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NOZZLE EFFECTS ON PULSE DETONATION ENGINES PERFORMANCE

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Abstract. *Pulse detonation engine is a new concept across air-birthing propulsion systems. Today, due to the unsteady behavior of this type of engine, design optimizations are not completed yet. In this regard, recent studies are focused on the effects of nozzle implementation in this propulsion system. In this paper, the effect of nozzle shape (angle & length) on the impulse and frequency of engine cycle performance is studied. Results show that the nozzle increases the impulse which the direct nozzle has the largest effect. In the other words, the greater the divergence angle and the length of the nozzle, the smaller the impulse. On the other hand, results indicate that the presence of a nozzle would increase the cycle frequency; to be exact, the greater the divergence angle and the length of nozzle, the higher would be the frequency. However, since thrust is a function of both the impulse and the cycle frequency, a system optimization has to be performed in order to find out the optimized design conditions. Further, since combustion phenomenon is not considered in the quasi one dimensional code utilized in this work, results do caution some degrees of error. However, a comparison with experimental data validates the trend obtained in this paper.*

1 INTRODUCTION

Pulse detonation engine (PDE) is a propulsion system which its concept is newer than the others. A basic PDE consists of a series of inlet valves, a detonation tube, and an exit nozzle. It is an unsteady device that uses a repetitive cycle to generate thrust. After World War II the concept of using pulse detonation engines in propulsion systems was propounded but, because of lack of accurate control systems with low response time and because of not comprehending the physic of flow, researches were stopped for some decades, it was attended again in 1990s. The advantages of these engines compared to conventional air breathing propulsion systems include high thermal efficiency, high specific impulse, mechanical simplicity, low weight and low cost. Although these characteristics are useful in aero propulsion systems but practical problems of using them with high impulse rate, initiation of detonation wave and keeping it at a controlled volume of fuel and oxidizer should be identified and overcame.

PDE is a device which allows periodic ignition, propagation, and transmission of detonation waves within a detonation tube, with associated reflections of expansion and compression waves which can act in periodic fashion to produce thrust. A summery of the relevant gas dynamics within the PDE tube is shown in figure 1. The figure indicates ignition and propagation of the detonation out of the PDE tube (figures 1a-c), reflection of an expansion fan into the tube (figures 1de), reflection of the expansion fan from the thrust surface (figures 1ef), allowing reactants to be drawn into the tube, and propagation of the expansion fan out of the tube (figures 1gh), with simultaneous reflection of a compressive disturbance into the tube (figures 1hi), which reflects from the thrust wall, ignites the fresh reactants, and reinitiates the cycle [5].

