بسم ا الرحمن الرحيم

**University of Khartoum**

The Graduate College

# Theoretical and Experimental Evaluation of Pulse Jet Engine

A thesis submitted in partial fulfillment of the requirements

for the degree of M.Sc. in Energy Engineering


Prepared by:

Hussain Sadig Hussain

Supervised by:

Dr. Ali Omer Ahmed



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# المستخلص

الهدف من هذا البحث هو دراسة ماكينة الدفع النفثي المتقطع (Pulse Jet Engine ) من ناحية ثيرموديناميكية بالإضافة لدراسة المعاملات البعدية و معاملات الأداء للماكينة و التي تشمل الاستهلاك النوعي للوقود ،الدفع و التردد.

تم التحصل علي الأبعاد المطلوبة لتصميم ماكينة دفع نفثي متقطع لإنتاج دفع مقداره 100 رطل. أيضاً تم تصميم منظومة للتحكم في دخول الهواء المطلوب لتغذية الماكينة من نوع (Petal Valve System).

## Abstract

The objective of this research is to understand the thermodynamic characteristics of conventional pulse jet engine.

The geometrical parameters and performance aspects of the engine were studied including specific fuel consumption, thrust and frequency limitations.

Calculation were made on geometrical parameters for a deign of a pulse jet engine of 100 lb thrust.

Petal valve were selected for their simplicity to control air flowing to the engine.

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## Nomenclature

| | |
|---|---|
| P | Pressure |
| M | Mach number |
| $\gamma$ | Specific heat rate |
| T | Temperature |
| $C_v^{'}$ | Specific heat at constant volume |
| $C_p^{'}$ | Specific heat at constant pressure |
| $h$ | Enthalpy |
| $v$ | Discharge velocity corresponding to p |
| $\rho$ | Density |
| a | Velocity of Sound |
| $\eta_b$ | Combustion efficiency |
| H | Heat value of the fuel per lb |
| $f$ | Frequency of oscillation |
| F | Thrust of the engine |
| $C_F$ | Thrust coefficient |
| | Pressure Ratio |
| S | Specific Fuel Consumption |
| V | Engine volume |
| L | Engine effective length |
| $V_a$ | Valve area |
| $A_h$ | Petal valve area |
| $D_h$ | Petal valve hole diameter |
| $D_c$ | Combustion chamber length |
| $L_c$ | Combustion chamber joint length |

# CHAPTER ONE

# INTRODUCTION

## 1.1 Pulse Jet Engines:

The pulsejet is a compressor less, unsteady flow jet engine without wave pre-compression of the combustible charge. A pulsejet is mechanically very simple and consists of a short inlet diffuser leading to a set of flow check valves, followed by a combustion chamber and a shaped tube, as shown in Figure 1.1. A fuel injection system is located downstream of the valves. The air flowing into the engine through the valves is mixed with a fuel spray, and the mixture is ignited. As a result of the pressure rise generated by the explosion, the inlet flow check valves close and the exhaust gases expand outside through the exhaust tube. The exhaust of the burned gases generates expansion waves that reduce the pressure behind the check valves until they open again and a fresh charge of air enters. The cycle is then repeated. A spark is required only to start because after the first cycle, the hot gases from the previous cycle ignite the fresh combustible charge. The most common version of the pulsejet is the valved pulsejet; however, there exist valve less pulsejets.

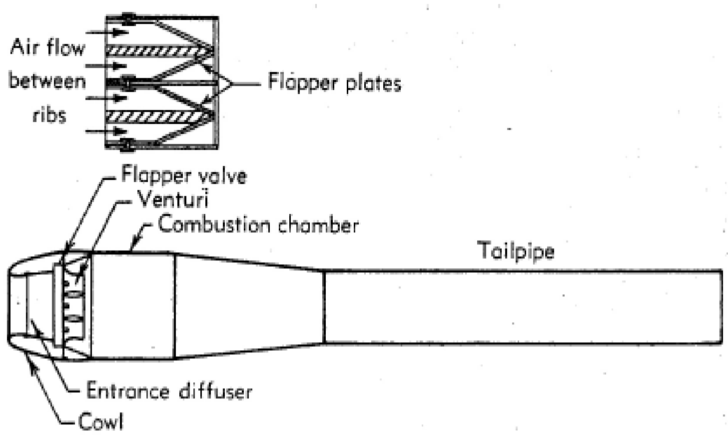


Figure 1.1: Schematic of a valved pulsejet

## 1.2 How Does Valve less Pulsejet Work?

Figure 1.2 shows one of the possible layout of a valve less pulsejet engine. It has a chamber with two tubular ports of unequal length and diameter. One port, curved backwards, is the inlet pipe and the other (flared at the end) is the tail pipe. In some other valve less engines, it is the exhaust pipe that is bent into the U-shape, but the important thing is that both ports point in the same direction.

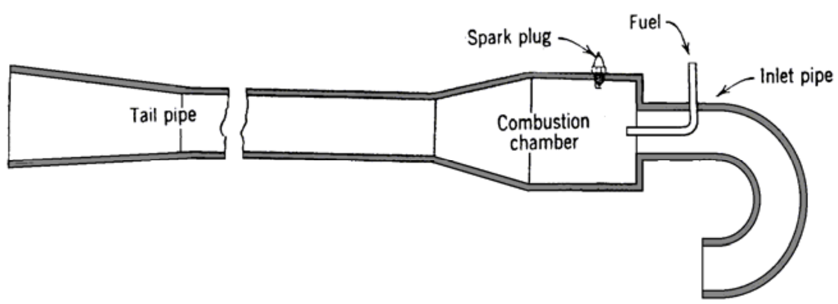


Figure 1.2: Valve less Pulsejet

When the fuel-air mixture combusts in the chamber, the pressure inside rises very suddenly. The rising pressure forces the hot gas to expand out of the chamber and pass through the two ports at high speed. As it leaves the engine, the hot gas exerts thrust.

As the gas expands, the pressure inside the chamber drops. Due to inertia, the expansion continues even after the pressure falls back to atmospheric. At the lowest point, there is partial vacuum in the chamber. At that point, the momentum of the expanding gas is spent and the expansion stops. The process reverses itself and fresh air starts rushing into the ends of the two ports to fill the vacuum.

At the intake side, it quickly passes through the short tube, enters the chamber and mixes with fuel. The tailpipe, however, is rather longer than the intake, so that it takes incoming air longer to reach the chamber that way. One of the prime reasons for the extra length is to have some hot exhaust gas remain inside the tailpipe at the moment the suction starts. This remaining hot gas will now be pushed back towards the chamber by the incoming fresh air. When it enters the chamber and mixes with the fuel/air mixture, the heat and the free radicals in the gas will cause ignition and the process will repeat itself.

In a small models pulsejet, it happens 100 to 250 times a second. The cycle is not much different, really, from that in the conventional flap-valve pulsejet. There, the rising pressure makes the valves at the front of the chamber snap shut and there is only one way for the hot gas to go into the exhaust tube. In the J-shaped and U-shaped valve less engines, the hot gas spews out of two ports. It does not matter, because they both face in the same direction.

Some valve less engine designers have developed designs that are not bent backwards, but employ various tricks that work in a similar fashion to valves i.e. they allow fresh air to come in but prevent the hot gas from getting out through the intake.

Great number of developers tried to come up with other ways of making the combustor tube irreversible, to have gases moving through the pulsejet in one direction only. It is not easy to do without a mechanical non-return valve, but the inventors have nevertheless come up with a variety of tricks supposed to do the job. Some, like Schubert, introduced ways to make the resistance to the passage of gas unsymmetrical. Others came up with ways to deflect gases in different directions.

Paul Schmidt and Jean Henri Bertin (among others) tested a number of designs featuring concave ring baffles in the intake tract, which offered great resistance to back flow but let fresh air in easily. A simple version of the Bertin baffle intake is sketched in figure 1.3.

Fresh air coming in from the left encounters a series baffles, but flows easily past them. The baffles have increasingly broader openings, forming a diffuser.

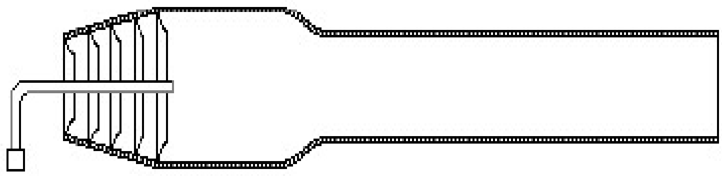

Figure 1.3: Pulse jet with concave ring baffles in the intake tract

In the opposite direction, however, the flowing is different. Hot exhaust gas will be trying to expand as it travels forward (towards the left in the figure) and increasing amounts will be trapped in the pockets between the baffles. Only a relatively small amount will ever be likely to escape. At least, that was what the designers hoped would happen.

However, all the configurations they had tried produced lower thrust and consumed more fuel than the equivalent engines with mechanical valves. Most also displayed at least some blow back, no matter how hard the designer tried to prevent it.

Numerous versions of tubes with similarly serrated walls have been tried, sometimes with baffles/serrations awaiting exhaust gas on more than one side. Figure 1.4 shows a typical design of that family, from the pen of a man better known for pulsejets with valves.

The problem with most serrated designs is that the return flow is not impeded as much as their inventors would like because the exhaust gas quickly fills the small concave ‘pockets’ in the tube sides and forms cushions of pressurized dead air or small trapped vortices, which offer little resistance to the passing stream. Under some conditions, the flow of gas in one direction will actually be very similar to the flow in the opposite direction.

