Computational Approach in Sizing of Pulsejet Engine

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1 Introduction:

The pulsejet has recently received more research interests due to its simple design, which can be developed into low-cost micro-scale propulsion devices for use in many new applications such as UAVs and UCAVs. Because of the relatively low thermal efficiency of pulsejets has always been the major obstacle in their development.

Pulsejet engine generally consist of an air/ fuel inlet valve, a combustion chamber and a resonance tube (tailpipe) for exhausting the combustion products. The combustion-driven oscillation of the pulsejet often causes boring noise, non-designed working conditions and even structural failure of the combustion system. However, such instabilities have some merits such as enhancing heat transfer, increasing combustion intensity and reducing NOX pollutants.[2] The pulse jet combustion is a positive use of the combustion-driven oscillations. The pulse combustion is intermittent (periodic) combustion of gaseous, liquid and fine powdered solid fuel. The pulsejet engine can used various fuel such as gases fuel (natural gas, LPG, Propane, etc), liquid fuel (gasoline, coal oil, heavy oil, alcohol, etc) and solid fuel (pulverized coal, wood coal, coal in water slurry, etc).[1]

The followings are known advantages of the Pulsejet engine apart from the relatively simple to manufacture and high power to weight ratio if properly designed:

a) Theoretically the pulse jet engine has higher fuel efficiency than a normal jet engine that keeps constant pressure. Intermittent rather than constant fuel combustion is another key factor in making the pulse-jet engine more fuel efficient, than ordinary turbojet engines.
b) Engines can be produced in many sizes with many different thrust outputs ranging from a few pounds to thousands of pounds.

c) They have a very high thrust-to-weight ratio, which means a lighter engine producing more pounds of thrust than it's weight.

d) They are mechanically very simple and have very little moving parts.

e) Pulsejet combustion is self-activated and pulse combustion can result in:

  i. Increased heat and mass transfer rate (by a factor 2 to 5)
  ii. Increased combustion intensity as quantified by the gas

  iii. mixing index (by a factor of up to 10)

  iv. Higher combustion efficiency with low excess air

  v. Reduced pollutant emissions (especially NOx, CO and soot)

  vi. Improved thermal efficiency (by up to 40 %)

  vii. Reduced space requirements for the combustion equipment.

Although a considerable amount of work has been done on developing different types of pulsejets, understanding of the operation of these jets is still very limited.

The engine design and understanding of pulse combustion will be enhanced by using proven equations and references for theoretical understanding of pulsejet engine design. It is important to choose accurate equations and references for design of pulsejet engine since it may be manufactured for unmanned aerial vehicle which requires cost effective and safe operation.

The challenge and motivation in the study of pulsejet is to optimize the design by using fundamental equations and computer programming to unravel the important theoretical understanding of the pulse jet and improve efficiency by optimizing the fuel consumption which will also maximize the thrust capability of the jet engine.

2 Objective of study

The research objective of this work was to investigate the fluid mechanic, acoustic, and thermodynamic processes of a generic valved pulsejets. Computational techniques using MATLAB are used to provide physical insights into the pulsejet's operation and help experimental personnel to build a micro scale pulsejet. The operating cycle of the pulsejet designs is studied and a more complex acoustic model that accounts for the combustion chamber volume, inlet and exhaust pipe geometry is proposed.

This research uses a computational approach to investigate the characteristics of pulsejets which is them compared with established pulsejet engine data to validate the program. The information and formulae used are based on collections of scientific papers, books and literatures form Russia, United States and European countries. Based on published data of known pulsejet, a comparison of published data and calculated data are studied to validate the computer results. The objective of this research is to investigate the possibility of using pulsejets in certain applications where the pulsejet can trade its low efficiency with low cost, simple design, and light weight. The research objectives include the principles of valved pulsejet design; optimize valved pulsejet geometries and the effect of geometry of inlet, combustion chamber and tailpipe.

To achieve this objective, the following goals are carried out:

- To write a MATLAB program to calculate size and dimension of main parts of engine(valve, valve head, valve retainer, combustion chamber, exhaust) using fundamental and derived equations to produce a pulsejet engine.

- To calculate design parameters and to design required pulsejet engine using CAD/CAM program provided.

- To validate the computer program by comparing computed data with published data of selected pulsejet engines.
- To provide guidelines for designing a small-scale pulse jet engine.

Development of Pulsating combustion started around the 17th century. Christian Huyghens, a mathematician and physicist, designed a pulsating engine powered by gun powder (Bertin, 1951). In 1777, the pulse combustion was discovered and many theoretical designs emerged utilizing this phenomenon (Zinn, 1986). At the beginning of the 20thcentury the Esnault-Peltrie push-pull combustion engine was patented. This engine used pulsed combustion to drive a turbine and from this turbine work was to be extracted (Zinn, 1986). Holzwarth is known for starting his research in 1908, which consisted of constant volume combustion using a passive valve mechanism similar to that of the valved pulsejet to supply air to his gas turbine. In 1909 Gorges Marconnet designed the first valveless pulsejet (Bertin, 1951).

Instead of using valves to control the intake and exhaust processes, his jet propulsion relied on the Kadenacy effect to regulate the flow of gasses through the jet.

