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An Experimental Study on Performance of a Kerosene Based Pulse Detonation Engine

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Abstract: **The paper concise experimental study on performance of kerosene based pulse detonation engine where vapor kerosene and pre-heated air is utilized in achieving detonation. The objective of this current work is to achieve detonation successfully at higher frequencies and also its corresponding detonation pressure, Jet thrust measurements. Thrust calculations are done in two ways i.e., Root Mean Square value (RMS) value of thrust and head end pressure thrust. RMS value of thrust provides the average thrust exhibited by PDE for a given period. Meanwhile, endeavoring thrust comparison between load cell thrust and head end pressure thrust. The pulse width of the detonation pressure for 1Hz is analyzed. Finally the specific impulse of the current PDE is investigated with the current available air breathing engines.**

Keywords: **Deflagration to Detonation transition (DDT), Equivalence ratio, Pulse Detonation Engine (PDE), Vapor kerosene.**

I. INTRODUCTION

Pulse jet engines are suitable for only subsonic flight where high pressure is achieved through combustion rather than using any compressor. So pulse jet engines can operate from static conditions itself. Whereas the PDEs are the enhanced form of the pulse jet engine that can operate from low speed subsonic to supersonic speeds nearly Mach 4. A detonation engine offers thermal efficiency up to 56.4% than that of 36.3% in deflagration engines. So this is the motivation behind this project.

All conventional jet engines in industrial sector currently works on deflagration combustion which has lower thermodynamic efficiencies than PDE. Thus it was the vital characteristics of PDE along with simplistic design that led researchers a wide area of interest. PDEs offer better performance than current propulsion system due to their constant volume heat addition process. PDEs thrust performance for multiple chambers increases linearly with frequency. This was the motivation for this current work on PDE detonation characteristics and its corresponding thrust performance.

S. M. Frolov et al. [1] Showed how PDE proves to be having higher thermodynamic efficiency than other air breathing engines. He also showed thrust performance can be enhanced by simply increasing number of chambers. If efficiency goes higher, then we are saving energy resources, so this was demonstrated by him. He also showed the operation of PDE can be stabilized by working with low volatility fuel like aviation kerosene rather than high volatility fuel like n - heptane or n - hexane. They even measured jet thrust at 2.2, 3.1 and 3.9Hz. It was continued till 8 Hz. The maximum thrust observed was 30±2N.

C.S. Wen et al. [3] worked on JP- 8 based pulse detonation engine where primary objectives was to study on initial temperature of fuel- air mixture prior to detonation. Then finally realized that gaseous fuel is more profitable than liquified fuel in terms of its specific energy, density and small volume requirements. They found temperature of the fuel vapors must be greater than 393K to achieve detonation successfully. In order to have lower DDT distance, 413K, 433K and 453K was found to be profitable for detonation.

Y. Huang et al. [4] worked on kerosene based pulse detonation engine where primary objective to build small scale propulsion system and to carry out high frequency detonation tests. Small scale PDE (SPDE) found to be structural simple and has high cycle efficiency. They finally found the pre – heating significantly enhances detonability of kerosene-air mixture. The SPDE operated steadily till 62.5 Hz but optimum performance was observed at 20, 42.5 and 50Hz.

Geraint Thomas et al. [5] worked on DDT in a long unobstructed piping system where fuels used are hydrogen, ethylene, methane, propane and acetone. They found that introducing bends in the pipe will trigger DDT. Also, gas mixtures are prepared by recirculation method. Thus detonation was observed for hydrogen- air mixture and ethylene- air mixture (only for higher initial temperature). They also found bends introduction in pipe enhance turbulence in the pipe.

The Chemical Equilibrium with Applications (CEA) [2] is a NASA's Computer program that calculates chemical equilibrium compositions and properties of complex mixtures. CEA program uses Chapman Jouguet (CJ) detonations model to get the pressure values which is used for validating the experimental detonation pressure values.

Vikram Atreya et al.[6] worked on kerosene based DDT with 1hz operational frequency for different equivalence ratio. The current work encloses the extended work of above author which encompasses PDE operation at different frequencies where detonation pressures are validated with theoretical CEA pressure values and also corresponding jet thrust, specific impulse are investigated and compared.[8]. From this result, it is found that the specific impulse of current PDEs are greater than that of ramjet and scramjet engines.