Figure 1.4: Pulse jet with baffles/serrations

## 1.3 Kadenacy Effect:

In the explanation of the working cycle, the inertia drives the expanding gas out until the pressure in the chamber falls some way below atmospheric. The opposite thing happens in the next part of the cycle, when the outside air pushes its way in to fill the vacuum. The combined momentum of the gases rushing in through the two opposed ports causes the chamber briefly to be pressurized slightly above atmospheric. There is thus an oscillation of pressure in the engine caused by inertia. The pressure swings from way above atmospheric to partial vacuum and back again, in damped oscillation (See Figure 1.5). This is called the Kadenacy Effect.

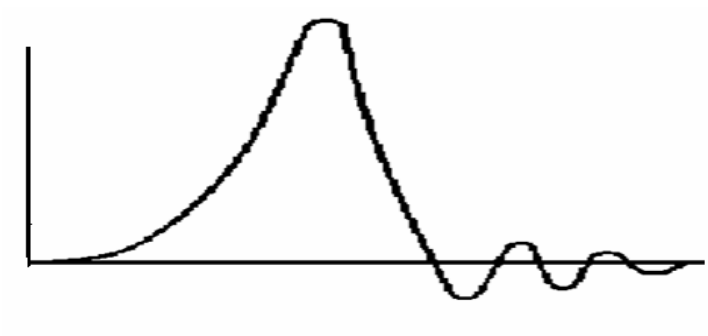

Figure 1.5: Pressure oscillations in the combustion chamber

It is what makes the aspiration (removal of burned gas and replacement with fresh fuel-air mixture) possible. Without it, pulsejets would not work.

**1.4 Advantages of Pulse Jet Engine:**

A key advantage of the pulsejet engine, to which no other mechanical thrust device compares, lies in its simplicity. Though the physical fundamentals of operation may be far from simple, the pulsejet's construction, especially that of the valve less design, is exquisitely unsophisticated. This fact alone places the pulsejet as a forerunner in the innovative field of miniature propulsion. Pulsejets have begun to receive renewed interest as a possible source of miniature and/or micro propulsion. However, a basis for powered thrust should not be considered its only application. The valve less pulse jet could be an excellent source for micro-heating. Past investments have been made toward the use of conventional-sized pulsejets in central heating systems. Cost is significantly reduced by the simplistic nature of valve less pulsejet construction.

The pulsejet engine has a peculiar property of pulsating combustion, it can be self-compressing. In the pulsejet, the fuel-air mixture does not burn steadily, at a constant pressure, as it does in the other jet engines. It burns intermittently, in a quick succession of explosive pulses. In each pulse, the gaseous products of combustion are generated too fast to escape from the combustor at once. This raises the pressure inside the combustor steeply, which increases combustion efficiency.

The pulse jet is the only jet engine combustor that shows a net pressure gain between the intake and the exhaust. All the others have to have their highest pressure created at the intake end of the chamber. From that station on, the pressure falls off. Such a decreasing pressure gradient serves to prevent the hot gas generated in the combustor from forcing its way out through the intake. This way, the gas moves only towards the exhaust nozzle in which pressure is converted to speed.

The great intake pressure is usually provided by some kind of compressor, which is a complex and expensive bit of machinery and consumes a great amount of power. Much of the energy generated in the turbojet engine goes to drive a compressor and only the remainder provides thrust.

The pulsejet is different; the exhaust pressure is higher than the intake pressure. There is pressure gain across the combustor, rather than loss. Moreover, the pulsejet does it without wasting the power generated by combustion. This is very important. About 5% gain in combustion pressure achieved by this method which improve overall efficiency

## 1.5 Limitations of Pulse jet Engine:

A big problem is that the gain in efficiency offered by pulsating combustion is not at all easy to utilize for propulsion. Paradoxically, the central problem here is the same as the Source of the benefit namely, pulsation. The very means of increasing combustion efficiency makes it difficult to take advantage of the result.

The real potential for the pulsejet has always been in its use as the combustor for a turbine engine, rather than as an engine in itself. Its ability to generate pressure gain is greatly multiplied in a high-pressure environment. Compared to the more usual constant-pressure combustor, it can either give the same power with much smaller mechanical loss and lower fuel consumption, or much greater power for the same amount of fuel.

Unfortunately, a turbine demands steady flows to function efficiently. Unsteadiness generates loss. Also, pulsations are dangerous for the brittle axial turbine blades. Radial turbines are tougher in that respect, but they are less efficient, especially so with intermittent flow. They are mostly used to exploit waste heat, as in a turbocharger, rather than as prime movers. Researchers have toyed with converting pulsations into a steady flow, but most methods proved inefficient.

## 1.6 Objectives of this Project:

Pulse jet engines have recently been recognized as promising propulsion technology that offers advantage in thermodynamic cycle efficiency, hardware, simplicity and operation scalability. The potential for self aspiration operation is highly attractive for the perspective of efficiency and operation.

One of the main questions in the pulse jet performance analysis is what the combustion type (mode)? It obviously a strong function of the cycle frequency and valve timing. A key issue in the conceptional design and analysis of proposed propulation system is the role of the combustion mode.

Our objective in this Project to understand based on thermodynamics the characteristics of the conventional pulse jet engine then we designed based on the geometrical aspect a pulse jet engine with 100 lb thrust.

# CHAPTER TWO

# LITERATURE REVIEEW

## 2.1 Historical Review:

Early attempts to utilize the power obtained from explosions for propulsion applications date back to late 17th–early 18th centuries and the contributions of Huygens and Allen are note worthy. In 1729, Allen proposed a jet propelled ship 'whose operation is owing to the explosion of gun powder' in a proper engine placed within a ship [7]. Before this archival contribution, gun powder was predominantly used in artillery for destructive purposes.

First exposure of gaseous detonations dates back to 1870–1883 period when Berthelot and Vieille, and Mallard and Le Chatelier discovered [7] a combustion mode propagating at a velocity ranging from 1.5 to 2.5 km/s. This combustion mode arose when gas was ignited with a high-explosive charge. Later on it was observed in long tubes even when gas was ignited by non explosive means (spark or open flame). In this case, flame acceleration along the tube, often accompanied with flame speed oscillations, was detected prior to onset of detonation. The most impressive findings of those times indicated that the detected detonation velocity was independent of the ignition source and tube diameter and was primarily a function of the explosive mixture composition. The main distinctive feature of detonation was a severe mechanical effect implying the development of a high pressure in the propagating wave. The mechanism of detonation propagation has been identified as governed by adiabatic compression of the explosive mixture rather than by molecular diffusion of heat. During those times, the interest in detonation was basically associated with explosion prevention in coal mines.

A few years later, based on the shock wave theory of Rankine and Hugoniot, Mikhelson in 1890, Chapman in 1899, and Jouguet in 1904, provided [7] theoretical estimates for the detonation parameters based on one-dimensional (1D) flow considerations and mass, momentum and energy conservation laws. In their theory, the detonation wave was considered as a pressure discontinuity coupled with the reaction front (instantaneous reaction). According to the theory, the detonation products possess density that is almost two-fold higher than the initial mixture density; temperature and pressure that are, respectively, 10–20% and two-fold higher than the corresponding values of constant-volume explosion; particle velocity that attains a value close to one half of the detonation velocity. Comparison of the theoretical predictions with experimentally observed detonation velocities showed fairly good agreement.

Since the end of the 19th–the beginning of the 20th century, significant progress has been made both in experimentation and analysis of detonations. In addition to explosion safety issues in coal mines and pits, other applications surfaced, in particular, those dealing with new technologies, balloon transportation, and reciprocating internal combustion engines. After the World War I, there was a considerable growth of interest to combustion in automotive and aircraft engines.

After World War II, the aviation industry saw a major advancement in flight capabilities with the development and implementation of the turbine engine. With this new technology, aircraft could fly higher, faster, and farther than ever before. However, along side early turbine development was a different type of jet power, commonly known today as the pulsejet. The pulsejet promised lower thrust specific fuel consumption, more robust operating characteristics, and, most importantly, a design that was significantly simpler mechanically than its turbine counterparts. However, interest in pulsejets subsided due to poor thrust performance versus size and horrific decibel performance. Improvements upon such limitations were never achieved owing mostly to a lack of fundamental understanding for the pulsejet's operation. This, in turn, caused the pulsejet to fade from history's timeline and the turbine engine to emerge as the dominant propulsion option. Today, pulsejet technology shows promise as a viable source for alternative propulsion purposes, but the general lack of fundamental understanding remains a foremost inhibiter.

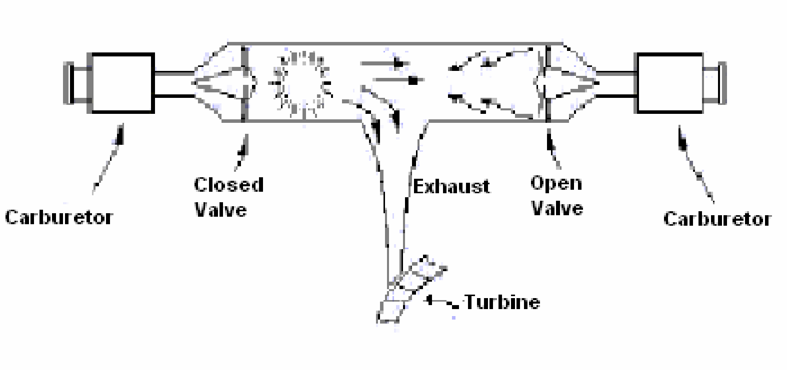


Figure 2.1: A schematic of the Esnaut-Peltr push-pull combustion engine**.**

Pulsejets operate on a cyclical combustion event, characteristic of its geometry and fuel. The discovery of the pulsating flame, or "sensitive flame," was first noted around 1777 [5]. Conceptual designs of pulsating combustion devices then followed almost one and a half centuries later. It was not until the turn of the 20$^{th}$ century that the possibility of a cyclical combustion engine was realized and documented. Two French engineers, Esnault and Peltrie, patented a design for an engine that drove a turbine wheel. This engine worked based on the principle of two opposing pulsating combustion columns fitted in a single straight, tubular chamber working out of phase from one another (Figure 2.1) [5]. Shortly thereafter, another Frenchman named Georges Marconnet patented a device that was essentially a variation to the Esnault-Peltrie design. Here, Marconnet replaced the flap valves with what he termed an “aerodynamic valve.” A simple area constriction served a similar purpose as the mechanical valve – to let fuel and air into the combustion chamber but inhibit exhaust gasses from escaping in the opposite direction. Shown in Figure 2.2, Marconnet’s engine is, in principle, half of Esnault and Peltrie’s combustor column without valves.

