The Numerical Study on Superdetonative Mode Ram Accelerator Affected by Aluminum Vapor

Kunmin Sung and In-Seuck Jeung
School of Mechanical and Aerospace Engineering, Seoul National University
151-742, Seoul, Republic of Korea

1 Introduction

A ram accelerator is a device used for accelerating projectiles with synchronized combustion through a tube filled with a pre-mixed combustible gas mixture. A projectile is accelerated continuously through a ram tube; a high final speed may be obtained with a long ram tube. Therefore, ram accelerators can be utilized as hypervelocity launchers or direct launchers for low earth orbits. Additionally, the gas dynamics of ram accelerators are based on oblique detonation waves and shock induced combustion. Therefore, study on ram accelerator operation will enhance the understanding of supersonic combustion and hypersonic propulsion systems.

ISL (French-German Research Institute of Saint-Louis) developed a rail tube version of a ram accelerator facility named RAMAC 30 version II, which directly launches projectiles at superdetonative speed. Figure 1~3 shows the schematics of RAMAC 30 test facility. A projectile is launched by a powder gun and accelerated in a ram accelerator tube having four or five guide rails [1]. The RAMAC 30 version II test facility is comprised of a pre-accelerator tube, a ram tube containing a combustible gas mixture with both ends sealed by diaphragms and a decelerator tube. The ram tube was composed of two tubes of which one tube was 2.4 m in length. Projectiles possess an inner magnesium core fully covered by aluminum or steel (different by experimental shot). The mass of the cylindrical projectiles is between 130 g and 150 g. The caliber is 30 mm and length is 153 mm with rounded tail. Projectiles are accelerated 1800 m/s at the exit of the pre-accelerator tube, accelerating through the mixture in the rail tube version II. Although the initial launching speed of the projectile was only 1800 m/s, the superdetonative launch was made possible by using an $H_2/O_2/CO_2$ mixture having a low C-J (Chapman-Jouguet) detonation wave speed. Experimental results showed successful ignition and acceleration with an aluminum projectile, but acceleration was not observed with a steel

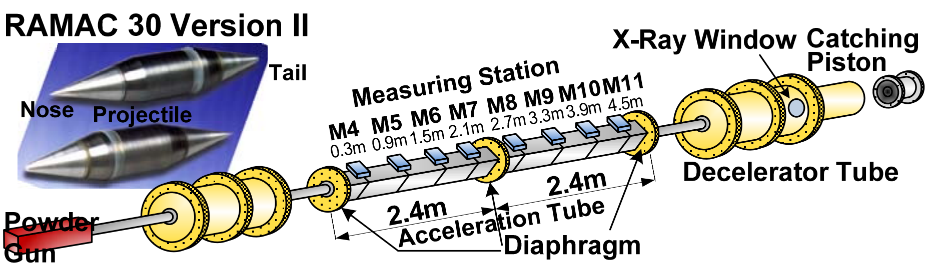

Figure 1. Schematic of RAMAC30 V II

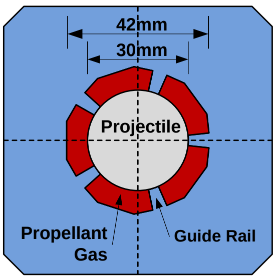

Figure 2.Acceleration Tube Cross Section

Correspondence to: enjis@snu.ac.kr

projectile. Test cases with an aluminum projectile showed significant ablation [2]. Thus, ablation of a projectile is certainly related to the ignition and combustion of a gas mixture.
In the early stages of ram accelerator studies, the superdetonative mode operation which is operated by an oblique detonation wave was considered. Computational studies by Yungster and Bruckner [3] and Li et al. [4] using an inviscid flow model and chemical kinetics showed that a ram accelerator can be operated by oblique detonation wave in very high velocity ranges. Yungster [5] and Choi et al. [6] demonstrated that combustion could be initiated in the boundary layer; shock wave/boundary layer interaction can initiate combustion in intermediate velocity ranges in which shock-heating is insufficient for the ignition of the mixture. However, previous studies on the combustion characteristics of the superdetonative mode operation are not applicable to the ISL ram accelerator experimental results. In this study, a numerical simulation was conducted on the S225 experimental case presented by the ISL in order to understand the combustion mechanism affected by aluminum.

