Numerical Study on Propulsion Performance Enhancement of Superdetonative mode Ram Accelerator by using strong mixture

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Abstract

A numerical study is conducted to investigate propulsion performance enhancement based on S225 experiment case of ISL (French-German Research Institute of Saint-Louis)'s superdetonative ram accelerator. For govern equation, multi-species Navier-Stokes equation coupled with Baldwin-Lomax turbulence modeling is used. Govern equation is discretized by Roe's FDS and integrated by LU-SGS time integration. Detailed chemical reaction about $H_2/O_2/CO_2$ for high pressure is considered. $2H_2+O_2+2.5CO_2$ mixture was used for propellant gas. For the same over-driven factor, the launching speed of computation was faster than one of S225. Another configuration and condition of S225 was applied. A flame structure is very different from S225. For strong mixture case, it shows ignition by viscous effect. Acceleration and speed increment is higher than S225 computation and experiment. By using more strong mixture, propulsion performance was enhanced.

Introduction

The concept of ram accelerator is that accelerating projectile with synchronized combustion in tube filled with pre-mixed combustible gas mixture. Projectile can be accelerated continuously along accelerating tube. Speed of ram projectile is limited by speed of combustion wave. Final speed of ram projectile can be very high by using multi-stage accelerating tube filled with optimum mixture. Ram accelerator is being developed for hypervelocity launchers or direct launcher to low earth orbit. Ram Accelerator facilities also have major benefits for hypersonic research. The gas dynamics phenomena in ram accelerator are very similar to those expected ones in scramjet and oblique detonation wave engines. Therefore, study on ram accelerator operation will enhance the understanding of supersonic combustion and hypersonic propulsion system.

Despite the number of research programs around the world, a maximum speed of 2.7 km/s was only available at the UW (University of Washington) ram accelerator facility starting with subsonic combustion behind the projectile which was moving initially at subdetonative speeds[1]. Thus, to obtain higher velocities than 2.7 km/s, combustion mode must be the superdetonative mode, where ignition and combustion occur at supersonic flow speeds in the space formed between projectile and tube wall.

Based on this motivation, ISL (French-German Research Institute of Saint-Louis) has developed a rail tube version of a ram accelerator facility named RAMAC 30 version II that directly launching projectile superdetonative speed (the speed faster than Chapman-Jouguet detonation wave speed). In this facility, a cylindrical projectile having conical fore- and after-bodies was launched by a powder gun and accelerated in a ram accelerator tube having four or five guide rails[2]. Although the initial launching speed of a powder gun was only about 1.8 km/s, the superdetonative launch was possible by using the $H_2/O_2/CO_2$ mixture having a lower C-J (Chapman-Jouguet) detonation wave speed.

ISL's RAMAC 30 demonstrated that ignition and acceleration was successful with an aluminum projectile but acceleration was not observed with a steel projectile. An aluminum projectile suffered severe ablation with significant mass loss[3]. These facts show that there is an important ignition mechanism which is strongly related to the melting and combustion of aluminum projectile by friction, and heat conduction.

At the earlier stage of ram accelerator studies, the superdetonative mode operation had been considered to be sustained by an oblique detonation wave in the combustor. Computational studies by Yungster and Bruckner[4] and Li et al.[5] using inviscid flow model and chemical kinetics showed that ram acceleration was possible through this concept at very high velocity ranges. However, more recent viscous analyses by Yungster[6] and Choi et al.[7] showed that combustion could be initiated in the boundary layer due to the aerodynamic heating associated with shock wave / boundary layer interaction at intermediate velocity ranges where shock-heating was insufficient for mixture ignition.

The ISL's ram accelerator experiments, however, revealed that the previous studies on superdetonative combustion characteristics were not applicable to the experimental case and the other combustion characteristics might be more important for the low speed superdetonative mode of operation. Therefore, to understand the combustion mechanism, numerical simulation [12][13] was conducted for ISL's RAMAC 30. In this paper, numerical study was conducted to investigate enhancement of propulsion performance by using stronger mixture.