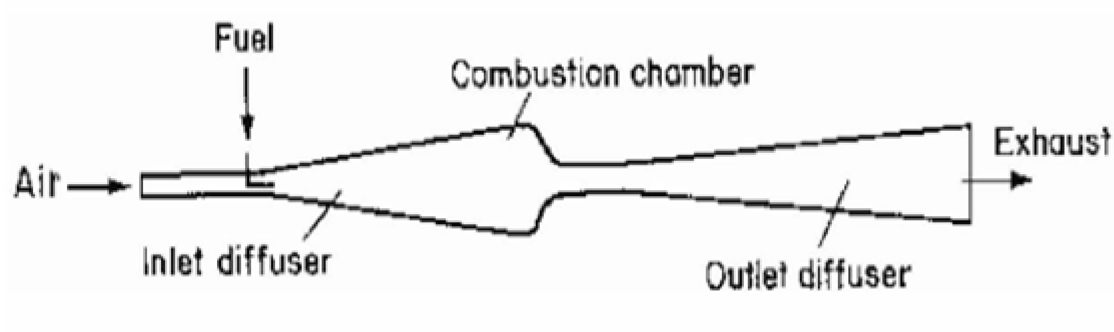


Figure 2.2: A schematic of the Marconnet valve less pulsejet.

Successful development of an operational pulsating combustion engine did not come about until the 1930’s when a German named Paul Schmidt [5] developed and tested the Schmidt tube, or a constant area chamber with flapper valves at one end and an opening at the other, shown below in Figure 2.3. During World War II, Germany incorporated Schmidt’s design into the development of their V-1 missile program, or the 'Buzz Bomb,' sister project to the infamous V-2 rocket. Schmidt's design served as the powerhouse behind Germany's V-1 weapon.

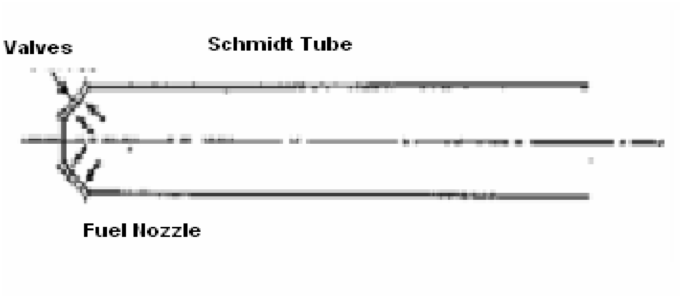


Figure 2.3: The Schmidt tube

The Buzz Bomb (Figure 2.4) terrorized England's countryside with its enormously loud namesake buzz heard from miles away and is given credit for being the first successful pulsejet utilized for thrust capabilities [5] . After the war, other countries continued development of pulsejet power. Specifically, the United States worked on developing a valve less variant to pulsejet engines through several secret, military-funded programs. From the declassified documents available today, it is clear that an understanding of the fundamental physics responsible for the successful operation of pulsating combustion engines was never truly achieved.

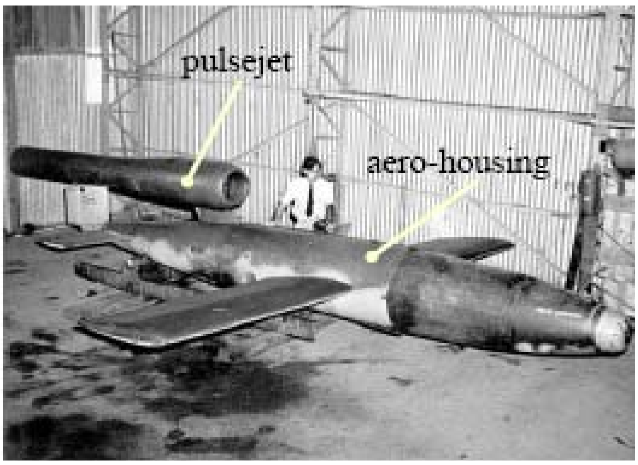


Figure 2.4: The V-2 'Buzz Bomb

## 2.2 Development in Valve less Pulse jet engine:

Valve less pulsejets were not an exclusive American development. The French company SNECMA (today a child company to the SAFRAN technology group of Paris, France), for example, was the first to use a valve less pulsejet for commercial use in powered flight [5]. The Escopette, illustrated in Figure 2.5, was a valve less design employed as a backup propulsion source for the French Emouchet sailplane in the early 1950's. Other foreign interests such as Russia, China, and Germany were involved in valve less development, as well. Still, the United States government made considerable advances in valve less pulsejet technology before eventually putting the idea to rest until recent years.

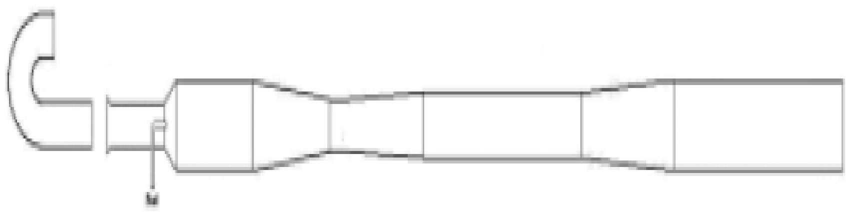

Figure 2.5: The French 'Escopette' valveless pulsejet.

Two prominent declassified American collaborations are noted for valve less pulsejet research in the 1950's to early 60's. Project Squid, a collaborated effort between the United States Navy and Air Force to research and develop all potential sources of jet propulsion available at that time [5], became greatly involved in the investigation of valveless pulsejets. Under the initial direction of J.G. Logan at the Cornell Aeronautical Laboratory, Project Squid's valveless pulsejet work began as an investigation into 'small scale models for fundamental research purposes and later grew to applications in helicopter rotor tip propulsion. Logan performed the majority of testing on a valveless design concept conceived from a hobby-scale valved pulsejet known as the Dynajet. Logan replaced the flapper valves by a flat plate, completely closing the jet at one end, and injected fuel and air directly into the combustion chamber. Project Squid investigated performance characteristics with hydrocarbon fuels on multiple geometric configurations of the 'Logan' pulsejet, respectively named after its chief designer. It has been suggested that the Logan jet improved rate of heat release and cycle efficiency.

The Bureau of Naval Weapons and the Advanced Research Division of Hiller Aircraft Corporation conducted a cooperative investigation of valve less pulsejet reactors for the development of lift-propulsion systems from 1961 to 1963 [5]. Numerous valve less designs were developed, produced, and tested in the course of the project. The most well known of these designs was the Hiller-Lockwood pulsejet illustrated and diagramed below in Figure 2.6. The Hiller company was successful in several developmental breakthroughs in pulsejet research, namely decreasing combustor size with the advent of converging bulkheads at the entrance and exit of the combustor section. Other accomplishments included the thrust-efficient design of the Hiller-Lockwood jet, tsfc improvements via effective thrust augmenters, and scaling studies on a range of size classes.

In a related concurrent program summarized in a report presented by Lockwood (1964), the Hiller Aircraft Corporation, under support from the United States Army Transportation Research Command (TRECOM), also performed work on conventional valve less designs resembling that of a Logan jet or the pulsejets utilized in the valve less work [5]. Investigations into miniature valve less pulsejets led the Hiller team to develop an engine with a minimum combustion diameter of 0.75 inches, an inlet to combustor area ratio of 0.34, and an overall length of 12.0 inches. However, poor response led to a lack of recorded data.

Figure 2.6 Schematic of the Hiller-Lockwood pulsejet

# CHAPTER THREE
# THEORY OF OPERATION

## 3.1 Unsteady Propulsive Devices:

Pulse detonation engines are characterized by their unsteady nature (pulse) and detonative combustion (detonation). Axial-flow engines with unsteady or intermittent combustion are relatively uncommon. The best known example is the V-1. The power plant of the V-1, has commonly been referred to as a pulsejet and operates in the following manner:

1. The combustion chamber is filled with air through a reed type inlet valve.

   Inside the chamber, the air is mixed with fuel and some residual hot gases.
2. The continued venting of the previous charge sends a compression wave from the tail into the chamber providing a slight pre-compression which closes the reed valve. The flow of the exhaust gases from the previous charge also reverses direction during this process. The combination of pre-compression and mixing with hot gases spontaneously ignites the new charge.
3. Upon ignition, rapid combustion of the reactants increases the pressure and ejects the products gases out of the tail.
4. The dynamics of the venting causes the inlet pressure to fall below atmospheric. This opens the reed valve and allows a fresh charge of air to enter the inlet valve, thus completing the cycle.

A summary of a generic pulse jet engine cycle is shown in figure 3.1.