II. EXPERIMENTAL SET UP

The components and its corresponding instruments for PDE are illustrated by block diagram in the below Fig.1. The PDE is suspended by steel cables along with stand. It comprises of a kerosene evaporator (compact heat exchanger), a pre- heater for air[4], nitrogen cylinder, 2 m long detonation tube of 43mm internal diameter, load cell, Shchelkinspirals, nozzle and associated measurement devices that include signal conditioner, oscilloscope, ignition electrodes, pulse generator, ignition transformer and pressure sensors. Schelkin spiral of Blockage ratio 43% is choosen as per vikram et. al [6] and load cell is included in the present test rig to capture thrust. PT4 is mounted at distance of 110mm from head end of the tube where as PT1, PT2, PT3 are mounted on the rearward of the tube at a distance of 1100mm, 1230mm and 1350mm from the head end.

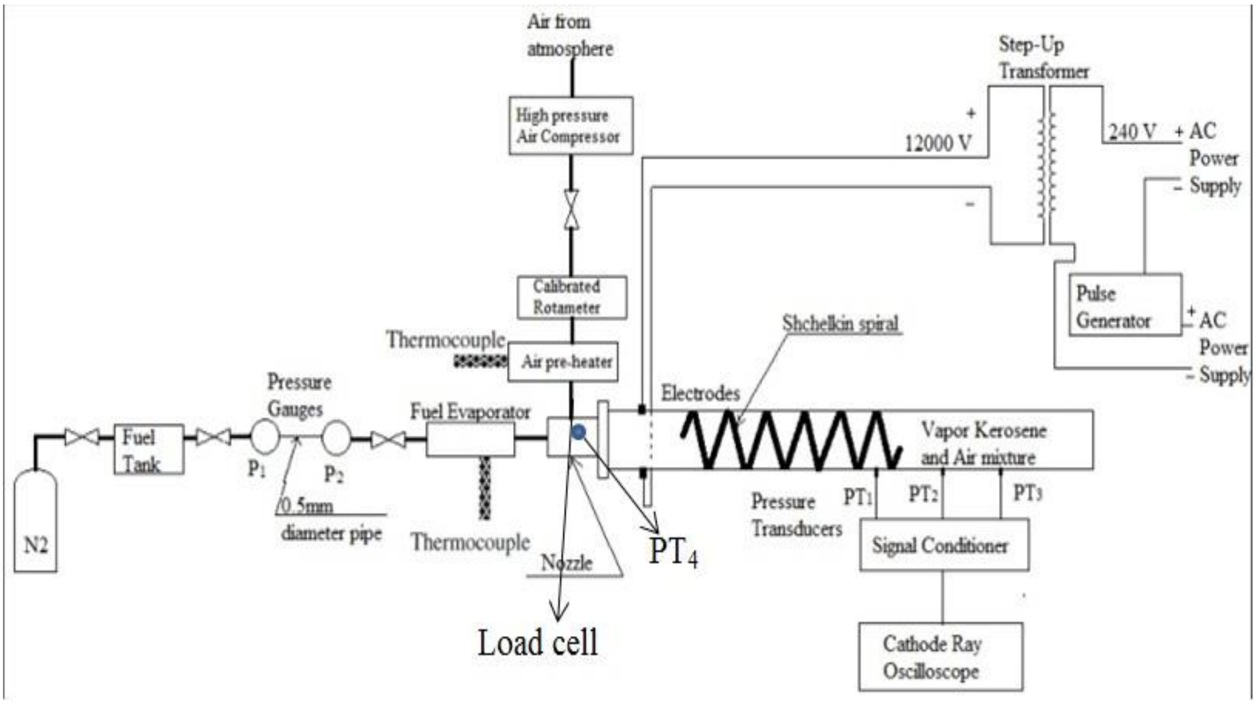

Fig.1. Schematic diagram of experimental setup

Vapour kerosene and pre-heated air are maintained at 180^0C . Gaseous mixture of air and fuel (vapourized kerosene) is injected in to the detonation tube continuously. Combustion is initiated with the pair of electrodes. Combustion starts with deflagration initially and then these deflagrated flames will compress the unburnt gaseous mixture to little extent.