3 Literature Review

Defense Advanced Research Projects Agency (DARPA), provides funding that covered most of the research performed in studies of pulsejet are at North Carolina State University Applied Energy Research Labs (NCSU-AERL). [3]

The current study is a continuation of the experimental work carried out by

Michael Schoen, Adam Kiker, and Rob Ordon. Michael Schoen's research was directed towards the miniaturization of valveless pulsejets so that the gap between hobby-scale pulsejets and micro-scaled pulsejets could be bridged. His efforts were to understand the physical effects on engine performance subject to the changes in jet geometry. He found that tail pipe length is a direct function of inlet length. In order to shorten the exhaust pipe of a valveless pulsejet the inlet must also be shortened.

He also concluded, as did Hiller, that the addition of a divergent exit nozzle allows for the jet to be shortened and run on a more consistent operating basis. The most notable conclusion drawn from Schoen's work is that at shorter lengths the chemical kinetic reaction rate (combustion time) becomes challenged by the period of fluid mechanic oscillations. As the jet gets smaller, its inherent operating frequency rises. A highly reactive fuel must then be used in order for the combustion process to keep up with the acoustic properties of the jet (Schoen, 2005).

Adam Kiker's work focused on the development of micro-scale pulsejets. He was able to design and operate a record 8 cm long, air breathing, hydrogen fueled pulsejet (Kiker, 2005). In his research he found that the frequency of the jet scales as one over the length. When he tripled the inlet length it had the same effect as increasing the overall length by fifty percent. He observed that the exhaust diameter had little effect on the operating frequency. While the exhaust diameter did not have an effect on operating frequency, it did have a pronounced effect on peak pressure rise in the combustion chamber. As the exhaust diameter was decreased the peak pressure increased.

Kiker also noticed that as the fuel flow rate was increased, the operating frequency increased. With an increase in the fuel flow rate, the peak pressure increased also. Kiker was also able to take instantaneous thrust data. The method of measuring this is questionable because when operating the jet at close to 1 kHz, there tends to be some interaction with the resonant frequencies of the test rig. However, these measurements should not be overlooked. When testing the pulsejet with forward facing inlets little positive thrust was noticed. When the inlets were faced rearward a marked improvement in thrust was recorded. Thrust increased by almost 500%. Kiker was also able to operate a 5 cm long pulsejet, but only with rearward facing inlets. He proposed that this configuration made for better mixing and air induction. Another step that helped to contribute to the starting of the 5 cm pulsejet was the application of a platinum coating on the combustion chamber walls. The platinum acted as a catalyst to help promote combustion in the chamber to increase the chemical kinetic reaction rate (Kiker, 2005).

4 Data Analysis

There are two methods currently used in studying the pulsejet engine design. They are experimental method which involves extensive engine testing and computer aided numerical investigations. For engine performance testing the speed range may vary from Mach number 0.2 to 0.9 in order to analyze the engine characteristic for all flight region. Difficulties arise when the test facilities are limited and involve higher cost to perform the studies. Therefore, the second method, computer aided investigation, is selected due to the fact that it provides accurate calculated data for analysis and the facilities are easily available and more analysis could be conducted at a very short period of time besides the low cost.

Numerical analysis is the most suitable method for analyzing the pulsejet engine design, considering the pulsejet engine design will require a lot of proven equations and graphs for theoretical understanding of design. [4]

Table 4-1: Given data for pulsejet engine design(produced 50lb thrust)

No	Symbol	Definition	Quantity (metric)
1	F	Thrust	$50(N)$

Table 4-2: main formula's for pulsejet engine design

No	Symbol	Definition	Formula	Result (metric)
1	A	Mean cross section area	$F = 1547A$	0.03232m^2
2	D	Diameter of engine	$D = 2\sqrt{\frac{A}{\pi}}$	0.20m
3	L	Length of engine	$L = 7 x D$	1.42m
4	A_v	Valve area	$A_v = 0.23 x A$	0.0074m^2
5	$\sum A_v$	Total valve area	$\sum A_v = \frac{A_v}{0.5}$	0.01486m^2
6	A_h	Area of hole	$A_h = \frac{\sum A_v}{12}$	0.01239m^2
7	D_h	Diameter of hole	$D_h = 2\sqrt{\frac{A_h}{\pi}}$	0.03971m
8	P	Circumference	P = $No\ of\ Holes\ x\ diameter + No\ of\ Gaps\ x\ GapSize$	0.5453m
9	C_{in}	Circle around valve	$C_{in} = \frac{P}{\pi}$	0.173m

10	C_{out}	Circle rounds around the outer edge of holes	$C_{out} = C_{in} + D_h$	$0.213\mathrm{m}$
11	A_c	Area of single circle cover ring valve holes	$A_c = \pi \times (\frac{C_{out}}{2})^{\square} + \sum A_v$	$0.5060\mathrm{m}^2$
12	d	exhaust pipe diameter	$d = 0.5\ D_c$	$0.1269\mathrm{m}$
13	d_p	Nozzle diameter	$d_p = 1.2\ d$	$0.1523\mathrm{m}$
14	L_{CH}	Combustion chamber length	$L_{CH} = D_c$	$0.2538\mathrm{m}$
15	L_E	exhaust pipe length	$L_e = 4.5D_c$	$1.142m$
16	L_{RP}	resonance pipe length	$L_{RP} = 0.8D_c$	$0.2030m$
17	l	nozzle length	$l = 0.5d$	$0.0634m$

5 Valved Pulsejet Engine Design

The outcome from this whole project is a preliminary design sizing and dimensions of pulsejet engine using petal type valves. The design drawings in CATIA provide the detail dimensions and the weight of engine. The calculated (computed) result of pulsejet engine parameters are provided by MATLAB program.