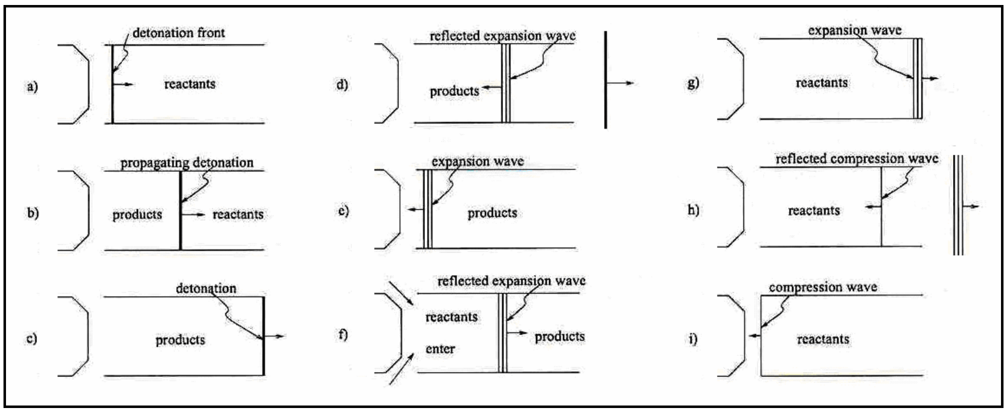

Figure 1: PDE cycle

The development of the concept of PDE has been traced back to pioneering work of Hoffmann in a number of papers in 1940. Both gaseous and liquid hydrocarbon fuels were employed with oxygen and intermittent detonation appears to have been achieved but attempts to determine an optimum cycle frequency were less successful. In 1957 Nicholls et al. were also exploring the concept of intermittent detonation waves for propulsion applications. The basic set up, was a simple detonation tube, open at one end with co-annular fuel and oxidizer injection at the closed end. For a hydrogen-air mixture, a specific impulse of 2100 seconds was attained along with a cycle frequency of 25 Hz. They also attempted initiation from the open end but were not successful. In the late 1980’s, the concept of using pulse detonations was re-examined by Helman et al. An ethylene-oxygen detonation in a small diameter tube was used as a pre-detonator to initiate detonations in a larger tube containing an ethylene-air mixture. Periodic fuel injection within the naturally aspirated tube resulted in an intermittent frequency of 25 Hz. Quasi one-dimensional numerical simulations were carried out to investigate the ideal performance of a PDE burning a stoichiometric mixture of hydrogen and air by Cambier and Adelman. The system simulated consisted of a 50 cm long main tube attached to a 43 cm long diverging nozzle. Issues of mixing, ignition and transition to detonation were all ignored. Overall performance calculated by integrating the instantaneous thrust and the fuel flow rates gave a specific impulse of about 6500 s and a potential operating frequency of 667 Hz. Five different nozzle shapes and their effect on performance were studied computationally by Cambier and Tegner [1]. Their results indicate that the presence of a nozzle can affect the performance of the PDE by increasing the thrust delivery during the ignition phase. The effect of various nozzle shapes, including converging, diverging and straight have been re-examined computationally by Eidelman and Yang. The overall conclusions of these studies was that nozzles can drastically increase efficiency of the PDEs, however, factors such as the effect of the nozzles on cycle frequency and the detailed structure of the flow have not been elucidated. The effect of direct nozzle on impulse of a cycle was investigated by Cooper and Shepherd [2]. They develop a partial-fill model to predict the impulse obtained from a detonation tube containing an extension (considered a partially-filled detonation tube). Increase of impulse was the conclusion of this model. The effect of divergent and convergent-divergent nozzle on Impulse of a cycle for different angle, length and ambient pressure condition was investigated experimentally by Cooper and Shepherd [3] and were compared with steady flow nozzle.

As mentioned, the effect of nozzles on the performance of PDEs has been the focus of many experimental and numerical studies. This work presents the results of a numerical study that investigate the effect of angle and length of nozzle on engine impulse and frequency from gas dynamics viewpoint.

Thrust of PDE depends on the cycle frequency. On the other hand, increasing the engine impulse causes some problems related to coordinate the exhausting of the previous cycle products and filling for next cycle. If the environment of injector is full of hot gaseous products, it may causes self ignition at the injection time and the deflagration causes to transmit heat of gas to the chamber and finally the engine will explode. Lack of very accurate control system, size of engine, type of fuel and oxidizer are some of restricting factors for high cycle frequency.

The use of nozzles in conventional steady propulsion systems is well understood and its results are known, since pulse detonation engines are unsteady and energy conversion is due to the waves, using nozzle for improving the system is complicated. When we use a diverging nozzle at the end of PDE, the detonation wave enters the nozzle and moves through it. Flow velocity is subsonic behind this wave and when it moves along nozzle, causes to increase the velocity of products and decrease their pressure due to unsteadiness. During the wave propagation in the nozzle, in the proper condition, velocity of products will be supersonic. If the products velocity remains subsonic in the nozzle, it will decrease along the nozzle. Since the major goal of nozzle using is to decrease the exhaust time, the flow condition at nozzle entrance and geometry are remarkable in nozzle design to increase efficiency.

2 GOVERNING EQUATIONS AND ASSUMPTIONS

The unsteady Euler equations in conservative form are used for the simulation of PDE to determine the nozzle effect. A perfect gas assumption for the working gas and a quasi one-dimensional flow assumption based on the problem geometry were made. The tube is divided to two zones, the head end has high pressure and temperature and the other has ambient condition. High pressure zone is instead of combustion products and low pressure zone is instead of reactants. Gas constant and specific heat ratio is assumed constant and equal in both zones. Since each reactant has unique product pressure and temperature after detonation, it sounds that the effect of various mixtures can be investigated by changing the pressure and temperature of head end zone.

Another problem in numerical simulation is the location of diaphragm. Its location in PDE is near the closed end of tube as much as possible. After the filling stage, initiation and propagation of detonation wave starts toward the open end and the expansion waves propagate vice versa. The last one reflects after contact the thrust wall (closed end) and move behind the detonation wave toward the open end. In this numerical simulation, to avoid the interaction between the reflected expansion waves with the detonation wave, the length of head end zone is selected appropriately.

