Journal of Aeronautics & Aerospace Engineering

Anvekar and Kallolimath, J Aeronaut Aerospace Eng 2013, 2:5
DOI: 10.4172/2168-9792.1000124

Research Article | Open Access

Deflgration to Detonation Transition in Kerosene Pulse Detonation Engine

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Abstract

The kerosene pulse detonation engine is an unsteady propulsive device in which the combustion chamber is periodically filled with a reactive gas mixture, a detonation is initiated, the detonation propagates through the chamber and the product gases are exhausted. The high pressures and resultant momentum flux out of the chamber generate thrust. To get the complete combustion of propellant the kerosene must be atomized at high pressure maintaining constant flow rate. The detonation is achieved here by discretizing the spark with continuous supply of air fuel mixture. The pulse detonation has got high specific impulse and very less specific fuel consumption as compared to other fueled pulse detonation engines. The velocity and pressure at the exit and all the intermittent points inside the tube is studied.

Keywords: Deflgration; Detonation; Shock wave; Schelkin spiral; Cell size

Introduction

Pulse detonation engine is an engine where the low pressure combustion is converted into high pressure detonation wave by changing the cross sectional area of the detonation tube. The cross section area will be converging type at the object placed inside the tube which holds the combustible mixture and provides a rapid combustion where the detonation wave is followed by the combustion flame [1-4]. Two distinct types of flame fronts occur within a pulse detonation engine called as deflagration and detonation. A deflagration wave is a subsonic flame front that propagates by heat transfer. A detonation wave is a supersonic flame front that consists of a shock wave coupled with a trailing reaction zone [3]. The principle differences between a deflagration and detonation wave are the wave speeds and pressure difference across the wave.

A detonation wave is a supersonic combustion wave consisting of a shock wave coupled with a reaction zone. The conditions behind an ideal detonation wave are dictated by the Chapman-Jouguet (CJ) condition that the flow behind the wave is sonic in a reference frame moving with the detonation velocity. The pulse detonation engine has a length of a half wavelength of the resonance frequency. This means that when detonation occurs a shockwave is travelling from valves to the end of the pipe. Then the shockwave turns and go back [1].

The combustion begins from left to right in the Figure 1. The deflagration transit to detonation at X_0 which has very high pressure showing a sudden rising spike as the pressure from I to N. The region N to F is reaction zone where the combustion reaction takes place which has lesser pressure region than detonation. The region FN will be having the deflagration flame which is following the detonation wave at a distance of X_F. The pressure in front of the detonation wave will be near to atmospheric. The liquid fuel pulse detonation engine is experimented using kerosene as fuel. The problem in using the liquid fuel is two phase generation. The liquid fuel must be atomized into mist using heated air which creates a part of gaseous state with small liquid droplets. The two phase problem will lead to improper combustion and the pressure cannot be achieved. In the practical applications for PDE, liquid fuel should be used to increase specific energy density and reduce volume requirements [3]. In aeronautics, kerosene-base fuels are used instead of high-volatility fuels. Therefore, the present study adopted JP-10 for experimentation.

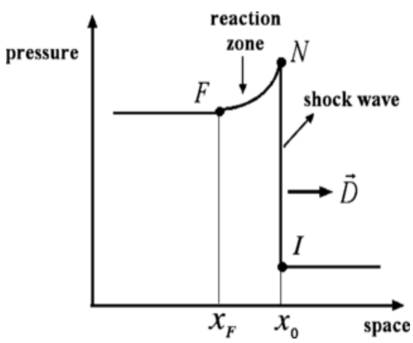

Figure 1: Detonation physics diagram.

Experimental Setup

In Pulse detonation engine, the detonation propagates at gallopian mode nothing but spinning mode. The experimental setup of kerosene pulse detonation engine is complex in design and the fuel throttling is difficult to maintain. The detonation tube is selected based on the cell size of the fuel. The cell size is defined as the height of the cell structure and is related to the direct detonation initiation energy [4]. The detonation tube length is selected based on the deflagration to detonation transition length. As the transition length decreases the length and weight of engine reduces. The minimum length for the deflagration to detonation transition is 6 times the tube diameter. A pulse detonation engine is a multi-cycle engine. A single cycle consists of four major steps: 1) Filling of the tube with the desired mixture; 2)

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Received October 03, 2013; **Accepted** November 21, 2013; **Published** November 28, 2013

Citation: Anvekar MR, Kallolimath P (2013) Deflgration to Detonation Transition in Kerosene Pulse Detonation Engine. J Aeronaut Aerospace Eng 2: 124. doi:10.4172/2168-9792.1000124

detonation initiation; 3) propagation of the detonation along the tube; 4) exhaust of the products to the atmosphere.

