

ROBERT COLLEGE SCHOOL OF ENGINEERING

THESIS FOR MASTER'S DEGREE

DEPARTMENT OF MECHANICAL ENGINEERING

THEORETICAL ANALYSIS OF THE PULSEJET

PREDICTION OF ITS PERFORMANCE

EXPERIMENTAL VERIFICATION OF THE CALCULATED PERFORMANCE

INSTRUCTOR AND ADVISOR

PROF. DECDET ERA SLAN

THESIS PREPARED BY

YORGO HACOPULOS

JUNE 1963

Bogazici University Library

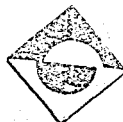


39001100540882

14

CONTENTS

<u>Page</u>	
I	Introduction to the pulsejet, Pulsejet
2	The JB- 2 Engine
4	Fuel and pressure sustem of the JB-2 engine
8	Intermittent jets
9	Cycle Efficiency
IO	Efficiency of nonuniformity
II	Propulsive cycles
I2	Factors affectinf cycle efficiency
I4	Analysis of flow phenomena
I6	Performance analysis
20	Gas dynamical investigation s of the pulsejet
	Mode of operation
22	Effects of constructional alterations
26	study of combustion
28	Combustion
35	Investigation of a streamlined tube
37	Experimental part of the thesis
45	Theoretical calculation of the static thrust
	Bibliography



124084

INTRODUCTION TO THE PULSE JET.

The pulse jet may be defined as compressorless, nonsteady flow jet engine without wave precompression of the combustible charge.

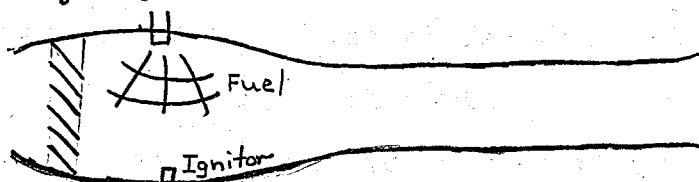
Actually a clear line of demarcation between pulsejet and wave engines cannot be drawn, the pulsejet being in effect a wave engine with a wave precompression ratio in the neighborhood of 1.0. The distinction is widely accepted, however, primarily because of the historical precedence of the pulsejet, to the development of which much separate work has been offered even in recent years. First we state its working principle in a general manner and then we will discuss in more detail the parts consisting the pulsejet as well as its working principle.

The pulsejet consists of a shaped tube fitted with flowcheck valves at the front end. The air flowing into the engine through the valves is mixed with a continuously sprayed fuel. The mixture is then fired. As a result of pressure rise which accompanies the explosion, the inlet valves close and the exhaust gases are forced out through the tailpipe. Expansion waves which are generated in the discharge reduce the pressure behind the check valves until they open again to admit a fresh charge of air, and the cycle is repeated. A spark plug is needed only for starting, once a regular cycle is established, each fresh charge of mixture is ignited by the hot gases from the preceding explosion and operation proceeds further without use of the spark plug.

PULSE JET

The engine receives its name from the pulseting manner in which the combustion process takes place. This engine is a little more complicated than the ram jet since it has a grill of shutters that are operated by the ram air pressure of incoming air and the rise or fall of pressure in the combustion chamber. The ram air pressure forces the shutters open, and the rapid rise in pressure which accompanies combustion closes the shutters. Fuel is injected into the air that enters through the shutter valves. The combustion chamber contains the spark plug which provides initial combustion.

Once started , combustion occurs at regular intervals without spark plug action because part of the exhaust gases return to the combustion chamber area to ignite the fresh charge. The tailpipe of the pulsejet increases the velocity of the exhaust gases and determines the frequency of the cycle.



The pulsejet is the simplest of the atmospheric thermal jets. It relies on heat energy for the force to accelerate the working fluid. The heat energy is usually supplied by a chemical reaction, in most cases by oxidation process. It obtains the oxygen necessary for fuel combustion from the earth's atmosphere and consequently it is confined to operation within the earth's atmosphere. It contains no mechanical means of compressing the inlet air, it obtains air compression by forward motion (ram) and the action of a diffuser.

This type of engine first drew international attention when it was used to propel the Buzz Bomb. The American version of the V-1 is known as the JB-2. Research and development in the field of pulsejet propulsion since World War 2 has advanced the operational characteristics of such engines considerably but the design remains basically the same.

The JB-2 Engine

The four major parts of a pulsejet engine are the diffuser, grill assembly (air valves, air injectors, and fuel injectors), combustion chamber, and tailpipe.

A- THE DIFFUSER. The diffuser is a duct of gradually increasing cross sectional area , designed to convert high speed airflow into low speed flow at an increased pressure. The pulsejet's air intake increases in cross section from the mouth to the grill assembly. As air flows through this section it undergoes an increase in pressure and a decrease in velocity. This increased pressure makes possible more rapid expansion when the air reaches the combustion chamber.

B- THE GRILL ASSEMBLY. It consists of an arrangement of air intake valves, three starting air injectors and nine fuel injectors.

The design of the air intake valves , or flapper valves as they are frequently called, is the most important feature of the grill assembly. These valves consist of V-section supporting members which are fitted with strips of spring steel. The open ends of the V's point toward the diffuser section and the closed ends point into the combustion chamber. The spring steel strips are spring loaded in a normally closed position, that is they exert pressure against their respective supporting members. When atmospheric pressure in the diffuser section is greater than combustion chamber pressure, the flapper valves are forced open. When combustion chamber pressure is equal to, or greater than atmospheric ram pressure, the valves are closed. The two diagrams show the construction and operation of one of the many air valves located in the grill assembly.

The flapper valve unit is designed so that any number of layers can be assembled to form a grill of desired dimensions.

The three starting air injectors shown in the illustration next page are connected to a pressurised external air supply which provides oxygen for initial combustion. They operate only during the starting phase not during flight.

The nine fuel injectors, are fed through a delivery tube connected to the pressurised fuel supply stored within the missile.

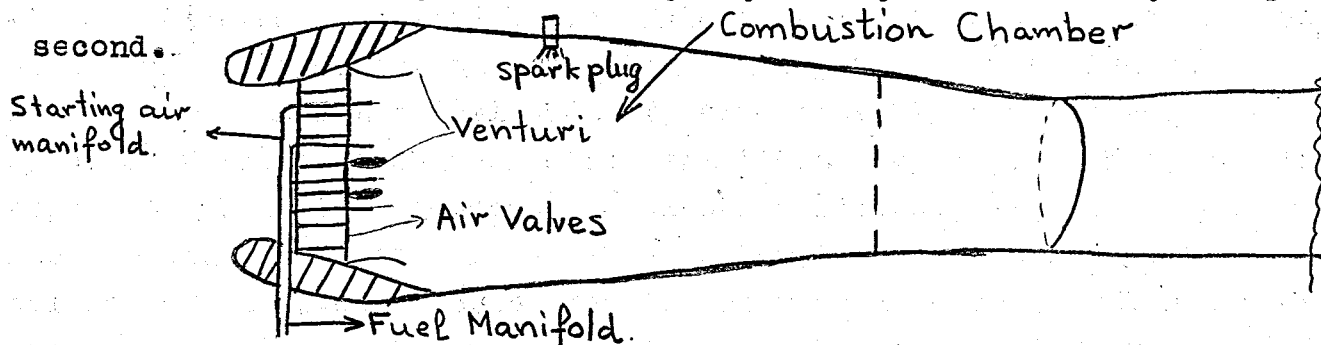
The venturi sections , immediately aft of the grill assembly insure proper fuel atomisation and increased mixing of atomised fuel with air that enters through the flapper valves.

G- The COMBUSTION CHAMBER. It contains the spark plug, which provides initial ignition. Once started, combustion occurs periodically without sparkplug action.

D-THE TAILPIPE of a pulsejet increases the velocity of the exhaust gases and determines the frequency of the combustion cycle. The frequency of operations is expressed by the following relationship

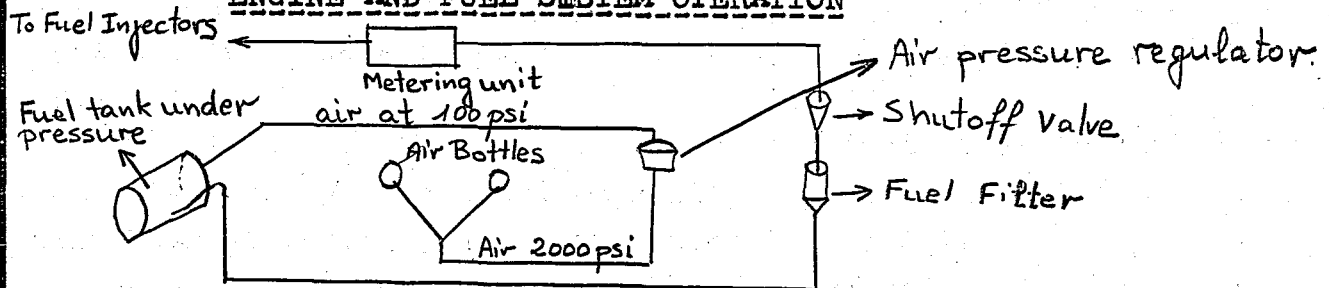
$$\text{Frequency} = \frac{\text{Velocity of Sound}}{4 \cdot \text{Length of Tail}}$$

The tailpipe frequency of operation of the JB-2 pulsejet is approximately 50 cycles per second. In small engines with short tailpipes, the combustion cycle frequency may easily exceed 200 cycles per second.



STRUCTURAL VIEW OF A PULSEJET ENGINE

ENGINE AND FUEL SYSTEM OPERATION



FUEL AND PRESSURE SYSTEM OF A PULSEJET.

In a JB-2, fuel is carried in a steel tank of 180-gallon capacity. Fuel is pressure-fed to the fuel manifold. Notice in the illustration, (Fuel and pressure system of Pulsejet Engine) that the two air bottles give an initial air pressure of 2000 pounds per square inch which is regulated to 100 psi by the air pressure regulator. This air pressure regulator keeps the air pressure on the fuel in the fuel tank from exceeding 100 psi. The fuel in the tank is forced through the fuel filter, the shutoff valve, and the metering unit to the

fuel injector.

The following description of the operation of the pulsejet fuel system applies to the diagram (Pulsejet Fuel System, see fig.)

For starting this engine an external air pressure of 180 to 200 psi is connected to the starting air disconnect fitting . This fitting is located on the outside of the missile fuselage. The internal air supply pressurises the fuel tank at 100 psi , forcing fuel through the fuel filter where it is stopped by the fuel shutoff valve. Now, when the line from the external air supply is opened , air under pressure forces the lines indicated in dashed lines. This starting air, so called because of its use only during the starting phase performs three functions,

1- The air enters the fuel shutoff valve assembly and pressurises the top side of the fuel shutoff diaphragm . This diaphragm pushes the piston type fuel shutoff valve down to a lower position , allowing fuel to flow up and around the valve. This fuel valve remains locked in the open position by the plunger connected to the manual shutoff arm. This plunger slips into a slot as the rod above the diaphragm goes down with the diaphragm and shutoff valve. In case of malfunction during starting, the fuel may be cut off by pushing the manual shutoff arm which pulls the plunger from the slotted rod, allowing the diaphragm and fuel valve to rise.

2- The air enters the cylinder above the fuel metering unit where it extends a plunger downward to contact the fuel metering arm inside (not visible in diagram), thus restricting the fuel flow to the grill to a predetermined amount. This operation prevents flooding of the engine during starting.

3- The air flows through the three starting air injectors into the combustion chamber, where it mixes with the fuel to form a combustible mixture. The spark plug is connected to a 10,000-volt ignition voltage source, and the fuselage is electrically grounded.

The starting air valve is opened and the ignition switch closed at approximately the same time. The fuel regulator adjusting screw is pre-set to control fuel flow to the fuel injectors. The fuel-air mixture is ignited by the spark plug . Spark plug operation and starting air supply are no longer needed once combustion is started.

When the initial charge of fuel and air is ignited , pressures force

created by the rapid combustion, accelerate the gaseous products in all directions. Since the flapper valves are closed, the high velocity gases going in that direction cannot escape. They do, however, exert a great force against the grill assembly. This force is a component of the thrust, it also acts on the nine fuel injector openings, preventing fuel from flowing during the high pressure stage of the combustion reaction.

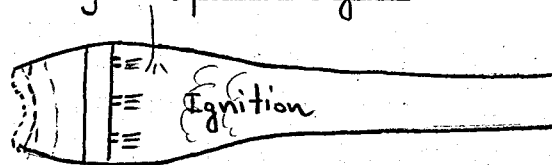
The diagram 'Stages of Pulsejet engine' indicates the various stages in the operating cycle of the JB-2 type Pulsejet engine.