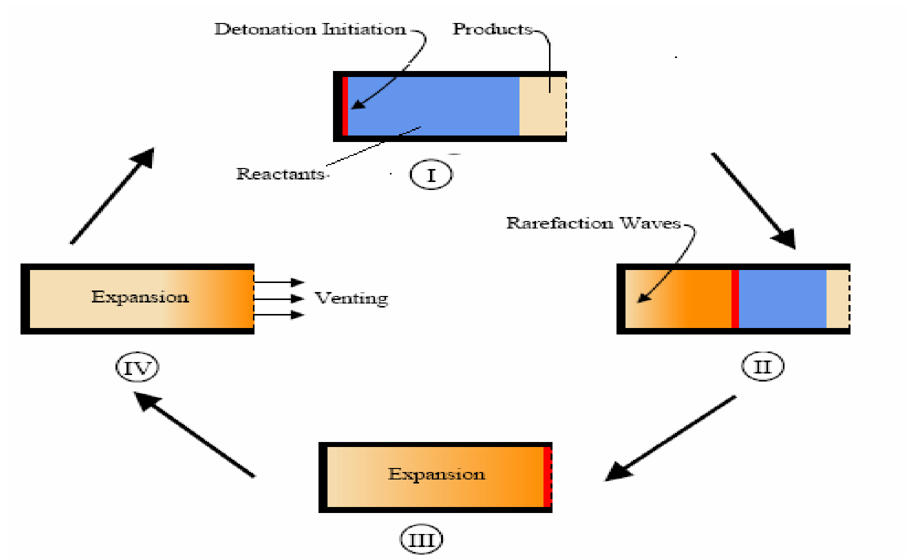


Figure 3.1: Summary of pulse jet engine Cycle

### 3.2 Pulsejet Cycle:

A pulsejet's operation can be explained by combining two-cycles: the Lenoir Cycle which consists of constant pressure compression followed by constant volume heat addition and then adiabatic expansion and the Humphrey Cycle, which operates similarly but has an isentropic compression added to the cycle. Pulsejets typically have a very small compression ratio that reaches a maximum at around 1.7. The Lenoir three cycle processes can be seen below in figure 3.2.

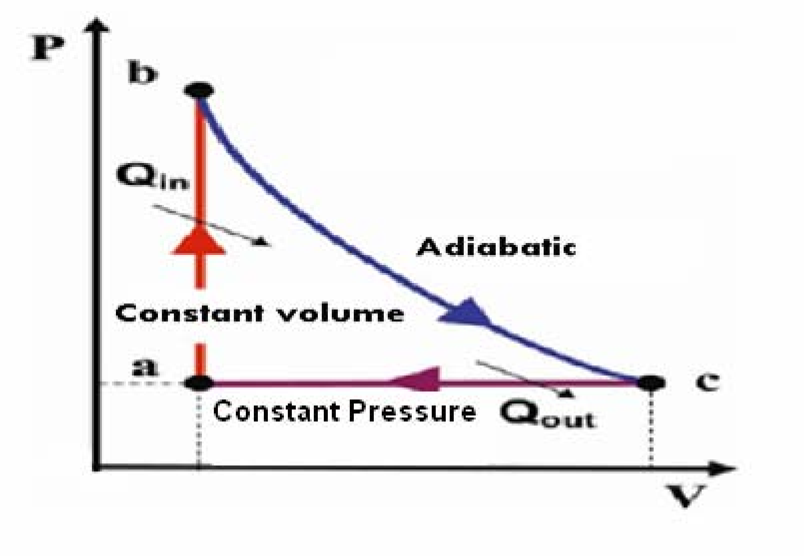


Figure 3.2 Lenoir Cycle

The process consists of the intake of air and fuel at point a, constant volume combustion from a to b, and an adiabatic expansion to c. The Humphrey Cycle is shown below, figure 3.3 and adds a small amount of compression before combustion, step a to b. This holds true for both valved and valve less models.

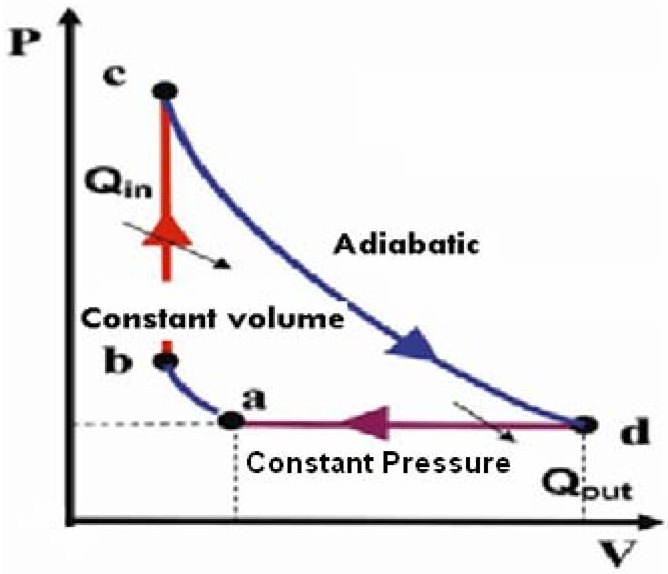


Figure 3.3: Humphrey Cycle

**3.3 Pulsejet Cycle Theory:**

Several prominent figures in the history of pulsating combustion research have offered theories based upon their respective areas of specialization on the fundamental physical processes responsible for the pulsejet's cycle of operation. F. H. Reynst, best known for his ‘combustion pot’ discovery, devoted most of his professional career to understanding the principles behind pulsating combustion engines. Reynst believed pulsejet engines operate on an acoustic resonating principle analogous to that of a ¼ wave organ pipe. In a 1955 journal article, Reynst relates the pressures and velocities in a characteristic Schmidt tube cycle to standing wave theory for small amplitude oscillations (i.e. linear acoustics). In a tube open at one end pressures and velocities can be represented by sine waves 90 degrees out of phase from each other. As is presented by the journal author (Figure 3.4), experimental velocity lags pressure by a quarter period if a correction factor of Z/4 is applied to the flow velocity. Reynst rightfully attributes the necessity of such a correction factor to the fact that the pressure and velocities were measured at opposite ends of the tube, simultaneously. In doing so, his ¼ wave hypothesis is shown to be arguably supported by experimental evidence. Regardless of his acoustic interpretations, Reynst, in several published works, expressed a keen understanding of the combustion and fluid dynamic processes involved in the intermittent cycles of a pulsejet engine .

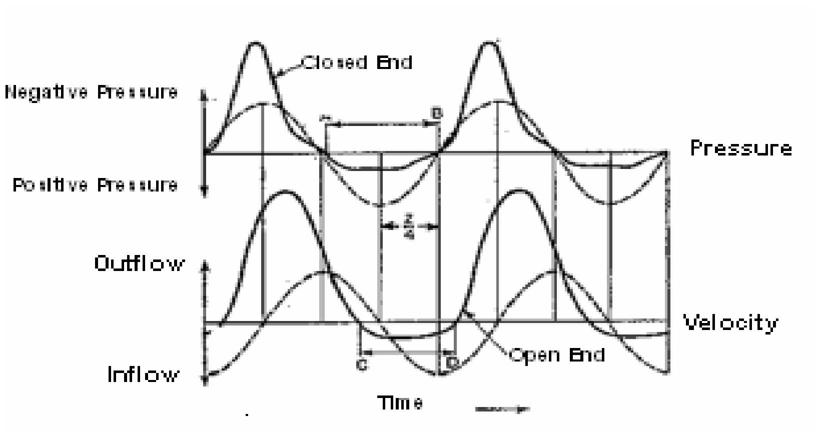


Figure 3.4: Diagram Showing Pressure and Velocities in the Schmited Tube C-D Air inflow at the open end,A-B vlved open,Z cycle time

In a collection of works edited by Felix Weinberg, the author Ben Zinn gives a very thorough development of pressure oscillations in a closed tube driven by linear heat addition (i.e. amplitudes of oscillation and heat addition are small). Starting from a system of wave equations, Zinn utilizes the Green's function technique to prove the validity of Rayleigh's empirical criterion for heat driven oscillations, similar to common techniques for investigating combustion noise. He derives a relationship between heat addition and pressure amplitude where proportionality constant may be used to determine the potential for modal excitation within the tube. By extending his results for boundary effects at the walls (i.e. momentum influx and out flux), they can then be well applied to pulsating combustor problems. As is the case, Zinn uses the practical example of the previously described Esnault-Peltrie combustor. Zinn suggests that the Esnault-Peltrie analysis can be easily adjusted for the ¼ wave structure of a pulsejet simply by substituting the fundamental mode approximation for that of a tube open at one end and closed at the other. In theory, such a solution would determine the characteristics of the oscillations inside the engine and the range of operating conditions for which pulsating operation is possible.

A detailed discussion on ideal pulsejet performance theory is presented by J.V. Foa (1960). An ideal pulsejet, as defined by Foa, is "a pulsejet in which ram pre-compression of the charge is fully utilized, all flow processes except combustion are isentropic, and the exhaust velocity is a square-wave function of time." It can be shown that the cycle efficiency, as well as the air specific impulse, inevitably approaches that of the ideal ramjet as free-stream Mach number increases. In reality, pulsejet performance differs strongly from ideal theory mainly due to the loss of ram pressure compression of combustible gasses. As was discussed above, pressure inside the combustion chamber immediately before ignition is generally equivalent to atmospheric free-stream conditions.