The detonation tube is purged before filling the mixture. Heat exchanger is used to preheat the atomizing air before mixing it with the liquid fuel. Atomizer which has two separate nozzles is used, where the fuel and air come in contact at the exit of the atomizer. Conventional spark plug is used to ignite the mixture. The spark timing is controlled with relay such that the sparking frequency can be varied. The stoichiometric air fuel ratio is supplied to the atomizer. The preheated air with temperature up to 110°C at the exit of the heat exchanger is fed into the atomizer for atomization. Raising the initial temperature of the fuel, air or the mixture reduces the ignition delay as well as the ignition energy requirements. The fuel is pressurized using air up to 2-3 bars. The atomizer exit is connected to inlet of the detonation tube and the fuel air mixture is injected. The mixture is combusted using the low frequency spark plug which is placed at the head end of the tube. The mixture in the tube is deflagrated and it is transited into detonation with the help of schelkin spiral and orifice plate combination [4]. The deflagration to detonation transition starts at the head of the schelkin spiral where the fuel air mixture is sufficiently available.

The blockage ratio where the transition begins is 14-16% for schelkin spiral and 25-30% for schelkin and orifice combination. The kerosene pule detonation engine shown in Figure 2 is the experimental setup which has following elements. 1-compressed air, 2-air heater, 3-detonation tube, 4-fuel tank, 5-secondary air supply, 6-power supply to heater, 7-Atomizer, 8-throttling valve, 9-pressure indicator, 10-temperature indictor, 11-Spark power supply.

The tube of 2 m length and 55 mm diameter is selected with 0.8m length and 54 mm outer diameter and 45 mm internal diameter shchelkin spiral in it. The fuel and preheated air is supplied continuously to the atomizer where the fuel gets atomized and then it is sprayed into the detonation tube. Based on the stoichiometric mixture flow rate the spark timing is fixed [3]. The time required to fill the tube and to purge the tube is considered before fixing the spark timing. When the length of the detonation tube is increased, the larger volume also provides for a larger mass flow per cycle, thereby increasing the thrust. However, longer tubes have larger frictional drag due to increases wetted area. Also, longer tubes take longer times to fill and purge and consequently reduces the operating frequency of the engine [2]. Thus, the volume (area and length) have to be selected carefully depending on the type of fuel used, the Mach number range of operation and the other factors, such as weight, drag, etc.

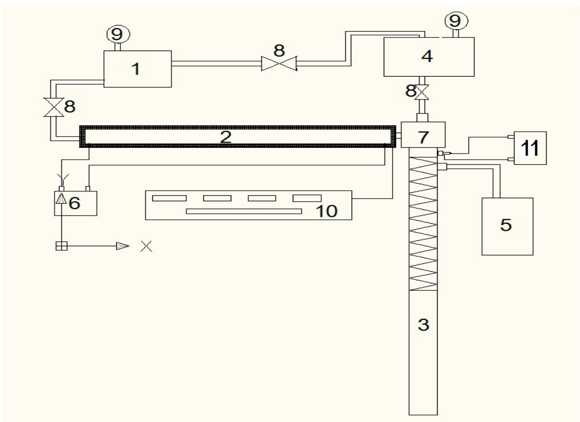

Figure 2: Kerosene pulse detonation engine.

The spark plug with flat electrode surface which produces multi sparks is used to ignite the mixture. The combustion proceeds due to convection mode of heat transfer inside the tube til the transition takes place. The deflagration to detonation transition leads to shock wave formation which helps to heat the mixture which is ahead of the combustion zone. The heating of mixture due to shock wave is much faster than the heating due to convection mode hence achieving detonation is necessary [3]. The detonation not only gives rapid combustion, it provides extra thrust due to shock wave. The detonation will help to get some more thrust and to increase the efficiency the engine as compared to pulse jet engine. The exothermic process starts with subsonic combustion which leads to supersonic detonation.

The engine runs at 5-6 Hz frequency where the spark is made discrete and the fuel air supply is continuous. The air is preheated which helps the fuel to atomize by shear mode and aerodynamic mode. The spark is produced using conventional spark plug which produces 0.2-0.5 mJ of energy at 12 kV. The pressure inside the tube increases rapidly near the transition zone and it decreases at the free end. Hence the velocity at the head end or transition zone is less as compared to the free end. The pressure inside the tube is around 20-25 bars with exit velocity of around 1100-1200 m/s. The schelkin spiral is made fix at the head end of detonation tube. To measure the pressure and velocity at different points inside the detonation tube ports are made where piezo electric pressure transducer and ion probes are used. Piezo electric pressure transducers are used because the signal capturing time is very small and to get the proper signal for weak detonation also. Ion probes are used to calculate the velocity of the flame inside the detonation tube.