In stage (I) the flapper valves are closed, and pressure on both sides of the grill is the same. Starting air from an externally pressurised source enters the combustion chamber through the starting injectors. Fuel under pressure is then injected to mix with the air, and the spark plug ignites the mixture. The combustion which follows raises the pressure in the combustion chamber high enough to shut off the fuel flow and hold the flapper valves closed. The flaming gases then rush down the tailpipe, creating a partial vacuum (low pressure area) in the combustion chamber. This low pressure allows the flapper valves to open as shown in diagram (4), to admit a new charge of air and fuel, at the same time, part of the exhaust gases are drawn back into the combustion chamber, igniting the fresh charge. Even without further use of the spark plug a self firing occurs in the gas, apparently in a central region near the section through the spark plug, and a regular cycle is established. The mechanism of the self firing is not clearly understood but it seems probable that pressure waves reflected from the ends of the motor cause a local heating and mixing of the gas sufficient for its ignition near the interface between the incoming (unburnt) mixture and the previously burnt gases. The flame apparently spreads from the region of re-ignition with a relatively slow speed, the process thus resembles a wave propagation rather than an instantaneous explosion. This cycle of events continuous as long as fuel is supplied to the engine. The main advantages of the pulsejet engine are that it is cheap and simple to construct and requires a minimum maintenance. These factors make the power plant ideal for target drones and test vehicles. Unfortunately most pulsejet engines do not develop enough static thrust to take off under their own power, but must be boosted to

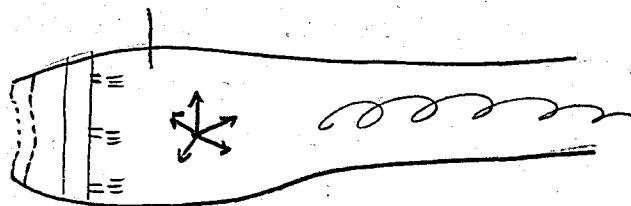
operating speed by some type of launching mechanism. Also the velocity of this engine is limited by the operation of the air valves. If the speed becomes too great, ram air pressure in the diffuser section is greater than combustion chamber pressure, consequently the valves do not close. At about a flight Mach number of 0.6 the engine ceases to operate in its normal pulsating manner. The Shrouded Pulsejet engine is able to operate in larger Mach numbers.

Diagram Stages of Pulsejet

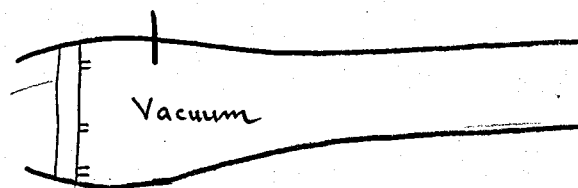
1)



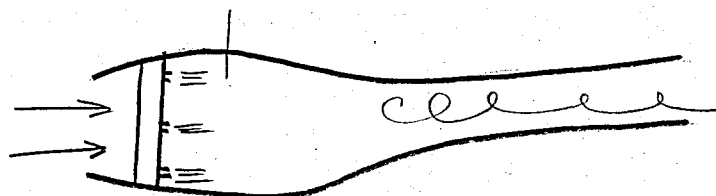
2)



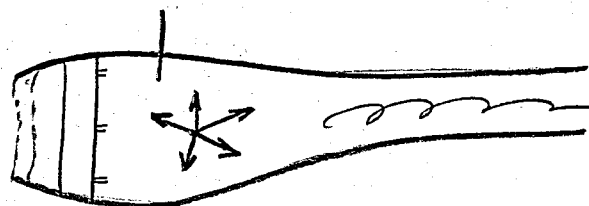
3)



4)



5)

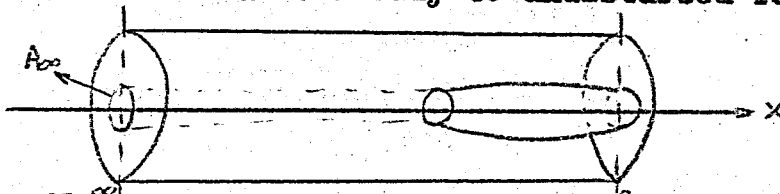


-Intermittent Jets-

General performance equations.

Thrust and impulse in Single flow engines.

Consider a cylindrical control surface enclosing the engine, extending upstream and transversely to undisturbed regions.



The flow external to the engine is assumed to be isentropic and unaffected by the flow pulsations so that there is no drag and flow separation on the external surface of the engine. We write the momentum

equation in the form: $F_i - (p_e - p_\infty) A_e = p_e A_e V_e^2 - p_\infty A_\infty V_\infty^2 + \frac{\partial}{\partial t} \int p V d\tau$ A-1
 where F_i is the instantaneous thrust produced by the engine

p pressures at stations and

ρ_e, ρ_∞ densities

V_e, V_∞ velocities

τ the volume of the internal flow region bounded by stations ∞ and e .

The state and velocity is assumed to be uniform at each instant across A_e .

Let f be the frequency of the cycle. Then by timewise integration of A-1 we obtain I_c (the impulse produced by the engine during one cycle). Since the flow is periodic upon integration the last term of A-1 vanishes. We let

$$\int_{1/f}^f p_e A_e V_e dt = \frac{1}{f} p_\infty A_\infty V_\infty = m_c$$

Denoting $\bar{V} = \frac{1}{m_c} \int V dm$, $F = f I_c$ (Average thrust) and $\dot{m} = f I_c$ (Mass flow rate through the engine) we obtain: $F = \dot{m} (\bar{V}_e - V_\infty) + \int_{1/f}^f (p_e - p_\infty) A_e dt$ [A-3]

Now let $\dot{m} V_e + (p_e - p_\infty) A_e = \dot{m} V_f$ f denotes flow conditions that would be established if the exhaust gases were fully expanded.

For a quasi-state steady isentropic expansion between p_e to p_∞

$$T_e + \frac{V_e^2}{2c_p} = T_e \left(\frac{p_\infty}{p_e} \right)^{\frac{\gamma-1}{\gamma}} + \frac{V_f^2}{2c_p} \quad \text{or} \quad \left(\frac{V_f}{V_e} \right)^2 = 1 + \frac{1 - \left(\frac{p_\infty}{p_e} \right)^{\frac{\gamma-1}{\gamma}}}{\frac{\gamma-1}{2} M_e^2}$$

Therefore

$$\phi = \frac{\dot{m} V_e + (p_e - p_\infty) A_e}{\dot{m} V_f} = \left[1 + \frac{1 - \left(\frac{p_\infty}{p_e} \right)^{\frac{\gamma-1}{\gamma}}}{\frac{\gamma-1}{2} M_e^2} \right] \left(1 + \frac{1 - \frac{p_\infty}{p_e}}{\gamma M_e^2} \right) \quad A-4$$

Since the MAXIMUM thrust is obtained with complete expansion, but since is normally so close to $\frac{p_f}{p_\infty} = 1.0$ that the exhaust may be treated in good approximation as completely expanded. Then A-2 and A-3 reduce

$$I_c = m_c (\bar{V}_f - V_\infty) \quad (A-5)$$

$$F = m (\bar{V}_f - V_\infty) \quad (A-6)$$

CYCLE EFFICIENCY η_{cy}

We define η_{cy} of a propulsive flow as $\eta_{cy} = \frac{\bar{V}_f^2 - V_\infty^2}{2E}$ A'-1 where E- total energy (heat and mechanical work) added to each unit of mass of the working fluid in that flow and $\bar{V}_f^2 = \frac{1}{m_c} \int V_f^2 dm$

To establish this relation we think as follows. We assume a mass m_c and an infinitesimal mass dm within m_c . The energy of mass dm will be $\int_{m_c} \frac{1}{2} V_f^2 dm$ where V is the velocity of dm . If $\bar{V}_f^2$ is the square average velocity of mass m_c , then the kinetic energy of it will be $\frac{1}{2} \bar{V}_f^2 m_c$

Equating these values we obtain the above relation.

Timewise integration of the energy equation between stations ∞ and e over the period of one cycle yields

$$\int_{m_c} \left(\frac{V_f^2}{2} + \int \bar{c}_{p_{\infty f}} T_f \right) dm - m_c \left(\frac{V_\infty^2}{2} + \int \bar{c}_{p_{\infty f}} T_\infty \right) = E m_c \quad A'-2$$

The first term of the left-hand side of A'-2 represents the energy after the pulsejet and the second term before it. So their difference represents the energy consumed $E m_c$. In A'-1 we denote

$$\bar{c}_{p_{\infty f}} = \frac{1}{T_f - T_\infty} \int_{T_\infty}^{T_f} c_p dT$$

All particles of a same flow emerge from the engine at the same entropy level and at the same pressure $p_f = p_\infty$ hence also at the same temperature:

$$T_f = T_\infty \exp \left(\frac{s_f - s_\infty}{\bar{c}_{p_{\infty f}}} \right) \quad A'-3$$

where s represents entropy per unit mass and

$$\bar{c}_{p_{\infty f}} = \frac{1}{\ln(T_f/T_\infty)} \int_{T_\infty}^{T_f} c_p \frac{dT}{T}$$

If we write $\int_{T_\infty}^{T_f} c_p \frac{dT}{T} = \int_{T_\infty}^{T_f} \bar{c}_{p_{\infty f}} \frac{dT}{T}$ and considering $\bar{c}_{p_{\infty f}}$ as a constant and we take it out of the integral sign we have

$$\bar{c}_{p_{\infty f}} \int_{T_\infty}^{T_f} \frac{dT}{T} = \int_{T_\infty}^{T_f} c_p \frac{dT}{T}$$

integrating the lefthand side and dividing both sides by $\ln \frac{T_f}{T_\infty}$

we obtain the relation for $\bar{c}_{p_{\infty f}}$.

From A'-1, A'-2, A'-3 we obtain

$$\eta_{cy} = 1 - \frac{\int \bar{c}_{p_{\infty f}} T_\infty}{E} \left[\exp \left(\frac{s_f - s_\infty}{\bar{c}_{p_{\infty f}}} \right) - 1 \right] \quad A'-4$$

When energy is added to the gas only in the form of heat the cycle efficiency reduces to the thermal efficiency. Equation A-4 PERmits the calculation of the cycle efficiency pertaining to each propulsive flow through computation of the entropy increments associated with all the processes to which the flow is subjected within the engine. Then

$$\overline{V_e^2} = 2\eta_{cy} E + V_{\infty}^2 \quad A-5$$

EFFICIENCY OF NONUNIFORMITY η_v

Thrust and impulse can be calculated by means of equations A-4, A-5 and A-6 provided that a relation is established between $\overline{V_f}$ and $\overline{V_f^2}$.

$\eta_v = (\overline{V_f})^2 / \overline{V_f^2}$ is defined by definition.

If $V_f = \overline{V_f} + V_f'$ where V_f' is a periodic perturbation then $\int_{m_c} V_f' dm = 0$ due to the fact that V_f' is a periodic function and

$$\overline{V_f^2} = (\overline{V_f})^2 + \frac{1}{m_c} \int_{m_c} V_f'^2 dm$$

Because if we square both sides of $V_f = \overline{V_f} + V_f'$ We get

$$V_f^2 = (\overline{V_f})^2 + 2\overline{V_f} V_f' + V_f'^2$$

we multiply by dm and integrate along m_c

$$\int_{m_c} V_f^2 dm = \int_{m_c} (\overline{V_f})^2 dm + 2 \int_{m_c} \overline{V_f} V_f' dm + \int_{m_c} V_f'^2 dm \quad \text{or}$$

$$\int_{m_c} V_f^2 dm = (\overline{V_f})^2 m_c + 2 \overline{V_f} \int_{m_c} V_f' dm + \int_{m_c} V_f'^2 dm \quad \text{or}$$

$$\frac{1}{m_c} \int_{m_c} V_f^2 dm = (\overline{V_f})^2 + \frac{1}{m_c} \int_{m_c} V_f'^2 dm$$

$$\text{or } \overline{V_f^2} = (\overline{V_f})^2 + \frac{1}{m_c} \int_{m_c} V_f'^2 dm$$

.From this we obtain

tain $\eta_v = 1 - \frac{1}{m_c \overline{V_f^2}} \int_{m_c} V_f'^2 dm$ according to the definition of η_v .

It should be noted that the value of the thrust is quite sensitive to changes of η_v under certain conditions.

From A-6 and A-5 one obtains $F = m \left\{ \left[\eta_v (2\eta_{cy} E + V_{\infty}^2) \right]^{1/2} - V_{\infty} \right\} \quad A-6$

because

$$\overline{V_f} = \sqrt{\eta_v \overline{V_f^2}} = \sqrt{\eta_v (2\eta_{cy} E + V_{\infty}^2)} \quad \text{so we substitute in A-6 and A-6.}$$

PROPULSIVE CYCLES.

Cycle efficiency of a propulsive flow is found to be

$$\eta_{cy} = 1 - \frac{J \bar{c}_{poo} T_{\infty}}{E} \left[\exp \left(\frac{S_f - S_{\infty}}{\bar{c}_{poo}} \right) - 1 \right] \quad \text{the symbols are as given previously.}$$

To apply the equation above we need to find the value of the entropy term. The various processes that may generally make up a cycle can be classified as follows

- 1- Isoenergetic Process
- 2- Flow through a fan or a compressor
- 3- Flow through a turbine
- 4- Combustion
- 5- Pressure exchange.