Two main objectives will discuss in this chapter, i.e. calculated pulsejet engine sizes and dimensions; and the pulse jet engine performance analysis. For the first objective the calculated engine size and dimensions are compared with published pulse jet engines. For this purpose, twelve engines around the world were collected to study the engine design and characteristics. The second objective is the engine performance analysis based on the altitude and Mach number of the vehicle that are powered by pulse jet engines.

6 Comparison of Calculated Data with Published Data of Known Pulse Jet Engines

Table 4-3 provides the lists of computed pulse jet design size and parameters which are based on engine thrust whilst Table 4-4 provides published data of known pulse jet engine. The dimensions (combustion chamber diameters and length; and exhaust pipe diameters) of calculated results are plotted in Figure 4-1(Thrust VS Combustion Chamber Diameter), and Figure 4-2 (Thrust VS Exhaust Pipe Diameter)

Table 6-1: Comparison of Published Data with Calculated Data (Combustion Chamber Diameters)

PULSEJET ENGINE TYPES	THRUST (g)	COMBUSTION CHAMBER DIAMETER (original design) (mm)	COMBUSTION CHAMBER DIAMETER (calculated design) (mm)
A-5ML	**700**	**48**	**47**
D-65-2	**1700**	**65**	**62**
RAMJET1	**1500**	**65**	**59**
LETMO MP-250	**2270**	**64**	**69**
AEROJET 2	**2500**	**75**	**71**

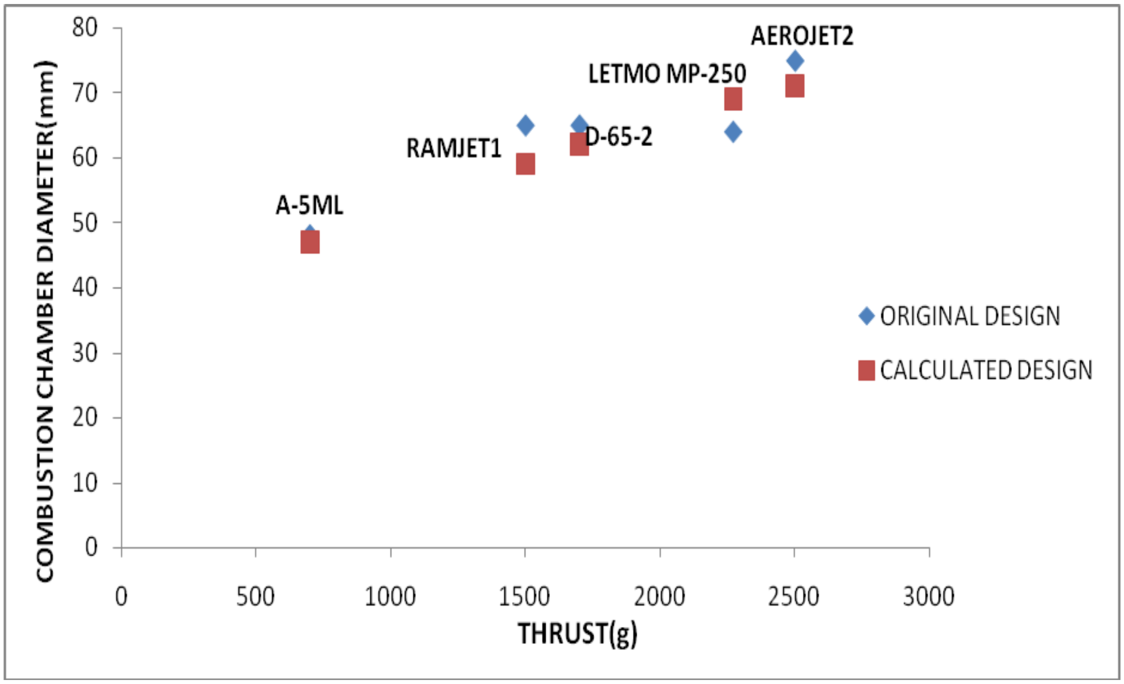

Figure 6-1: Combustion Chamber Diameter VS Thrusts Showing Published and Calculated Data

Table 6-2: Exhaust Pipe Diameter (Calculated and Published Data)

PULSEJET ENGINE TYPES	THRUST (g)	EXHAUST PIPE DIAMETER (original design) (mm)	EXHAUST PIPE DIAMETER (calculated design) (mm)
D-65-2	**1700**	**33**	**31**
RAMJET2	**2500**	**38**	**35**
MEW-307	**1360**	**32**	**29**
TIGERJET M1	**800**	**22**	**24**
DYNAJET	**1830**	**32**	**32**

