Chemically-Augmented Pulsed Laser-Ramjet

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Abstract: A preliminary study of a chemically-augmented pulsed laser-ramjet was conducted, in which chemical propellant such as a gaseous hydrogen/air mixture was utilized and detonated with a focused laser beam in order to obtain a higher impulse compared to the case only using lasers. CFD analysis of internal conical-nozzle flows and experimental measurements including impulse measurement were conducted to evaluate effects of chemical reaction on thrust performance improvement. From the results, a significant improvement in the thrust performances was confirmed with addition of a small amount of hydrogen to propellant air, or in chemically-augmented operation. In addition, use of a laser-ablation plasma induced from a solid target further enhanced the impulse generation.

I. Introduction

There have been a large number of efforts in development of grand-based laser ramjets, in which a laser beam is irradiated from a grand-base and focused in the nozzle to heat an airstream taken from atmosphere to generate a thrust. [1-3] From these results, it has been concluded that a laser-beam power of 1 MW is to be needed to launch a mass of 1 kg. This limitation is still further from current laser facilities based on the viewpoints of its practical launch mass, launch cost and availability.

To overcome these frustrating issues, authors propose the use of chemical energy, or chemical augmentation, by introducing a small amount of gaseous fuel into the nozzle. The fuel is then mixed with a breathed air. When a laser beam is focused in this combustible mixture, a chemical detonation in addition to a pure laser detonation will occur, inducing an augmented thrust. With this method, some amount of chemical energy will be added and augmentation of the thrust performance will be achieved with an assist of a small amount of fuel.

Examples of calorific energies of stoichiometric fuel-air mixtures presuming perfect combustion in air for several practical fuels are listed in Table 1. For example, use of 1 mg of hydrogen corresponds to generation of chemical energy of 120 J, which can be relatively high enough compared to laser-pulse energy available with conventional facilities. Suppose use of the 1 mg hydrogen propellant per laser pulse at 50 Hz for 200 sec in a transatmospheric part of a grand-to-LEO flight, a total amount of propellant for the transatmospheric flight will be only 10 g. Since much lager amount of propellant will be needed for the post-atmospheric flight, or in vacuum, the

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addition of 10 g will be insignificant. In this study, to elucidate an effectiveness of the chemically-augmented laser ramjet, an experimental study and numerical simulation are conducted for optimum nozzle geometries and operational conditions.

Table 1 Low-calorific energies of stoichiometric fuel/air mixtures.

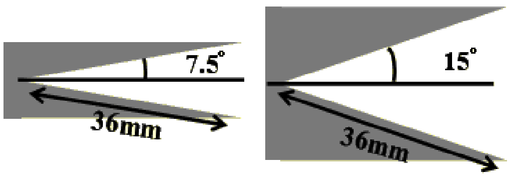
Fuels	Energy [J/mg]
Hydrogen	120
Methane	50
Propane	45
Ethanol	30

II. Experimental

Thrust performance tests were conducted to elucidate an effectiveness of chemically-augmented laser ramjets. Two types of conical nozzle parts of the chemically-augmented laser ramjets used in this study are illustrated in Fig.1. The nozzles consist of aluminum rods with their lengths of 36 mm.

To measure a single impulse of μNsec-class, a thrust stand was developed and utilized. The thrust stand, shown in Fig.2, consists of a ballistic pendulum. As for its pivot, a knife edge was used. The pendulum is made of an aluminum member of 456 mm in length and 25 mm x 25 mm in cross section. An eddy-current type displacement sensor was used to measure the displacement of the pendulum. The displacement induced at each impulse generation was calibrated with an impact of an aluminum ball at each shot.

A schematic of an experimental setup for impulse-bit measurement is also shown in Fig.2. A laser pulse from an Nd:YAG laser (QUANTEL LPY 150-10/20, wavelength: 1064 nm, maximum pulse energy: 335 mJ/pulse, pulse width: 5 nsec) was irradiated and focused with a focusing lens of f = 100 mm into a center part of the conical nozzle filled with a hydrogen-air mixture of a controlled equivalence ratio through a solenoid valve in advance. Then with a laser-induced plasma, a chemical reaction is initiated, and an impulse is generated on the nozzle. The pendulum receives a reaction force and then a displacement, namely an impulse, is to be measured. Each measurement was performed under atmospheric pressure.



(a) 7.5 deg. (b) 15 deg.
Fig.1 Schematics of conical-nozzle thrusters with different half-cone angles.