1- ISOENERGETIC PROCESSES.

These processes are characterised by changes of stagnation pressure without change of stagnation temperature. Therefore the entropy increment produced by all such transformations in a flow through the engine is $\Delta S_g = -R \ln \eta$ B-1 where η is the product of all the downstream-to-upstream stagnation pressure ratios associated with such losses within the engine. Examples are flow through stationary shocks sharp changes of cross section, narrow passages and bends. In the equation above the temperature terms vanish.

2- FLOW THROUGH A FAN OR COMPRESSOR.

From the definition of polytropic or small stage efficiency η_c $T_{rc}^{\circ} = (p_{rc}^{\circ})^{\frac{\gamma-1}{\gamma \eta_c}}$ where T_{rc}° is the exit-to-inlet stagnation temperature ratio across fan or compressor and p_{rc}° is the compression ratio then

$$\Delta S_c = \frac{1 - \eta_c}{\eta_c} R \ln p_{rc}^{\circ} \quad \text{B-2}$$

3- FLOW THROUGH A TURBINE.

From the definition of polytropic turbine efficiency η_t $T_{rt}^{\circ} = (p_{rt}^{\circ})^{\frac{\gamma-1}{\gamma \eta_t}}$ where T_{rt}° and p_{rt}° are the exit-to-inlet stagnation temperature ratio and stagnation pressure ratio then

$$\Delta S_t = -(1 - \eta_t) R \ln p_{rt}^{\circ} \quad \text{B-3}$$

4- COMBUSTION.

For a polytropic change, the first law of thermodynamics yields

$$\frac{T}{T_i} = 1 + \frac{n-1}{n-\gamma} \frac{q_a}{C_p T_i} \quad \text{B-4 where subscript i refers to initial conditions}$$

and q is the heat added per unit mass from the beginning of the transformation. When q_a is the total amount of heat added and (h) denotes average values in the heating process the final temperature and pressure is given by

$$\frac{T_2}{T_1} = 1 + \frac{n-1}{n-\gamma_h} \frac{q_a}{C_{v_h} T_1} \quad B-5 \quad \frac{P_2}{P_1} = \left(1 + \frac{n-1}{n-\gamma_h} \frac{q_a}{C_{v_h} T_1} \right)^{\frac{n}{n-1}} \quad B-6$$

Then
$$\Delta S_h = C_{v_h} \frac{n-\gamma_h}{n-1} \ln \left(1 + \frac{n-1}{n-\gamma_h} \frac{q_a}{C_{v_h} T_1} \right) \quad B-7$$

$$\Delta S_h = -C_{v_h} \frac{n-\gamma_h}{n-1} \ln \left(1 - \frac{n-1}{n-\gamma_h} \frac{q_a}{C_{v_h} T_2} \right) \quad B-8$$

5-PRESSURE EXCHANGE.

It is commonly defined as a process in which a flow, or a region of a flow, is compressed by the piston like action of another flow (or another region of the same flow) expanding between the same pressure limits. It plays an important role in the operation of wave engines. Entropy increment due to pressure exchange is denoted by ΔS_g .

FACTORS AFFECTING CYCLE EFFICIENCY.

The effect of precompression is to increase T_2 hence to decrease the entropy rise in accordance with B-7. Therefore pressure exchange may be a very effective means of increasing the cycle efficiency.

With constant T_1 and q_a , ΔS_h decreases as $n \rightarrow -\infty$ (B-7). When $n < 0$ (B-8) the opposite occurs when T_2 and q_a are fixed. In the first case the highest η_{cy} would be obtained with an isochoric process in the second case η_{cy} is found to decrease as the heat addition process approaches the isochoric mode. This seems to put steady flow engines at a disadvantage over their nonsteady flow counterparts in those cases which material properties impose a limitation on the peak temperature of the cycle. It should be noted however that the use of nonsteady processes offers the possibility of avoiding the continuous exposure of part of the engine to very hot gases. Therefore the MAXIMUM allowable gas temperature is often considerably higher in nonsteady than in steady flow engines. For this reason a comparison of cycle efficiencies of the two classes of engines for equal peak cycle temperatures would be of doubtful significance.

The cycle efficiency of a jet engine may be adversely affected

Flow fluctuations occurring in certain regions of the engine. For example

Flow fluctuations in a supersonic intake diffuser can generally be expected to reduce the pressure recovery and hence the cycle efficiency of the engine. Indeed, it is often possible to establish a shock pattern that will minimize the diffuser shock losses for a given operating condition but it is obvious that this pattern can be steadily maintained only if the flow itself is steady. However the amplitude of the shock motion in any given diffuser in the presence of fluctuating back pressure decreases considerably when the frequency of these pressure pulsations increases, their amplitude remaining constant because compression and expansion waves being generated in closer succession, their neutralizing interaction takes place over a shorter distance. Therefore the diffuser length required to prevent the back pressure disturbances from reaching the intake is inversally proportional to the disturbance frequency.

It appears then that the losses associated with the oscillations of diffuser shocks may be greatly reduced by increasing the diffuser length or the operating frequency. In a diffuser conveying the air to a sufficiently large number of intermittent flow chabbers operating out of phase, it should be possible to achieve a diffuser efficiency comparable of those of steady flow diffusers. Shock losses in pulsating flow diffusers may also be reduced by the use of surge chambers, connected to the diffuser passage through slits in the walls. In any case, the effect of the diffuser shock fluctuations may conveniently be accounted for by an equivalent reduction of λ in B-L.

ANALYSIS OF FLOW PHENOMENA.

Analytic solutions There are flow situations which are simple enough to lend themselves to explicit analytic solution. The most notable simplifications of this sort are those which are introduced in the treatment of nonsteady combustion processes. These simplifications may appear to be extreme in some cases, but they are well justified when it is considered that the use of quite arbitrary and far reaching approximations is at any rate inevitable in the description of what goes on in the combustion chamber of an intermittent jet engine.

The stipulation that the state be spatially uniform in the combustion region is the first simplifying assumption that suggests itself in the analysis of a volume mode of combustion involving high rates of entropy production, particularly when the initial conditions are substantially uniform.

Consider a volume mode combustion process taking place within a body of gas in a frictionless flow in a duct of constant cross section. If the initial conditions are uniform throughout, one may assume, within the combustion region $\frac{\partial s}{\partial x} = 0$ and $\frac{\partial a}{\partial x} = 0$ where (a) is the local velocity of sound. Then the continuity and momentum equations become

$$\frac{2}{\gamma-1} \frac{\partial \ln a}{\partial t} + \frac{\partial v}{\partial x} - \frac{1}{R} \frac{\partial s}{\partial t} = 0 \quad C-1$$

and

$$\frac{\partial v}{\partial t} = 0 = \frac{\partial v}{\partial t} \frac{dt}{dt} + \frac{\partial v}{\partial x} \frac{dx}{dt} = \frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = 0 \quad C-2$$

From C-1 we can get $V = gx + h$ where (g) and (h) are functions of time only. Using a coordinate system with respect to which the gas is at rest at $t=0$, and with the origin at the midsection of the combustion region, (h) vanishes and C-2 yields $g = \frac{1}{t+\beta}$ then (β being a constant)

$$V = \frac{x}{t+\beta} \quad C-3$$

The relation $g = \frac{1}{t+\beta}$ is obtained as follows:

$V = gx + h$. At $t=0$, $V=0$

$x=0$, $h=0$ so $V=gx$.

In $\frac{\partial v}{\partial t} + v \frac{\partial v}{\partial x} = 0$ we substitute $V=gx$, $\frac{\partial v}{\partial t} = x \frac{dg}{dt}$ $\frac{\partial v}{\partial x} = g$ so

$$x \frac{dg}{dt} + g^2 x = 0 \quad \frac{dg}{g^2} = -dt \quad \frac{1}{g} = t + \beta \rightarrow g = \frac{1}{t+\beta}$$

During the time (t), the layer which is initially at $x=x_1$ moves at the constant velocity $\frac{x_1}{\beta}$ to $x=x_1 + \frac{x_1}{\beta} t$ therefore the ratios of specific volumes become $v/v_1 = 1 + t/\beta$ C-4 where subscript (1) denotes initial condition.

Since $\frac{p}{p_1} = \left(\frac{v}{v_1}\right)^{-n}$ for a polytropic process then

$$p/p_1 = (1 + t/\beta)^{-n} \quad \text{C-5}$$

$$a/a_1 = (1 + t/\beta)^{\frac{1-n}{2}} \quad \text{C-6}$$

If during the total combustion time t_c the volume of the burning gas increases to (k) times the initial volume, one has from C-4

$$\beta = \frac{t_c}{k-1}$$

From the first law of thermodynamics and the above relations, one obtains for the rate of heat addition in a polytropic process:

$$\frac{dq}{dt} = \frac{\gamma-n}{\gamma-1} p \frac{dv}{dt} = \frac{k-1}{t_c} (\gamma-n) C_v T_1 \left[1 + (k-1) \frac{t}{t_c} \right]^{-n} \quad \text{C-7}$$

whence $\frac{q_a}{C_v T_1} = \frac{\gamma-n}{1-n} k^{1-n} \quad \text{C-8}$

From C-7 we see that, in a polytropic explosion with $n < 0$ and a given heat addition it is seen that the time rate of heat addition increases with time during the process.

From C-7 we see that, in a polytropic explosion with $n < 0$ and a given value of $q_a/C_v T_1$ the absolute value of (n) may be increased by decreasing 'restrictors', enlarged combustion chambers or constrictions in the passage leading out of the combustion chamber.

PERFORMANCE ANALYSIS..

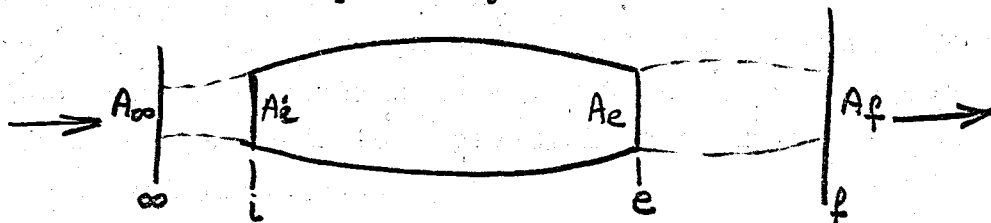
In the pulsejet, wave precompression of the fresh charge is, by definition, absent or negligible. Pressure exchange processes do, however, take place in the tailpipe and may under certain conditions introduce appreciable entropy increments. In general : $S_f - S_\infty = \Delta S_j + \Delta S_h + \Delta S_e$

where: ΔS_j is entropy rise in isoenergetic processes

ΔS_h is the entropy rise due to heat addition

ΔS_e is entropy rise due to pressure exchange..

If p_∞ is the pressure of the uniform atmosphere infinitely far upstream and downstream we consider two sections A_i and A_f perpendicular to the engine axis where pressure p_∞ exists. Letters i and e denote inlet and exhaust respectively.



s_f and s_∞ are the entropies at section f and ∞ respectively. It is to be noted that these sections are to be located as near as possible to A_i and A_e .

The flow velocity in the combustion chamber at the time of ignition is usually very low, and because of the absence of a compressor and of any appreciable pressure exchange before combustion, the temperature of the charge just before ignition can be assumed to be equal to the free stream stagnation temperature T_∞^0 . Furthermore energy being added to the flow only in the form of heat, one has $E = q_a J$ Where J is 778 FT-LB/BTU, q_a : total heat added. Also we assume constant specific heats.

Considering equations giving η_{cy} , ΔS_j , ΔS_h and F we obtain

$$\eta_{cy} = 1 - \frac{C_p T_\infty^0}{q_a} \left[\lambda^{-\frac{\gamma-1}{\gamma}} \left(1 + \frac{n-1}{n-\gamma} \frac{q_a}{C_v T_\infty^0} \right)^{\frac{n-\gamma}{\gamma(n-1)}} \exp \frac{\Delta S_e}{D-1} - 1 \right]$$

$$I_a = \frac{F}{mg} = \frac{1}{g} \left\{ \left[\eta_r (2J q_a \eta_{cy} + V_\infty^2) \right]^{\frac{1}{2}} - V_\infty \right\} \quad D-2$$

The IDEAL PULSEJET is one in which ram precompression of the charge is fully utilized, all flow processes except combustion are isentropic, and the exhaust velocity is a square wave function of time. The

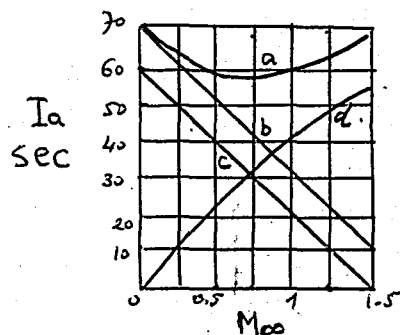
performance of the ideal pulsejet can be calculated by means of Eq D-1 and D-2 With $\lambda = \exp\left(\frac{\Delta S_g}{C_p}\right) = \eta_r = 1.0$

When $n=0$ (isobaric combustion) the amplitude of the pressure fluctuations becomes zero and the ideal pulsejet becomes the ideal ramjet. More generally with any value of n as M_∞ increases, T_∞^* also increases and the cycle efficiency of the ideal pulsejet approaches the value $\eta_{c\gamma} = 1 - \frac{T_\infty}{T_\infty^*}$

which is the ideal cycle efficiency of the ramjet. Thus the air specific impulse of the ideal pulsejet approaches asymptotically that of the ideal ramjet as the flight mach number increases indefinitely. A comparison of ideal ramjet and pulsejet performance is presented in the figure which follows for the following conditions:

$T_\infty = 500^\circ R$, $n = -1$, air/fuel = 30, $\gamma = 1.4$ throughout, heat liberated in combustion = 18,000 / BTU lb of fuel.