ISL's RAMAC 30 II Test Facility

Based on the needs of hypersonic launching facility, ISL built two ram accelerators: a 30-mm-caliber-tube, called RAMAC 30, and 90-mm-one, RAMAC 90. The superdetonative mode operation has been mainly tested in RAMAC 30 which was implemented with rail tube version II since 1997. Figure 1 shows the schematics of RAMAC 30 test facility, which consisted of a pre-accelerator tube, a ram tube containing a combustible gas mixture with both ends sealed by diaphragms, which were broken by the moving projectile fore-body nose tip, and a decelerator tube. Two tubes with each length of 2.4m each were used forming a total ram tube length of 4.8m. Projectiles had an inner magnesium core which was fully covered by an aluminum or steel (different by experimental shot. Cylindrical projectiles of 130g~150g, 3.0 cm caliber, and 16.1 cm long, could be accelerated to 1800 m/s at the exit of the pre-accelerator tube before penetrating through the mixture in the rail tube version II.
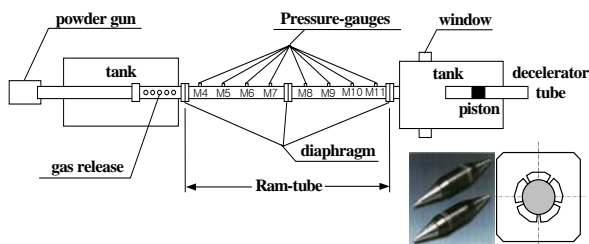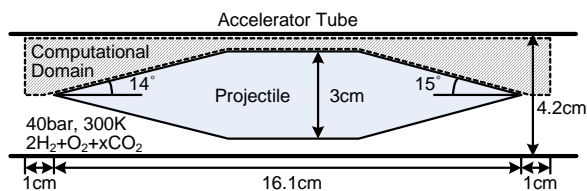

Fig. 1 Configuration of ISL's RAMAC30

Fig. 2 Computational Domain

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. Because typical operational pressure of ram accelerator is higher than 50atm, reduced kinetic mechanism for low pressure is not valid. Therefore finite-rate chemistry model for high pressure should be considered. Petersen and Hanson[8] developed reduced mechanisms to model the combustion characteristics of typical ram accelerator mixtures at pressures approaching 300atm based on the GRI-Mech. In this study, fully detailed 10 species (H, H_2, O, O_2, OH, H_2O, HO_2, H_2O_2, CO, CO_2) and 29 step reaction model for reaction of $H_2/O_2/CO_2$ mixture was considered. 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 integrated over time by using LU-SGS scheme[11]. Thrust can be evaluated by surface integration of pressure and viscous drag on surface of projectile. Acceleration and speed of projectile is computed from thrust. By accelerating of projectile, inflow speed is updated by every iteration step.

Table 1 Summary of conditions

	S225	Stronger mixture case
Gas Mixture	$2H_2+O_2+5CO_2$	$2H_2+O_2+2.5CO_2$
Speed of Sound	320.0 m/s	353.8 m/s
C-J speed	1316.8 m/s	1650 m/s
Launching Speed	1800 m/s	2255 m/s
Mach Number	5.63	6.37
Ratio of Combustible Gas	0.375	0.545
Over-driven factor	1.367	
Pressure	40 bar	
Temperature	300 K	
Mass of Projectile	150 g	

Computational Modeling

Figure 2 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 this study assumed circular for the axisymmetric simulations. The computational domain for the simulation was extended by 1cm before and after the projectile, and it was covered by the 380x100 computational grids that was uniformly distributed in the axial direction and clustered to both walls in the radial direction. Since these simulations had to cover overall flow features of the scale of the entire projectile, the computational resolution was limited. Therefore, details of the detonation structure, such as the induction region, might not be well resolved. But our purpose was exploring the overall performance and development, so current grid resolution is enough to represent the shock and detonation position because the local transit time was sufficiently smaller than the induction time of $2H_2+O_2+2.5CO_2$ mixture behind the reflected shock where mixture ignition occurred.