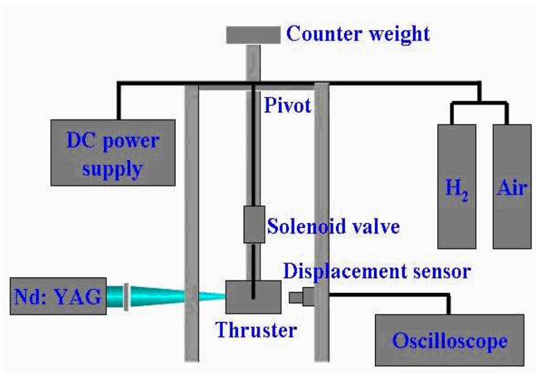


Fig.2 Schematics of pendulum-type thrust stand and experiment setup of impulse-bit measurement.

III. Experimental results and discussion

A conclusion section is not required, though it is preferred. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

A. Effect of half-cone angle of nozzles

Comparison of impulse-bit versus laser-pulse energy for nozzles with half-cone angle of 7.5 deg. and 15 deg. for a stoichiometric mixture of $\phi = 1.0$ is shown in Fig.3. In both angle cases, impulse-bit increases with laser energy, and higher values can be obtained with a smaller angle nozzle of 7.5 deg. in each energy case, showing an advantage in impulse generation in smaller angle case. This is probably due to the difference of axial component of velocity vectors at nozzle exit between two cases, i.e., in smaller angle nozzle the component is larger, while in larger angle nozzle it is smaller and radial component being larger. Moreover in the smaller angle case, since its inner nozzle wall is narrower, shockwaves induced inside tend to reflect and interact with each other, or to be confined and augmented. This will increase internal pressure and namely strength of the shock wave. Detailed mechanisms of this process are to be described through computational simulation in the next section. Presuming an identical nozzle length, a nozzle volume is smaller in the narrower nozzle. Therefore, an amount of propellant consumed with the narrower nozzle in each impulse-bit generation can be smaller.

Effect of half-cone angle of nozzles on momentum coupling coefficient versus laser-pulse energy is shown in Fig.4 for stoichiometric mixture of $\phi = 1.0$. It can be seen that in the most cases the coupling coefficient increases with the laser energy and higher values are obtained with a smaller angle nozzle of 7.5 deg. in each energy case. Therefore, it is shown that the higher laser energy and smaller angle nozzle are more efficient in generating impulses. As described above, the narrower nozzle is more efficient in inducing stronger pressure waves due to the confined shockwave. When the laser energy becomes higher, an initial shockwave becomes stronger and this will result in the higher impulses.

In the 15 deg. nozzle, the coupling coefficient increases with energy up to its peak value of 430 μNsec/J at 220 mJ, and then it gradually decreases. While in the 7.5 deg. nozzle, it increases with energy, however, its increment gradually being decreased at higher energy cases indicating existence of the peak value. The existence of the peak coupling coefficient will be explained as follows. When the laser energy is high enough, an initial blast wave induced through the focused laser irradiation can be too strong to maintain most of the reactants and heat release inside the nozzle.

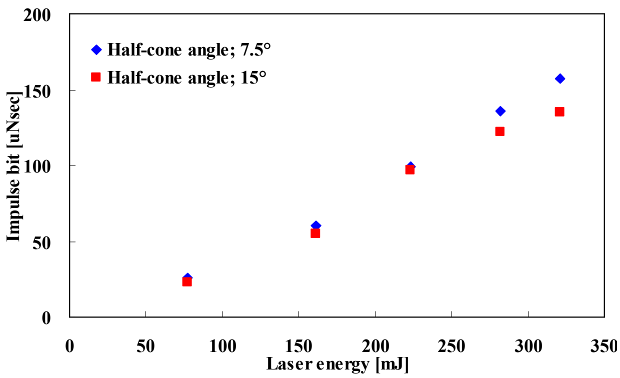


Fig.3 Comparison of impulse-bit versus laser-pulse energy for nozzles with half-cone angle of 7.5 deg. and 15 deg. for stoichiometric mixture of $\phi = 1.0$.