The value $n = -1$ corresponds to explosion pressure ratios in the neighborhood of 2.5 according to Eq. B-6 under the stipulated conditions and is believed to lead to a plausible description of the explosion process in current pulsejets.



a: ideal pulsejet

b: standard pulsejet with $\eta_\gamma = 1$

c: standard pulsejet with $\eta_\gamma = 0$

d: ideal ramjet

Fig I

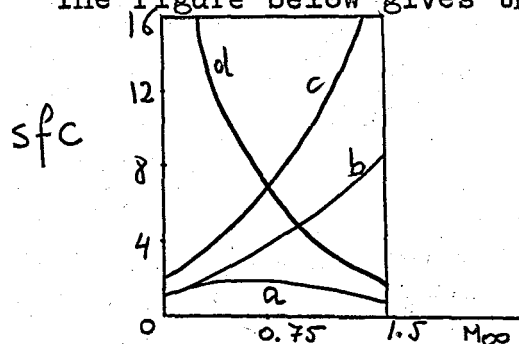
In the standard pulsejet, the most important departure from the ideal behaviour is that resulting from the inability of the engine to sustain ram pressure in the combustion chamber during the charging phase of the cycle. Indeed the wave diagrams reveal that the charge pressure at the time of ignition, being primarily determined by the exit boundary conditions, is generally very close to the free stream static pressure. As a matter of fact, the charge pressure level is believed to be depressed further as the flight speed increases, because, during these phases of the cycle in which the exhaust velocity is lower than that of the surrounding stream, the exhaust pressure is at a base-pressure level. This difficulty can be remedied, however, by means of a tailpipe constriction. Therefore, the charge pressure level will be assumed to be e-

qual to the free stream static pressure at all speeds. With this assumption the entropy rise in the inflow process is $\Delta s_g = -R \ln \frac{P_{\infty}}{P_{\infty}^0} = C_p \ln \frac{T_{\infty}^0}{T_{\infty}}$

Then the cycle efficiency becomes :

$$\eta_{cy} = 1 - \frac{C_p T_{\infty}}{q_a} \left[\frac{T_{\infty}^0}{T_{\infty}} \left(1 + \frac{n-1}{n-\gamma} \frac{q_a}{C_p T_{\infty}^0} \right)^{\frac{n-\gamma}{\gamma(n-1)}} - 1 \right]_{D-3}$$

The figure below gives the specific fuel consumption against M_{∞}



a: ideal pulsejet

b: standard pulsejet with $\eta_v=1$

c: standard pulsejet with $\eta_v=0$

d: ideal ramjet

Fig II

Δs_g for the entropy rise associated with pressure exchange, it should be borne in mind that this increment must be considered only insofar as it results from wave phenomena occurring outside of the burning regions, because the effect of pressure waves within the region is already accounted for in the description of the heating mode. Therefore, consideration must be given to this entropy increment only if the heating mode is such as to produce pressure waves that are steep enough to form early shocks and thus to affect a significant portion of the tailpipe gases. In general, the entropy rise caused by these shocks is found to be insignificant unless the rate of heat release is very high i.e. unless the absolute value of n is very large, as in isochoric combustion. In the latter case, the shock losses of pressure exchange may under certain conditions be high enough to offset much of the entropy advantage that would otherwise be associated with a high value of $|n|$. On the other hand Fig. III shows that even in the absence of pressure exchange losses, it is only in the lower range of $|n|$ that changes of heating mode have a pronounced effect on performance.

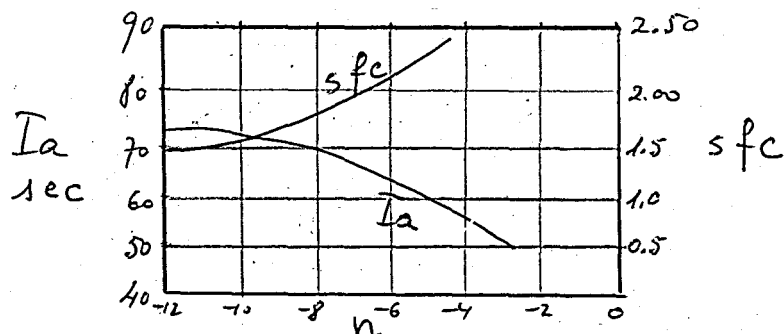


Fig. III

Fig.. III shows the effect of change of (n) on performance of standar pulsejet with $\eta_v = 1.0$ at $M_\infty = 0.5$..

Since it has been shown that (See Article C) $|n|$ increases with time rate of heat release, it follows that it would be not profitable to seek performance improvements by increasing the rate of heat release to the point at which pressure exchange losses become appreciable. Therefore Eq.. D-3 may be used to calculate the cycle efficiency of the standart pulsejet in all operating conditions that may be of practical interest. The performance of the standart pulsejet can then be calculated by means Of Eq.. I3-3 and I3-2 . AN accurate estimate of the efficiency of nonuniformity, which appears in the latter equation, can only be obtained through inspection of pertinent wave diagrams or experimental data. Values of η_v in excess of 0.8 are believed to be easily achievable in most pulsejets. Major discrepancies between calculated and measured sfc are attributable to errors in the estimate of the combustion efficiency.

It will later be shown the effect of the tube shape on the performance of the pulsejet.. A reduction of tailpipe cross- sectional area can be expected to produce a decrease of frequency and an increase of $|n|$. The former effect alone would be reflected in a decrease of thrust without change of specific impulse, while the increse of $|n|$ has a beneficial effect on beth thrust and specific impulse. Therefore a reduction of tailpipe area is likely to result in a decrease in specific fuel consumption and may produce a decrease or an increase of thrust, depending on the relative importance of the effects of shape on the frequency and on the mode of combustion. There may exist, for some operating conditions, a tailpipe contraction ratio that maximises the thrust, but the value of the optimum ratio is best determined through systematic experimentation in each spesific case .

GAS DYNAMICAL INVESTIGATIONS OF THE PULSEJET TUBE .

In the article which follows we will study the motion of the gases within the pulsejet tube. The assumptions that we make are to assume adiabatic processes and that at the beginning of the cycle there is present, adiabatically compressed relative to the surrounding air, a column of fresh charge, which suddenly expands.

We use the following notation:

$$\xi = \frac{x}{R} \quad \text{and} \quad \tau = \frac{a_1 t}{R} \quad \text{where:}$$

R: tube length

x: any length along the tube

a_1 : sonic velocity at local atmosphere

t: time

It is suggested to take the initial pressure of the column of fresh charge to be 2.5 times as great as P_0 , then the velocity of sound in the compressed column is denoted by a .

Also we denote $\xi' = \frac{R'}{R}$ where R' is the length of compressed column of fresh charge. We use the parameter z which we define as: $z = \frac{F_E}{F_R}$

where: F_E is intake cross section (Effective flow area of the valves)

F_R is tube cross-section.

Mode of operation of the jet tube at rest.

The following discussion originates from the work of Schults-Grunov on the performance of the pulsejet. (Refer to the figure where in τ, ξ plane the different wave forms are plotted).

Apart of the excess pressure of the column of fresh charge travels toward the right as the condensation shock wave a which is so small that the change of state in it may be regarded as adiabatic. The other part travels leftward as a rarefaction wave. The rarefaction wave is shown as divided into two elementary waves b and c in order to allow for the lesser velocity of propagation of later wave elements than the of earlier ones. A further subdivision proves to be unnecessary. The rarefaction wave is reflected at the left end of the tube as from a solid wall because the valves are closed. Finally, therefore shock a and the two waves b and c are travelling toward the right. The states of the gas and conditions of motion created by the shock and the waves are e

numerated by the figures in circles. In fig. it may be seen that behind the last rarefaction wave travelling to the right, atmospheric conditions are again attained. At the right-hand or open end of the tube, the shock is reflected as a rarefaction wave, which is likewise divided into two elementary waves d and e. The rarefaction waves are here reflected at the open end as condensation waves, which soon combine themselves into the shock h. The rarefaction wave d creates condition I2, for which the pressure p_1 is lower than the outside atmosphere. As soon as this state reaches the left-hand end of the tube, the valves open and at the moment T_A fresh charge begins to flow in. Consequently the finely dotted line representing propagation of the boundary of the fresh charge begins here. The intake process is strengthened by the subsequent rarefaction wave e.

Because of the shock h, which now arrives, the fresh charge front is forced ~~not~~ merely to stop but to reverse its motion, whereby the fresh charge is compressed. As soon as the shock strikes the valves, the intake period is ended and we have at this moment T_E a compressed column of fresh charge of the length $\frac{1}{3}''$ in the tube. It is assumed that at the moment T_E the explosion of the column of fresh charge occurs, so the length $\frac{1}{3}''$ then attained has the same significance for the second working cycle as $\frac{1}{3}''$ for the first. Because it turns out that $\frac{1}{3}'' < \frac{1}{3}''$ it must be concluded that the jet tube could only operate if $\frac{F_E}{F_R} > 0.4$. The explanation of the fact that in reality it operates even when $\frac{F_E}{F_R} = 0.2$ lies in the choice of prescribed conditions. In spite of this inconsistency with reality this figure shows a number of noteworthy particulars that do correspond to reality.

I- The intake process is set in motion by the rarefaction waves d and e into which the condensation shock wave a is transformed without loss of strength by its reflection at the right hand side of the tube.

II- It appears that the condensation shock wave h, into which the rarefaction waves b and c are transformed by reflection at the right-hand side of the tube, plays a part in the ignition of the fresh charge.

III- At small F_E/F_R ratios of the order of magnitude of 0.3 or less, the rarefaction waves d and e, which start the intake process, are reflected as the waves i and k of the same kind and in fact, produce a gas velocity directed toward the left so the working cycle ends with

an inflow at the exhaust end. In actual fact there has been observed with the Argus tube an inflow at the exhaust end preceeding the exhaust of the next cycle when $F_E/F_R = 0.3$

At $F_E/F_R = 0.4$ waves 1 and k no longer set in motion a negative velocity, only k is a rarefaction wave. It is thus to be expected that, in agreement with the cited observation, at $F_E/F_R > 0.4$ this inflow at the exhaust end does not occur. - - - - -

EFFECTS OF CONSTRUCTIONAL ALTERATIONS. TUBE AT REST.

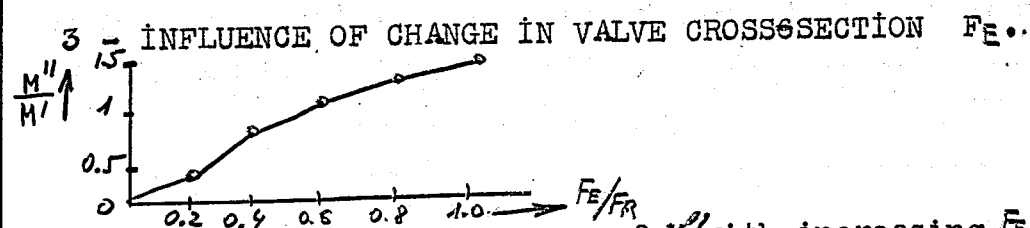
Schults-grunow experimented with many types of pulsejet with many constructional differences and concluded in the following points:

I- Influence of l length $\frac{l}{\lambda}$, tube length remaining the same..

THE GREATER $\frac{l}{\lambda}$, the LONGER is the path of the rarefaction waves b and c so much later is the shock h formed from them and so much longer is the intake period $\tau_E - \tau_A$ and the duration of the working cycle.. The effect on the duration of the working cycle is negligible, amounting to 5 %. The increased intake period results in an increased quantity of fresh charge M'' at beginning of second working cycle that is at the end of the working cycle..

II- Influence of length of tube R' , absolute length of R R' remaining the same.