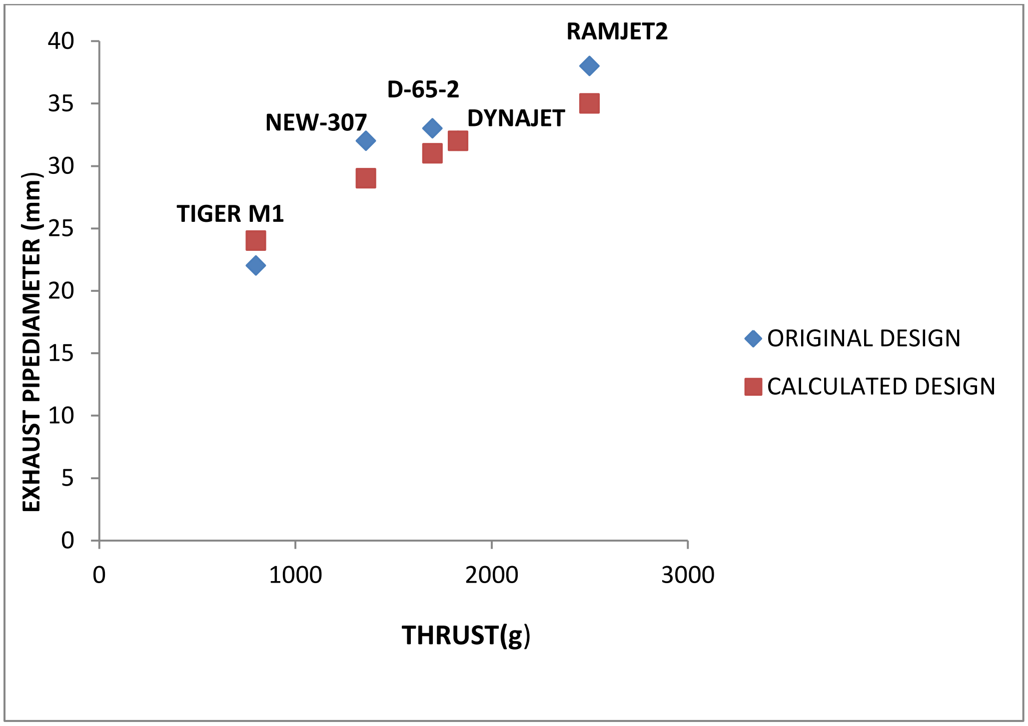

Figure 6-2:Exhaust Pipe Diameter VS Thrusts Showing Published and Calculated Data

Both Figures 4-1 and figure 4-2 shows good resemblance of calculated results with the published data of the specific pulse jet engines. This provides a better assurance of the MATLAB program in terms of its accuracies and representations of real pulsejet engine that had been tested and used in various propulsion applications.

7 Comparison of Calculated Parameter (Frequencies) With Published Data of Known Pulse Jet Engines

Table 4-5 present a list of pulse jet engines and their respective frequencies whilst Figure 4-5 is a plot of Thrusts VS Frequencies of various pulse jet engines showing the calculated result and published data.

Table 7-1- Pulse Jet Frequency

PULSEJET ENGINES TYPES	THRUST (g)	APPROXIMATE FREQUENCY (original design) (g/cycle)	APPROXIMATE FREQUENCY (calculated design) (g/cycle)
RAMJET1	1500	150	315
A-7	200	280	538
OS-11	1700	240	302
TIGERJET M1	800	250	383
DYNAJET	1830	220	294