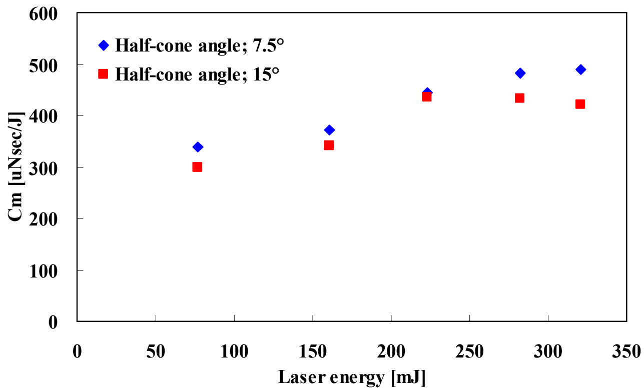


Fig.4 Comparison of momentum coupling coefficient versus laser-pulse energy for nozzles with half-cone angle of 7.5 deg. and 15 deg. for stoichiometric mixture of $\phi = 1.0$.

B. Effect of chemical energy release

Variations of impulse-bit with laser-pulse energy for various equivalence ratios measured by the thrust stand for a conical nozzle with the half-cone angle of 7.5 deg. are plotted in Fig.5. It can be seen that the impulse-bit increases with laser-pulse energy in various equivalence ratio cases. At $\phi = 0.5$ of a fuel lean mixture, lower impulse-bits are obtained, which are about 20 % smaller than those of a stoichiometric mixture of $\phi = 1.0$. However, it can be seen that these values are still four-times as large as the pure air case of $\phi = 0$. From these results, it is shown that use of the heat released through combustion reaction of a combustible gaseous mixture can be significantly effective to improve the impulse-bit even under fuel lean mixture cases.

Replotting Fig.5, relations of impulse-bit versus equivalence ratio for various laser-pulse energies are shown in Fig.6. As shown in this figure, the maximum impulse-bit for each laser energy case can be given at equivalence ratios of between $\phi = 1.25$ and 1.5. In particular, the ratios giving the maximum impulse-bit at lower laser energy cases are about $\phi = 1.5$, whereas those at higher energy cases are about $\phi = 1.25$, slightly shifting toward the leaner side.

Variations of momentum coupling coefficient with laser-pulse energy for various equivalence ratios for a conical nozzle with the half-cone angle of 7.5 deg. is shown in Fig.7. Where, these coupling coefficients were estimated through the division of the measured impulses by only laser pulse energies, which were not added by ideal chemical energies released from the combustion reaction of propellant mixtures. It can be seen that the coupling coefficient increases with laser pulse energy at each equivalence ratio. Similar to the above results, the maximum coupling coefficient for each laser energy case can be obtained at an equivalence ratio of about $\phi = 1.25$. In this case, improvement of the coupling coefficient with increase of the laser energy is relatively insignificant. On the other hand, it is more significant at lean mixture of $\phi = 0.5$. This means that at lower laser energy cases use of fuel lean mixtures for the propellant results in lower efficiencies, or for near-stoichiometric mixtures in higher efficiencies.

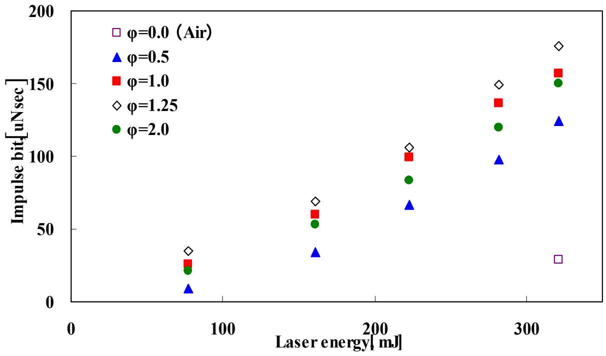


Fig.5 Variations of impulse bit with laser-pulse energy for various equivalence ratios measured by thrust stand for a conical nozzle with half-cone angle of 7.5 deg.

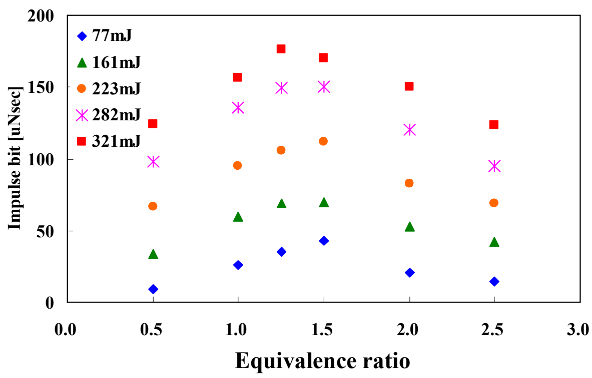


Fig.6 Variations of impulse bit with equivalence ratio for various laser-pulse energies measured by thrust stand for a conical nozzle with half-cone angle of 7.5 deg.