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Subsequently this leading to turbulent flames mixing with unburnt gaseous fuel-air mixture on expansion through the Schelkin spiral. Thus pressure and temperature build up in the detonation tube causing the fuel air mixture to explode leading to detonation. Thus detonation is accomplished as per Ciccarelli et al[1] and Wen, K. M et. Al[3], Thus on the exiting of the detonation wave from the tube produce impulse which is captured by the load cell. The pressure transducers mounted along the tube recorded the pressure exhibited with the help of a oscilloscope and signal conditioner.

III. RESULTS AND DISCUSSIONS

A. Detonation pressure capture:

The pressure exhibited at different locations along the detonation tube during PDE operation at 1 Hz for equivalence ratio of 1 is shown in Fig.2. Fig.2 clearly dictates a jump in pressure between pressure slots 1 and 2, thus the peak pressure is 24.156 bar. Where as the CEA pressure[2] at CJ point of detonation is found to be 19.775 bar. Thus the pressure at 2nd slot had well crossed CEA pressure, giving the conformity of detonation. Detonation conformity can also be seen from Vikram Atreya et. Al [6].

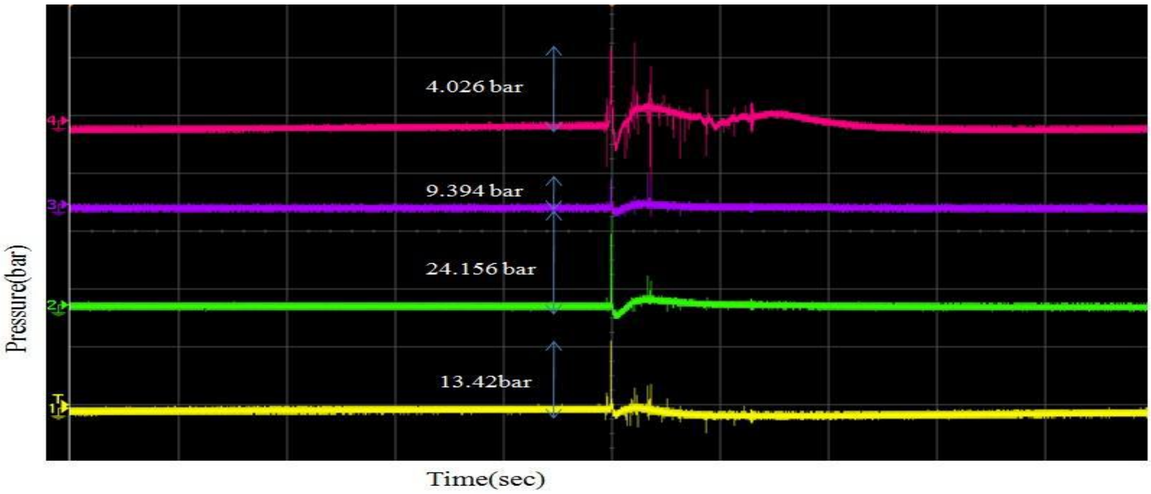

Fig.2. Pressure vs Time plot for PDE operated at 1 Hz

The pressure exhibited at different locations along the detonation tube during PDE operation at 2 Hz for equivalence ratio of 1.39 is shown in Fig.3. Fig.3 clearly dictates a jump in pressure between pressure slots 1 and 2, thus the peak pressure is 26.17 bar. Whereas the CEA pressure at CJ point of detonation is found to be 21.45bar. Thus the pressure at Second slot had well crossed CEA pressure, giving the conformity of detonation. The same results was also observed by cooper et al [7].