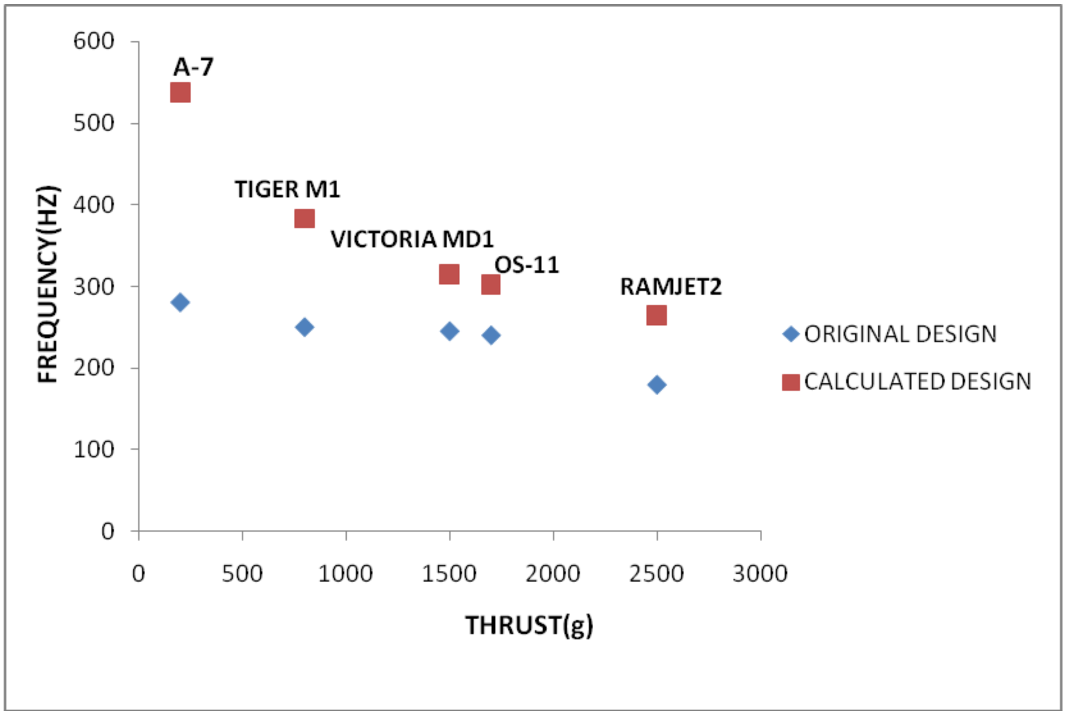

Figure 7-1: Frequency VS Thrust Plot of Original and Calculated Data

Figure 4-3 shows that the calculated results are slightly higher at higher thrusts but deviates at lower thrust. This can be explained in terms of combustion chamber operating principles of the various pulse jets.(e.g. Schmidt type is based on the principles of the quarter-wave sound resonator; Helmholtz type is operated under the principles of the standard acoustic Helmholtz resonator and Rijke type which is based on the operating principles of the Rijke tube). For this program the operating principle of pulse combustion is based on quarter wave sound resonator. Information on the combustion operating principle of the known pulsejet engines is not readily available.

Table 7-2: Given data for engine analysis

1	M	Mach number	$0.2-0.9$
2	R	Universal gas constant	$287(\frac{J}{kg.k})$
3	C_D	Drag coefficient	0.7
4	γ	Specific heat ratio for air	1.4
5	γ_m	Specific heat ratio for mixture	1.3
6	LCV	Lower calorific value	44(MJ)
7	η	Combustion efficiency	95%

Table 7-3: Pulsejet engine Performance Data (Mean Sea Level) and (mach number=0.2)

No	Symbol	Definition	Formula	Result (metric)
1	F_i	**Thrust**	$D = F_i = \frac{1}{2}\rho V^2 A_c C_D$	$71N$
2	V	**Flight speed**	$V = M\sqrt{\gamma RT}$	$68\frac{m}{s}$
3	m_a	**Mass of air**	$m_a = \rho V A_c$	$4.2kg$
4	m_f	**Mass of fuel**	$m_f = \frac{1}{15} m_a$	$0.28kg$
5	m_m	**Mass of mixture**	$m_m = m_f + m_a$	$4.5kg$

6	P_0	**Free atmospheric pressure**	$P_0 = P_S + \frac{1}{2}\rho V^2$	$2938(KPa)$
6	P_1	**Pressure after closing valve**	$P_1 = \left(P_S + \frac{1}{2}\rho V^2\right)\left(1 + \frac{\gamma - 1}{2} M_0^2\right)^{\frac{\gamma}{\gamma - 1}}$	$3021(KPa)$
7	T_1	**Temperature after closing valve**	$T_1 = T_0\left(1 + \frac{\gamma - 1}{2} M_0^2\right)$	$290K$
8	P_2	**Pressure in combustion chamber**	$p_2 = \frac{1}{2} p_1$	$1510(KPa)$
9	T_2	**Temperature in combustion chamber**	$T_2 = T_1$	$290K$
10	T_3	**Temperature at the end of combustion**	$T_3 = \frac{\eta * m_m * LCV}{C_P m_a} + T_2$	$2840K$
11	P_3	**pressure at the end of combustion**	$P_3 = \frac{P_2 T_3}{T_2}$	$14777(KPa)$
12	M_e	**Exit mach number**	$1 = \left(\frac{\gamma + 1}{2}\right)^{-\frac{\gamma+1}{2(\gamma-1)}} \frac{\left(1 + \frac{\gamma - 1}{2} M_e^2\right)^{\frac{\gamma+1}{2(\gamma-1)}}}{M_e}$	9.8
13	P_e	**Exit pressure**	$\frac{P_e}{P_2} = (1 + M_e^2 \frac{\gamma - 1}{2})^{-\frac{\gamma}{(\gamma-1)}}$	$843(KPa)$
14	T_e	**Exit temperature**	$\frac{T_e}{T_2} = (1 + M_e^2 \frac{\gamma - 1}{2})^{-1}$	$253K$
15	V_e	**Exit velocity**	$V_e = M_e \sqrt{\gamma R T_e}$	$301 \frac{m}{s}$
16	Q_{in}	**Internal heat**	$Q_{in} = C_P m_a \Delta T$	$12627kJ$
17	h	**Specific enthalpy**	$h = \frac{Q_{in}}{m_a}$	$2806K$

18	s	**Specific fuel consumption**	$S = \frac{3600h}{778\,LCV\eta(V_e - V)}$	$0.0012kg$
19	**f**	**frequency**	$f = \frac{a}{4L_e}$	**74Hz**