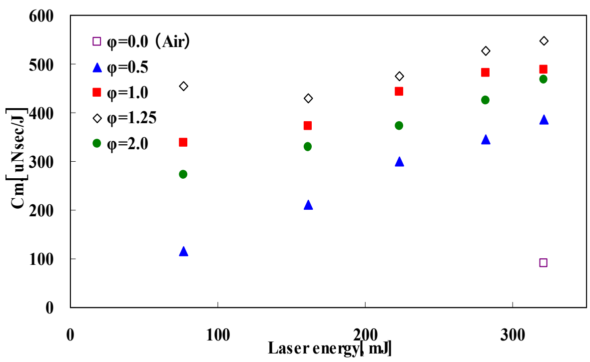


Fig.7 Variations of momentum coupling coefficient with laser-pulse energy for various equivalence ratios measured by thrust stand for conical nozzle with the half-cone angle of 7.5 deg.

C. Effect of laser ablation plasma on thrust performance

To compare the effect of a laser ablation plasma with that of laser breakdown plasma, a laser pulse was irradiated and focused onto a carbon surface fixed to a nozzle wall. The carbon piece, 3 mm-diameter x 0.2 mm-thick, was attached to a nozzle wall at 20 mm deep from the nozzle exit in axial direction.

Relations of impulse-bit versus equivalence ratio for the laser ablation plasma cases for a half-cone angle of 15 deg irradiated with 275 mJ laser pulse are shown in Fig.8, in which for comparison plots of laser breakdown plasma cases are also shown. As shown in this figure, the maximum impulse-bit for each case can be given at equivalence ratios of $\phi = 1.25$. In addition, except the case at equivalence ratio of $\phi = 1.5$, higher values can be obtained with the laser ablation plasma cases. This means that at equivalence ratios of near-stoichiometric to lean conditions, or $\phi \leq 1$, the use of laser ablation plasma can be effective in generating higher impulses.

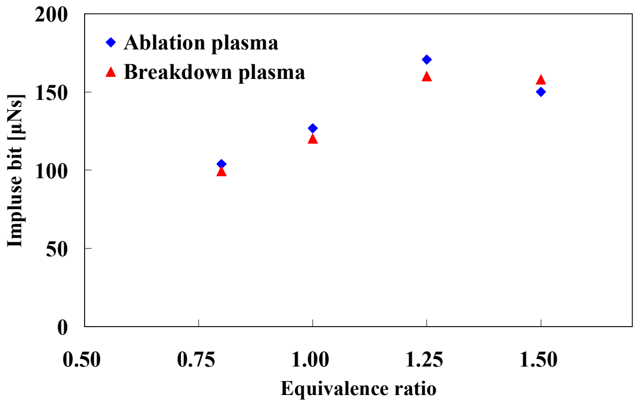


Fig.8 Relations of impulse-bit versus equivalence ratio for laser ablation plasma and breakdown plasma for a nozzles with half-cone angle of 15 deg., laser energy of 275 mJ.

IV. Numerical simulation

A. Simulation model

Numerical simulation was conducted to investigate effects of conical angles and mechanisms of impulse generation for an internal flow of conical nozzles. In this simulation, a commercial computational fluid dynamic (CFD) simulation code, CFD2000 (Adaptive Research) was utilized. With this code, a time-dependant 2-dimensional Navier-Stokes equation with finite rate chemistry of hydrogen/air reactions was solved. A 2-dimensional flow field model simulating an internal flow of a conical nozzle is shown in Fig.9. Seven elementary reactions for seven species (H_2, O_2, O, H, OH, H_2O, and N_2) employed in this simulation are listed in Table 2.[4] As for modeling of a focused laser beam or laser induced plasma, several attempts have been conducted.[5-11] Since a laser pulse is shorter than 1 μsec, its short-duration heating process can be regarded as that occurring under a constant volume condition. For this reason, a high-enthalpy laser-induced plasma kernel is assumed as a hot-gas spot with finite size to which it has developed from an initial micro-plasma nucleus.[11] Since it is confirmed from our experiment that an initial plasma, or hot spot, is as big as 1 ~ 2 mm in diameter at initial 100 nsec, initial size of the spherical hot spot used in this simulation is assumed to be 1 ~ 2 mm in diameter depending on laser pulse energies.

