Influence of Nozzle Type, Divergence Angle and Area Ratio on Impulse of Pulse Detonation Engine

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Abstract: *The influence of nozzle geometry on the impulse produced by the single cycle Pulse detonation engine (PDE) was experimentally investigated. For each experiment the nozzles were attached at the end of the engine. The impulse produced by the pulse detonation engine was calculated from the measured thrust. The thrust measurement was done by sliding the engine on the central bar of the thrust stand. The main structure of the basic PDE has a detonation tube with one terminal closed, a Schelkin spiral used as deflagration to detonation device, and a thrust stand to support the structure. Stoichiometric acetylene and oxygen mixture were used as detonation mixture. Various nozzles with a range of divergent angle and area ratios were tested. The calculations of the impulse were made from the thrust pulse for the duration it lasted. The effect of the type of nozzle, divergent angle and area ratio were observed. The bell shaped nozzle with large angle of divergence produced maximum specific impulse of 80 Sec with 20° divergence angle and area ratio of 6.942; maximum impulse was produced by the bell shaped nozzle with a small area ratio of 2.969 and 10° divergence angle. The maximum total impulse obtained was 1200 N-sec.*

Key Words: *Pulse Detonation Engine, Nozzle area ratio, Impulse, Bell shaped nozzle*

1. INTRODUCTION

Among researchers, the popularity of the Pulse Detonation Engine (PDE) has increased in a few years due to its high efficiency capabilities, light weight, less cost and simplicity of design [1], [2]. The impulse produced by an engine is an important performance parameter. Being one of the essential performance parameters of PDE, it is desirable to have consistent determinations of the impulse generation from the detonation of the fuel-oxidizer mixture. The factors that can influence the performance of the engine include formation of mixtures, inlet losses and the extension we provide at the end of the tube. It has been observed that the

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inclusion of a nozzle at the open end of the tube affects the thrust produced by the engine [3], [4], [5]. On the same way it is quite evident that an extension of the tube will affect the impulse produced in the engine. In the recent past, there have been numerous experimental and numerical studies on the performance enhancement of the Pulse Detonation Engine. Some of the cases using different fuel combinations and engine configurations along with partial or full filled tube can be summarized as under:

Nicholls et al. [6] used the ballistic pendulum and taking hydrogen oxygen mixture and with multi cycle experiment determined the specific impulse. However, their measured values of impulse were found to be lower in comparison with modern data. Zitoun and Desbordes [7] determined the impulse by summing up the pressure calculated at the blocked side of the detonation tube for both single-cycles as well as multi-cycle operation and found a 30% reduction in impulse for multi-cycle operation because of poor detonation tube filling. Zhdan et al. [8] performed ballistic pendulum experiments to determine the impulse, for a short tube length with acetylene-oxygen mixture operation on single-cycle. Harris et. al. [9] also studied the impulse change with variation in DDT distance by ballistic pendulum method. If no combustion mixture is expelled from the free end of the tube, the impulse obtained remains almost the same in both the cases of direct initiation of detonation or DDT assisted detonation. M. Cooper et al. [10] measured impulse of pulse detonation engine using three dissimilar lengths to diameter ratios of detonation tubes. They conducted experiments on a ballistic pendulum type of engine and compared the measured impulse to the impulse obtained from the analytical model. Various tests were conducted on tubes with and without obstructions. The blockage ratio was 0.43 in case of tube with obstruction. For the same operating conditions, the impulse obtained in case of tube without obstruction was 25% higher in comparison with tube with obstruction. The effect of tube extension on the impulse was observed to be positive and addition of divergent nozzle affected the impulse slightly. Daniel Allgood et al. [11] used exhaust nozzles and thrust stand with damper to enhanced the performance of a multi-cycle PDE-engine, with a tube length of 1.88m and 30 Hz frequency. The tests were conducted for bell shaped nozzles having 0.25 as convergent and 4.0 as divergent area ratios, respectively. For fill friction of 0.5 and below, the engine gave optimum performance without any extension i.e., without nozzle. For fill friction greater than 0.5 and in the rage closer to one, the use of convergent nozzle improved the thrust produced by the engine. Divergent nozzles also indicated increased thrust values but showed their sensitiveness to ignition delay. Cambier and Tenger [12] used the computational fluid dynamics with single pulse computation to check the changes in design and potential and observe that PDE thrust is affected by use of nozzle at tube exit and specific impulse is improved with fueling methods.