To achieve the subsonic flow behind the shock wave, although the specific heat ratio for usual products is about 1.2, we are obliged to choose it equal to1.6.

In this work, the PDE is modeled as a shock tube and the combustion is ignored and the gas dynamics phenomena have been studied. Therefore, the incident expansion waves are stronger than tailor waves in reality and wall pressure decreases more. So the impulse will be different and its prediction is qualitative. Impulse is calculated until 85% of products are exhausted and the head end pressure reaches to ambient pressure.

To measuring the discharge time, two particles before and after diaphragm are considered. The x-t diagram of these particles is calculated. When the gases after diaphragm are exited, system filling will be initiated. It is a qualified condition for discharge process. On the other hand, decreasing the internal pressure of tube to ambient pressure is important to have sufficient impulse of the cycle.

3 NUMERICAL SIMULATION

A finite volume method is utilized for the discretization of the governing equations in which the information is stored at the cell centers. To implement this method, conservation equations are first integrated along the cell as follows:

$$\int_x \left(\frac{\partial Q}{\partial t} + \frac{\partial F}{\partial x} = st \right) dx \tag{1}$$

$$\int_x \frac{\partial Q}{\partial t} dx + \int_x \frac{\partial F}{\partial x} dx = \int_x st\, dx$$

$$Q^{n+1} = Q^n + \frac{\Delta t}{\Delta x}\left(F_{i+\frac{1}{2}} - F_{i-\frac{1}{2}} \right) + st\,\Delta t$$

The convective flux is calculated using upwind Roe’s scheme. In this scheme, flux terms are calculated as follows:

$$F_{i+\frac{1}{2}} = \frac{1}{2}\left(F_i + F_{i+1}\right) - \frac{1}{2}\sum_j \left|\overline{\lambda_j}\right| \delta w_j \overline{r}^{\,j} \tag{2}$$

To prevent numerical shock expansion, the appropriate entropy condition is made. To reach a stable solution, the time step is restricted according to the local velocity and grid size:

$$\Delta t \leq \frac{\Delta x}{|u+c|} \tag{3}$$

Appropriate boundary conditions are applied at the nozzle exit according to the flow regime. At supersonic exit conditions, all characteristics are extrapolated from interior and applied at the external artificial cell. At subsonic exit conditions, however, a physical condition is required and ambient pressure is set at the artificial cell and the other two characteristics are extrapolated from inside. At the head wall, solid wall boundary conditions are applied. Velocity at the artificial cell is negative of the main cell and its density and energy are equal to the main cell.

To ensure the validity of the numerical scheme, several benchmark problems including the compressible airflow are simulated. The comparisons indicate the accuracy of the numerical scheme.

4 RESULTS AND DISCUSSION

Focus in this research is on the nozzle effects on the propagation of detonation wave and discharging stage. The filling time is assumed constant. In PDEs, the filling velocity is subsonic (about 100 to 200 m/s) and depends on size, number and injection velocity of injectors. In this work the filling velocity of system is chosen 150 m/s. By considering the tube length, filling time is defined and by adding it to discharge time, total cycle period and frequency can be calculated. All of the results are from gas dynamics viewpoint and combustion has been ignored here.

The impulse of cycle is obtained by integrating the thrust surface pressure during cycle period:

$$I = A\int_o^\infty \Delta P(t)dt \tag{4}$$

An example of calculated pressure-time history at closed end is shown in figure 2. In PDE, both pressure magnitude of thrust wall and cycle frequency are important. The thrust is determined by the product of the impulse and the cycle frequency.

$$T = I.f \tag{5}$$

To investigate the nozzle effect, a 1m length and 0.1m diameter tube is considered. The pressure is 15atm and temperature is 1500K in head end zone, and for low pressure zone these amounts are 1atm and 300K respectively. Then some nozzles with 0.2 and 0.4 length and divergence angle of 0, 3, 5, 10 degrees are added to the tube. (0 degree angle is an extension of initial tube). By calculation the impulse in these conditions, the effect of nozzle will be studied.