In the limiting case of very weak waves, one would expect, according to the laws of acoustics, an increase in the duration of the working cycle proportional to R . In this case it slowly increases as much as 5% because as R increases the rarefaction waves b and c shift nearer to the shock a, thereby reducing the extend of the regions through which the waves d and e move more slowly. The results of lengthening the tube are favorable, of course there is for reasons of heat leakage a practical limit of about $R = 3.5$ meters.

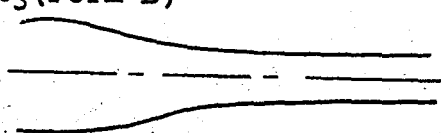
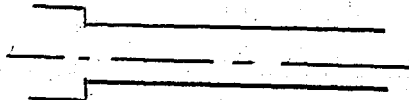


This figure shows the increase of M'' with increasing F_E/F_R on the basis of the $\tau, \frac{l}{\lambda}$ figure.

Influence of tube shape (tube of varying cross-section)

We study the following cases:

a) Reduction of cross-section at $\frac{1}{3}$ (Form B)



Form used for investigation

Actual form

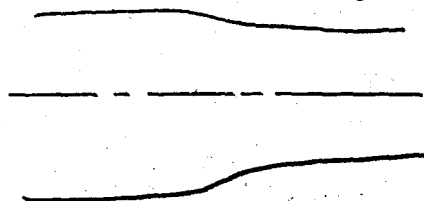
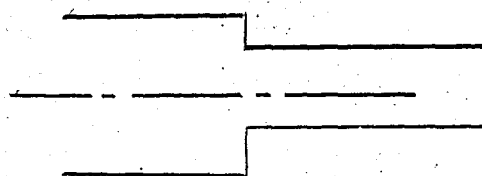
The pulsejet shown above as well as the other forms that will follow will be compared with the performance of the pulsejet having a constant cylindrical cross-section called ~~xx~~ form A. Another assumption made is that we assume that the fresh charge front lies a little to the left of the constriction.

The results of the performance of these different types of pulsejets are taken from the data established by the experimental work of Schul Grunow. The pulsejet that I will use in our propulsion laboratory is similar to the type that we analyse in this paragraph. At a latter section of this work the reader will find an investigation done by me experimenting with our pulsejet.

In the type of the tube shown above is found that the intake period is longer than in the case of form A, a substantially larger column of fresh charge being thus drawn in. The ~~xx~~ fresh charge is sucked in with a weaker vacuum but in spite of this the intake period is sufficiently lengthened that form B yields a 60% increase in charge. It is noted that the ~~xx~~ returning waves are weakened at the point of change of cross-section. Through the weakening of the subsequent wave of condensation, the ignition of the new column of the new (fresh) charge is made doubtful. Of course, the condensation shock wave creates a higher absolute pressure than in form A.

Remark : The optimal constriction is that at which the exhaust occurs with a velocity equal to that of sound in the surrounding atmosphere.

b) Reduction of cross-section at center of tube length (Form C)



It is noted that the intake period $\tau_E - \tau_A$ is not as long as that of form B. Beside this, there occurs a still smaller pressure drop across the valves and found that the improvement over form A still amounts to 39 %. The pressure ratio in the condensation shock wave which produces the ignition is just a little smaller than with form B, however, the absolute value of the compressing pressure is greater.

c) reduction of cross-section at exhaust end (form D) .

The automatic operation of the jet tube is based on the fact that at the open end a condensation wave is reflected as a rarefaction wave, and a rarefaction wave as a condensation wave, namely, at full strength because at the exhaust end only outflow takes place. Consequently, the first to strike the valves is the rarefaction wave, which starts the intake period, after which the igniting condensation shock wave reaches them.

But if the ~~xxxxx~~ reduction of cross-section is located at the exhaust end, this means that there is a half-open tube end at which the condensation wave is reflected as such with lessened strength and likewise the rarefaction wave is reflected as such with lessened strength. In this case, the condensation and rarefaction waves strike the valves in reverse sequence and the tube does not function.

d) Two reductions of cross-section (Form E)

In this case a longer intake period $\tau_E - \tau_A$ but a lesser intake producing pressure difference is obtained. likewise the pressure ratio in the igniting condensation shock wave is the smallest of those for all tube forms

In practice the absolute compression pressure is of equal magnitude to that obtained with form C. This tube form gives the greatest increase in charge over the simple tube of form A .

e) Increase of cross-section at open end of tube (Form F)

In this case a remarkable circumstance exists that during one working cycle of the tube , intake and explosion occur twice and that the change is therefore almost doubled by this increase in the cross-section. Of course the doubled frequency of opening of the valves must be regarded as unfavorable to their length of life ..

The above 5 cases have been investigated by Schults- Grunow and the results published in a form of paper. In this work the reproduction of the results seemed to be of a great importance for the reader because experimental results are not abundantly available.

Though to prepare this theoretical part of the thesis I consulted the works of the greatest authorities on Jet-Propulsion and Gas-Dynamics I was astonished to realise that no therey deep enough to take up each part of the subject exist but instead a great amount of results depend on experimental work .Trough my investigation I frequently met author to state that ' A lot of work yet has to be done in this field' .
In the part to follow I am going to describe my own work and state the results that I have obtained .

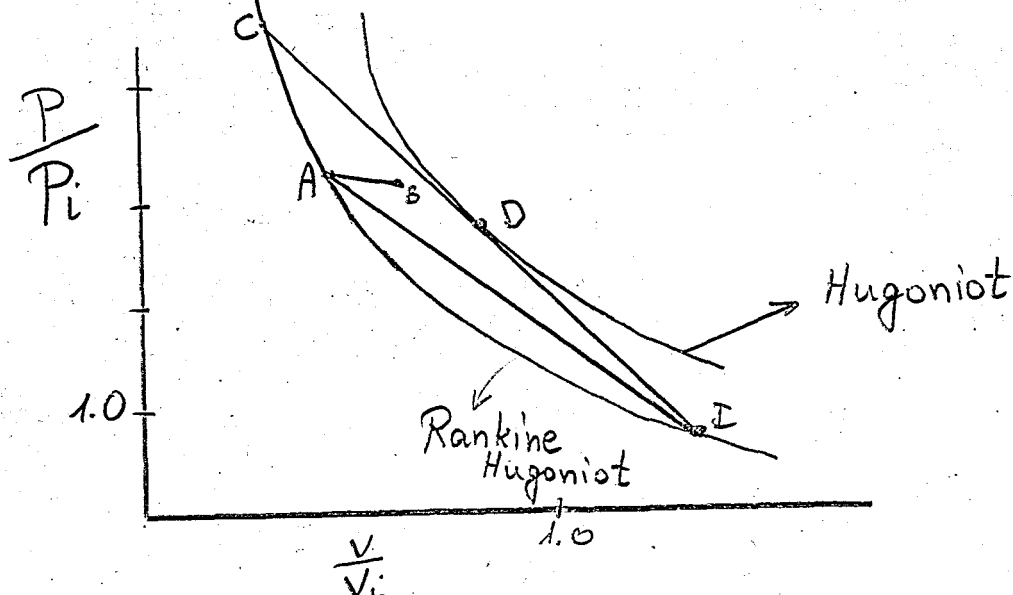
STUDY OF COMBUSTION

Intermittent jets give their designer at least in principle a certain measure of freedom in the selection of the combustion mode. A question such as which mode is more advantageous may come to our mind and then the evaluation of the merits of each mode should follow. We shall try to attempt such an evaluation. We assume that $\gamma = 1.4$. Also changes in specific heat or molecular weight are neglected. The error resulting from this assumption is believed to be overshadowed by the errors involved in the inevitable idealization of the combustion process.

As far ~~the~~ as the entropy rise is concerned, the compression produced by the shock has a favorable effect. The energy transfer to the unburnt gas produces a rise in temperature which in turn reduces the entropy increment created during combustion. This reduction more than offsets the large entropy rise produced by the shock itself. Indeed, though the Chapman-Jouguet deflagration state is the point of maximum entropy in each Hugoniot curve, the Chapman-Jouguet detonation, which is composed of both a strong shock and a Chapman-Jouguet deflagration, produces the overall minimum of entropy rise of all Rayleigh transformation involving the same amount of heat release from the same initial condition.

A similar effect will of course take place in nonsteady detonation (pseudo detonations). This observation suggests the possibility that such nonsteady processes may under certain conditions produce an even lower entropy rise than the corresponding Chapman-Jouguet extremum.

Whereas in true detonation, the shock and flame front travel together, in a pseudo-detonation the two fronts are propagated at different speeds. The nature of this process is illustrated



In the p,v plane, the pseudo-detonation may be represented by a "nonsteady" path such as i-A-B if the flame lags behind the shock. The Chapman-Jouguet detonation (i-C-D) may be considered a special case of this more general type of process. The total entropy rise.

$$\Delta S_t = \Delta S_g + \Delta S_h = c_p \ln \frac{V_A}{V_i} \frac{V_B}{V_A} + c_v \ln \frac{P_A}{P_i} \frac{P_B}{P_A} \quad (3)$$

I: Upstream condition

G: Pertaining to pressure exchange

H: " " combustion -

Using the relations.

$$\frac{P}{P_i} = \frac{\frac{\gamma+1}{\gamma-1} + \frac{2}{\gamma-1} \frac{q_a}{c_p \theta_i} - \frac{V}{V_i}}{\frac{\gamma+1}{\gamma-1} \frac{V}{V_i} - 1}, \quad \frac{P}{P_i} = \frac{\frac{\gamma+1}{\gamma-1} - \frac{V}{V_i}}{\frac{\gamma+1}{\gamma-1} \frac{V}{V_i} - 1}, \quad \frac{V}{V_i} = \frac{(\gamma-1) M_s^2 + 2}{(\gamma+1) M_s^2}$$

S: means across a shock, we can express eq. 3 in terms of $\frac{V_A}{V_i}$, $\frac{V_B}{V_A}$ and q_a where q_a is total heat added per lb of air the transformation path which produces the minimum entropy rise for a given heat release can then be determined from the vanishing of the partial derivatives of the total entropy increment with respect to the two volume ratios.

$$\left(\frac{V_B}{V_A} \right)^2 - 2 \left(1 + \frac{q_a}{c_p \theta_i} \frac{\theta_i}{\theta_A} \right) \frac{V_B}{V_A} + \left(1 + \frac{2\gamma}{\gamma+1} \frac{q_a}{c_p \theta_i} \frac{\theta_i}{\theta_A} \right) = 0 \quad (5)$$

$$\frac{V_B}{V_A} - \frac{\gamma+1}{\gamma-1} \left[1 - \frac{2q_a}{c_p \theta_i} \frac{V_i}{V_A} \frac{1}{(M_s^2 - 1)^2} \right] = 0 \quad (6)$$

From 5 and 6 we obtain

$$\frac{q_a}{c_p \theta_i} = \frac{(M_s^2 - 1)^2}{(\gamma+1) M_s^2} Z \left\{ 1 \pm \sqrt{1 - \frac{2\gamma M_s^2 (\gamma-1) \times ((\gamma-1) M_s^2 + 2)}{(\gamma+1) M_s^2}} \right\} \quad (7)$$

where $Z = \frac{(\gamma-1) M_s^2 + 2}{(\gamma+1)} - \frac{(\gamma+3)(\gamma-1)}{4(\gamma+1)^2} \left(\frac{M_s^2 - 1}{M_s} \right)^2$ and M_s refers to the optimum precompression shock ($M_{s\text{opt}}$)

COMBUSTION IN INTERMITTENT JET ENGINES

Combustion in each cycle of intermittent jet engines is accompanied by the generation of pressure and expansion waves which, in some cases, reverberate throughout the duct and in turn affect the combustion in subsequent cycles we shall examine here two kinds of combustion modes.

1-Front Modes

In this type of motion the gas is assumed to burn through a thin, plane flame front, propagating upstream from the exit end of the combustion chamber.

The ideal frontal combustion which minimizes the overall entropy rise for a single cycle is a Chapman-Jouguet detonation preceded by a shock, the strength of which is uniquely determined for given initial conditions and heat liberation. The practical difficulties of obtaining such a form of combustion in engines are, however, very great. Furthermore, even if these difficulties could be overcome, it is doubtful that this mode could be maintained throughout the combustion process. Indeed, the front of the detonation being itself a shock would rapidly overtake the leading shock and coalesce with it thereby generating large parasitic entropy increments and departing sharply from the condition of minimum entropy production.