Takuma Endu et al. [13] analyzed the gas dynamics of a PDE and formulated the parameters by integration of pressure values over thrust wall. Wei Fan et al. [14] found that thrust produced is linear to volume and frequency of detonation, by experimentally investigating a two phase PDE model.

M. Cooper et al. [15] applied the correlation with single and multiple cycles to determine the impulse increase with change in filling of detonation tube. Impulse increased with increase in fill fraction of the tube and maximum impulse was obtained for fully filled tube.

Jiro Kasahara et al. [16] used the spring-damper mechanism to measure the thrust pulse. By measuring the mass of fuel and oxidizer, the impulse was calculated. The specific impulse was found to be decreasing with decrease in fill fraction of the tube. CI Morris [17], used computational fluid dynamics to study the PDRE with four different geometries and to check out the potential improvements of performance in comparison with conventional designs and observe that at high pressure ratios, C-D nozzle are better than straight extension.

Shigeri, Sato [18] numerically studied the pulse detonation rocket engines by changing the various parameters and found that mass fraction of the fuel-oxidizer mixture affected the specific impulse and hence the performance more than other parameters. E. Wintenberger et al. [19] analytically modeled the pressure values on the closed end wall of single-cycle PDE tube using the fuel-oxygen-nitrogen mixture and observe that the impulse is affected by initial conditions and energy released by detonation.

2. EXPERIMENTAL PULSE DETONATION ENGINE SETUP

The research team at Punjab Engineering College developed a single cycle PDE. It consists of a valve less combustion tube, a Schelkin spiral as a deflagration to detonation transition (DDT) device, fuel injection system and spark plug as ignition system.

The detonation in the engine is produced using acetylene-oxygen or acetylene-air mixture and a load cell was attached at the front end of it to measure axial thrust.

The constructional details of a basic PDE engine can be seen from the following simplified diagram.

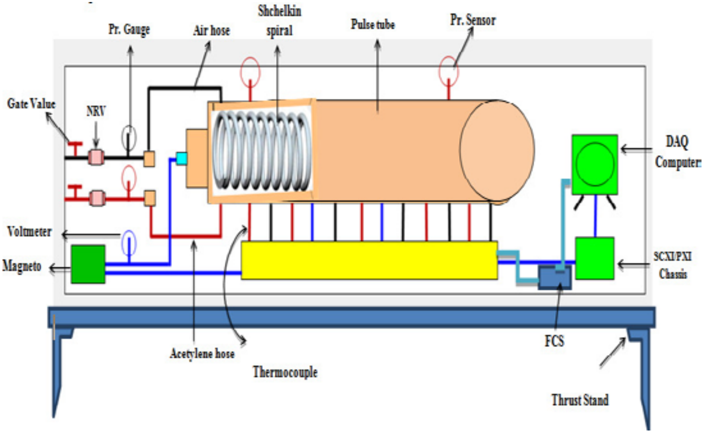

Fig. 1 Simplified layout of a basic PDE system

The engine used for experiment has a hollow detonation tube of 80 cm length having 48 mm internal diameter and 60 mm external diameter made of Grade 304 stainless steel, designed to operate for high pressure waves caused by the detonation. A thrust stand is designed for the tube to slide on the middle rest bar.

The reduction in the thrust obtained due to vibration and friction of the sliding bar was found to be 35 N.

A fuel injector delivery system is designed for the Stoichiometric ratio of the fuel/air mixture. A flow controller & electronic microcontroller-based system is used to control the supply with a self-sufficient injector system.

Just before entering into the detonation tube, acetylene and oxygen is mixed. A 12 V DC spark plug was provided for ignition. Using a mobile application spark was initiated when the tube was filled with the required ratio of fuel and oxidizer.