2 Numerical Methods

For computational study of ram accelerator, a fully coupled form of multi-species conservation equations and Reynolds averaged Navier-Stokes equations coupled with Baldwin-Lomax turbulence modeling was used for axisymmetric geometry. Typical operational pressure of ram accelerator is higher than 50atm and reduced kinetic mechanism for low pressure can not applicable. This study applied reduced kinetics mechanisms for Ram Accelerator developed by Petersen and Hanson [7]. The CO_2 reaction steps of GRI-Mech 3.0 is appended and Al reaction mechanism developed by Catoire et al. [8] is applied for $H_2/O_2/Al$ reaction : 17 species (H, H_2, O, O_2, OH, H_2O, HO_2, H_2O_2, CO, CO_2, Al, AlO, AlO_2, AlOH, Al_2O, Al_2O_2, Al_2O_3) and 39step reaction. Govern equation is discretized by finite volume cell vertex approach. Viscous flux is discretized by central differencing and convective flux is obtained by Roe's flux difference splitting method [9]. Primitive variables are extrapolated at cell interface by MUSCL (Monotonic Upstream method for Scalar Conservation Law) scheme [10]. Discretized equation is time integrated by LU-SGS scheme [11]. Previous studies validated the computational code for the current study [6, 12]; exceptional results were obtained for the analysis of shock induced combustion and detonation waves.

3 Computational Modeling

Figure 3 shows computational conditions and domain. Diameters of a projectile and a tube are 3.0 cm and 4.2 cm, respectively. For the experiment, the tube wall had a decagonal cross-section with five rails but in this study assumed circular for the axisymmetric simulations. Initial launching speed was 1800m/s from the experiment. The thrust is computed from summation pressure drag(area integrals on projectile surface) and viscous drag. Acceleration of projectile is evaluated and speed is updated by every step. Mixtures for shot 225 had a pressure and temperature of 40 bar and 300K, respectively.

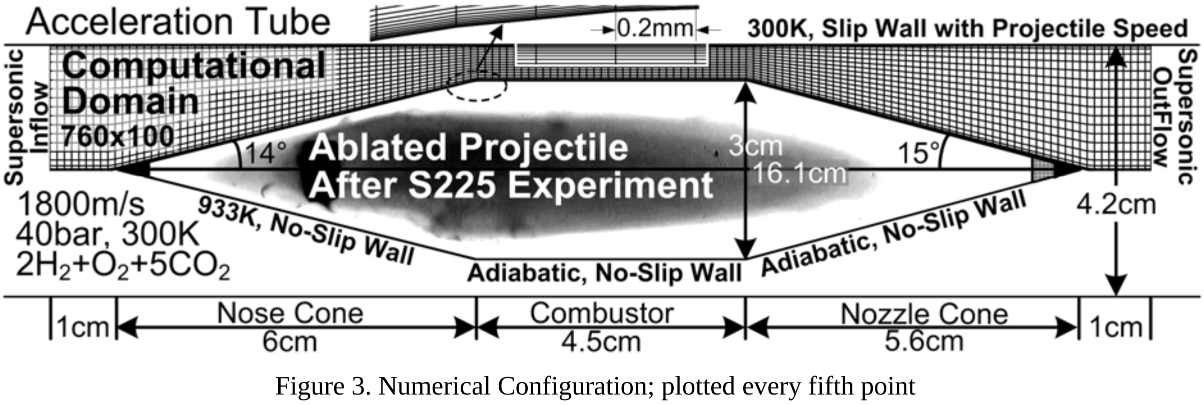

Figure 3. Numerical Configuration; plotted every fifth point

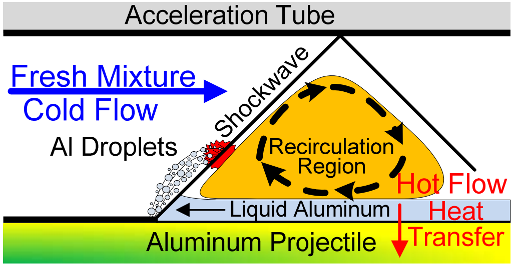

Figure 4. Aluminum Input Model

The gas composition used for shot 225 was $2H_2$+O_2+$5CO_2$: a stoichiometric H_2/O_2 mixture diluted with 5 moles of CO_2.

The computational domain for the simulation was extended by 1cm before and after the projectile, and it was covered by the 760x100 computational grids that was uniformly distributed in the axial direction and clustered to both walls in the radial direction. This resolution is higher than the previous study about superdetonative mode ram accelerators [6]; the resolution of mesh is enough to represent the shockwave and combustion wave system.

