## Numerical Study of Normal Start and Unstart Processes In a Superdetonative Speed Ram Accelerator

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A numerical study was conducted to investigate the combustion phenomena of normal start and unstart processes based on ISL's RAMAC 30 experiments with different diluent amounts and fill pressures in a ram accelerator. The initial projectile launching speed was 1.8 km/s which corresponded to the superdetonative speed of the stoichiometric  $H_2/O_2$  mixture diluted with 5CO<sub>2</sub> or 4CO<sub>2</sub>. Experiments with same condition except for projectile surface material demonstrated that ignition was successful with an aluminum projectile, but no combustion was observed in case of a steel projectile. In this study, it was found that neither shock nor viscous heating was sufficient to ignite the mixture at a low speed of 1.8 km/s, as was found in the experiments using a steel projectile. However, we could succeed in igniting the mixtures by imposing a minimal amount of additional heat to the combustor section and simulate the normal start and unstart processes found in the experiments with an aluminum projectile. For the numerical simulation of supersonic combustion, multi-species Navier-Stokes equations coupled with a Baldwin-Lomax turbulence model and detailed chemistry reaction equations of  $H_2/O_2/CO_2$  suitable for highpressure gaseous combustion were considered. The governing equations were discretized by a high order accurate upwind scheme and solved in a fully coupled manner with a fully implicit, time accurate integration method. The viscous terms were discretized by central difference and the convective terms were expressed as differences of numerical fluxes at cell interface. The numerical fluxes containing artificial dissipation were formulated using Roe's FDS(Flux Difference Splitting) method. MUSCL (Monotone Upstream Method for Scalar Conservation Law) scheme was used for the extrapolation of primitive variables at cell interface. The discretized equations were solved by a fully implicit, time integration method based on a LU-SGS scheme.

Figure 1 presents the numerical results for shot 225 without any forced ignition mechanism. For the frozen flow result in Fig. 1 (a), the pressure contours show that a regular shock reflection pattern and a separated flow region was formed at the projectile's surface from shock wave / boundary layer interaction. It is readily understood that the separated flow region will be a point of self-ignition due to the high temperature by flow stagnation.

Reactive flow solution in Fig. 1 (b) starting from the frozen flow solution shows burnt gas region bounded by a strong temperature gradient. Combustion generated by thermal dissipation was largely confined to the thin combusting layer near the projectile's surface and didn't ignite the flow outside the boundary layer. So, the combustion region started from the enlarged separated flow region and extended to the exit remaining as a boundary layer flame.

Figure 2 shows the numerical results of shot 225(5CO<sub>2</sub>) and shot 228(4CO<sub>2</sub>) which demonstrated normal start and unstart process according to the diluent composition, respectively. At an earlier stage of ignition, the flame front was created perpendicular to the tube wall by the ignition energy. In case of shot 228 with more energetic mixture, ignition energy imposed on the front section of combustor was 1/4 the amount of shot 225(Fig. 2 (a) S1, Fig. 2 (b) U1). As time proceeded, the flame front interacted with the conical shock which was reflected on the tube wall. The reflected shock and reaction front created a large separation bubble just forward of the interaction point at the projectile surface. But, the flame between projectile and tube wall was forced to move downstream by supersonic flow for both cases because the flame front was coupled to the reflected shock front and hence a detonation was formed near the tube wall. In case of shot 225 the location of detonation was same in the beginning but it was forced to move downstream, where the reflected shock and separation-induced shock were focused due to a relatively weak mixture(Fig. 2 (a) S3, Fig. 2 (b) U3). As the separation bubble grew, the separation-induced shock had more strength.

Therefore, the focusing point of reflected shock and separation-induced shock moved ahead of the detonation wave, where a strong shock-induced combustion was occurred. Accordingly, the detonation wave of shot 225 was forced to move downstream by supersonic flow because the flame front was not strongly sustained(Fig. 2 (a) S4). In case of shot 228, strong shock-induced combustion was occurred where the separation-induced shock was reflected as the separation bubble grew and moved upstream. But initially formed detonation wave looked

stationary because of the energetic mixture, although it gradually weakened by expansion waves behind the separation bubble(Fig. 2 (b) U4).

Finally, the flame front of shot 225 was blown off downstream near the tube wall and strong reattached / reflected shock created a second separation bubble at the projectile surface. The edge of the separation bubble acted as a flame front around the projectile surface, while detonation was formed near the tube wall where the strong reattached shock was reflected. Accordingly, the whole flame structure became stable and continuous acceleration was plausible with the  $2H_2+O_2+5CO_2$  mixture(Fig. 2 (a) S5). In case of shot 228 the separation bubble near the shoulder greatly enlarged and moved upstream. Furthermore, the combustion wave, basically driven by a very strong shock-induced combustion, also traveled upstream in front of the projectile. The projectile now moved into a high pressure flow field sustaining high drag forces, called unstart, followed by a strong projectile deceleration(Fig. 2 (b) U5)

In order to analyze the relationship between the wall pressure and the combustion mechanisms in a ram accelerator, schematics are presented in Fig. 3. Figure 3 (a) represents the flow result S4 of Fig. 2 (a), while Fig. 3 (b) is from the flow results U4 of Fig. 2 (b). In the tube wall pressure curve of Fig. 3 (a), (a1) is 40 bar, the initial mixture pressure in the ram tube, (a2) represents the pressure of about 1700 bar raised by the incident / reflected shock combined with the separation-induced shock and its associated reflected shock. After that, pressure is decreased to about 1500 bar by expansion waves generated in front of the separation bubble. The pressure peak (a3) corresponding to about 2900 bar is due to a strong shock-induced combustion and considered as a Von Neumann spike. After the pressure peak, pressure is decreased considerably due to strong expansion waves behind the separation bubble. Point (a4) shows the pressure increased to 950 bar by combination of a reattached and associated reflected shock produced by compression waves behind the separation bubble. The pressure is modestly stationary due to the expansion waves generated from the combustion wave but second pressure peak of 2600 bar (a5) appears again due to a normal detonation wave. Behind the detonation wave, the pressure level is decreased to about 600 bar, denoted by (a6), as a result of the expansion accompanied behind the detonative combustion. Fig. 3 (b) of shot 228 can be understood in the same way, noting that the first separation bubble stabilized at the projectile's nose cone is considerably larger than its counterpart in Fig. 3 (a).



Fig. 1 Temperature and Pressure Contours from Numerical Simulation of Shot 225 without Any Forced Ignition Mechanism. (a) Frozen Flow, (b) Reactive Flow.



Fig. 2 Initiation and Evolution of Detonation with External Ignition Source.



Fig. 3 Comparisons of Acceleration between Experiment and Numerical Simulation (a) Experimental Result, (b) Numerical Simulation Result