A more probable form of intermittent combustion is a pseudodetonation of the type described by path i-A-B in previous figure the flame front propagates at low speed relative to the unburned gas. The entropy rise during deflagration is quite insensitive to changes in flame speed for the low frontal Mach numbers which apply to a transformation of this type. Hence it becomes permissible, in the computation of the entropy increments alone, to assume that combustion takes place at constant pressure as with $M=0$. On the basis of the information provided by wave diagrams, it may also be assumed that all internal entropy increments produced by shock waves are the result of upstream passage of the strong, flame-energized shock,

that this shock sweeps the length of the engine with no appreciable change in its strength and that each particle is subjected to K passes of this shock before it finally undergoes combustion. The value of K will in general depend on the engine configuration and on the density distribution at the time of ignition. The present study concerns only that portion of the cycle which precedes and includes combustion. If all other entropy increments produced by isoenergetic transformations upstream of the combustion chamber are denoted by ΔS_g where γ is the product of all the corresponding downstream to upstream stagnation pressure ratios the entropy level of the gas immediately before combustion is

$$\Delta S_g + \Delta S_s = K \Delta S_s + \Delta S_g = K [C_p \ln(\theta_r)_s - R \ln(P_r)_s] - R \ln \gamma \quad (8)$$

where ΔS_g is the entropy increment produced by the K internal shock waves and subscript s refers to conditions across each of these shocks and γ refers to the ratio of downstream to upstream p is static pressure and θ static temperature denoting by π the ratio of the static pressure of the charge before the final shock pass to the static pressure of the free stream then also

$$\Delta S_g + \Delta S_s = C_p \ln \frac{\theta_A}{\theta_o} - R \ln(P_r)_s - R \ln \pi \quad (9)$$

where subscript o denotes free stream and subscript A denotes conditions in the unburned gas immediately before combustion from Eq 8- and 9 we obtain

$$\frac{\theta_A}{\theta_o} = \left(\frac{\pi}{\gamma}\right)^{\frac{\gamma-1}{\gamma}} (\theta_r)_s^K (P_r)_s^{-K \frac{\gamma-1}{\gamma}}$$

The entropy rise through isobaric combustion is

$$\Delta S_h = C_p \ln \left[1 + \frac{q_a}{C_p \theta_A} \right]$$

or by virtue of Eq 10

$$\Delta S_h = C_p \ln \left[1 + \frac{q_a}{C_p \theta_o} \left(\frac{\gamma}{\pi}\right)^{\frac{\gamma-1}{\gamma}} (\theta_r)_s^{-K} (P_r)_s^{K \frac{\gamma-1}{\gamma}} \right]$$

Finally the total entropy rise is

$$\Delta S_t = \Delta S_g + \Delta S_s + \Delta S_h$$

whence

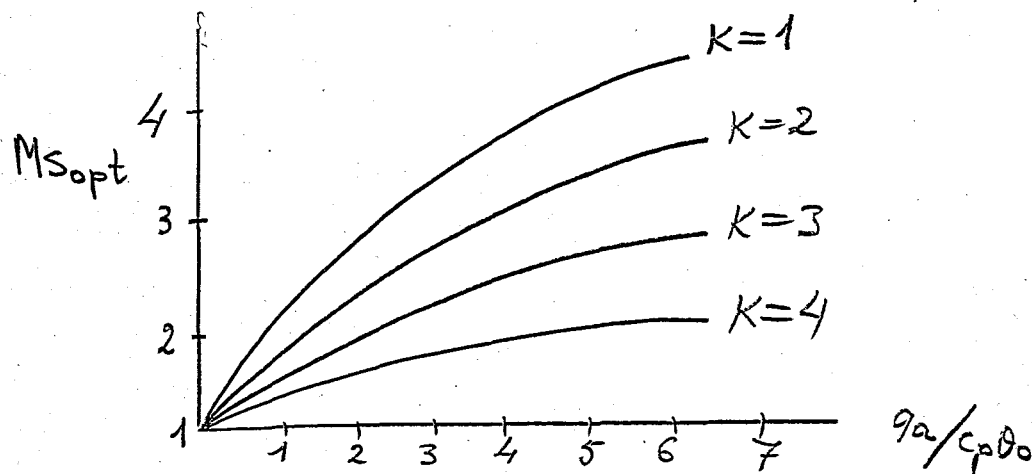
$$\exp \frac{\Delta S_t}{C_p} = \gamma^{-\frac{\gamma-1}{\gamma}} (\theta_r)_s^K (P_r)_s^{-K \frac{\gamma-1}{\gamma}} + \frac{q_a}{C_p \theta_o} \pi^{-\frac{\gamma-1}{\gamma}} (P_r)_s^{-\frac{\gamma-1}{\gamma}} \quad (11)$$

Since minimization of overall entropy rise results in maximum engine cycle efficiency and air specific impulse and minimum specific fuel consumption the vanishing of the first derivative of the right hand side of Eq 11 with respect to M_s yields the relationship for which the optimum engine performance is realized

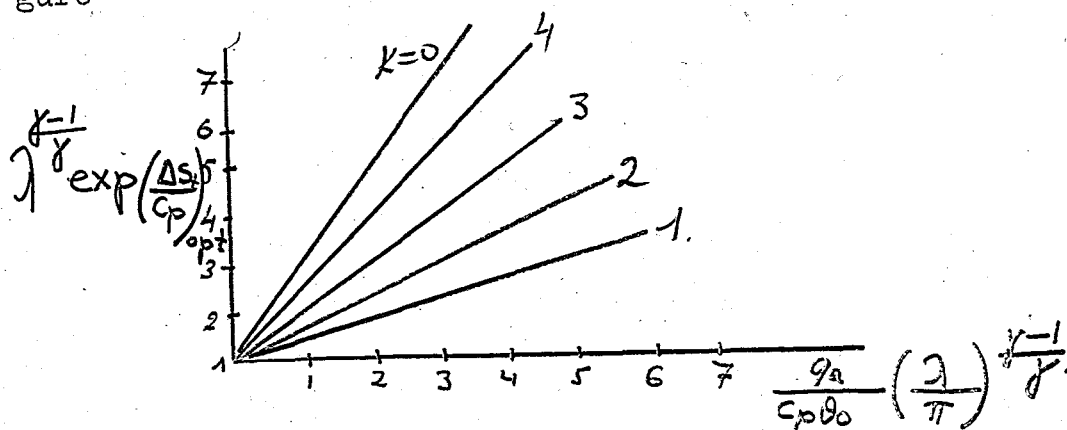
$$\frac{q_a}{C_p \theta_o} \left(\frac{\gamma}{\pi}\right)^{\frac{\gamma-1}{\gamma}} = \frac{K}{\gamma+1} (P_r)_s^{\frac{K+\gamma-1}{\gamma}} (V_r)_s^{K-1} \left(\frac{M_s^2-1}{M_s^2}\right)^2 \quad (12)$$

where the shock parameters are again those pertaining to the optimized Mach number. The parameters π, γ, K are constants the values of

which depend primarily on the engine configuration the boundary conditions and the operating conditions. The results of Eq 12 are plotted in the following figure for values of K from 1 to 4



and the corresponding overall entropy increments are shown in this figure



It may be seen that the strength of the shock required to optimize engine operation decreases as ΔS_1 and K increase. Also is shown the isobaric combustion ($K=0$). Here again the advantage of precompressing shocks is effectively illustrated for even the particles which are subjected to four optimum shock passes before undergoing combustion are discharged with lower entropy than those which undergo combustion alone.

Volume Modes (Explosions), which

Volume modes are those modes in combustion is assumed to take place simultaneously over a region in space. They represent approximations to burning processes in which the flame front is turbulently distorted and broken up around widely scattered "pockets" of hot combustion products. With the exception of the instantaneous isochoric explosion volume modes involve gradual changes of state hence gradual changes of state hence formation of the pressure exchange waves. The history of this formation and the final strength of the fully developed waves depend not only on the details of the combustion transformation but also on the initial and boundary conditions. Therefore no unique relationship can be established in this cases between the combustion mode and

the entropy increments through the waves which may be associated with it. General observations can however be made with regard to the optimization of engine performance with volume modes in the same way as was done in the preceding section for front modes.

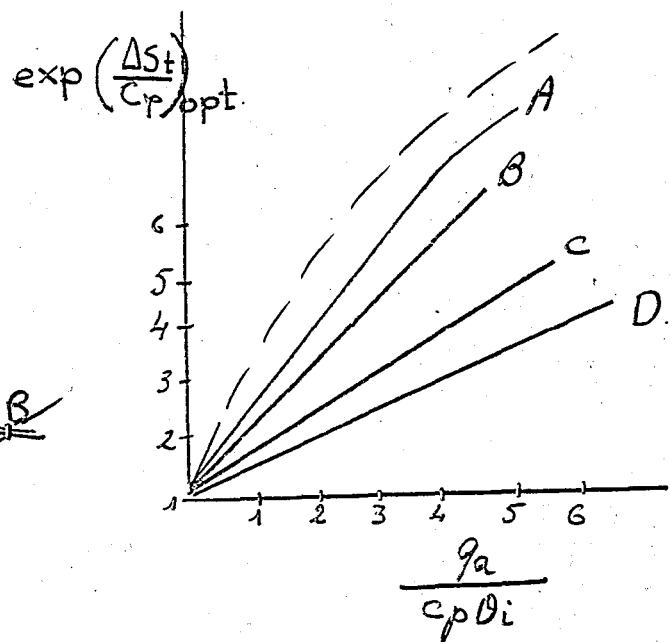
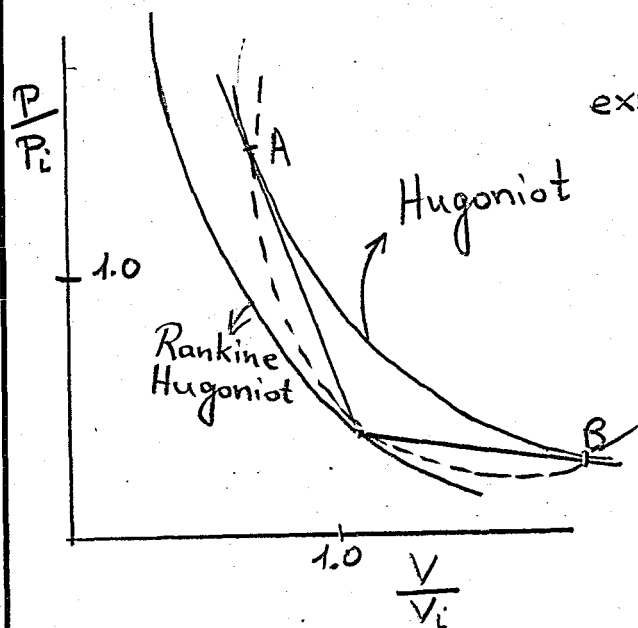
In front modes combustion of each layer energizes the shock which precompresses the unburned layers in the same charge. This cannot happen in the volume mode where the shock forms as a result of the burning of the entire charge. In the latter mode however the wave which is produced in each cycle produces precompression in later cycles through the extended phase of pressure exchange which takes place with wave reverberation. The extended phase of pressure exchange can assume very complex forms. Ideally however precompression in the volume modes can be assumed to be produced by the passage of a single shock as with the front modes. With this assumption the optimization of volume modes is brought within the scope of the previous analysis. Indeed volume mode transformations of the Rayleigh type as previously noted may have end points anywhere within the locus of Chapman-Jouguet states in the p, v plane. It follows that all optimized entropy increments within those of the two nonsteady Chapman-Jouguet extrema of Fig. which shows the optimized pseudo-detonations with A, B, C, D combustion modes where

A=c-j deflagration

B=isobaric

C=isochoric

D=Cj detonation



may be viewed as corresponding to volume mode transformations so long

as only a single optimum precompressing shock is involved. The results are of course modified when account is taken of the parasitic shocks. One may suspect, on the basis of previous remarks, that ~~the~~ any upstream entropy increment, regardless of its genesis may be beneficial to the engine performance because of the increase in temperature, and hence of the decrease in combustion entropy rise which it causes. (Note) [It can be shown that this is not the case.]

The effect of phenomena which increase the entropy but not the pressure of a fresh charge prior to its combustion through a ~~the~~ linear transformation is to increase the overall entropy of the thermodynamic cycle. Since $(S_A - S_0)$ denotes all entropy increments preceding combustion, one has :

$$\Delta S_t = (S_A - S_0) + \Delta S_h = (S_A - S_0) + C_p \ln \frac{V_B}{V_A} + C_v \ln \frac{P_B}{P_A} \quad (13)$$

A: subscript showing state prior to combustion

B: subscript showing state following combustion

O: subscript showing state of free stream

V: specific volume

p: static pressure

ΔS_t : total entropy increment

ΔS_h : entropy increments pertaining to combustion.