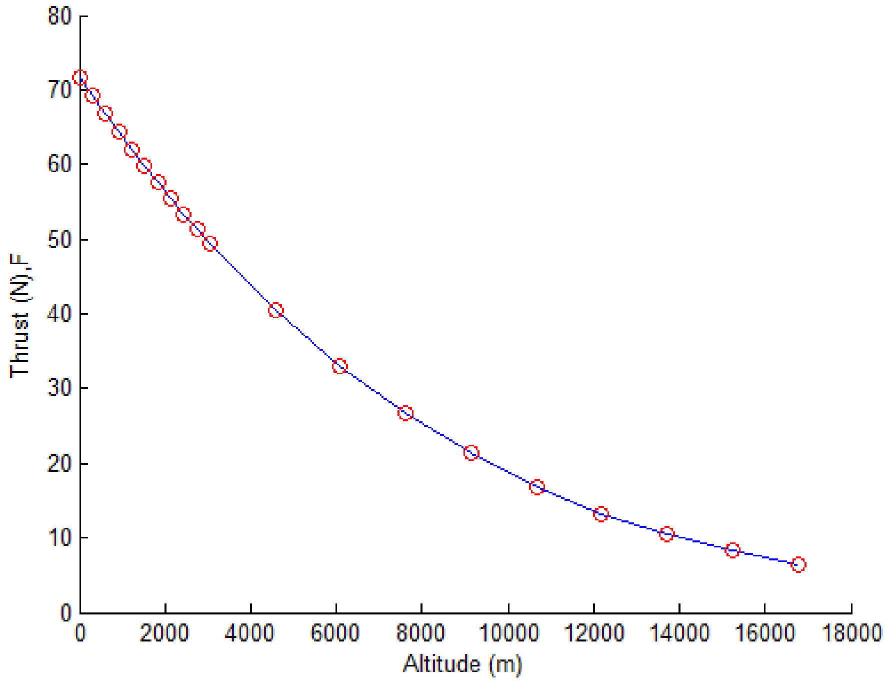

Figure 7-2: Thrust VS Altitude Graphs

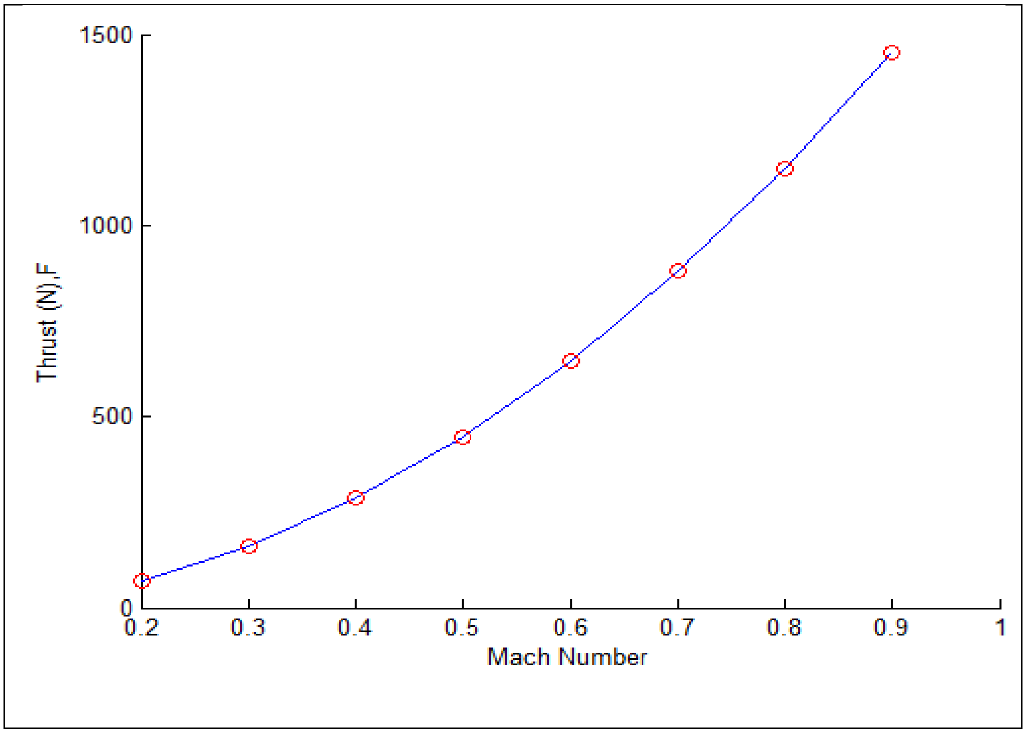

Figure 7-3: Mach number-Thrust graphs

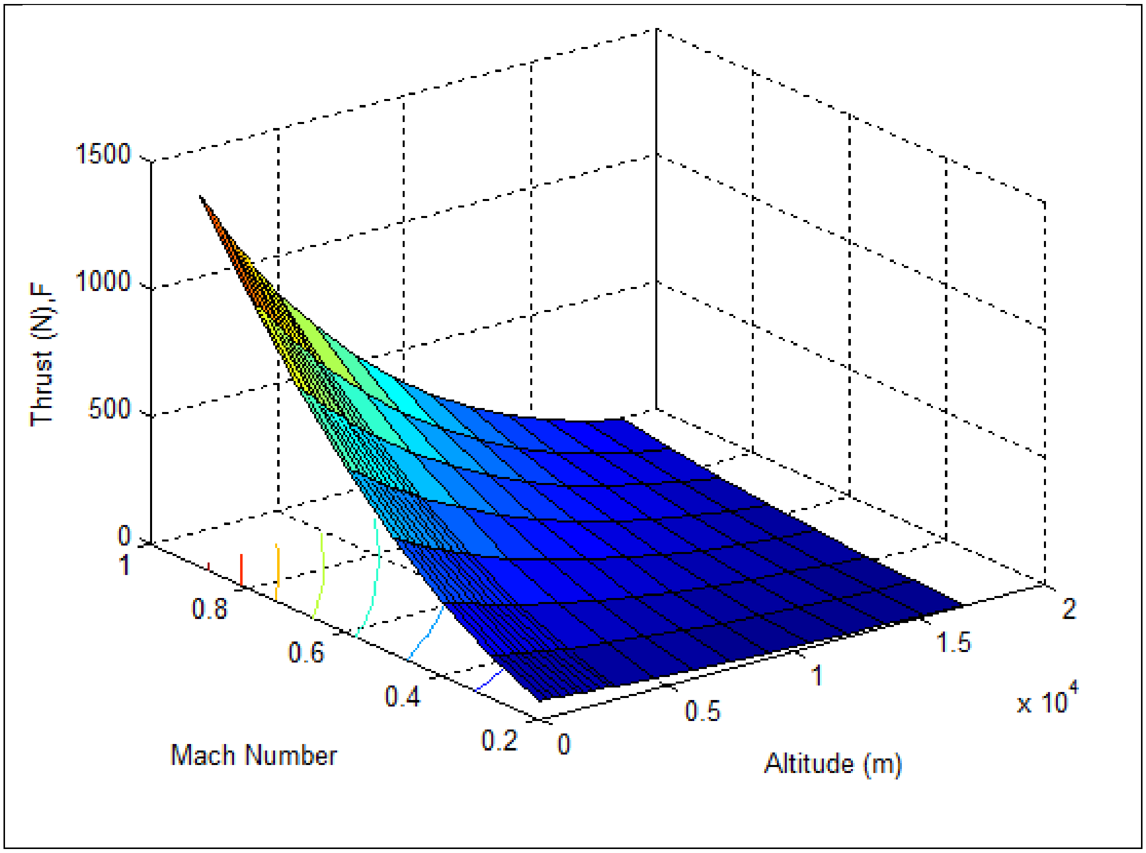

Figure 7-4: Mach number-VS Thrust graphs

Figure 4-10 shows thrust decreases as altitude increases. Because the air is less dense at higher altitudes, drag reduces, but for the same reason thrust reduces. The balance of these two effects in any particular case determines the altitude at which the maximum envelope airspeed will be reached.

In the denser air at low altitudes, both drag and thermal heating are much greater than at high altitudes. Figure4-11 shows that thrust increases with Mach number. High airspeeds in dense air are limited by airplane structure considerations. Since engines work by taking whatever flows into the intake and accelerating it backwards, as this air becomes less dense, there is less air to be accelerated backwards, so the thrust force decreases. Thrust is the product of the rate of airflow through the engine per second and added speed to that air. When air is less dense, the engine can accelerate it more, but with very thin air at high altitudes, the volume of air put through the engine per second is small and so the thrust decreases even though the air is being ejected from the engine as fast as the engine can push it. [5,6]

which the engine gives

Other factors also limit achievable thrust when the air is very thin: The ratio of fuel to air burnt in an engine needs to be within a certain range and with a reducing supply of air, less fuel can be burnt.[7]

