Numerical Study of the Effect of Shock Strength on the Normal Start and Unstart Process in a Superdetonative Mode Ram Accelerator

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The concept of accelerating a projectile flying in a tube at supersonic speed by projectile-synchronized ignition of a pre-mixed combustible gas mixture, the ram accelerator, has the similar gasdynamic phenomena as those expected to occur in scramjet and oblique detonation wave engines. Therefore, investigating the different realms of ram accelerator operation enhance the understanding of hypersonic propulsion phenomena in general. ISL (French-German Research Institute of Saint-Louis) has developed a ram accelerator facility named RAMAC 30 version II that bypassed the gasdynamic transition directly from subdetonative to superdetonative ignition. In this facility, a cylindrical projectile having conical fore- and afterbodies was accelerated in a ram accelerator tube having five guide rails.

Numerical simulations based on ISL's RAMAC 30 experiment of shot 225[1] with an aluminium projectile, were carried out to understand the effect of shock strength on the combustion mechanism in a superdetonative mode ram accelerator. Initial launching speed was set to 1,800m/s from the experiment and the gas composition used for shot 225 was $2H_2+O_2+5CO_2$. Initially the mixture had a pressure and temperature of 40 atm and 300K, respectively. Conical shock strength was varied by increasing the nose cone angle. For the numerical simulation of supersonic combustion, multi-species Navier-Stokes equations

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coupled with a Baldwin-Lomax turbulence model and detailed chemistry reaction equations of $H_2/O_2/CO_2$ suitable for high-pressure 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.

By the way, experiments in the ISL's RAMAC 30 with same condition except for projectile surface material demonstrated that there was an important ignition mechanism to initiate detonation, which was strongly related to the aluminium projectile surface's friction, heat conduction, and combustion. Therefore, we assumed that the aluminum surface burning contributed just to initiate detonation in the ram accelerator and consequently modelled it by imposing external ignition energy on the whole combustor section.

Figure 1 shows the numerical results of θ_1=12.5° and θ_1=14° which demonstrated weak shock unstart and normal start process according to the nose cone half angle, respectively. At an earlier stage of ignition, the flame front was created perpendicular to the tube wall by the ignition energy(Fig. 1 (a) A1, Fig. 1 (b) B1). 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 not strongly sustained(Fig. 1 (a) A2, Fig. 1 (b) B2). The flame was coupled to the reflected shock front and hence a detonation was formed near the tube wall(Fig. 1 (a) A3, Fig. 1 (b) B3). As the separation bubble grew, the separation-induced shock became strong. 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. The flame was coupled to the reflected shock front and hence a detonation was formed near the tube wall(Fig. 1 (a) A3, Fig. 1 (b) B3).

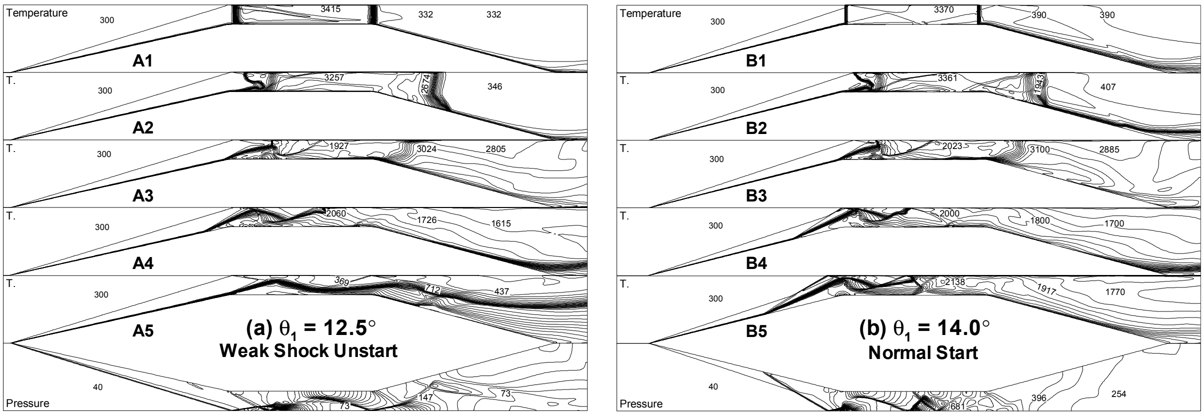

Fig. 1 Initiation and evolution of detonation in case of θ_1=12.5° and θ_1=14°, respectively.

As the separation bubble grew, the separation-induced shock became strong. 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 was forced to move downstream by supersonic flow because the flame front was not strongly sustained(Fig. 1 (a) A4, Fig. 1 (b) B4). Finally, the flame front of θ_1=14° 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 θ_1=14°(Fig. 1 (b) B5).

In case of θ_1=12.5° detonation was not sustained because the reattached shock behind the first separation bubble was not strong enough. So, the combustion region started from the enlarged separated flow region, extended to the exit remaining as a boundary layer flame. As such, this case does not produce any thrust and the combustion mode corresponds to that of weak shock unstart.