For easy combustion, the inlets for fuel and oxidizer were situated near to the spark plug. Impact Sensors used were capable of measuring compression and impact forces to the range of 4 N to 22.4 kN.

The engine stand dimension are 365cmx91cmx184cm, having a curved cowl covering of 35 cm for safety of people working on the engine.

3. THE NOZZLES USED IN THE EXPERIMENTS

The detonation in the tube causes a high intensity pressure wave that travels in the tube at very high speed. The exhaust gases form the engine expands to the surrounding atmosphere. When a nozzle is fastened at the open side of the tube, some of the kinetic energy of the exhaust gases produces additional thrust. There has been already work done on the use of nozzle for performance enhancement of PDE.4, 5, 6.

Table 1: Conical divergent nozzles used in experiments

S. No.	Nozzle Geometry	Nozzle Type	Divergence angle	Area Ratio
1		Divergent nozzle-1	5°	1.862
2		Divergent nozzle-2	10°	4.419
3		Divergent nozzle-3	15°	10.451
4		Divergent nozzle-4	20°	22.956

Table 2: Bell shaped nozzles used in experiments

S. No.	Nozzle Geometry	Nozzle Type	Divergence angle	Area Ratio
1		Bell Nozzle-1	5°	3.343
2		Bell Nozzle-2	10°	2.969
3		Bell Nozzle-3	15°	6.0943
4		Bell Nozzle-4	20°	6.942

With reference to literature available, there is no fixed geometry of a nozzle that was found to give optimum performance of engine. Therefore, we fabricated and tested eight different nozzle configurations to predict the impulse improvement of the engine. Two different types of nozzles (Conical and Bell shaped) with various angles of divergence/expansion and area ratios (A_{exit}/ A_{throat}) were tested. Table-1 shows the conical divergent nozzles of various divergent angle and area ratios and in Table-2 Bell shaped nozzles with various expansion angle and area ratios are depicted. The primary engine consists of the detonation tube of 80cm alone. In the next configuration the tube was extended to 100cm, i.e., straight nozzle of 20cm was attached to the tube.

Further attachment to the tube includes four conical nozzles of different configuration as shown in Table-1, and subsequent geometries include bell shaped nozzles as in Table-2. The following figure shows the experimental setup with attached nozzle.

Fig. 2 Experimental setup with nozzle attached

4. IMPULSE DETERMINATION

The impulse was calculated by measuring the thrust for each pulse of the shot. The load cell, which is situated between the blocked end of the tube and engine stand, measures the thrust. The total impulse of the engine can be calculated using the following relation [11].

$$\mathrm{I} = \int \mathrm{F}\, \mathrm{dt} \tag{1}$$

The impulse was determined by measuring the peak thrust for each pulse of the engine and the time interval of the pulse.

And the specific impulse, defined as the ratio of total impulse to weight of the detonable mixture, can be calculated using the following relation [11].

$$\mathrm{I_{sp}} = \frac{\int_0^t \mathrm{Fdt}}{\mathrm{g} \int \dot{\mathrm{m}}\, \mathrm{dt}} \tag{2}$$

By measuring the pressure drop in the settling chambers prior and after the detonation, the mass flow rate of fuel and oxidizer was calculated, which subsequently was used to calculate the specific impulse. The governing equation to calculate the mass flow rate [11], assuming that the gas temperature remains constant, is

$$\Delta \mathrm{m_c} = \Delta \mathrm{p_c} \frac{\mathrm{M_c V_c}}{\mathrm{RT_c}} \tag{3}$$

5. RESULTS

The basic engine arrangement consists of 80 cm detonation tube, a 24 cm Schelkin spiral with 1.7 cm pitch and 0.8 cm wire diameter. The fill pressure was kept 40 and 70 psi for acetylene and oxygen, respectively. Using the mobile application, the ignition was initiated through spark plug.