### 3.4 Thermodynamic Analysis of Pulsejet Engine:

Let us subscript 0 denote quantities corresponding to the free atmospheric condition, the subscript 1 denotes stagnation conditions when the valve are closed, the subscript 2 denotes the condition in the combustion chamber at the end of the charging process and the subscript 3 denotes the condition at the end of combustion. Since the compression from free stream to the stagnation pressure is really the inverse of isentropic expansion, the chamber condition is now the stagnation condition, and the exit condition are now the free stream conditions. Thus we have the equation

$$\frac{P_1}{P_0} = \left(1 + \frac{\gamma - 1}{2} M_0^2\right)^{\frac{\gamma}{\gamma - 1}} \qquad (3\text{-}1)$$

The temperature ratio is then:

$$\frac{T_1}{T_0} = \left(1 + \frac{\gamma - 1}{2} M_0^2\right) \qquad (3\text{-}2)$$

When the valve is opened, there is a rush of air into the combustion chamber and the velocity in the throat of the venture must be very close to the velocity of sound. In other words, the pressure at the throat is roughly one-half that of $P_1$. Due to the diffuser shape, very little of the kinetic energy is recovered as pressure energy. Thus we can assume that:

$$P_2 = \frac{1}{2} P_1 \qquad (3\text{-}3)$$

The temperature $T_2$, being a representation of the total energy of the gas at rest, must be the same as $T_1$, since no appreciable heat loss can occur.

$$T_2 = T_1 \qquad (3\text{-}4)$$

It will assume that the combustion is carried out at constant volume. Thus, if the small additional fuel flow is neglected, the heat added ($h$) per unit mass of air is

$$h = C_v^{'}(T_3 - T_2) = \frac{1}{\gamma} C_p^{'} T_3 \left(1 - \frac{T_2}{T_3}\right) \qquad (3\text{-}5)$$

The prime quantities are referred to the combustion products. Since the combustion is carried out at constant volume,

$$\frac{T_2}{T_3} = \frac{P_2}{P_3} \qquad (3\text{-}6)$$

Therefore:

$$h = \frac{1}{\gamma} C_p^{'} T_3 \left(1 - \frac{P_2}{P_3}\right) \qquad (3\text{-}7)$$

To calculate the discharging process, we assume that the velocity of discharge at every instant is the same as the isentropic steady expansion from the chamber pressure P to $P_0$, the atmospheric pressure in the chamber .Due to the removal of mass in the chamber, the pressure in the chamber will also drop. The expansion of gas in the chamber is also isentropic if heat loss to the atmosphere is not counted. This really corresponds to a physical situation of a very large chamber and a very small discharge nozzle so that the pressure variation in the chamber is very slow and a steady discharge is approximated. We shall calculate the total impulse due to this charge process and say that the impulse of such a slow discharge is good approximation of the actual rapid discharge.

Let $v$ be the discharge velocity corresponding to p, then we have

$$v = -\sqrt{\left(\frac{2}{\gamma}\frac{\gamma}{\gamma - 1}\right)\frac{P}{\rho}\left[1 - \left(\frac{P_0}{P}\right)^{\frac{\gamma - 1}{\gamma}}\right]} \tag{3-8}$$

The impulse due to a discharge dm at this velocity is

$$dI = v\ dm \tag{3-9}$$

If $m$ is the mass before the removal of $dm$, then the ratio of the density in the chamber after the removal of dm to that before the removal is

$$\frac{m - dm}{m}$$

Similarly the pressure ratio is

$$\frac{P + dP}{P}$$

Since the process in the combustion chamber is isentropic, we have

$$\frac{P + dP}{P} = \left(\frac{m - dm}{m}\right)^{\gamma}$$

Hence by neglecting infinitesimals of high order, we obtain

$$\gamma \frac{dm}{m} = -\frac{dP}{P} \qquad (3\text{-}10)$$

This show that a discharge of $dm$ will decrease the pressure in the chamber, as expected. Now $m = \rho V$ where $V$ is the volume of the combustion chamber. Thus we can replace the $dm$ in equation (3-9) completely by $dp$. The result is

$$dI = \sqrt{\frac{2}{\gamma}\frac{\gamma'}{\gamma'-1}\frac{P}{\rho}\left[1-\left(\frac{P_0}{P}\right)^{\frac{\gamma'-1}{\gamma'}}\right]}\ \frac{1}{\gamma}\rho V\frac{dP}{P} \qquad (3\text{-}11)$$

To find the total impulse due to the discharge, we have to integrate $dI$ for pressure variations from the initial pressure $p_3$ the final pressure $p_0$. Therefore

$$I = \frac{1}{\gamma}\sqrt{\frac{2\gamma'}{\gamma'-1}}V\int_{P_0}^{P_3}\sqrt{\frac{P}{\rho}\left[1-\left(\frac{P_0}{P}\right)^{\frac{\gamma'-1}{\gamma'}}\right]}\frac{\rho}{P}dP$$

$$= \frac{1}{\gamma}\sqrt{\frac{2\gamma'}{\gamma'-1}}(V\rho_3)\sqrt{\frac{P_3}{\rho_3}}\int_{P_0/P_3}^{1}\sqrt{\frac{1}{\eta^{\frac{\gamma'-1}{\gamma'}}}\left[1-\left(\frac{P_0}{P_3}\right)^{\frac{\gamma'-1}{\gamma'}}\frac{1}{\eta^{\frac{\gamma'-1}{\gamma'}}}\right]}d\eta \qquad (3\text{-}12)$$

Where $\eta = {}^{P}/_{P_3}$. But $V\rho_3$ is the total mass in the combustion chamber at the beginning of the discharge and $\left(\gamma\frac{P_3}{\rho_3}\right)^{\frac{1}{2}}$ is the velocity of sound $a_3$ corresponding to the condition in the combustion chamber at the end of combustion. Thus if we call the effective exit velocity $V_e$ then

$$\frac{V_e}{a_3} = \frac{1}{\gamma}\sqrt{\frac{2}{\gamma'-1}}\int_{P_0/P_3}^{1}\frac{1}{\eta^{\frac{\gamma'-1}{\gamma'}}}\left[1-\left(\frac{P_0}{P_3}\right)^{\frac{\gamma'-1}{\gamma'}}\frac{1}{\eta^{\frac{\gamma'-1}{\gamma'}}}\right]^{\frac{1}{2}} d \qquad (3\text{-}13)$$

If we have an average mass rate flow of one unit per second, the average thrust is $1.V_{e.}$ This thrust is diminished by the intake momentum of $1.V_o$ where $V_o$ is the flight velocity. Thus the actual thrust for a mass flow of one unit per second is 1. $(V_e\text{-}V_o)$. If H is the heat value of the fuel per lb and $\eta_b$ the combustion efficiency then the specific fuel consumption S in lb per hr per lb thrust is

$$S = \frac{3600h}{778H\,\eta_b\,(V_e - V_0)} \qquad (3\text{-}14)$$

Substituting the value of h from equation (3-7)

$$S = \frac{3600\,a_3\,\left(1-\frac{P_2}{P_3}\right)}{778\,H\,\eta_b\,\left[\frac{V_e}{a_3} - M_0\left(\frac{a_0}{a_3}\right)\right]}\,\frac{1}{\gamma'\,(\gamma'-1)} \qquad (2\text{-}15)$$

$$\left(\frac{a_3}{a_0}\right)^2 = \frac{\gamma'\,R'\,T_3}{\gamma'\,R\,T_0} = \frac{C_p'}{C_p}\,\frac{\gamma'-1}{\gamma-1}\left(\frac{P_3}{P_2}\right)\left(\frac{T_1}{T_0}\right) \qquad (2\text{-}16)$$

Therefore, the specific fuel consumption can easily determined if we know the pressure ratio $P_2/P_3$ and the combustion efficiency $\eta_b$

**3.5 Frequency of pulsation of pulse jet Engines:**

The Frequency in pulse jet engines is directly connected with the non-steady pulsating flow. In order to have estimate of the frequency, we shall adopt another simple picture of operation. We shall assume that explosion pressure ratio $P_3/P_2$ to be very nearly equal to unity. In other words, we shall assume the pressure amplitudes to be very small and then calculate the frequency by the elementary considerations to small pressure amplitudes. We then say that the frequency so calculated for very small pressure amplitudes should be representative of that for large pressure amplitude.

