Direct measurement of detonation tube impulse in low pressure environments and the effect of nozzles

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January 30, 2003

The motivation of the present study is the application of nozzles to improving the performance (specific impulse) of pulse detonation engines. We present a combined numerical and experimental study of the flow in a nozzle that is impulsively started by the diffraction of a detonation from a tube into a diverging or converging-diverging nozzle. The goals of the study are to determine the conditions under which a quasi-steady supersonic flow can be set up and also, the maximum performance gains that can be expected from nozzles under various operating conditions.

The use of nozzles in conventional steady propulsion systems is well understood and specific impulse increases of up to a factor of two are possible when a diverging nozzle is used under optimal conditions on a rocket motor. The optimal conditions are that the flow stays supersonic throughout the diverging section and the streamlines follow the nozzle contour until the exit

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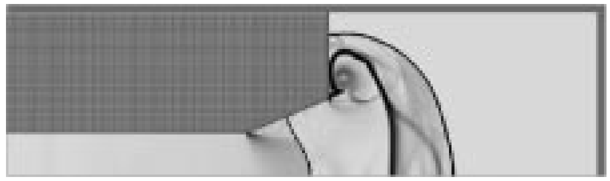
is reached. This can be achieved by making sure that the flow starts correctly and that the ratio of combustion chamber to surrounding atmosphere pressure results in a pressure-matched condition at the exit of the nozzle. At this highly efficient operating condition, a maximum amount of the propellant's chemical energy is converted into thrust.

Obtaining optimal results for a pulse detonation engine is more challenging than for a steady rocket motor since the flow is intrinsically unsteady and the ratio of chamber to atmosphere pressure is much more modest, 20-40 for the most common mixtures. To date, studies of detonation tube impulse with or without nozzles have not addressed the effect of varying the pressure in the surrounding atmosphere. A detonation tube filled to 1 atm and exhausting into 1 atm surroundings will convert only 46-64% of the propellant mixture's chemical energy that is available for doing mechanical work into impulse [1]. Adding straight, cylindrical extensions [2, 3, 4, 5] or various shapes of diverging nozzles [2, 4, 5] to detonation tubes resulted in only modest increases in the impulse which can be attributed entirely (in the case of a straight extension) and partially (in the case of a contoured nozzle) to the tamping provided by the air mass contained in the extension [1]. Another issue with previous studies is that when an extension to a short tube is used, apparent performance gains can be measured which are really due to the extension enabling transition to detonation [5].

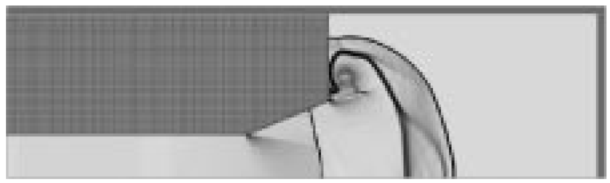
In order to clarify the issues surrounding nozzle applications to pulse detonation engines, we are carrying out a series of experiments systematically examining the pressure ratio. In order to get a much wider range of pressure ratios than in previous studies, we are carrying out experiments in a tank that can be evacuated to very low pressures. These experiments will be used to directly measure the impulse from a single-cycle detonation tube as a function of nozzle geometry and pressure ratio. We seek to find the operating conditions that maximize the nozzle efficiency converting some or all of the remaining 36-54% of the mixture's available chemical energy into impulse.

The detonation tube, with an internal diameter of 76.2 mm and length of 1.016 m, will be suspended in a ballistic pendulum arrangment inside a 335-L pressure vessel. The vessel can be evacuated to less than 100 Pa, and the pressure within the tube will be between 20 and 100 kPa. A 25 μm thick Mylar diaphragm at the tube exit separates the initial ethylene-oxygen-nitrogen mixture from the nozzle inlet or the surroundings (if no nozzle is attached). Wave velocities will be measured by pressure transducers and ionization gauges located along the tube length while the impulse is calculated from the tube's maximum deflection.

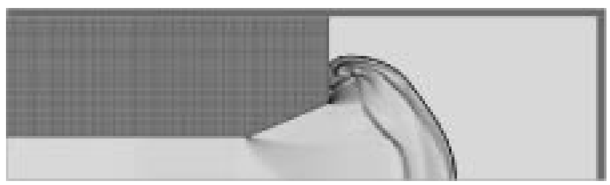
We have carried out a preliminary investigation of the startup process through diverging nozzles with different pressure ratios through numerical simulation with Amrita [6]. The simulations were started assuming the detonation wave with Chapman-Jouguet parameters of $M_{CJ} = 5.6$ and $P_{CJ}/P_1 = 17.5$ had just reached the nozzle inlet. Each nozzle has an area ratio of 3.6 and a half angle of 24 degrees. The results show that a shock wave is formed within the diverging nozzle during the startup process of a detonation exhausting into air at 1 atm, corresponding to a peak pressure ratio P_{CJ}/P_a of 17.5 (Fig. 1a), and exhausting into air at 0.54 atm, corresponding to a peak pressure ratio P_{CJ}/P_a of 32 (Fig. 1b). This shock wave prevents the flow from becoming supersonic within the diverging section and no performance benefit will be obtained from this nozzle. Increasing the nozzle pressure ratio, by a decrease in the environment pressure, decreases the strength of this upstream shock eventually resulting in choked flow within the nozzle throat and supersonic flow within the nozzle (Fig. 1c). Results will be presented on further computations that explore the parameter space and the single-cycle impulse values.



(a) P_{CJ}/P_a=17.5



(b) P_{CJ}/P_a=32



(c) P_{CJ}/P_a=300

Figure 1: Numerical schlieren images of flow through nozzles with different pressure ratios. Initial conditions were calculated with the Taylor wave similarity solution and the one-γ model for detonations for a non-dimensional energy release of $q/RT_1 = 40$ across the detonation and $\gamma = 1.2$ for the reactants and products. Quiescent gas with a γ of 1.4 fills the region to the right of the nozzle exit.

References

[1] Cooper, M. and Shepherd, J., "The Effect of Nozzles and Extensions on Detonation Tube Performance," 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 7–10, 2002, Indianapolis, IN, AIAA 02–3628.

[2] Zitoun, R. and Desbordes, D., "Propulsive Performances of Pulsed Detonations," *Comb. Sci. Tech.*, Vol. 144, 1999, pp. 93–114.

[3] Zhdan, S. A., Mitrofanov, V. V., and Sychev, A. I., "Reactive Impulse from the Explosion of a Gas Mixture in a Semi-infinite Space," *Combustion, Explosion and Shock Waves*, Vol. 30, No. 5, 1994, pp. 657–663.

[4] Falempin, F., Bouchaud, D., Forrat, B., Desbordes, D., and Daniau, E., "Pulsed Detonation Engine Possible Application to Low Cost Tactical Missile and to Space Launcher," 37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 8–11, 2001, Salt Lake City, UT, AIAA 2001–3815.

[5] Cooper, M., Jackson, S., Austin, J., Wintenberger, E., and Shepherd, J. E., "Direct Experimental Impulse Measurements for Detonations and Deflagrations," *Journal of Propulsion and Power*, Vol. 18, No. 5, 2002.

[6] Quirk, J. J., "AMRITA - A Computational Facility (for CFD Modelling)," VKI 29th CFD Lecture Series, ISSN 0377-8312, 1998.