Gas mixture used for S225 was $2H_2+O_2+5CO_2$: a stoichiometric H_2/O_2 mixture diluted with 5 moles of CO_2. For this study, $2H_2+O_2+2.5CO_2$ gas mixture is
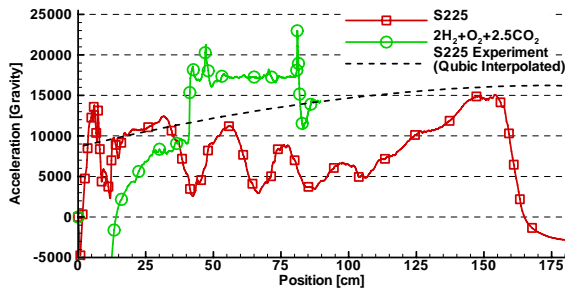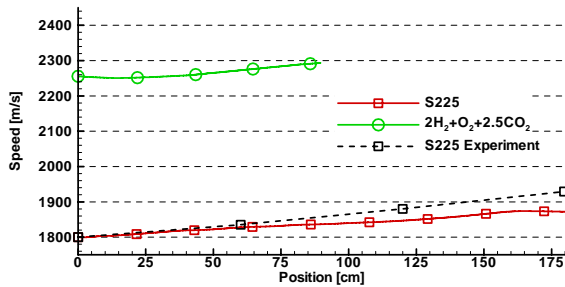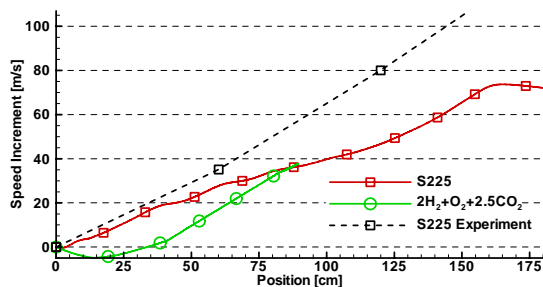
Fig. 3 Acceleration of Projectile

Fig. 4 Speed of Projectile

Fig. 5 Speed Increment of Projectile

used: CO_2 dilution decrease to half. Stoichiometric mixture ratio is 0.375 for $5CO_2$ dilution and 0.545 for $2.5CO_2$. $2.5CO_2$ mixture is 45% stronger than $5CO_2$ dilution. C-J detonation wave speed is 1316.8m/s for of $5CO_2$ dilution and 1650m/s for $2.5CO_2$ dilution. Over-driven factor of S225 experiment was 1.367. For same over-driven factor, initial launching speed of $2.5CO_2$ dilution case was 2255m/s. Mixtures for S225 experiment had a pressure and temperature of 40bar and 300K, respectively. The same condition is used for this study. Conditions for S225 experiment and computation of $2.5CO_2$ dilution are summarized in Table 1.

Result and Analysis

Acceleration and Speed

Figure 3 shows acceleration of projectile for two result of computation and experiment result of S225. S225 experimental result shows increasing of acceleration from 10000G to 16000G by advance of projectile. Computational result of S225 shows fluctuation by detonation/shockwave oscillation [12]. An initial acceleration of computational result of $2.5CO_2$ dilution is negative, but it increase to 9500G near at 37cm. It jumps to 21000G near at 47cm and

stay at 17000G between 50cm and 80cm. An average acceleration is 17218G between two points. It suddenly jumps to 23000G at 81cm and decreases to 11000G at 83cm.

Figure 4 and 5 shows speed and speed increment of projectile. S225 experimental and computational results are agree about initial behavior, but computational result has difference by detonation/ shockwave oscillation. For $2H_2+O_2+2.5CO_2$ case, speed decrease between starting point and 14cm. Speed increases after 14cm and recover starting speed near 34cm and continuously increasing to 50 cm. Between 50cm and 80cm, speed increasing rate is almost constant and speed increment between two points is 22.24m/s.