The peak thrust is measured by the load cell for each shot of the engine. The fuel pressure gauge and oxidizer pressure indicated the pressure before and after each shot. The volume of the settling chamber being constant, the mass flow of fuel and oxidizer was calculated from the difference in pressure using equation (3). The total impulse and specific impulse were calculated using the relations in equation (1) & (2), respectively. The measurements were done for the basic engine, using straight nozzle, four conical divergent nozzles with varying divergent angle and area ratios and four bell shaped nozzles with varying expansion angles and area ratios. The results obtained are as follows:

Specific Impulse variation with divergent angle

The specific impulse produced by the engine was calculated from the thrust obtained and the change in mass of fuel and oxidizer before and after the shot.

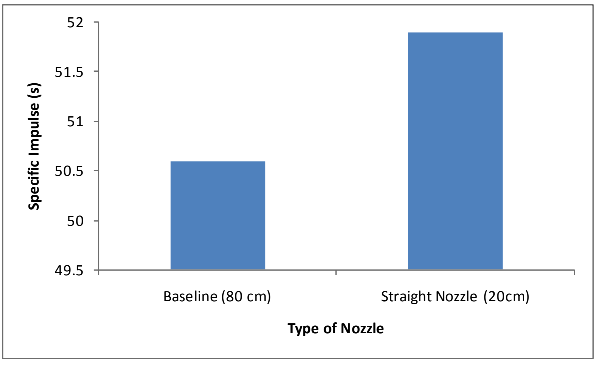

Fig. 3 Specific impulse for baseline engine and straight nozzle

As shown in fig. 3, the specific impulse for the baseline engine was calculated to be 50.589 sec. The specific impulse improved a bit with straight nozzle and was found to be 51.898 sec, i.e., 1.02 times of baseline engine.

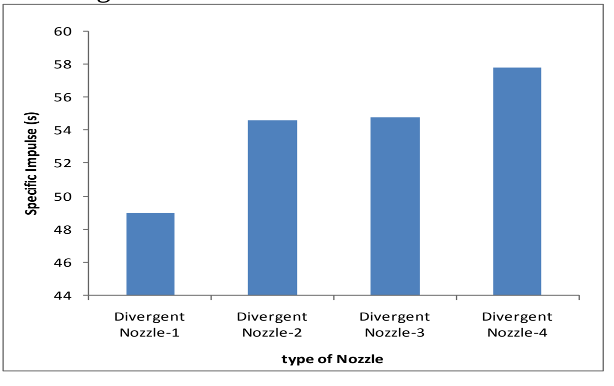

Fig. 4 Specific impulse for divergent nozzles

Fig. 4 shows the variation of specific impulse for divergent nozzles with various divergent angles. When a divergent nozzle of 5° angle attached to PDE, the specific impulse produced reduced to 48.972 sec.

But with an increase in the divergent angle of the nozzle to 10°, an increase in specific impulse was observed. The specific impulse was calculated to be 54.593 sec. A further increase in divergence angle to 15° increased the impulse very little to 54.747 sec. Again, when the divergent angle of the nozzle was kept 20 specific impulse improved further and was found to be 57.75 sec.

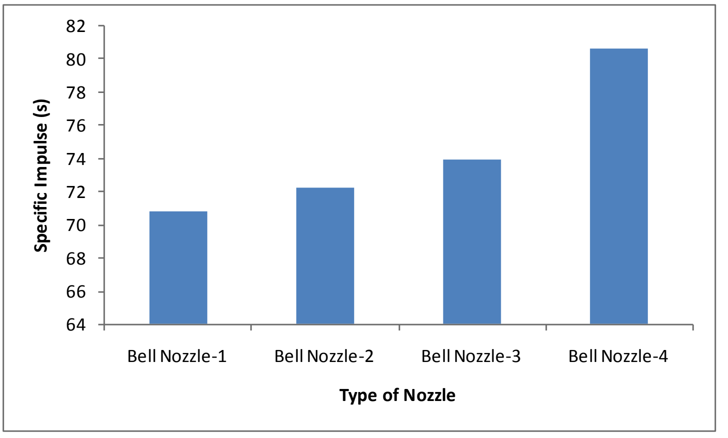

Fig. 5 Specific impulse for Bell shaped nozzles

The specific impulse calculated for Bell-shaped nozzles with various expansion angles are depicted in fig. 5.