The experiment shot number 225 of ISL showed successful acceleration of projectile with the severe damage of projectile; figure 3 shows the projectile after test shot 225. The experimental result shows molten aluminum affected the combustion process. The projectile is severely heated in high temperature environment. The exhaust gas temperature overs 2000K, is enough to melting aluminum (the melting temperature is 933K) projectile. Although the projectile is melted by heat transfer, the molten aluminum doesn't have enough momentum to across the fast flow field. The liquid aluminum cannot vaporize because of heat loss to the solid aluminum. Without vaporizing, the liquid aluminum cannot react with $H_2/O_2/CO_2$ mixture, which can move on the projectile surface along supersonic

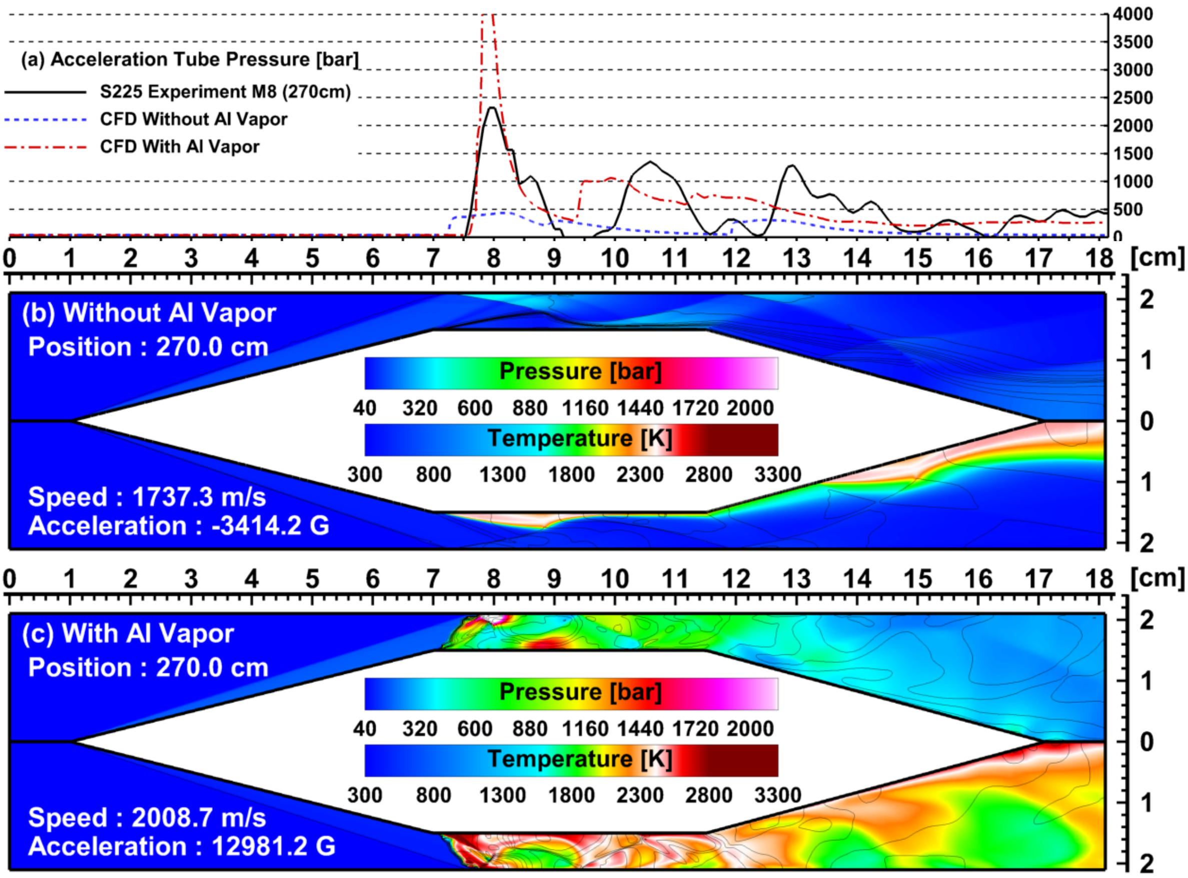

Figure 5. Comparison of the case with Al vapor and the case without Al vapor

flows. In recirculation region, the liquid aluminum can move reverse direction of inflow. If liquid aluminum reaches the stagnation point of separation bubble, aluminum can be ejected into flow at stagnation point and break up. The aluminum droplet is vaporized immediately when it meets high temperature region of separation bubble. Figure 4 shows the schematics of Aluminum input modeling. In order to research the effect of aluminum by the chemical reaction, it is enough to consider of gas phase aluminum. Therefore, in this study aluminum input was modeled as aluminum vapor in front of separation bubble. In axial direction, stagnation point can be found by searching the flow direction change from positive to negative. The spread range of aluminum vapor is assumed like 0.2~0.8mm height from combustor surface.

4 Results

The role of aluminum vapor which reduce the ignition delay of $H_2/O_2/CO_2$ mixture was studied by Catorie[8]. However, the interaction between aluminum mechanism and supersonic flow in ram accelerator is not unveiled. In this study, two cases are presented; the computation case without aluminum vapor and with al vapor.