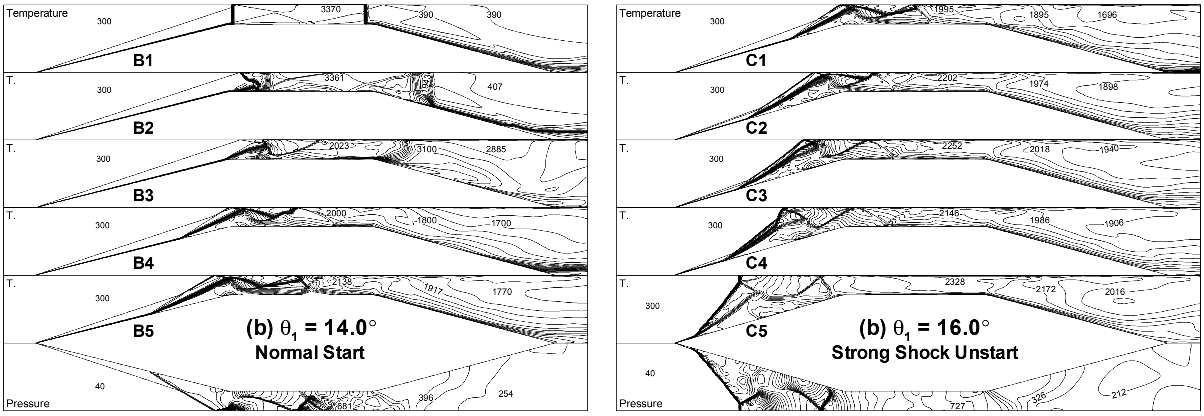

Fig. 2 Initiation and evolution of detonation in case of θ_1=14° and θ_1=16°, respectively.

Figure 2 shows the numerical results of θ_1=14° and θ_1=16° which demonstrated normal start and strong shock unstart process according to the nose cone half angle, respectively. In case of θ_1=16° the intermediate combustion process was the same as the whole process of θ_1=14° discussed previously(Fig. 2 (a) B1~B5). But, the detonation wave near the tube wall where the reattached shock behind the first separation bubble was reflected, moved upstream again to meet the force balance between supersonic unburnt gas and burnt gas(Fig. 2 (b) C1~C2). This might happen because the reattached shock was relatively strong even though heat release due to combustion was same for both cases. Hence, 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) C3~C5). The combustion mode corresponds to that of strong shock unstart.

Figure 3 shows the numerical results of θ_1=18° and θ_1=20° which demonstrated both strong shcok unstart process, respectively.

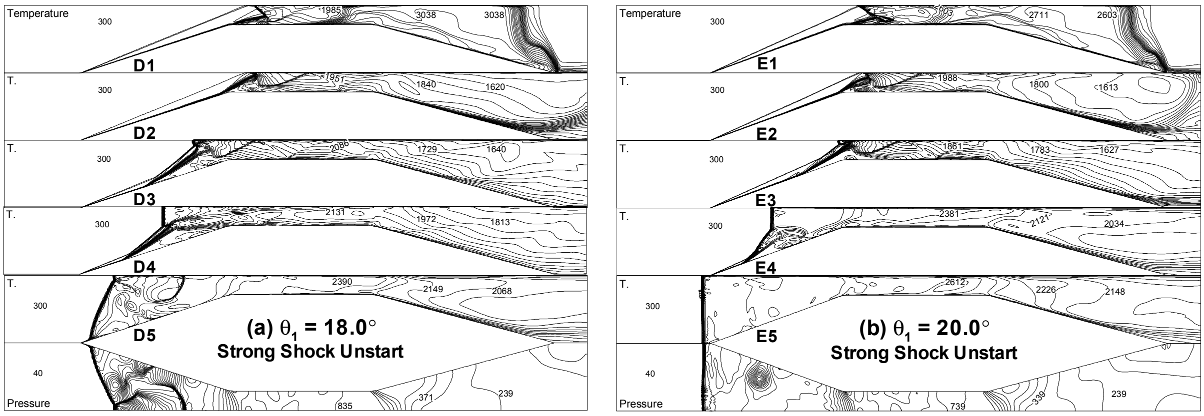

Fig. 3 Initiation and evolution of detonation in case of θ_1=18° and θ_1=20°, respectively.

The flame front created perpendicular to the tube wall by the ignition energy, was coupled to the reflected shock front and hence a detonation was formed near the tube wall(Fig. 3 (a) D1, Fig. 1 (b) E1). As the separation bubble grew and moved upstream, strong shock-induced combustion was occurred behind the separation-induced shock(Fig. 3 (a) D2, Fig. 1 (b) E2).

Also, new detonation was formed near the tube wall and replaced the initially formed detonation due to the very strong separation-induced shock(Fig. 3 (a) D3, Fig. 1 (b) E3). Accordingly, the flame traveled upstream in front of the projectile, called unstart, followed by a strong projectile deceleration(Fig. 3 (a) D4~D5, Fig. 1 (b) E4~E5).

Mach stem of θ_1=20° was appeared earlier than that of θ_1=18° due to the geometry of nose cone angle(Fig. 3 (a) D3, Fig. 1 (b) E3).

References

[1] Seiler, F., Patz, G., Smeets, G. and Srulijes, J., “ Influences of Projectile Material and Gas Composition on Superdetonative Combustion in ISL’s RAMAC 30,” AIAA Paper 98-3445, July 1998, Cleveland, OH.