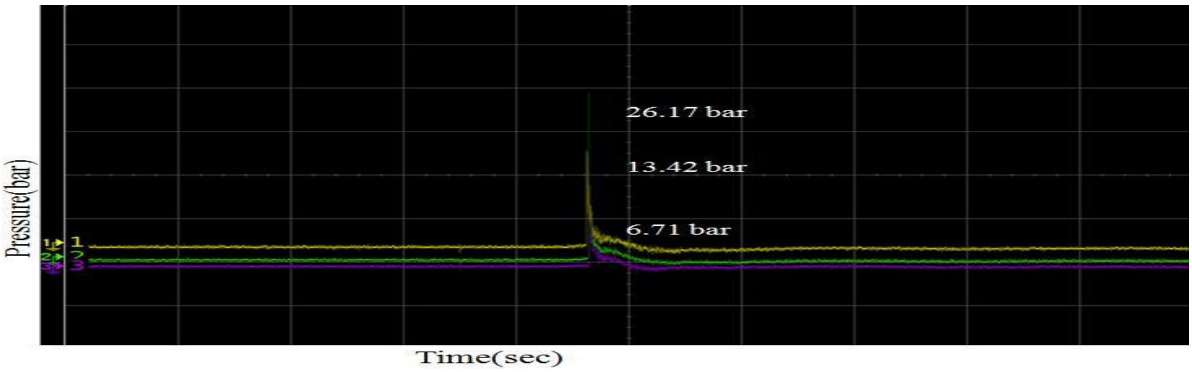

Fig.3. Pressure vs Time plot for PDE operated at 2 Hz

Detonation pressure is also captured for 3 Hz operational frequency. The required fuel-air mixture supply is available but in order to push into the detonation tube was not successful. We have achieved detonation only for a few seconds but not steadily for 3Hz. This is due to insufficient presence of fuel-air mixture inside the detonation tube. The pressure variations along the detonation tube at different locations for all the operational frequencies is tabulated and peak pressure is compared with CEA pressure below in TABLE I

TABLE I: COMPARISON BETWEEN DETONATION PRESSURE AND CEA PRESSURE AT DIFFERENT FREQUENCIES

Sl.no	Frequency	Equivalence ratio(ϕ)	PT1 (bar)	PT2 (bar)	PT3 (bar)	CEA pressure (bar)
1	1	1	13.42	24.15	9.39	19.77
2	2	1.39	13.42	26.17	6.71	21.45
3	3	1.56	5.09	33.55	24.15	23.67

B. Thrust determination of PDE at 1HZ:

As detonation is initiated, the detonation wave propagates along the chamber and product gases are exhausted. The pulsating type of combustion produces pulsating thrust. Thrust is captured from the data acquisition system (DAQ), which provides output in the form of voltage. The load cell is calibrated as 0.2V/kg.

The thrust output captured from the Data Aquisation(DAQ), when the PDE operated at 1 Hz is shown in the Fig.4, where the sampling rate maintained is on the lower side and also, the impulse is not steady for the overall period. Thus the peak thrust from this perception is 1.3V-0.7=0.6V=3kg. The similar kind of impulse was also observed by M.Cooper et al[7].