Flame Structure

Figure 6 and 7 show pressure and temperature contour for computation result of $2H_2+O_2+2.5CO_2$ at 5.9cm. Pressure contour shows simple shockwave structure. Conical shockwave generated by fore-body is reflected on accelerator tube wall and hit projectile surface. Flame exists only at near projectile surface and does not contribute to thrust. Because initial acceleration is negative, speed is deceasing between starting point and 14cm. Figure 8 and 9 show results at 31.5 cm. Figure 8 shows fully developed shockwave reflection structure. Two figures shows typical shock induces combustion. Combustion is following shockwave and combustion wave is separated from shockwave. At this point, acceleration is about 8000G. Pressure of aft-body surface is relatively higher than one of fore-body. Figure 10 and 11 show results at 42.3cm. Two figures also show shock induced combustion. But, compare to figure 8 and 9, gap between combustion wave and shockwave is decrease. Pressure after shockwave is much higher than one of 31.5cm. Acceleration at this point is about 18000G. Figure 12 and 13 show results at 47.1cm. Combustion wave and shockwave is coupled at near the accelerator tube wall and developed to detonation wave. Global shockwave structure behind combustor section is similar to one of 42.3cm but pressure of expansion section is higher than one of 42.3cm by the detonation wave. Acceleration at this point is 21000G and higher than one of 42.3cm. Figure 14 and 15 show results at 56cm. High pressure region behind detonation wave contribute to high acceleration. Acceleration is almost constant between 50cm and 80cm. Figure 16 and 17 show results at 81cm. Detonation wave becomes stiffer than one of 56cm. And expansion wave behind combustor is almost canceled by reflected shockwave at tube wall. As result this point shows maximum acceleration (about 23000G). Figure 18 and 19 show results at 83.2 cm. The shockwave/detonation wave structure is not so much different. But impinging point by reflected shockwave move ahead and expansion wave is stronger than one of 81cm. So acceleration decreases to 10920G at this point.
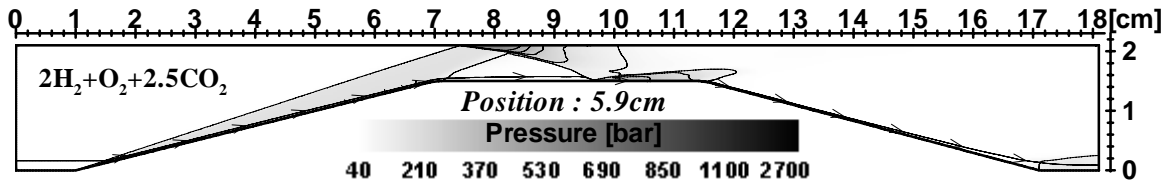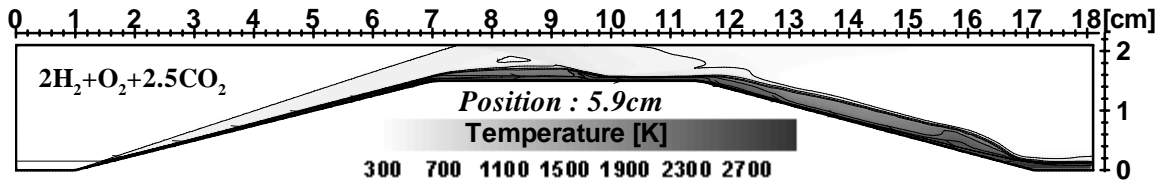
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Fig. 6 Pressure Contour ($2H_2+O_2+2.5CO_2$, 5.9cm)

Fig. 7 Temperature Contour ($2H_2+O_2+2.5CO_2$, 5.9cm)