Consider the pulse jet engine as a pipe closed at one end and open at another. Then the pulsation in the pipe can be considered as a quarter wave length oscillation with maximum pressure amplitude at the closed end and zero pressure amplitude but maximum velocity amplitude at the open end, As shown by figure 3.5. If $a^*$ is the velocity of sound propagation and L the length of the pipe, the frequency of oscillation is

$f = \frac{a^*}{4L}$ Cycle per second (2-17)

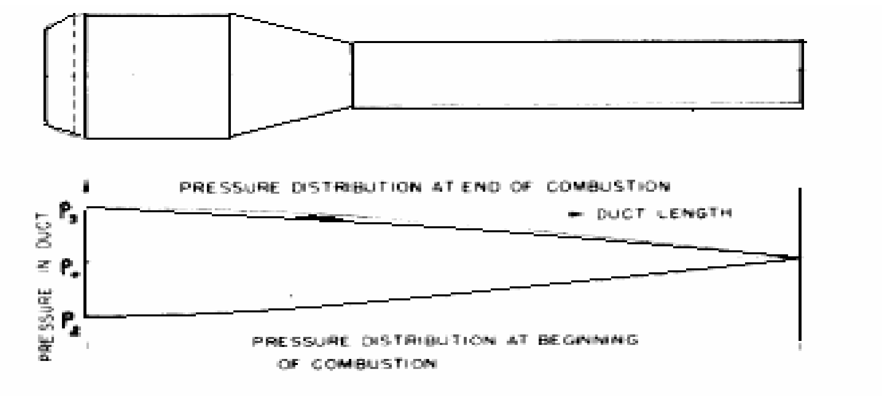


Figure 3.5: Pressure Distribution at the Beginning and the End Of combustion

For the application to the pulse jet we must use $a^*$ corresponding to the mean condition of the flow in the duct. Since the temperature at end of expansion in the duct is

$$T_3\left(\frac{P_0}{P_3}\right)^{\frac{\gamma'-1}{\gamma'}}$$

The mean value $a^*$ for the velocity of sound is

$$a^* = \frac{1}{2}a_3\left[1 + \left(\frac{P_0}{P_3}\right)^{\frac{\gamma'-1}{2\gamma'}}\right]$$

$$= \frac{1}{2} a_0 \left(\frac{a_3}{a_0}\right) \left[1 + \left(\frac{P_0}{P_3}\right)^{\frac{\gamma' - 1}{2\gamma}}\right] \quad (3\text{-}18)$$

**3.6 Thrust of pulse jet Engines:**

The average thrust of the pulse jet engine depends on the rate of air flow and the mixture ratio. The rate at which the air is taken into the duct per second is, in turn, depended upon the charge per cycle and the number of the cycle per second. All three factors, however, are interrelated. For instant, if the cycles per second are very large, the charge pressure in the chamber will be low, due to the rapid acceleration necessary to push the air in the chamber. In other words, the charge per cycle tends to decrease as the frequency were increase. Furthermore, the combustion process also tends to limit the mixture ratio that could be effectively used at lower values if the frequency were increased as the combustion time was shortened. Thus the average thrust of the engine, being an increasing function of the product of all these factors, has maximum with respect to the rate of fuel injection and the frequency, or the length of the tail pipe. The actual prediction of the thrust of pulse jet is thus rather complicated. The calculation is based upon empirical data, as the effects of the volumetric efficiency or breathing capacity and combustion conditions are very difficult to calculate.

If the ratio of the pressure at the beginning of the combustion to those at the end of the combustion is maintained and the frequency and flight mach number kept the same, the thrust of the engine will be directly proportional to the atmospheric pressure, as everything can then be referred to the atmospheric pressure, if $F'$ is the thrust corresponding to $P_0'$ and F for $P_0$ then under the condition stated

$$F' = F\left(\frac{p_0'}{p_0}\right) \qquad (3\text{-}19)$$

Actually the ratio of pressure of the combustion and frequency depend upon the mixture ratio and atmospheric temperature. The fact that the atmospheric temperature enters the relation can be seen by the following reasoning. If the atmospheric temperature is low, the temperature at the beginning of combustion will also be low, with everything else the same. Now keeping the mixture ratio and combustion efficiency the same, the heat due to the combustion per unit mass of gas and the temperature rise of the gas will be the same, but the ratio of the absolute temperature and hence the pressure ratio will be higer due to the lower temperature at the start of the combustion. This fact tends to give higher thrust at altitudes other than those calculated from Eq. (3-19). However, the more sluggish combustion at lower pressure, and hence lower frequencies, may balance this tendency. Thus, for lack of more accurate information, Eq. (3-19) can be used to calculate the altitude performance of the pulsejet, provided the mixture ratios at two altitudes are the same.

The mixture ratio and the frequency are maintained, then the thrust is directly proportional to the size or the sectional area of the combustion chamber. Since Eq. (3-17) shows that frequency is a function of the distance between the air flow valve and the exit of the duct, this distance must be kept the same for the same frequency. Actually the change in the flow condition with change in combustion chamber size will produce a small deviation from this simple rule. However, it is certain that, with increasing thrust, the pulsejet engine will become less slender in overall dimensions.

To compare the thrust output of pulsejet with other power plants, it is advantageous to express the net thrust $F_{net}$ in terms of a thrust coefficient defined as

$$C_F = \frac{F_{net}}{\frac{1}{2} * \rho_0 V_0^2 A} \quad (3\text{-}20)$$

Where A is the combustion chamber cross-sectional area. The maximum value of the thrust coefficient ($C_F = \infty$) which occur at static condition ($V_0 = 0$). However the coefficient decreases rapidly with the increase in velocity.

# CHAPTER FOUR

# DESIGN PRINCIPLES

The design of pulse jet must be based upon a wealth of well performed experiments giving the fundamentals relations between dimensions, frequency, thrust and mixture ratio.

**4.1 Engine Diameter:**

One of the texts on pulse jet engine designing was written by C.E.Tharratt he was staff scientist at the Chrysler Space Division in the late $1950_s$.The simple formula that Tharratt proposed to be the core of the pulse jet design is

$$\frac{V}{L} = 0.00316\,F \tag{4-1}$$

Where:

V = Engine Volume (Cubic ft)

L = Effective length (ft)

F =Thrust (lb)

The constant 0.00316 sq ft/ lb is a factor from experimental.

The validity of formula (4-1) has been verified at a wide number of different pulse jet engines including V1. From this formula when keep the engine volume (V) constant and increase the effective length (L), then the power would reduce. In order to do this, the diameter (and cross-section area) of the engine would need to be reduce. So there is a definite relationship between cross-sectional area and power.

Also when the length (L) is kept constant and increase the volume (V) the power would increase; to accomplish this there will be increasing in the diameter (cross-sectional area) of the engine.

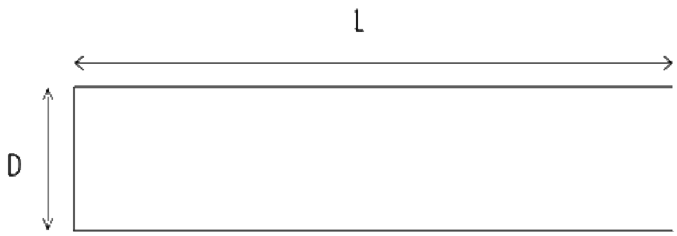


Figure 4.1: Engine Dimension

Manipulate equation (4-1) in a simple form

$$\frac{V}{L} = 0.00316\,F$$

But V= A × L

$$F = \frac{A \times L}{L \times 12 \times 12 \times 0.00316}$$

Where:

A = Area (inches)

Then:

$$F = 2.2 \times A \qquad (4\text{-}2)$$

The constant 2.2 ${}^{lb}/_{sq\ in}$ is derived from the formula that includes the engine total volume as a factor.

**4.2 Engine Effective Length:**

Engine Effective Length does not effect on the output power, but only effect on the frequency at which the engine will operate. The length of engine always given as a ratio ($L/D_m$) which governed by relation:

$${}^{L}/_{D_m} > 7 \qquad (4\text{-}3)$$

When ($L/D_m < 7$) the combustion with chemical fuels is difficult to sustain, from experimental work it found that $L/D_m$ must not exceed 15. Table (4.1) show ( $L/D_m$ ) ratio in Dynajet and V1 engines.

| Engine | $L/D_m$ |
|---|---|
| Dynajet | 15 |
| V1 | 9.6 |

Table 4.1: The ratio ($L/D_m$) in Dynajet and V1 engines

**4.3 Valve Area:**

The valve area ($V_a$) for an engine of given size and power is found using empirical formula as:

$$V_a = 0.23 \times \text{Mean cross-section area} \qquad (4\text{-}4)$$

**4.4 Valve System:**

One of the most critical components of a traditional pulsejet engine is the intake valve system.

Valves have to open and close several hundred times a second while being exposed to the thermal stresses associated with being alternately blasted by searing hot combustion gases and cold incoming air. At the same time, these thin strips of spring steel must resist metal fatigue and fracture resulting from the high Mechanical stresses imposed.

It have to do all this while providing a 100 percent seal against combustion gases when closed, and allowing the smooth, unimpeded flow of fresh air when open.

To make life even harder, the only power available to open them is the tiny difference in pressure between the outside air and the small vacuum created inside the engine by the kadenacy effect of escaping exhaust gases down the tailpipe.

### 4.4.1 Petal Valves:

Small engines always use a petal-valve system. A petal valve system consists of a ring of holes over which spring steel valve, consisting of matching number of petals is laid. There would a space between the outer edge of the valves holes and the side of the engine which. From experimental works found that this area is equal to the total area of the valve holes. Petal valves offer the following benefits:

1. Simplicity. The valve can be etched or cut from a single piece of spring-steel.
2. Low cost. As a side effect of their simplicity, petal valves can also be very economical to manufacture especially when valve plate consists of a simple piece of aluminum with a ring of holes drilled in it.

The petal valve also has a number of disadvantages:

1. Poor aerodynamic performance. Since the air passing through a petal valve bends near 90 degree on its way into the engine, the efficiency of such a system is not particularly high.
2. Low durability. Because the tips of the petals are directly exposed to the hot Combustion gases, petal valves often suffer from premature tip cracking or fracture.

3. High maintenance. Since petal valves are usually made as a single piece, the failure of individual petal requires the replacement of the entire spring-steel valve.