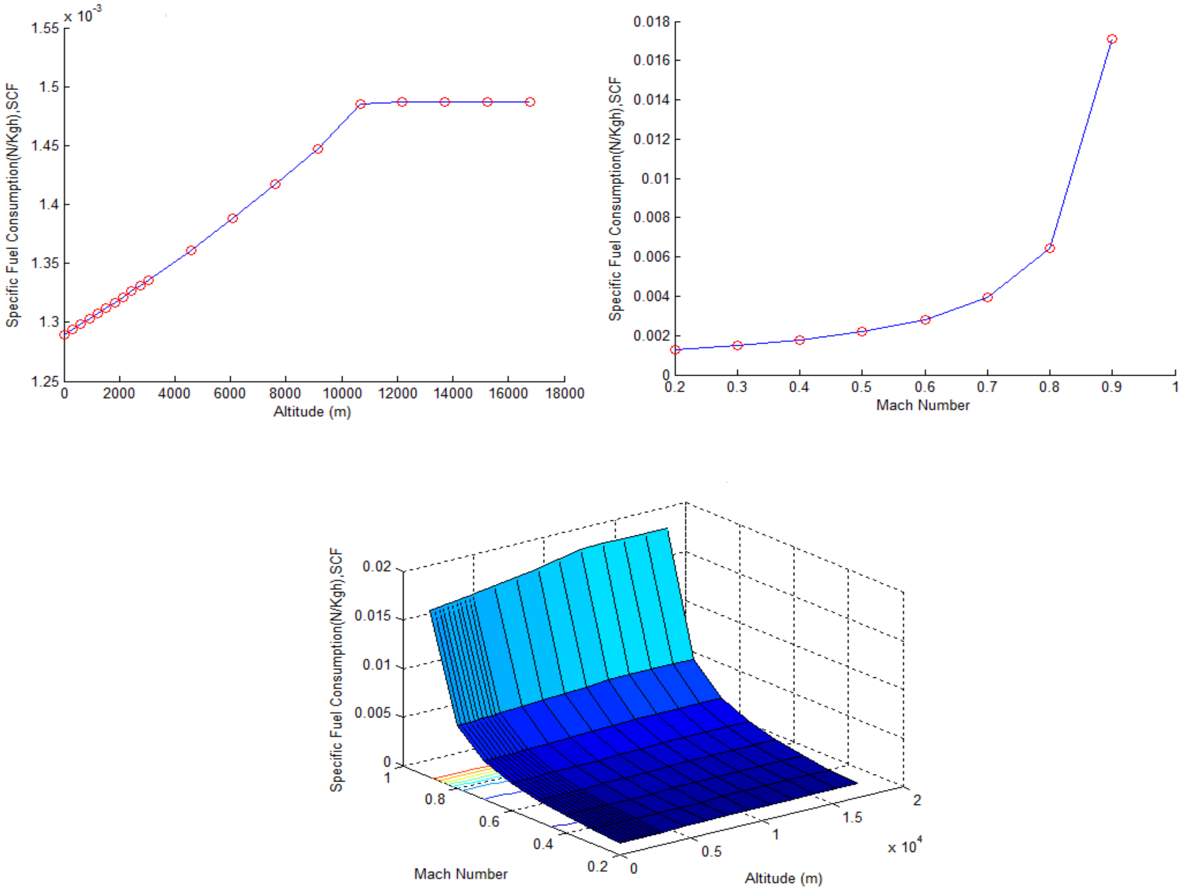

Figure 7-5: Specific fuel consumption

As shown in Figure 4-16 by increasing the amount of fuel, the thrust of the unit will increase due to higher explosion pressure. Higher explosion pressure gives better efficiency of explosion or lower specific fuel consumption.

The combustion process is such that the amount of fuel which can be effectively burned is smaller at lower flight mach numbers. Therefore, the explosion pressure is lower and the specific and the specific fuel consumption higher .at higher velocities richer mixtures can be burned. Altitude has only slight influence on the specific combustion.

8 General Conclusions

The research accomplished in this work attempts to provide sizing and dimensions of valved pulsejet engines and to evaluate its performance. To determine characteristics of performance, chamber pressure and temperature, thrust, and operating frequency were computed and are presented for comparison with published engine data. The computed results agree well with published data. The comparisons show good agreement between computed data and published data which provides confidence in the analysis of valved pulsejet engine.

From the computer analysis presented above, the following relevant conclusions drawn from this work are as follows:

1. There is a direct correlation between frequencies and diameters of exhaust pipe/combustion chamber. The frequencies reduce with increase in diameters. However the frequencies reduce rapidly with increase in combustion chamber diameter as compared to that of the exhaust pipe.
2. There is also a direct relationship between thrust and combustion chamber diameter and length. The thrust increases with increase in chamber diameter and length. This relationship provides good trade off in

3. the choice of combustion chamber size depending on the application of the pulsejet engine.

4. The pulsejet engine combustor that shows a net pressure gain between the intake and the exhaust. The exhaust pressure is higher than the intake pressure. There is pressure gain across the combustor, rather than loss. This is very important, accordingly, a small percent gain in combustion pressure achieved by this method gives about the same improvement in overall efficiency as a high percent gain produced by a compressor, all other things being equal. Hence efforts in increasing combustion efficiency of pulsejet engines are the main roles of scientific research in pulse detonation engine.

5. The pulsejet thrust decreases as altitude increases. Because the air is less dense at higher altitudes, drag reduces, but for the same reason thrust reduces. The balance of these two effects in any particular case determines the altitude at which the maximum envelope airspeed will be reached. When air is less dense, the engine can accelerate it more, but with very thin air at high altitudes, the volume of air put through the engine per second is small and so the thrust decreases even though the air is being ejected from the engine as fast as the engine can push.[8]

6. For valved pulsejet, the thrust increases with Mach number. Since engines work by taking whatever flows into the intake and accelerating it backwards, as the mass flow rate of air increases, there is an increase in the thrust force. Thrust is the product of the rate of airflow through the engine per second and added speed which the engine gives to that air. [9]

7. Other factors also limit achievable thrust when the air is very thin, the ratio of fuel to air burnt in an engine needs to be within a certain range and with a

reducing supply of air, less fuel can be burnt.

8. From the point of view of acoustics, the valved pulsejet behaves like a 1/6 wave tube and the operating frequency is a function of the exhaust pipe length and the combustion chamber length.[10]
9. Kerosene is a practical fuel for valved pulsejet applications as the computer program use the calorific value of kerosene as combustible fuel.
10. The following was observed when studying the effects of fuel flow rate on pulsejet performance:
    a. Plots of mean, maximum, and peak to peak pressures with respect to fuel flow rate indicate a performance envelope.
    b. Pulsejet with more constricted inlets or shorter exhaust lengths demonstrate higher fuel efficiencies.
    c. Sound pressure level increases with a decrease in inlet diameter.

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