With an expansion angle of 5°, the bell-shaped nozzle when fastened to the open end of the detonation tube produced specific impulse of 70.84sec.

When the expansion angle of the bell-shaped nozzle increased to 10°, the specific impulse increased to 72.226 sec.

When the expansion angle increased to 15°, the specific impulse of 73.92sec was produced. Finally, when a bell-shaped nozzle of expansion angle 20° was tested, the specific impulse increased to 80.696sec.

Specific Impulse Variation with Area Ratio

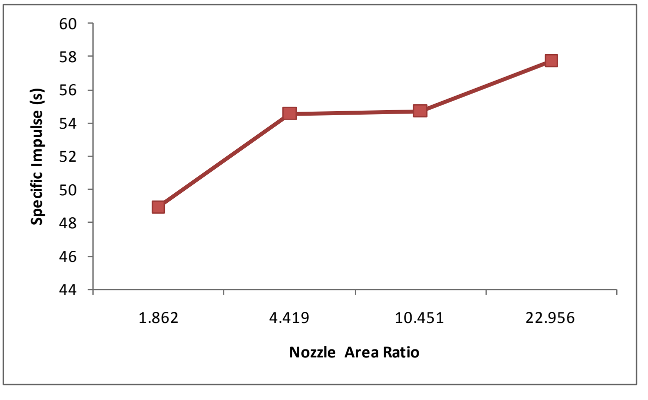

Fig. 6 Specific impulse variation with area ratio for divergent nozzles

The specific impulse produced by the Pulse Detonation Engine with variation in area ratio of conical divergent nozzles is shown in fig. 6.

When a divergent nozzle of area ratio of 1.862 was attached to PDE, the specific impulse produced was reduced to 0.968 times compared to the baseline case. But with an increase in the area ratio to 4.419, an increase in specific impulse was observed. The specific impulse was calculated to be 1.079 times the baseline case.

A further increase in area ratio to 10.451 increased the impulse very little to 1.082 times the baseline value. Again, when the area ratio of 22.956 was used, specific impulse improved further and was found to be 1.142 times the baseline value.

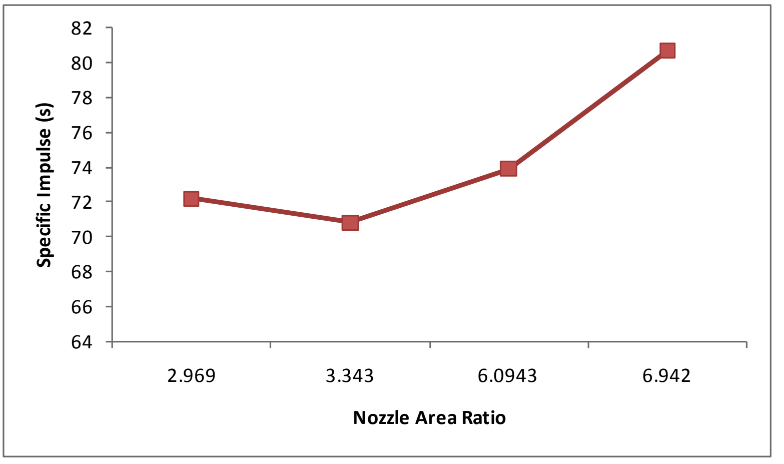

Fig. 7 Specific impulse variation with area ratio for Bell shaped nozzles

The specific impulse calculated for Bell-shaped nozzles with various area ratios are shown in fig. 7. With an area ratio of 3.343, the bell-shaped nozzle produced specific impulse 1.4 times in comparison with baseline engine.

When the area ratio reduced a bit to 2.969, specific impulse increased to 1.427 times the baseline value.

A further increase in area ratio to 6.1 increased the specific impulse to 1.461 times the baseline value.

Finally, when a bell-shaped nozzle of area ratio of 6.94 was tested, the specific impulse increased 1.595 times in comparison to the baseline case.