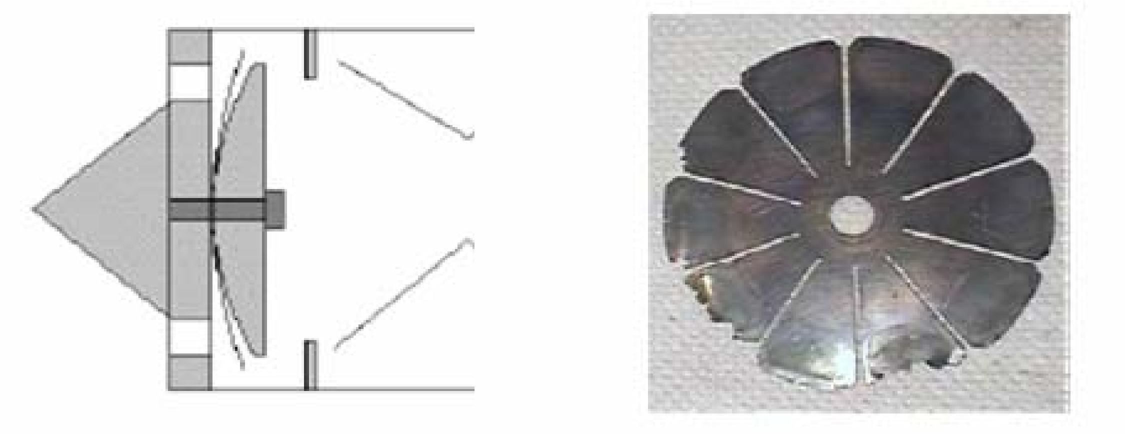

Figure 4.2: Petal valve

**4.4.2 The V or multi-V valve:**

Generally use on larger engines, these valves is more efficient than petal valves because they produce less deflection of the airflow when they are in an open position.

There are two basic methods of constructing such a valve system one involves the use of two or more flat metal plates with holes in them, joined at an angle 45 degrees.

The other method of forming a V valve is the one used in the Argus V1 where a cast or machined spacer with multiple ribs is used to hold the valves in position and limit their movement as in figure 4.3.

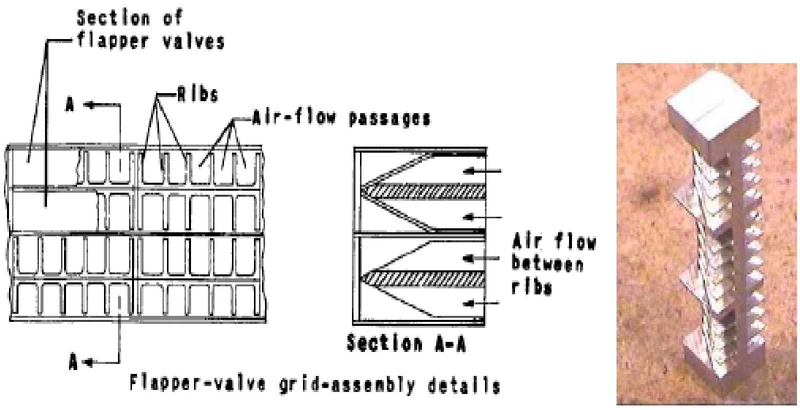


Figure 4.3: V- Valve

V valves provide the following benefits:

1. Higher efficiency than a simple petal valve. Since the incoming air has a far straighter pathway into the engine, more air is able to flow for a given size of valve opening when compared to a petal-valve.
2. Lower maintenance costs. Since the individual spring steel valves in a V-valve system can be replaced as/when they fail, maintaining the engine becomes a less expensive task and all valves can be used to the full extent of their lifespan.
3. Scalability. Unlike the petal-valve, a V-valve can be easily scaled to create the required valve area by simply increasing the length or number of V-valves in the array.

Of course there are downsides too:

1. Greater complexity. A V-valve generally requires more machining steps and a higher component count than a petal-valve setup.
2. Increased expense. As a side effect of this complexity, the production cost for a V-valve system is significantly higher than for

a petal-valve. This is another reason why most cheap model engines don’t use V-valving.

**4.5 Combustion Chamber:**

Pulse jet engines have much larger diameter section at the front, from where they funnel down to narrower tail pipe. Most of air / fuel mixture is burned inside this front section which is called combustion chamber.

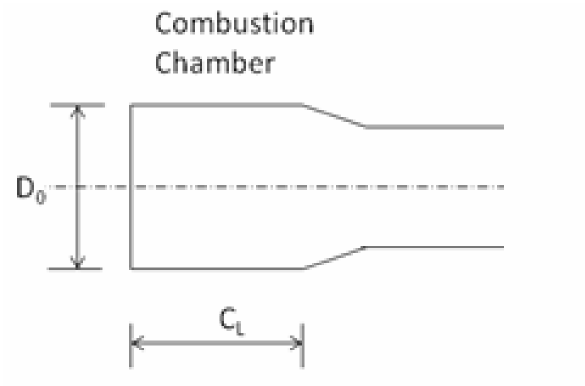


Figure 4.4: Engine combustion chamber

It’s important that the combustion chamber be of a shape and volume that the rest of the engine is able fill it with a fresh charge of air and fuel during each operating cycle.

When the combustion chamber is too small then some of the intake charge will be drawn down into the tailpipe where it may not be burnt as efficiently. Also when the chamber is too large then it will likely contain too much contaminating residue from the previous combustion cycle and that can also reduce the efficiency. A too large combustion chamber will also reduce the magnitude of the vacuum which draws in the fresh charge of air and that will mean a further power loss.

The combustion chamber volume can be found using Schmidt's (Designer of V1) empirical results that indicate the following:

"During the intake phase of the pulsejet's operation it will draw in a fresh charge of air equal to 15%-20% of the total engine volume"

**4.6 Joint The Combustion Chamber With Tail Pipe:**

Dynajet is hardly a cone at all, more of an abrupt transition. By comparison, the Argus V1 engine uses a very long, shallow angled cone to join the two sections.

Figure 4.5: Dynajet engine

Coming up with a suitable angle for this cone requires balancing a number of factors.

1. If simply flat plate is used to join the two sections of the engine then the hot exhaust gases would have a rather torturous path to follow. Some of those gases would have to travel around two 90 degree bends to get from the combustion chamber to the tailpipe and that would potentially reduce the speed at which they were able to exit from the engine. The speed at which the gases leave the engine affects the thrust.

The fact that it is so hard for the combustion gases to get into the tailpipe means that immediately after ignition, pressure will build up inside the combustion chamber as all those gases try to rush around a tight bend and down the tailpipe. Those higher pressures can improve combustion efficiency and actually increase the speed of the gases in the tailpipe.

It’s also worth noting that in the case of a flat plate, the hot gases that return from the engine's tailpipe and ignite the fresh air-fuel charge may do so far more efficiently. This is due to an effect that occurs in the way they form a narrow jet that reaches deep into the chamber rather than a larger diffuse front that ignites the fuel more slowly.

The faster the fuel burns, the more power our pulsejet will develop because it will have less time to expand as it burns, thus producing the higher internal pressures that will, in turn, result in higher tailpipe gas velocities.

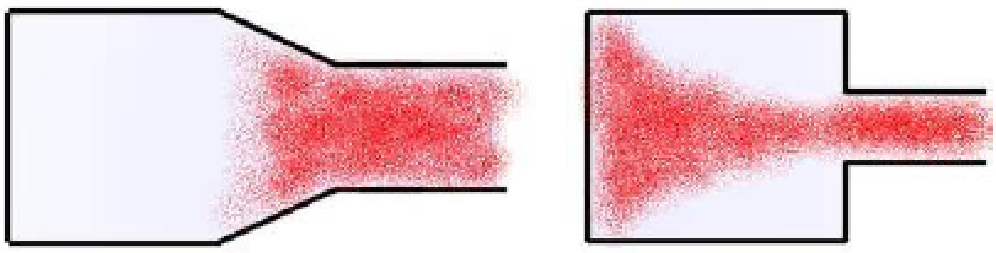

Figure 4.6: Jointing Combustion chamber with tail pipe

Figure (4.7) shows how ignition differs based on the angle of the cone between combustion chamber and tailpipe. In the second diagram, the distance between the hot gases and the engine body is far less than in the first.

The speed at which the combustion flame-front travels through the fresh air/fuel mixture is relatively slow (just a few tens of feet per second) in a low-compression engine like the pulsejet. Because of this, the mixture in the second diagram will be burnt far more quickly than that in the first, since the flame-front will be wider with a much shorter distance to travel.

2. If very long cone that had a shallow taper all the way to the end of the engine is used to join the two sections of the engine then it would obviously be much easier for the combustion gases to flow out under pressure. However, there would also be significantly reducing the ability of the engine to create a vacuum after combustion is completed because a much smaller percentage of the exhaust mass would be travelling at maximum velocity inside the engine.

Force exerted by the escaping gases is equal to their mass times the velocity to which they are accelerated (F=MA). For a given size of engine, the mass will always be the same but the velocity to which those gases are accelerated will depend very much on the design of the tailpipe. There need plenty of velocity to get the force required to establish a strong Kadenacy effect.

Tests conducted by the NACA during the 1950s indicated that an engine designed with just a long convergent cone instead of a straight tailpipe was very difficult to get running at all.

**4.7 Fuel Systems:**

One of the great advantages of pulsejet engines is that they can, at least in theory, be made to run on almost any type of combustible liquid or gas. Pulsejets aren’t limited to liquid or gas fuels however on at least two occasions, coal dust has been used as a fuel. It is rumored that the Germans attempted to run the Argus V1 engine on coal dust when liquid fuel supplies became almost unobtainable near the end of WW2 and some of pulsed combustors were designed specifically to use this unusual fuel.

There is a report published by Princeton University in 1947 that summarized a large amount of the research done into pulsejet engines up to that time. It said “the pulsating jet engine of contemporary design ran on almost any common fuel with negligible variations in performance.” The only caveat the report included was that “principal differences were in the degree of body heating and the rapidity of valve destruction.”

There are two main types of fuel system used in pulsejet engines.