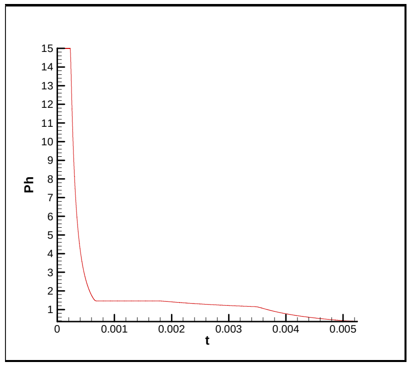

Figure 2: Pressure-time history on thrust wall

The variation of impulse versus nozzle angle for three cases, without nozzle, 0.2m and 0.4m nozzle length are plotted in figure 3. Results show that a nozzle presence increases the impulse and the greater its length, the greater the impulse and these results are independent of divergence angle. On the other hand, if the nozzle length is constant, increasing the divergent angle has inverse effect on the cycle impulse so the direct nozzle has the largest effect.

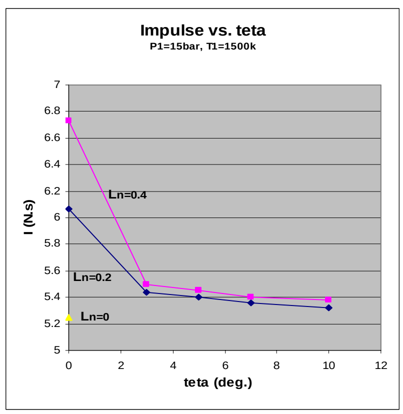

Figure 3: The effect of nozzle on cycle impulse

After determination the nozzle presence effect on PDE performance, its geometry effect is investigated. For this reason the total engine length is assumed 1m and the following geometries are checked numerically. The impulse, frequency and thrust are individually studied.

a) 0.9m is the tube length and 0.1m is the nozzle length for divergent angle of 0, 5, 7, 10 degrees.

b) 0.8m is the tube length and 0.2m is the nozzle length for divergent angle of 0, 5, 7, 10 degrees.

c) 0.7m is the tube length and 0.3m is the nozzle length for divergent angle of 0, 5, 7, 10 degrees.

d) 0.6m is the tube length and 0.4m is the nozzle length for divergent angle of 0, 5, 7, 10 degrees.

The impulse versus products pressure and divergence angle in which the nozzle length and products temperature is constant is shown in figure 4. The length of nozzle is assumed 0.2, 0.3 and 0.4 meter, product temperature is 2500K, product pressure varies from 10 to 20bar, and divergence angle varies from 0 to 10 degrees. Results indicate that, the greater the product pressure (which depends on the reactants), the greater the impulse; the smaller the nozzle angle, the greater the impulse because adding a nozzle increases the exhaust velocity and decrease the discharge time. In this figure the upper surface is related to a nozzle with 0.2 meter length and the lower is for 0.4 m. from this figure it is understood that the smaller the nozzle length (the products pressure and divergent angle are constant), the greater the impulse. It should be noticed that increasing the nozzle length means decrease the tube length and vice versa because the total length is constant. These results are similar to conclusion of reference 8.

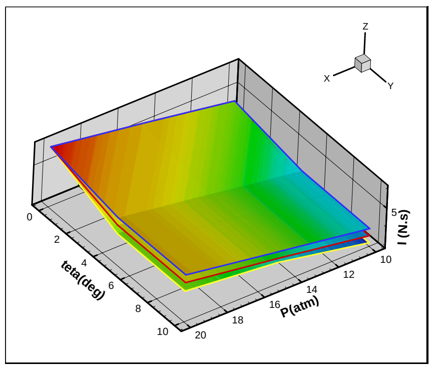

Figure 4: Impulse vs. products pressure and divergence angle for different nozzle length

The frequency versus products pressure and divergent angle is plotted in which the length of nozzle and products temperature is constant in figure 5. The length of nozzle is assumed 0.2, 0.3 and 0.4m, products temperature is 2500K, products pressure varies from 10 to 20bar, and divergence angle varies from 0 to 10 degrees. When the flow enters the diverging nozzle, its velocity increases and it will often be supersonic so the velocity of burned gases increases and discharging process will become faster. Results show that the greater the product pressure, the greater the frequency because higher pressure causes to increase the gases velocity; the greater the nozzle angle, the faster the velocity of products and the smaller discharge time and so the greater the frequency. In this figure the upper surface with higher frequency is related to a nozzle with 0.4m length and the lower is for 0.2m. From this figure it is understood that the greater the nozzle length (the product pressure and divergence angle are constant), the greater the frequency.