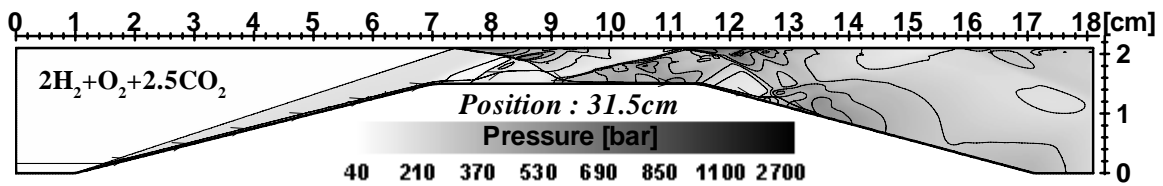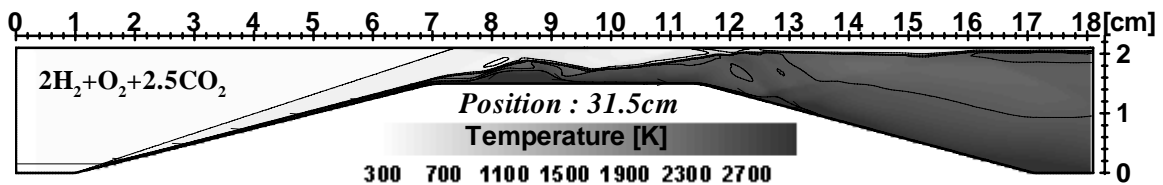Fig. 8 Pressure Contour ($2H_2+O_2+2.5CO_2$, 31.5cm)
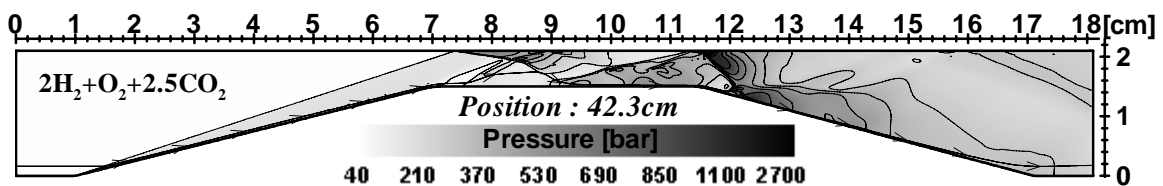
Fig. 9 Temperature Contour ($2H_2+O_2+2.5CO_2$, 31.5cm)
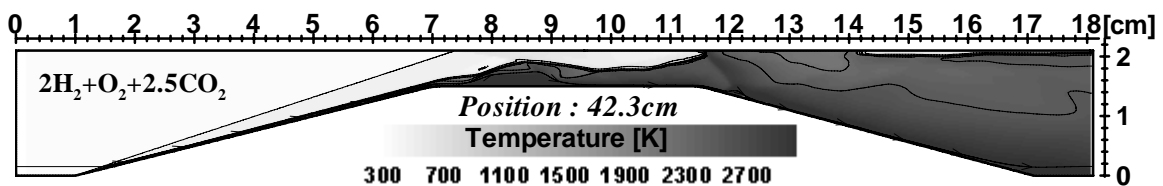
Fig. 10 Pressure Contour ($2H_2+O_2+2.5CO_2$, 42.3cm)
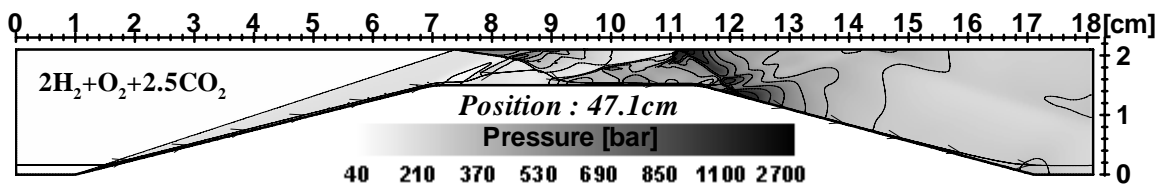
Fig. 11 Temperature Contour ($2H_2+O_2+2.5CO_2$, 42.3cm)
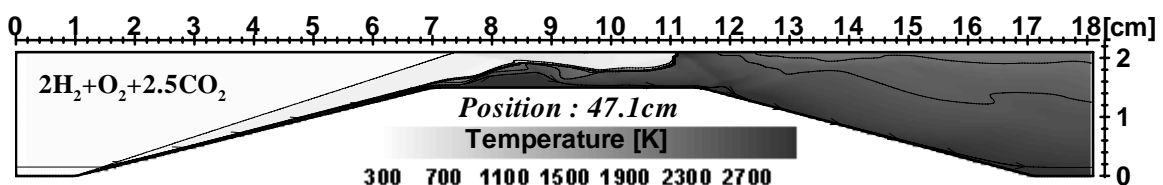
Fig. 12 Pressure Contour ($2H_2+O_2+2.5CO_2$, 47.1cm)
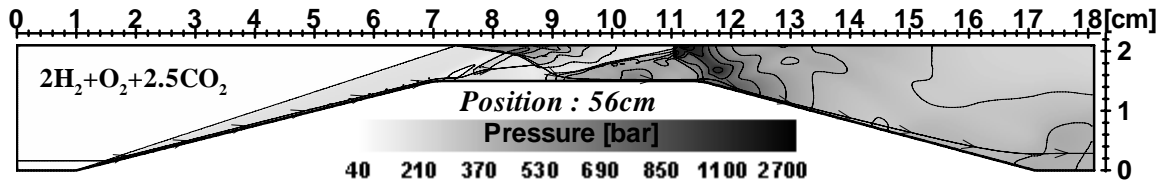
Fig. 13 Temperature Contour ($2H_2+O_2+2.5CO_2$, 47.1cm)
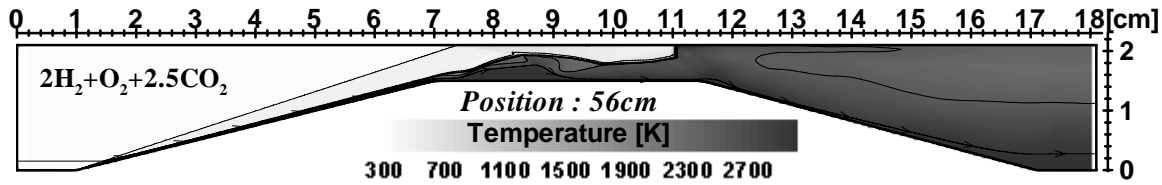
Fig. 14 Pressure Contour ($2H_2+O_2+2.5CO_2$, 56cm)