### 4.7.1 Atomization:

Smaller engines such as the Dynajet have traditionally used a very crude form of carburetor that using the incoming air to create a spray of rather coarsely atomized fuel droplets. This atomizing process occurs right at the front of the engine when the incoming air is forced through a slight venturi.

The atomizer on small pulsejets uses a venturi to squeeze the incoming air through a narrowing in the intake. As it squeezes the pressure drops, although this system does work, the magnitude of the low-pressure area created in the pulsejet’s venturi is quite small and this means that there’s not much energy available to suck that fuel through.

Another problem with the simple atomizer is that the fuel droplets created tend to be very large and therefore do not vaporize particularly. however, the inside of a pulsejet engine is a very hot place so, despite the fact that the simple atomizer does a poor job of converting liquid fuel into a nice fine spray, the high internal temperatures of the engine greatly assist the conversion of those large droplets of fuel into vapor.

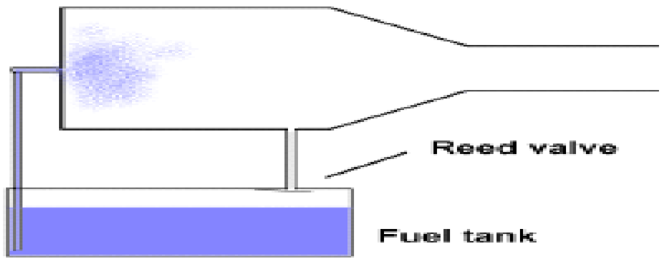


Figure 4.7: Simple diagram for atomization

Small pulsejets are extremely sensitive to just where the fuel tank is placed relative to the atomizer assembly. If the tank too low then the engine won't have enough "suck" to pull the fuel up to the atomizer nozzle. When the tank is too high the gravity will draw the fuel through effectively flooding the engine.

**4.7.2 Injection:**

Virtually all engines over 20lbs of thrust use direct fuel injection rather than atomization. In such a system, the fuel is injected directly into the engine's combustion chamber under some form of pressure. This makes the engine's operation far more reliable and adds the additional benefit that by varying the amount of fuel being injected, the engine's power can be varied.

There are two ways to inject the fuel, using a fuel pump or pressurize the entire fuel tank. The simplest injection system for a petal-valved engine simply involves locating a cross-drilled injection nozzle directly behind the valve-retainer plate. This nozzle is drilled so that the incoming fuel is sprayed out directly towards the side of the combustion chamber. This ensures optimum mixing with the air and (in the case of liquid fuels) means that any droplets of fuel that aren't vaporized by the incoming air will be instantly flashed into vapor when they hit the hot combustion chamber walls.

### 4.7.3 Timed Injection:

One disadvantage of direct fuel injection is that simple systems such as the one used in the Argus V1 engine tend to spray fuel throughout the engine's operating cycle. Fuel will only burn efficiently when mixed with exactly the right amount of air. This combustible mixture of air to fuel is referred to as the "stoichiometric ratio" and it varies depending on the type of fuel being used. Using timed fuel injection would be a way to improve the fuel-efficiency of pulsejet engines.

The pressure inside the engine falls to below 1 atmosphere during the intake phase and rises to as much as twice atmospheric during combustion and exhaust phases. A valve placed over the fuel jet is sufficient to provide a degree of injection timing and the addition of this mechanism can provide a noticeable improvement in the fuel-efficiency of a large pulsejet.

# CHAPTER FIVE

# RESULTS AND RECOMMENDATIONS

In this study we consider a conceptional design of pulse jet engine with a thrust 100 lb, the goal of present study is to estimate in very simple fashion the dimensions of pulse jet engine. We have not considered important aspects such as inlet diffuser and exhaust nozzles effects. All these factors will be significant in real applications.

**1-Engine Diameter:**

from equation (4-2), using the amount of thrust of the engine, the mean cross-sectional area:

$$100 = 2.2\ A$$

$$A = 45.45 \text{ sq in}$$

The mean diameter of the engine

$$D_m = \sqrt{\frac{45.45 \times 4}{\pi}}$$

$$= 7.61 \text{ in}$$

**2- Engine Length:**

Using relation (4-3), assume ( $L/D_m$ ) = 12, then engine length can be calculated:

$L/D_m$ = 12 then the effective length

$$L = 12\ D_m$$

$$= 12 \times 7.61$$

$$= 91.32 \text{ in}$$

**3- Total Petal Valve Area:**

From relation (4-4), total valve area:

$$V_a = 0.23 \times 45.45$$

$$= 10.45 \text{ sq in}$$

Relation (4-4 ) assume that the intake is an open hole, with no loss due to the presence of valves, but when there is valves there will be losses, petal valves have Poor aerodynamic performance. Assume that the efficiency of intake valves is 50%, then the actual area ($V_{actual}$) of valves required

$$V_{actual} = \frac{V_a}{\eta}$$

$$= \frac{10.45}{0.5}$$

$$= 20.91 \text{ sq in}$$

**4- Petal Valve:**

Increase the size of hole would increase the pressure on the valves themselves which cause them to bend so that it begins to dish into the holes which affects their operation. Assume using valve with 12 hole, then hole area will be:

$$A_h = \frac{Total\ valve\ area}{number\ of\ holes}$$

$$= \frac{20.907}{12}$$

$$= 1.74 \text{ sq in}$$

Then each hole diameter ($D_h$) will be:

$$D_h = \sqrt{\frac{4 \times 1.74}{\pi}}$$

$$= 1.49 \text{ in}$$

**5- Combustion Chamber Diameter:**

Petal valve holes will place in a ring around the edge of the pipe, so there is need of a certain amount of space between the holes .

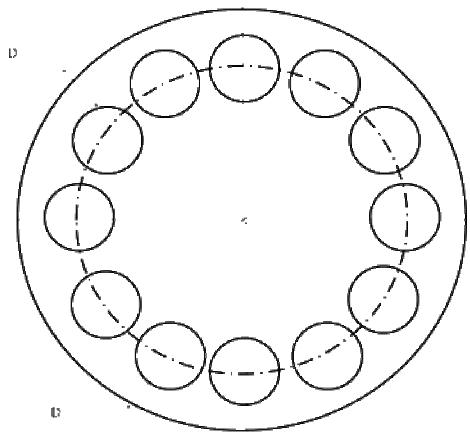

Figure 5.1: Petal valve front view

Assume there is ¼ inch gap between the holes, then the total circumference of the circle drawn through the center of each hole will be

$$= \text{Number of holes} \times \text{Diameter} + \text{Number of Gaps} \times \text{Grip size}$$

$$= 12 \times 1.49 + 11 \times .25$$

$$= 20.63 \text{ in}$$

Diameter of the Circle which runs through the center of each hole

$$D = \frac{20.63}{\pi}$$

$$= 6.07 \text{ inches}$$

The diameter of the circle which runs around the outer edge of the ring of holes:

$$D_0 = 6.566 + 1.49$$

$$= 8.06 \text{ inches}$$

There would be a 20.907 square inches of space around the ring of holes, then the overall combustion chamber area will be

$$A_O = \frac{\pi}{4} \times (8.057)^2 + 20.907$$

$$= 71.89 \text{ square inches}$$

Then the combustion chamber diameter

$$D_C = \sqrt{\frac{4 \times 71.89}{\pi}}$$

$$= 9.57 \text{ inches}$$

**6- Combustion chamber length:**

Using Schmidt's empirical results in chapter four (4.5), then the engine will suck in a volume of air equal to:

$$V_{air} = 91.32 \times \frac{\pi}{4} \times (7.61)^2 \times 0.2$$

$$= 830.72 \text{ cubic inches}$$

Combustion chamber length will be:

$$C_L = \frac{830.72}{\pi \times (8.792)^2}$$

$$= 13.683 \text{ inches}$$

**7- Joint The Combustion Chamber With Tail Pipe:**

Using an angle of 30 degrees for the section between the combustion chamber and the tailpipe. This will provide some post combustion confinement to increase the internal operating pressures while ensuring that the engine still has good internal mass-flow speeds to provide maximum Kadenacy effect.

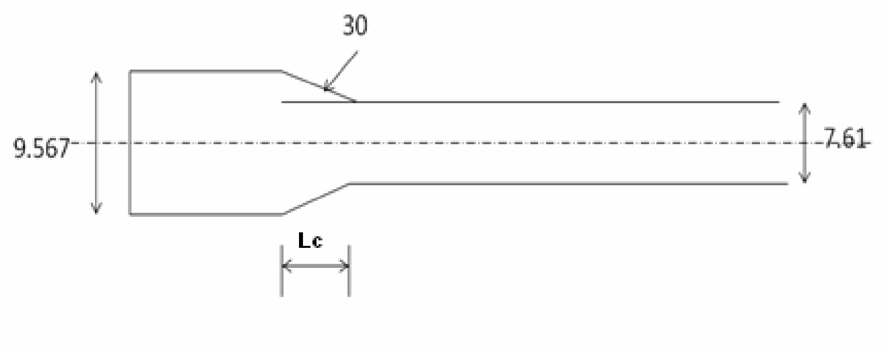


Figure 5.2: Joint combustion chamber with tail pipe using $30^0$ cone

From the figure above, the length of joint ($L_c$) will be

$$\tan 30 = \frac{0.9785}{L_c}$$

$L_c$ = 1.69 inches

**Recommendations:**

While this study present very much through investigation on the geometrical design of pulse jet engine, continued work is needed on designing fuel and ignition systems.

For more study of engine, the design need to be built using suitable material and tested in lab to compare the actual thrust with the theoretical, study the effect of changing dimensions on engine performance. Combustion chamber volume and shape, valve system type as well as, the inclination of the transition section have ability to improve engine performance.

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