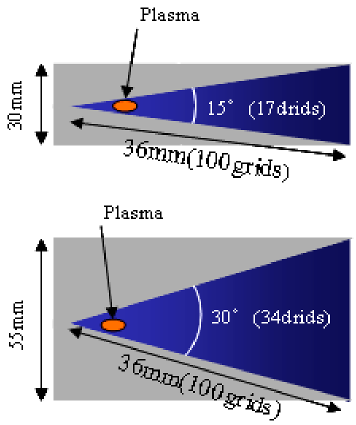


Fig.9 Simulation models.

Table 2 7 elementary reactions with 7 species for hydrogen-air mixture.

1	$H_2 + O_2$	⇔	$OH + OH$
2	$H + O_2$	⇔	$OH + O$
3	$OH + H_2$	⇔	$H_2O + H$
4	$O + H_2$	⇔	$OH + O$
5	$OH + OH$	⇔	$H_2O + O$
6	$H + OH$	⇔	$H_2O + M$
7	$H + H$	⇔	$H_2 + M$

B. Simulation results of conical nozzle for half-cone angle of 15 degrees

Temporal evolutions of propagation of pressure wave and H_2O mass fraction distribution for laser energy of 167 mJ for half-cone angle of 15 deg. and stoichiometric mixture of $\phi = 1.0$ are shown in Fig.10. Also, temporal evolutions of shockwave and reacting wave fronts for the case of Fig.10 are plotted in Fig.11. At initial phase, a high-pressure region or a shockwave is induced through irradiation of a focused laser pulse. As it propagates radially in initial process, upper- and lower- wave fronts impinge and reflect on both upper and lower nozzle walls, interacting with each other causing increase of internal pressure, and then a primary shock front propagates toward the nozzle exit. Since the nozzle is divergent, diffusion of the shockwave as it propagates is more remarkable.

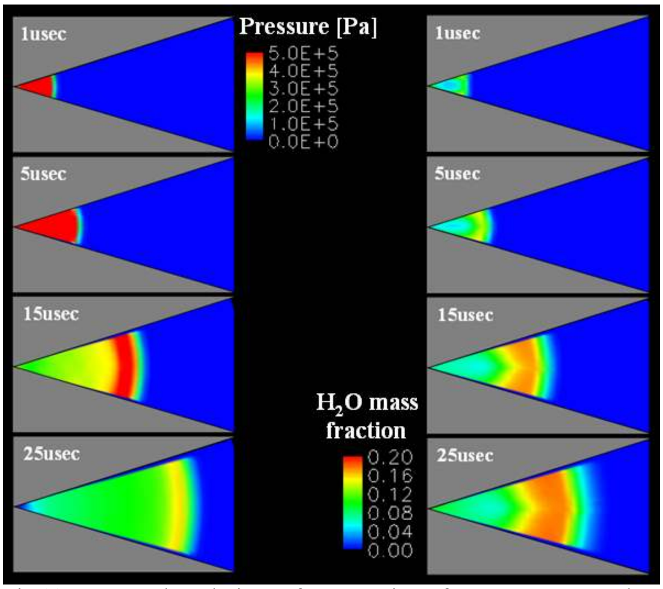


Fig.10 Temporal evolutions of propagation of pressure wave and H_2O mass fraction distribution for laser energy of 167 mJ for half-cone angle of 15 deg. and stoichiometric mixture of $\phi = 1.0$.

As for H_2O distribution, it can be seen that its formation region or a reacting wave is propagating along with the shockwave in initial phase, and then it becomes slower than the shock wave as it propagates for about 15 μ sec. From these plots, average propagation speeds of the shockwave and reacting wave are estimated, which are 1,070 m/sec and 840 m/sec, respectively.

Although not shown, when the laser energy was increased up to 333 mJ, higher peak pressure of the shockwave was maintained even if it propagates in the divergent nozzle. In this case, average propagation speeds of the shockwave and reacting wave were identical, about 1,440 m/sec.