Thrust is defined as product of impulse and cycle frequency. We should find an optimum condition because in some cases the impulse is higher and the frequency is lower, in other cases the frequency is higher and the impulse is lower. Thrust versus length and angle of nozzle for products pressure of 10bar and products temperature of 2500K is plotted in figure 6. Maximum thrust is happened for nozzle with 0.1m length and 6 to 10 degrees angle;

Minimum thrust is happened for nozzle with 0.4m length and divergence angle equal to 5 to 10 degrees. Figures 7, 8 are similar to figure 10 and the only difference is products pressure which arises to 15 and 20 bar. In these figures maximum thrust is happened at a direct tube (no nozzle); minimum thrust is happened at a nozzle with 0.4m length and divergence angle equal to 5 degrees. Selection of optimum thrust depends on design; by selection of reactants (pressure and temperature of products), the best geometry for the higher thrust will be achieved.

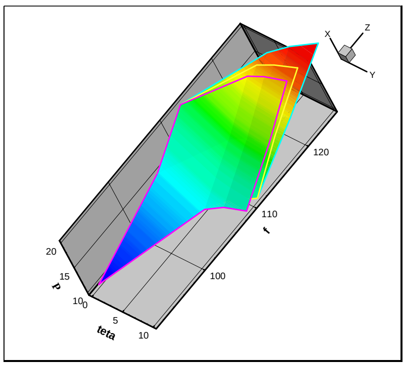

Figure 5: Frequency vs. products pressure and divergence angle for different nozzle length

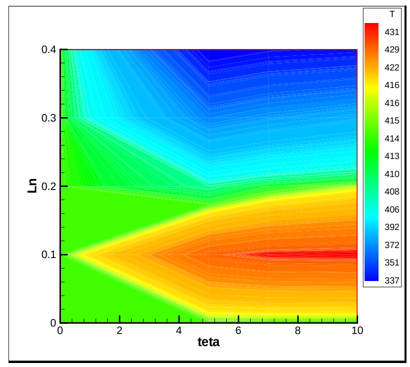

Figure 6: Thrust variation vs. length and divergence angle (10bar)

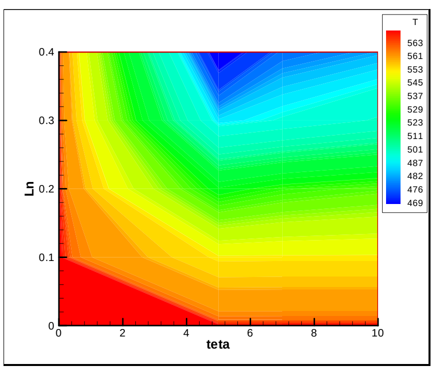

Figure 7: Thrust variation vs. length and divergence angle (15bar)

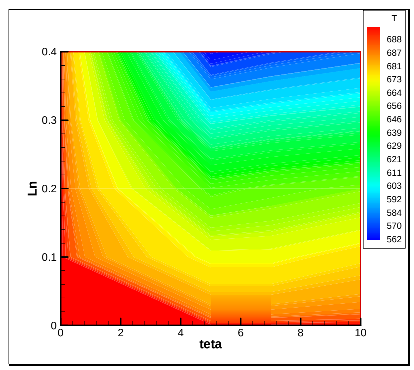

Figure 8: Thrust variation vs. length and divergence angle (20bar)

The higher the products pressure, the greater the impulse and cycle frequency because the higher pressure causes to increase the products velocity and pressure level on the thrust wall. Temperature increase has positive effect on the velocity of products but it's not as important as pressure, and is not studied here.

5 CONCLUSIONS

In this study, a quasi-1D code to solve the Euler equations is used. The combustion is ignored so results do caution some degrees of error. The results agree qualitatively with experimental results [3] and can be useful in the PDE design. The following considerations are important:

- Nozzle is useful to increase the cycle impulse. A tube with direct nozzle produces higher impulse than a diverging nozzle. The greater the nozzle length, the greater the impulse. The maximum length is restricted by vehicle geometry.
- By adding a diverging nozzle to the end of the tube, the cycle frequency increases. The greater the divergence angle, the greater the frequency. Flow separation and the maximum angle in which the flow becomes supersonic in the nozzle, should be considered for angle selection. Besides, the engine geometry determines the maximum exit area.
- To increase the thrust, a direct nozzle with acceptable maximum length or a diverging nozzle with a small length and high divergence angle at the end of the tube are preferred.
- A fuel with high P_{cj} (pressure after detonation) is better than others, high P_{cj} causes high frequency, impulse and thrust.

Finally, by these considerations, we can produce 3D design maps and from these maps of pressure-angle-impulse and angle-length-impulse we can design the engine and select the reactants for a specific mission.

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