Fig. 15 Temperature Contour ($2H_2+O_2+2.5CO_2$, 56cm)
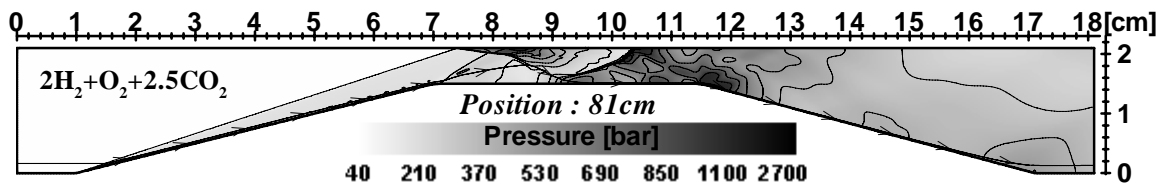
Fig. 16 Pressure Contour ($2H_2+O_2+2.5CO_2$, 81cm)
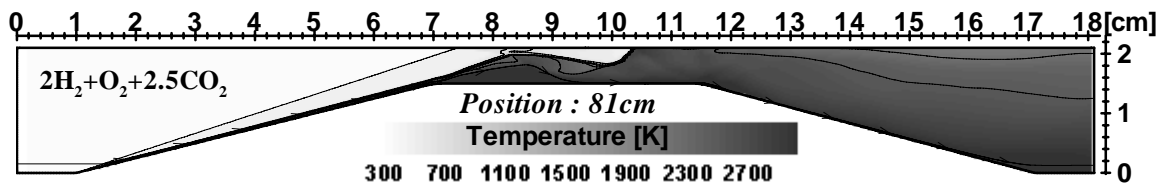
Fig. 17 Temperature Contour ($2H_2+O_2+2.5CO_2$, 81cm)
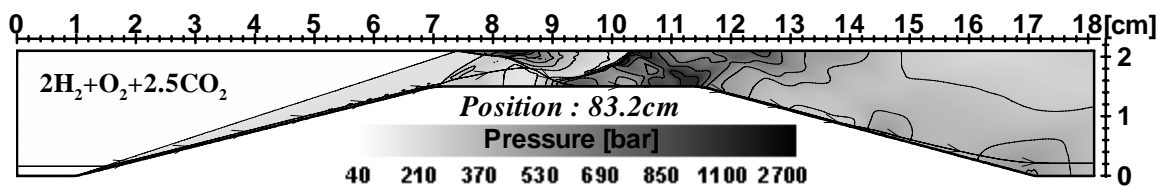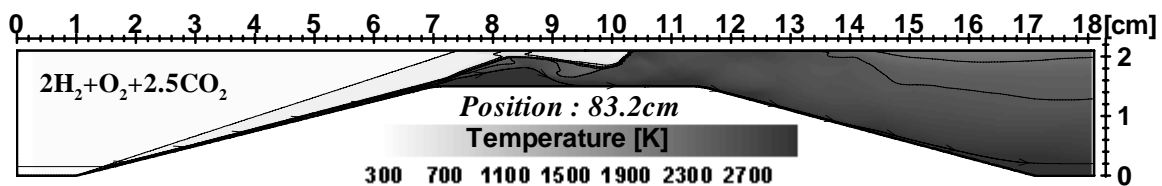

Fig. 26 Pressure Contour ($2H_2+O_2+2.5CO_2$, 83.2cm)

Fig. 27 Temperature Contour ($2H_2+O_2+2.5CO_2$, 83.2cm)

Compare of Propulsion Performance

Acceleration of S225 experiment is increasing as advanced of projectile. An averaged acceleration near 50cm is about 12000G. For the case of $2.5CO_2$ dilution, steady acceleration between 50cm and 80cm is about 17200G. Steady acceleration performance is 43% higher by changing the mixture. For $2.5CO_2$ dilution, 3 mole is combustible in total 5.5 mole ($2H_2+O_2+2.5CO_2$, ratio of combustible gas is 37.5%). For $5CO_2$ dilution, 3 mole is combustion in total 8 mole ($2H_2+O_2+5CO_2$, ratio of combustible gas is 54.5%). $2.5CO_2$ dilution mixture has 45% more effective combustible mixture and energy than $5CO_2$ dilution by simple theory. It shows good performance increasing according to ratio of acceleration versus input energy.

Conclusion

A numerical study was conducted to investigate enhancement of propulsion performance by using stronger mixture. As result, acceleration increase by proportion of energy in gas mixture.

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