Hugoniot equation (2) can be expressed as,

$$\frac{V_B}{V_A} = \frac{\frac{\gamma+1}{\gamma-1} + \frac{2}{\gamma-1} \frac{\gamma_a}{C_v \theta_0} \frac{\theta_0}{\theta_A} + \frac{P_B}{P_A}}{\frac{\gamma+1}{\gamma-1} \frac{P_B}{P_A} + 1} \quad (14)$$

and accounts for the

effect of upstream increments in the temperature ratio θ_0/θ_A

Since $S_A - S_0 = C_p \ln \frac{\theta_A}{\theta_0} - R \ln \frac{P_A}{P_0}$ then

$$\frac{\theta_A}{\theta_0} = \left(\frac{P_A}{P_0} \right)^{\frac{\gamma-1}{\gamma}} \exp \frac{\Delta S_A}{C_p} \quad (15)$$

and then $E_9 = I_3$ by virtue of I4 and I5 becomes.

$$\frac{\Delta S_t}{C_p} = \frac{S_A - S_0}{C_p} + \ln \left\{ \frac{\frac{\gamma+1}{\gamma-1} + \frac{2}{\gamma-1} \frac{\gamma_a}{C_v \theta_0} \left(\frac{P_A}{P_0} \right)^{-\frac{\gamma-1}{\gamma}} \exp \left(\frac{S_0 - S_A}{C_p} \right) + \frac{P_B}{P_A}}{\frac{\gamma+1}{\gamma-1} \frac{P_B}{P_A} + 1} \right\} + \frac{1}{\gamma} \ln \frac{P_B}{P_A}$$

The pressure ratio of the gas before combustion ~~is~~ ^{$\frac{P_A}{P_0}$} is in most engines primarily determined by the downstream boundary conditions and can be assumed to be independent of the upstream entropy increments. The rate of change of ΔS_t with $S_A - S_0$ is then:

$$\frac{\partial \left(\frac{\Delta S_t}{C_p} \right)}{\partial \left(\frac{S_A - S_0}{C_p} \right)} = 1 - \frac{\frac{2}{\gamma-1} \frac{\gamma_a}{C_v \theta_0} \left(\frac{P_A}{P_0} \right)^{-\frac{\gamma-1}{\gamma}} \exp \left(\frac{S_0 - S_A}{C_p} \right)}{\frac{\gamma+1}{\gamma-1} + \frac{P_B}{P_A} + \frac{2}{\gamma-1} \frac{\gamma_a}{C_v \theta_0} \left(\frac{P_A}{P_0} \right)^{-\frac{\gamma-1}{\gamma}} \exp \left(\frac{S_0 - S_A}{C_p} \right)}$$

from which it can be seen that unless $\frac{PB}{PA} < -\frac{\gamma+1}{\gamma-1}$

which is of course an impossible condition the derivative is always positive and no overall benefit can be derived from an increase in the upstream entropy.

The fact that an entropy increment prior to combustion has a favorable effect on the overall entropy rise in some cases and an adverse effect in other cases is explainable through consideration of the relation between entropy and temperature increment that are associated with various types of precompressing process. If compression could be achieved isentropically a monotonic performance improvement could be achieved by increasing the compression ratio indefinitely, thereby indefinitely increasing the temperature at ignition. When, on the other hand, a relation exists between precompression ratio and entropy rise in compression, then the beneficial effect of the temperature rise is partly offset by this entropy increment. An optimum precompression ratio can generally be determined in such cases. Finally, when no precompression is present, the beneficial effect of a temperature rise associated with any entropy increment is more than offset by the adverse effect of the entropy increment itself. It follows that in volume modes where the strength of the precompressing shock may be controlled independently of that of the parasitic shocks the optimum pressure exchange process is one in which all parasitic waves are isentropic and the precompression shock is the optimum determined in the preceding section.

Ideally, therefore, the economic merit of volume modes is comparable to that of the front modes. In practice, however, the avoidance of large parasitic losses is believed to be more easily possible with front than with volume modes. More exact comparisons of the two modes can be made only with reference to specific engine configurations and operating conditions.

Remarks on both combustion modes

Entropy increments occurring upstream of the combustion chamber are found, under certain conditions, to have the effect of decreasing the overall entropy rise through the engine. This effect is the result of the temperature rise which these increments produce on the fresh charge prior to combustion. From this standpoint, therefore, it appears that the combustion chamber of an intermittent jet engine should, whenever possible, be placed at the downstream end of the engine flow passage.

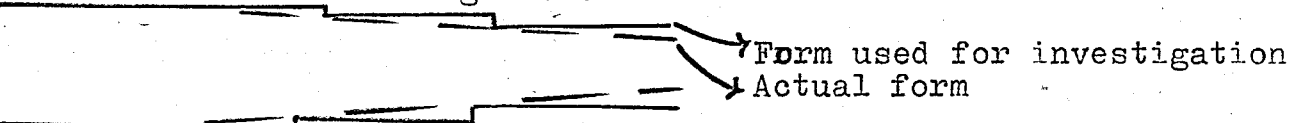
With front modes of combustion the optimum strength of the precompressing shock is found to depend primarily on the amount of heat released in combustion, on the initial conditions, and on the number of parasitic shock passes to which each particle is subjected within the engine. The flame propagation velocity has a relatively minor effect on the optimum strength of this precompressing shock. Within the current range of heat release values in air breathing intermittent jet engines the optimum shock Mach number in pressure exchange is found to vary from about 3.5 to about 2.0 as the number of parasitic shock passes for each particle increases from 1 to 4.

The optimum volume modes are found to be substantially equivalent to the optimum front modes, but the practical realization of the ~~most~~ economical pressure exchange process is believed to be more difficult with the former than with the latter modes. A more exact comparison between the two modes must wait for further experimental data and for such information on the wave processes associated with volume modes as can be obtained by the method of characteristics which is studied at another section of this work.

Investigation of a streamlined tube

Referring to the pulse-jet that we have in the laboratory we see that its shape is not streamlined at all but the inlet section and the tailpipe are of a different diameter with a sudden constriction. One may ask why the shape of the tube is not streamlined since in that case the drag force will be diminished.

Some tests have been carried out and showed that "The tube proved itself incapable of operation on the test stand". The first investigation is for the following case:



The result of experiments showed that the conditions at the end of the tube are such that for all practical purposes the condensation shock wave is not reflected at all. This is of serious consequence for the operation of the tube because the automatic operation of the tube depends on the reflection of the condensation shock wave from the end of the tube as a rarefaction wave and on the opening of the inlet valves by this returning rarefaction wave. Since there is no returning rarefaction wave the valves do not open and the tube cannot function.

Now the following tube shape has been investigated.

In this case the investigation gave significantly better results, and the tube was seen to operate. Comparing the two tubes we see that the outer step-curve is more rounded-in at the exhaust end and the automatic operation of this tube must be considered impossible while the inner step-curve is more elongated and cylindrical at the exhaust end and it ought to be operable especially in flight, where the intake conditions are more favorable than in the stationary test-stand that has been considered.

Conclusion: THE investigation shows that the automatic operation of the tube is very sensitive to the influence of the shape of its exhaust end. The end of the tube must be as cylindrical in form as possible.

JET TUBE IN FLIGHT

Though in the experimental part of this work we deal only with the study of the pulse-jet in static operation it would be a good idea to mention in this article some of the concepts that arise when the tube is in flight.

In this case the first modification arises from the fact that the outside pressure on the inlet valves is the impact pressure. Another problem is the leakiness of the valves. Under the force of the impact pressure the valve flaps must be held forward with spring pressure in order to remain closed. Hence, they will be opened by the wave of lower pressure only so wide as corresponds to the additional load im-

posed by the lower pressure, which at various flight speeds will naturally vary in proportion to the impact pressure. As to the effect of leakiness it is seen that a limited leakiness has an advantageous effect inasmuch as it increases the weight of new charge induced and only slightly affects the waves. Greater leakiness results in a weakening of the returning compression shock and therefore has an unfavorable effect on the ignition, as does also the cooling of the tube and the less rapid spread of ignition throughout a larger as compared to a smaller quantity of fresh charge.

The flight speed has also an influence on the quantity of new charge flowing in ~~increases slowly~~ As flight speed increases the quantity of new charge flowing in increases slowly at first and then more and more markedly.

Another important practical observation is made by Paul Schmidt that the ratio of the effective value cross sectional area to the tube cross section may not be of any random magnitude and that at too great flight speeds the jet tube ceases to operate. In the previous article it was shown that the occurrence of the condensation waves was found as a criterion of the tube operability, from which it was evident that tubes with a constriction at the exhaust end are not operable. Paul Schmidt observed that in addition to this requirement for operability operability is affected by the opening ratio of the valves, that is, the ratio of maximum effective open cross-sectional area of the valves to the cross sectional area of the tube. In other words, with too great an opening ratio the tube will not operate. With too great a valve-opening ratio the process of continuous flow through the tube is too predominant over the oscillatory process.

As the speed of the tube increases the impact pressure increases and at a sufficiently high flight speed the increase is so great that the pressure of the indrawn fresh charge is not lower than the exhaust-gas pressure in the tube and the same phenomenon appears as in the case of a too great valve opening ratio. Thus at a certain flight speed, the tube will cease to be operable for the same reasons as in the case of a too great valve-opening ratio.

As an alternative it can be mentioned the possibility of shrouding the pulsejet engine where the flow around the engine is kept at a ~~low~~ Mach number at all times whereas the engine can fly in greater Mach numbers. FOR more information on shrouded pulsejets one is interested may refer to the paper by Rudinger /On the performance Analysis of the ducted Pulsejet / which is available in ME Department.

PART TWOEXPERIMENTAL PART OF THE THESIS

In part (I) a theoretical investigation of the working principle of the pulsejet was carried out. In this part the experimental part will be explained.

The main part of the thesis was to determine the thrust both experimentally and theoretically. The pulsejet under consideration has the following specifications.

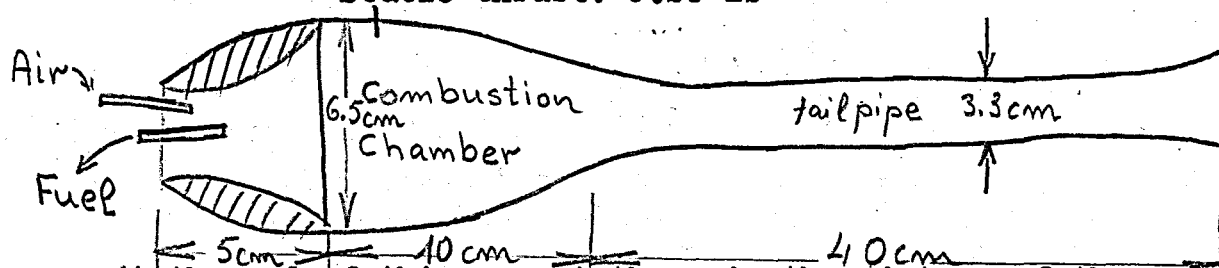
Length: 21.75 in

Name: H1 Pulse

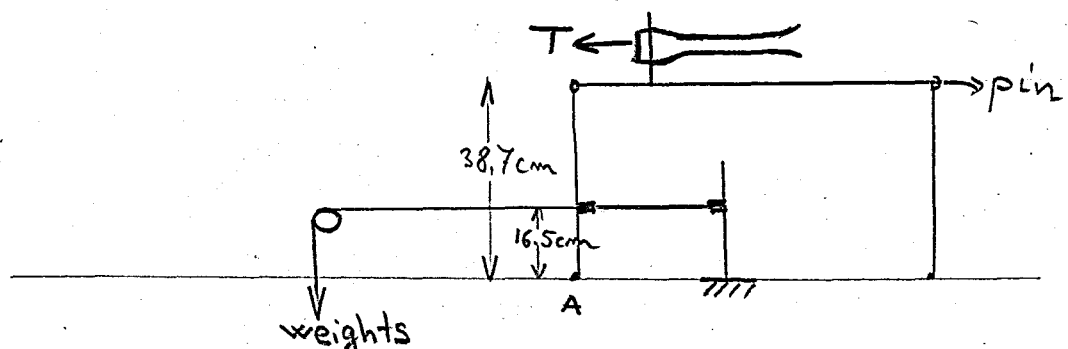
Weight: ~~1400 g~~ 1.4 kg

Max. Diam? 2.5 in

Static thrust: 3.25 lb



At the end of this report there is the picture of the pulsejet mounted on a test stand which has been designed for the purpose of measuring the thrust. In diagrammatic form the test stand is as follows:



At a height of 16.5 cm from the lower pin we located an aluminum bar on which a strain gage is fixed. Using this strain gage we are going to determine the thrust. At the same height and in the opposite part of the link there is a string which passes over a pulley and at the

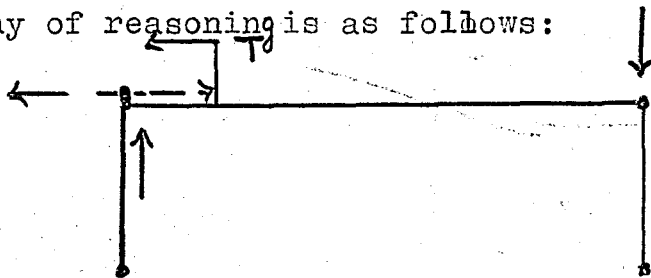
end of which we put some weights to calibrate the instrument called (Strain Bridge). Suppose that the measured thrust at height 16.5 cm (at point O) is F . Then writing the moment equation about point A I get

$$F \cdot 16.5 = T \cdot 38.7$$

$$T = \frac{F \cdot 16.5}{38.7}$$

so what I have to do is to try to measure F .