The non-aluminum case(Fig. 5(b)) shows the regular reflection of weak shockwaves and boundary layer flames, whereas the aluminum case(Fig. 5(c)) shows the strong shockwave reflection and combustion. While the most of mixture pass through combustor without reaction for non-aluminum case, all mixture reacts in aluminum case. The tube wall pressure of aluminum case increases enough to accelerate projectile. The case without aluminum shows deceleration of projectile.

If aluminum exists in front of separation bubble, ignition delay time decreases and rapid heat release make stiff shockwave(Fig. 6(a)). This shockwave is composited with incident shockwave under the acceleration tube(Fig. 6(b), (c)). Although the combustion is induced by shockwave, the combustion wave is detached from shockwave; the shockwave is not enough to strong to develop stable detonation (Fig. 6(d), (e)). The next strong combustion wave due to aluminum vapor is generated (Fig. 6(f)) and

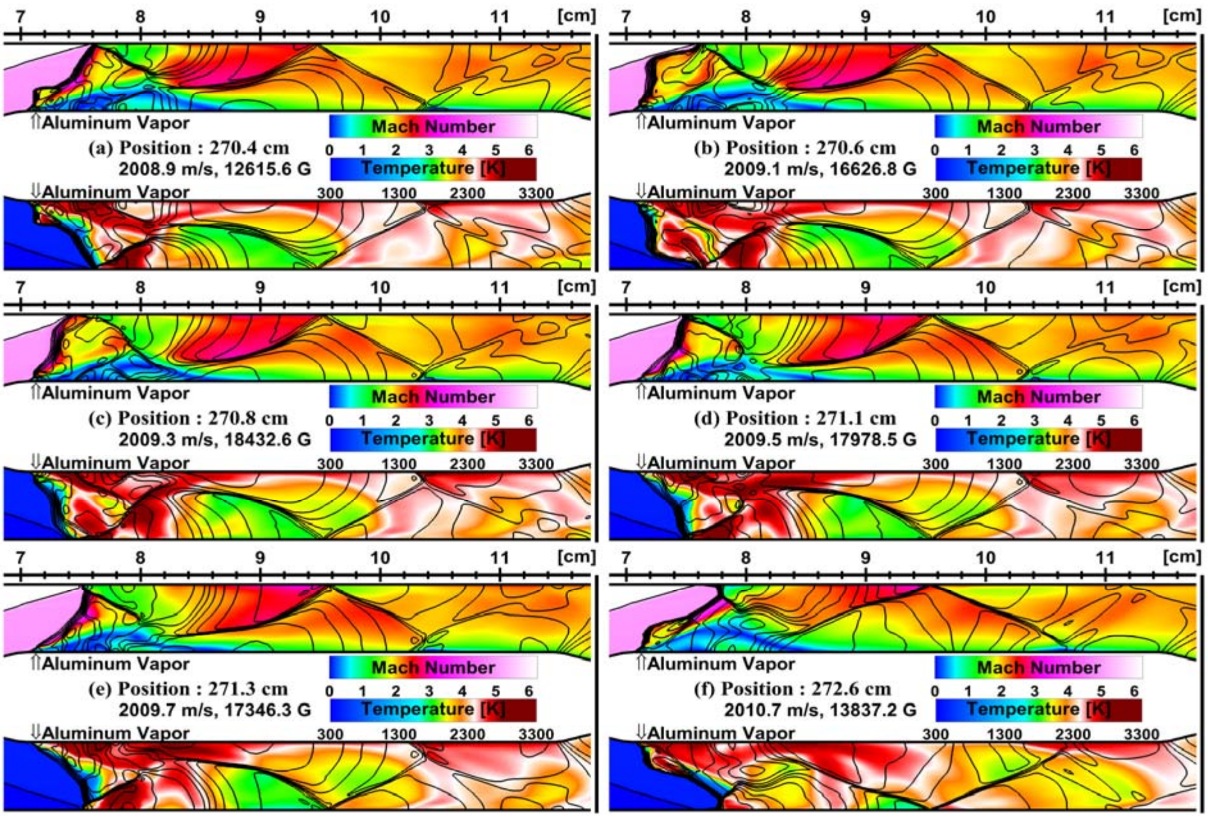

Figure 6. Evolution of Flame with Al vapor; Mach contour overlaid with pressure contour line and temperature color contour overlaid with pressure contour line

these sequence is repeated.

5 Summary

This study shows the flame structure of superdetonative mode ram accelerator which is affected by aluminum vapor. Although the aluminum vapor helps to make small reaction zone in front of separation bubble, this small pilot flame propagate to fresh mixture. The comparison of aluminum case and non-aluminum case shows that aluminum vapor strongly affects to combustion; aluminum vapor dramatically prompt the overall combustion processes and the ram accelerator can successfully accelerate.

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