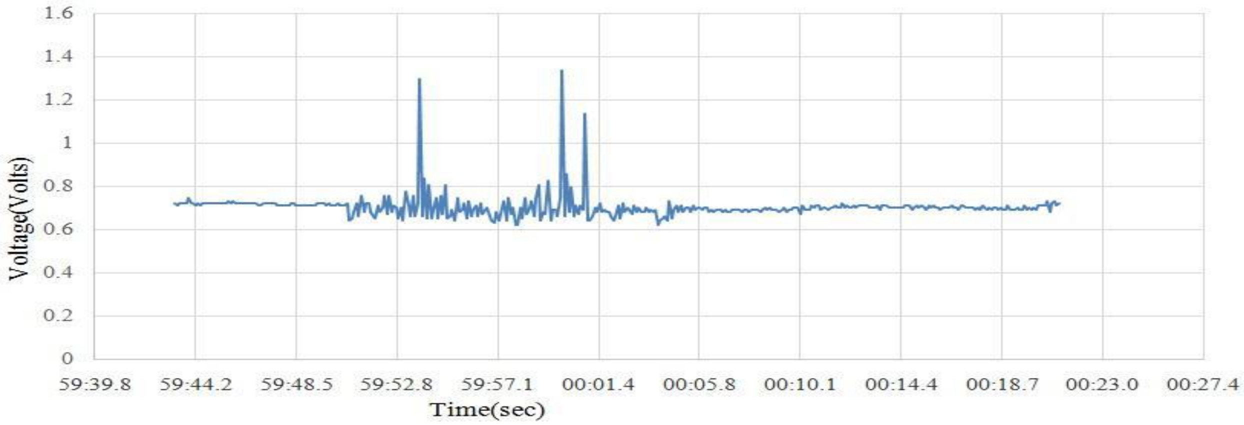

Fig.4. Voltage vs time plot for PDE operation at 1Hz with lower sampling rate

C. RMS value of thrust determination for 1hz:

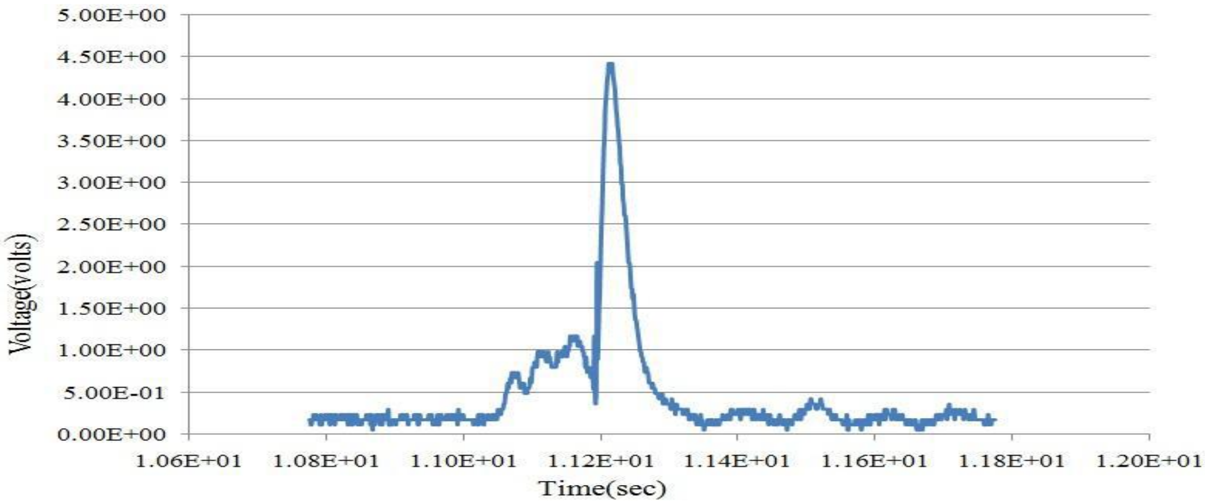

Fig.5 Voltage vs time plot of PDE at 1 Hz with higher sampling rate

The thrust output captured from the oscilloscope at higher sampling rate is shown in Fig.5 where instead of many peak voltages only one peak with wide area distribution under it is observed. This complete area is utilized to calculate the RMS value of the thrust. Nearly 1000 samples is captured for the below peak voltage graph. The RMS value is found to be 0.382 which is equivalent to 1.91kg.

D. Thrust calculation from head end pressure for 1hz:

The integrated effect of high pressure over the head end produces the thrust. Thus the overall thrust of the PDE is determined from the head end pressure. The head end pressure captured from the oscilloscope when PDE is operated at 1 Hz is shown below in Fig.6. From the Fig.6, it is clear that 4.026 bar of pressure is exerted at head end of the detonation tube, where pulse width is 6ms and time interval per division is 10ms. Thus overall time interval is 0.1s.

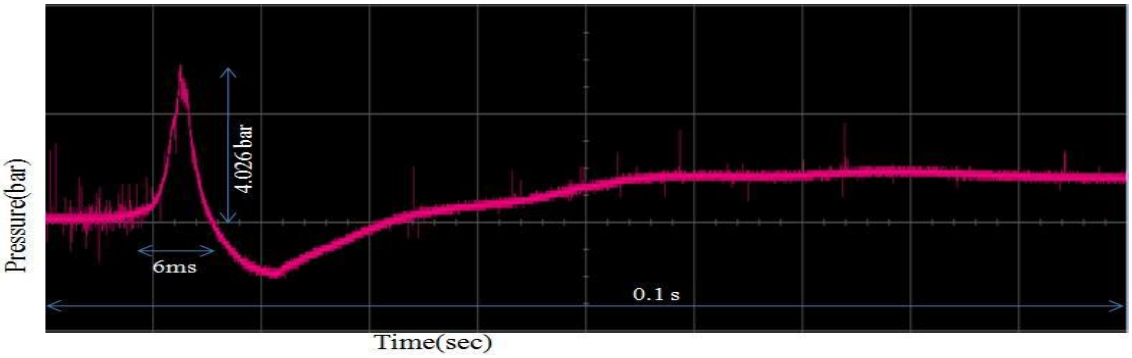

Fig.6. Head end pressure captured for PDE at 1Hz with higher sampling rate

E. Calculation of impulse from the head end pressure curve:

Impulse $= \int_0^t p\, dt$* cross sectional area of detonation tube

$\int_0^{0.006} p\, dt$=½*4.026*105*6*10-3 =1207.8 N-sec

Impulse $= \int_0^{0.006} p\, dt$* cross sectional area of detonation tube

=1207.8*1.4186*10-3

=1.7134 N-sec

Thrust = 17.134 N

Thus, thrust is found to be equal to 1.75 Kg.