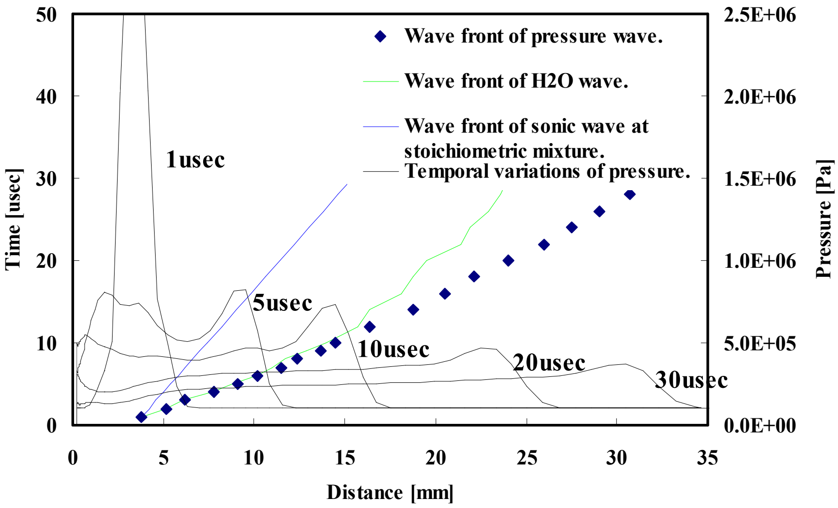


Fig.11 Temporal evolutions of shockwave and reacting wave fronts for laser energy of 167 mJ for half-cone angle of 15 deg. and stoichiometric mixture of $\phi = 1.0$.

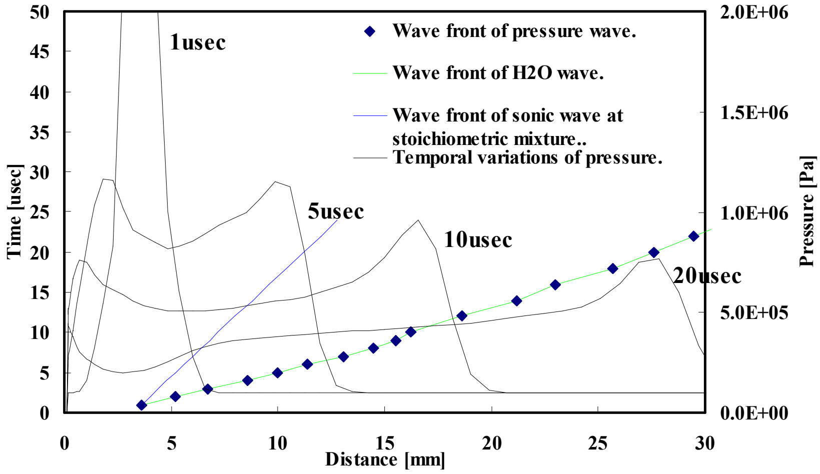


Fig.12 Temporal evolutions of shockwave and reacting wave fronts for laser energy of 167 mJ for half-cone angle of 7.5 deg. and stoichiometric mixture of $\phi = 1.0$.

C. Simulation results of conical nozzle for half-cone angle of 7.5 degrees

Temporal evolutions of shockwave and reacting wave fronts for laser energy of 167 mJ for half-cone angle of 7.5 deg. and stoichiometric mixture of $\phi = 1.0$ are shown in Fig.12. With smaller nozzle angle, higher peak pressure of the shockwave is maintained even if it propagates in the divergent nozzle. From these plots, average propagation speeds of the shockwave and reacting wave are identical in this case, about 1,340 m/sec. Therefore, it is shown that a reacting wave is propagating along with the shockwave in entire nozzle region.

V. Conclusion

A preliminary study of chemically-augmented laser-ramjets was conducted, in which chemical propellant such as a gaseous hydrogen/air mixture was utilized and detonated with a focused laser beam in order to obtain a higher impulse compared to the case only using lasers. We also compared the effect of a laser ablation plasma with that of laser breakdown plasma. Thrust performance tests and CFD analysis of internal conical-nozzle flows were conducted to evaluate effects of chemical reaction on thrust improvement.

From the results, a significant improvement in the thrust performances was confirmed with addition of a small amount of hydrogen to propellant air, or in chemically-augmented operation. It was shown that the impulse-bit increased with energy. Also, there seemed to be an optimum laser energy which gave the maximum momentum coupling coefficient for each angle nozzle. Moreover, it was shown that higher thrust performance was obtained with narrower nozzle. Furthermore, the case at equivalence ratio of $\phi \fallingdotseq 1$, using ablation plasma gains higher impulse bit.

Detailed mechanisms of this process were clarified through computational simulation. Since its inner nozzle wall was narrower, shockwaves induced inside tended to reflect and interact with each other, or to be confined and augmented. This increased internal pressure and namely strength of the detonation wave. Presuming an identical nozzle length, a nozzle volume was smaller in the narrower nozzle. Therefore, an amount of propellant consumed with the narrower nozzle in each impulse-bit generation could be smaller.

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