusa T., Taki S., Shock Waves Vol.12, pp235-240 (2002)
- [7] Yatsufusa T., Taki S., 18th Int Colloquium on the Dynamics of Explosions and Reactive Systems (2001)
- [8] Knowlen C, Bruckner A.P., Shock Waves, Springer-Verlag, Berlin, pp617-622 (1992)