In the similar fashion, thrust is captured for higher frequency i.e, for 2 and 3 hz. The thrust obtained from the head end pressure and load cell is compared and its associated specific impulse is tabulated in TABLE II.

TABLE II: THRUST COMPARISONS AND ITS ASSOCIATED SPECIFIC IMPULSE FOR DIFFERENT FREQUENCY

Sl.no	Frequency(Hz)	Impulse (N-sec)	Thrust from the load cell(RMS value in kg)	Thrust from the head end pressure (kg)	Specific impulse(I_{sp})
1	1	1.713	1.91	1.75	87.69
2	2	1.999	2.33	2.03	175.382
3	3	2.284	2.92	2.33	263.07

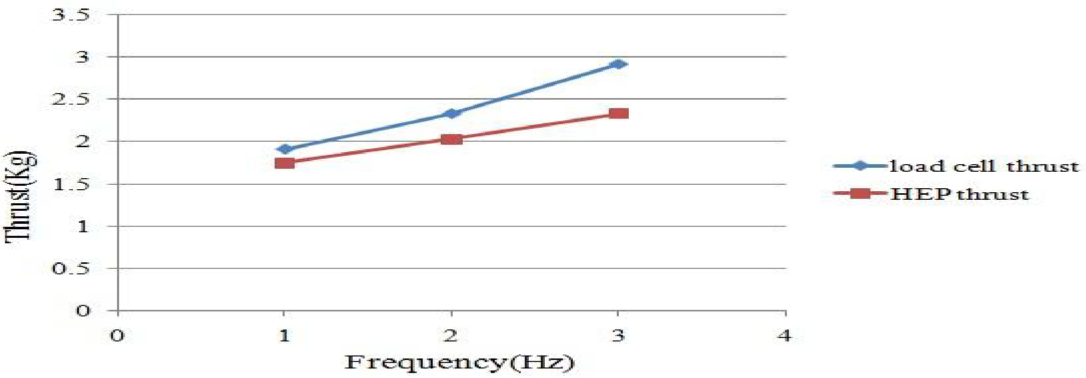

Fig.7. Thrust variation with frequency

Fig7, illustrates thrust variation corresponding to its frequency like 1Hz, 2Hz and 3Hz. There is about 15% difference between load cell thrust and head end pressure thrust.

E. Specific impulse determination and subsequent analysis for higher frequency:

Pulse width * (T/m dot) = 6*10-3*1.9/0.13*10-3=87.69

Maximum no of pulses achieved from the PDE is 1/0.006=166

Assuming 20 pulses/sec is achievable, the engine (Isp) is 87.69*20=1753.

If we can achieve 30 pulses/sec, then (Isp)=2630. Thus the current PDE proves to be better than many current air breathing engines according to Piotr et al.[8] with respect to specific impulse.

IV. CONCLUSION

The present work established there is necessity of higher supply of fuel-air mixture in detonation tube to sustain the PDE operation at higher frequency. Thus PDE is operated successfully at equivalence ratio of 1, 1.39 for 1and 2 Hz respectively where as its operation at 3 Hz was partially successful. This can be achieved to its optimum level, only when we are able to push required fuel-air mixture into the detonation tube. The corresponding thrust measured from load cell at 1Hz, 2Hz and 3Hz are 1.91kg, 2.33kg and 2.92kg respectively where as head pressure thrust is 1.75kg, 2.03kg and 2.33kg. The difference in load cell thrust and head end pressure thrust can be minimized by using load cell of higher sensitivity. The specific impulse for the current PDE when it is operated at 30 impulse/sec is 2630. Thus the current PDE is proved to be better than other air breathing engines. In order to aid the efficiency of current PDE , detonation is achieved from the gaseous mixture of fuel and air. Thus the present work gave the linear thrust increment on operation of PDE at higher frequency.

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