Total Impulse Variation with Divergent Angle

The total impulse produced by the engine was calculated by integrating the peak thrust obtained over the duration of the pulse.

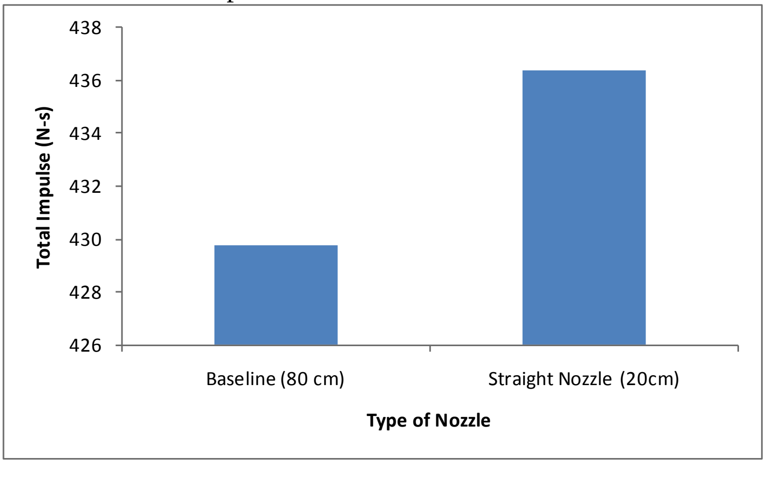

Fig. 8 Total impulse for the baseline engine and straight nozzle

The total impulse for the baseline engine was found to be 429.74 N-sec. When straight nozzle was added to it the total impulse improved to 436.411 N-sec or 1.0155 times the baseline value (fig. 8).

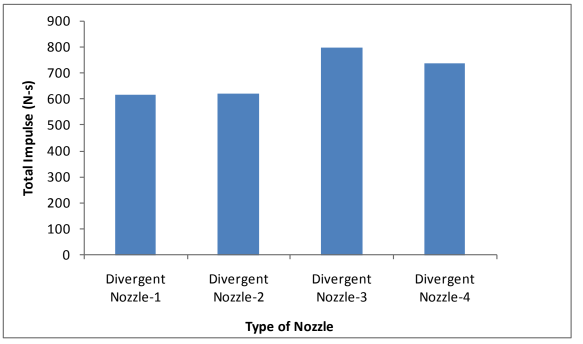

Fig. 9 Total impulse for divergent nozzles

Fig. 9 shows the variation in value of total impulse obtained with conical nozzles having different angle of divergence. When a divergent nozzle with 5° divergence angle was attached, the impulse produced was found to be 617.77 N-sec. But with an increased divergent angle of 10°, the impulse increased a little to 618.337 N-sec. The impulse increased to 797.248 N-sec with an increase in divergence angle to 15° and again, when the divergent angle kept 20°, the impulse decreased a bit to 735.856 N-sec. In fig. 10 we can see the change in value of total impulse using different expansion angles of Bell shaped nozzles. With an expansion angle of 5°, the bell-shaped nozzle produced an impulse to the tune of 1031.6 N-sec. With an increase in the expansion angle of the bell-shaped nozzle to 10°, the impulse calculated increased to 1227.08 N-sec. But a further increase in expansion angle to 15° leads to a decrease in impulse to 941.896 N-sec. The impulse decreased to 632.761 N-sec with an expansion angle of 20°.