Results and Discussion

The pulse detonation engine was run by supplying the fuel air mixture at equivalence 1, leads to complete combustion of fuel. On sparking, the mixture gets combusted at high temperature and the temperature increases at the transition zone. The shock wave will be seperated from the combusted flame by induction zone where the transition from deflagration to detonation starts and the reaction zone where the fuel air reaction begins. The gap between the flame and the shock wave goes on decreases as the detonation propogates. The detonation is stable because the shock wave is followed by combustion flame and after some propogation inside the tube the flame gets very close to the shock wave nothing but the induction zone goes on decreases. The reaction inside the detonation tube is shown below. One mole of kerosene needs 18.5 moles of oxygen to produce energy with carbon di oxide and water as by products.

$$C_{12}H_{26}(l)+\frac{37}{2}O_2(g)\rightarrow 12CO_2(g)+13H_2O(g)$$

The energy release can be improved only when the air fuel ratio is stochiometric. The pressure inside the tube goes on decreases from closed side to open side which can be studied by capturing the pressure readings using piezo electric pressure transducer. The velocity goes on increases from closed end to open end which is measured using ion probes placed parallel to the pressure transducers. The maximal pressure during one cycle obtained inside the detonation tube for different air fuel ratio was plot in Figure 3. For different air fuel ratio the engine can be run at 6 Hz but the pressure developed inside the tube will vary which leads to change in thrust determination.

The detonation tube which is selected for the experimentation generates considerable high pressure for the flow rate of 70% of tube volume per second. A little variation in flow rate reduces the pressure development inside the detonation tube which affects the thrust

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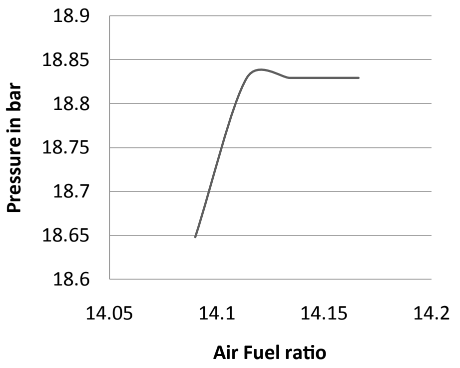

Figure 3: Effect of Air fuel ratio on combustion pressure.

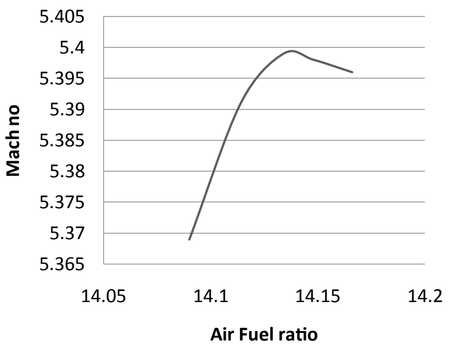

Figure 4: Effect of Air fuel ratio on combustion Mach number.

Figure 5: Kerosene Pulse Detonation Engine Cycle.

generation. The flow rate should be maintained constant with same amount of spaking to maintain the pressure development.

The velocity of shock wave generated inside the detonation chamber for little variation in Air fuel ratio is shown in Figure 4. The shock wave generated was in supersonic, gains velocity as it moves to open end of the detonation tube. The velocity generated gives maximum value when the Air fuel flow rate is 75% of the detonation chamber volume per second. The shock wave velocity impacts a major effect in the generation of the secondary thrust. The secondary thrust will lead to increase in the efficiency.

The pressure reading gives the position and pressure of detonation wave where as the ion probes gives the position and velocity of the combustion flame. The distance between shock wave and combustion flame (induction zone) can be calculated, shock wave is leading the combustion flame with 100-200 μsec.

The detonation transition from the deflagration can be seen in Figure 5. This Figure 5 which is a picture taken using a high speed camera at different intervals. To study the actual transition distance and time, a transparent detonation tube is used with a spiral inside it for a single cycle detonation. The total interval for a complete cycle is around 100 msec. First two images show the deflagration combustion where as next two images of the Figure 5 show the transition of detonation from the deflagration. The final two images show the end stage of the pulse detonation cycle.

Conclusion

The deflagration to detonation transition for kerosene can be achieved without heating the liquid kerosene. The achievement of detonation at 6Hz is done by giving a flow rate of 70-75% of the tube volume per second and by heating the atomizing air. The tube diameter and length affect the detonation pressure and shock wave velocity. Typically tube lengths of the order of 1 to 2 m are needed for a deflagration flame front to form a shock wave and then to couple with it. The specific fuel consumption and the specific impulse of the engine are same as that of the engine with liquid kerosene vaporizing method.

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