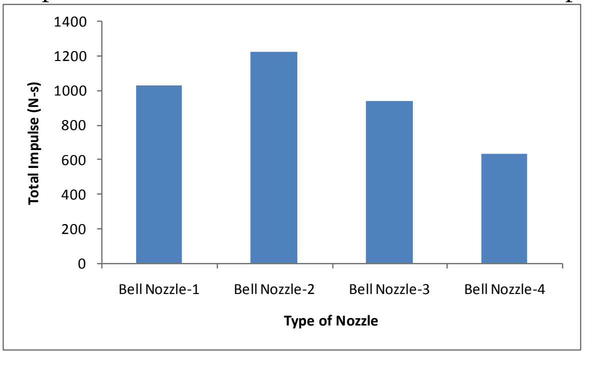

Fig. 10 Total impulse for Bell Shaped nozzles

Total Impulse variation with Area Ratio

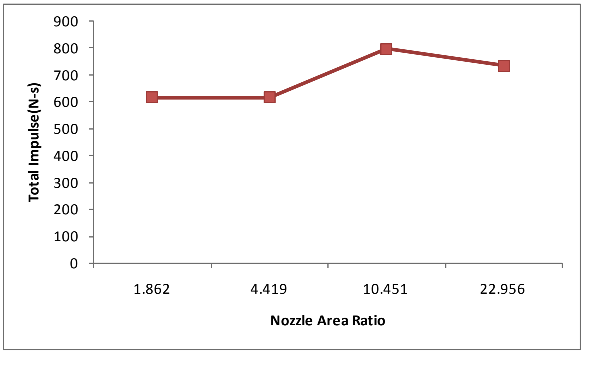

Fig. 11 Total impulse variation with area ratio for divergent nozzles

As it can be observed from fig. 11, when a divergent nozzle with an area ratio of 1.862 was attached, the impulse produced was found to be 1.437 times the baseline value. But with an increased area ratio of 4.419, the impulse increased to 1.438 times the baseline value. The impulse increased to 1.855 times the base value with an increase in area ratio to 10.451. Again, when the area ratio is of 22.956, the impulse decreased to 1.712 times the baseline value.

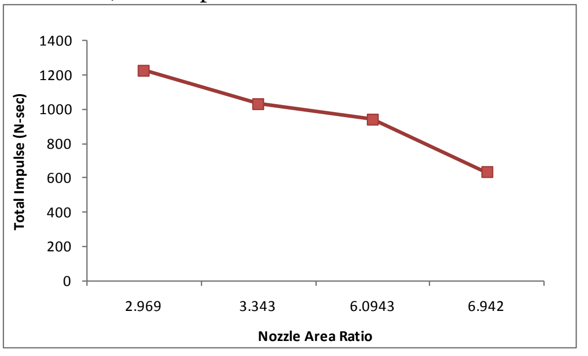

Fig. 12 Total impulse variation with area ratio for Bell shaped nozzles

Fig. 12 shows the effect of change in area ratio on to the total impulse of the PDE. With a 3.343 exit area to throat area ratio, the bell-shaped nozzle produced an impulse of 2.4 times the impulse obtained for baseline case.

With a little reduced area ratio to 2.969, the impulse calculated increased to 2.855 times the baseline value.

But a further increase in area ratio to 6.0943 leads to a decrease in impulse to 2.192 times the baseline value. The impulse decreased to 1.472 times the base value with an area ratio of 6.94.

6. CONCLUSIONS

The variation in peak pressure in tube was found to be inconsistent with the nozzle type, angle of divergence and area ratio. The peak pressure in tube was measured to be higher in case of bell shaped nozzle with a smaller divergence angle.

The specific impulse improved with each nozzle used except for conical nozzle with the smallest angle of divergence.

Bell shaped nozzles produced the maximum specific impulse, which grew with an increase in divergence angle or area ratio. The Bell shaped nozzle produced 80 Sec of specific impulse with 20° divergence angle and an area ratio of 6.942.

The total impulse produced in each pulse improved with the use of extensions. With conical nozzles, the impulse improved with the divergence angle and the area ratio up to a certain value and then started decreasing.

The maximum value of 800 N-sec was obtained using a 15° divergence angle and an area ratio of 10.451. Again, the bell shaped nozzles outperformed the conical nozzle by producing the maximum value of the total impulse.

The maximum impulse of 1200 N-sec produced by the bell shaped nozzle was for small area ratio of 2.969 and a10° divergence angle. An increase in divergence angle or area ratio decreased the impulse produced as seen in figure 15.

It is concluded that the bell shaped nozzle with a large angle of divergence produced the maximum specific impulse whereas the maximum total impulse was obtained using bell shaped nozzles with small divergent angle and area ratio.

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