(Note: It would seem more logical to the reader to use the moment arm 44.2 in the moment equation but some more deep investigation of the problem reveals the fact that the proper moment arm to be used is 38.7 cm. The way of reasoning is as follows:



We substitute thrust T by two equal and opposite forces at the upper pin (Shown as dotted lines, so we are left with a force T at the upper pin and a torque. Since this torque can be taken care of by the vertical reactions on the vertical bars then the only effective force is force T at the upper pin).

We are going now to state how we measure force F . Though we could use other mechanical means we rather preferred to use the strain gage method. This depends on the following principle:

The resistance of a wire is given by the following relation:

$$R = \frac{\rho l}{A}$$

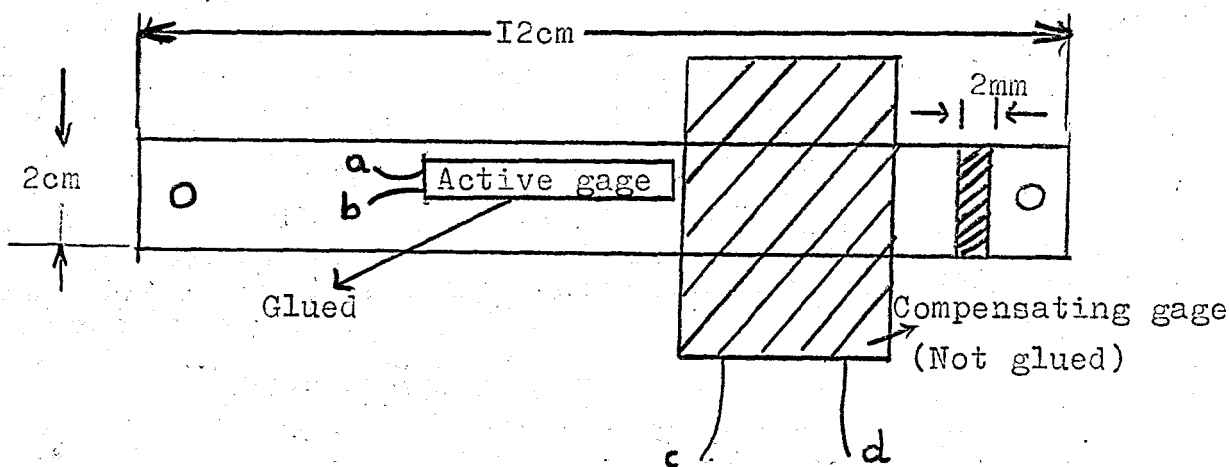
R : Resistance

ρ : constant

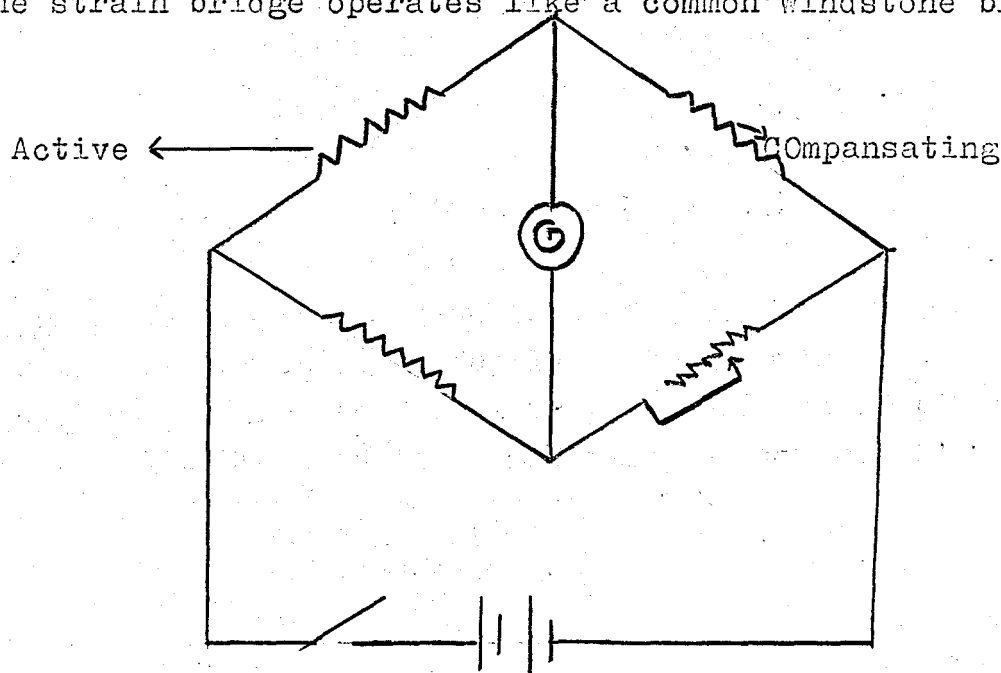
l : length of the wire

A : cross section of the wire.

Then if we apply a force F on this wire the length of the wire increases to l' and the cross section decreases to A' . Since the increase in l is not equal to the decrease in A the resistance R changes. This change in resistance is detected by the strain gage and the strain bridge. Since the resistance changes also with the temperature I use one active gage and one compensating gage. The active gage is sensitive to both the strain and temperature while the compensating gage is sensitive only to temperature. The diagram of the aluminum bar with the strain gage on it is as follows:

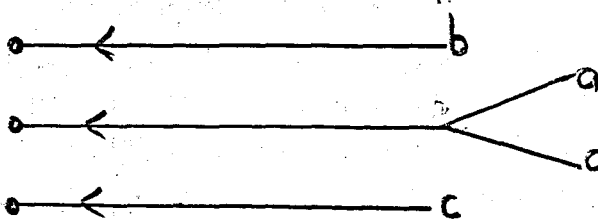


The strain bridge operates like a common Wheatstone bridge.

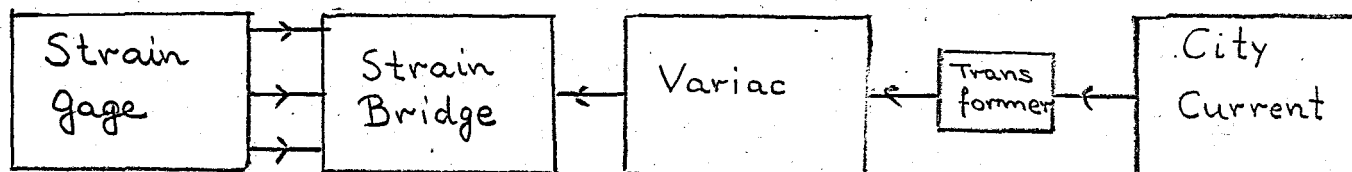


In our case what we do is to solder wires (b) and (c) and connect them to one of the 11 channels of the strain indicator. Also we connect wires (a) and (d) to the same channel. We have:

(8) -- Number of branch ..



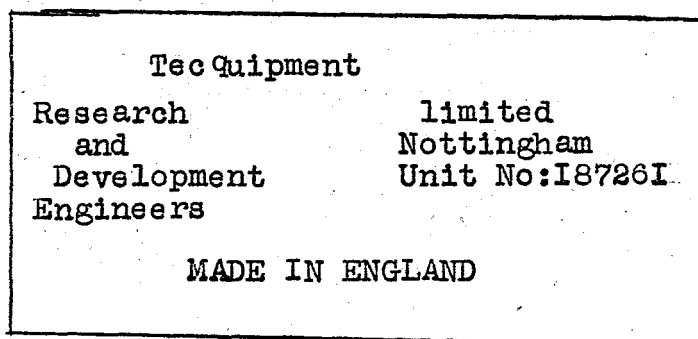
The instrument set up for thrust determination is as follows :



The instruments have the following specifications:

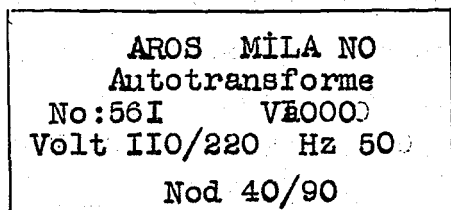
Strain bridge: (Manufactured according to specifications set up by Cambridge University)

Strain Bridge name plate :



Variac: We supply to it voltage of 220 Volts through a transformer. The function of variac is to supply voltage in the range of 0- 220 volts.

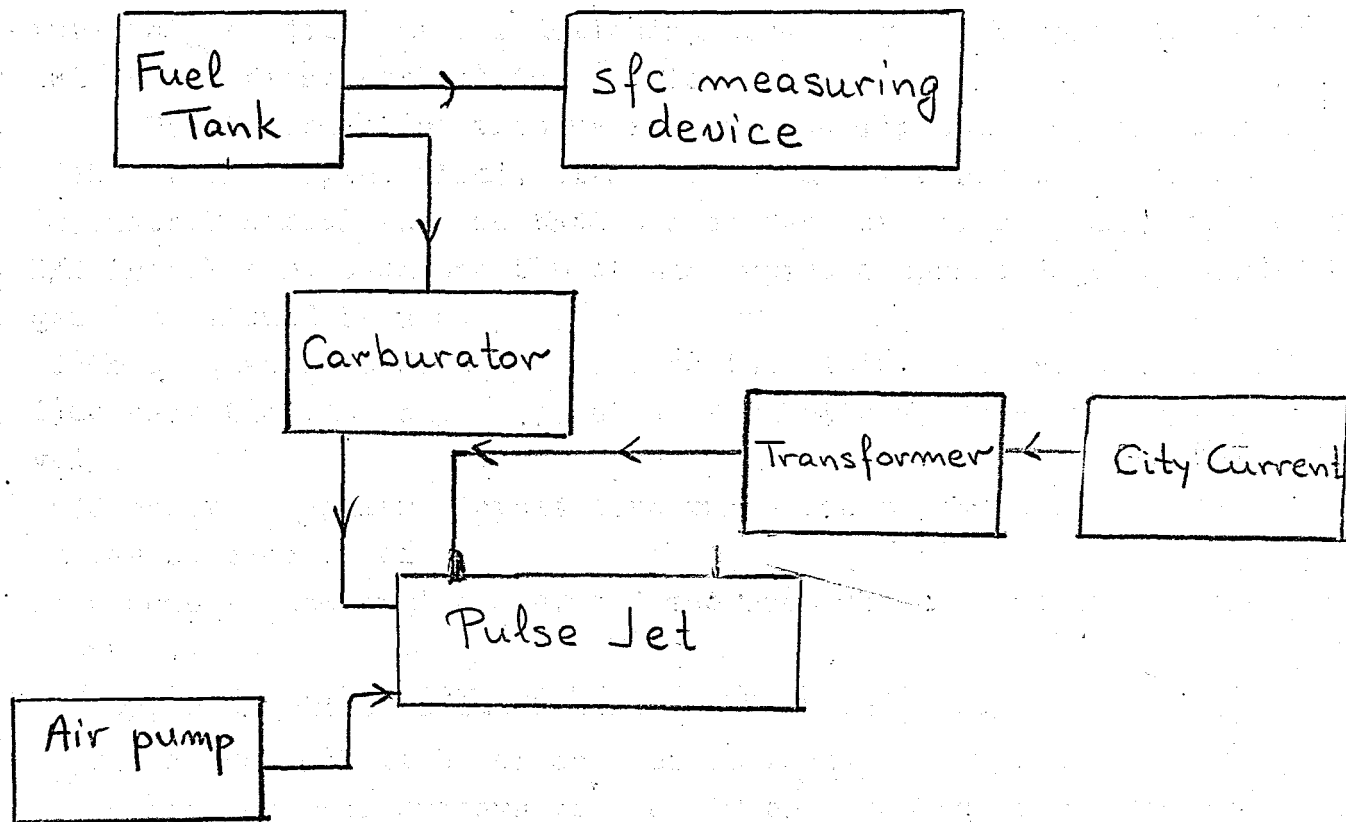
Transformer: It is used to step up the voltage of 110 volts (City current) to 220 Volts and feed it to the variac. Its specification are:



Having set up the apparatus needed for experimental determination of thrust I will draw the following diagram which will include the following ((Pulsejet , test stand etc) they are shown in the picture at the end of this thesis: (For diagram see next page)

The working principle is as follows:

We fill the fuel tank with common car gasoline. The fuel from the tank through suitable valves may go either to the sfc measuring device or to the carburetor. The function of the carburetor is not to prepare a fuel air ratio as it is when used in the cars. It is an aircraft carburetor equipped with a float. So the function of the carburetor is to keep the fuel level always constant. It is obvious that we used it



because of the float. The fuel from the carburetor goes to the fuel spray orifice at the inlet to the pulsejet. Air is blown to the air orifice by an air pump. The spark plug is ignited by the current sent through a transformer. The transformer takes current from city current and steps it up to 10,000 Volts. Its specifications are:

IGNITION TRANSFORMER

THE FOREST ELECTRIC
COMPANY

Forest park
Illinois

Cat no: KIOM60MODRS
PRI-115 Volts -60 CYCLES
Sec..10000 V 250 VA
23 MA Secondary
M point grounded

We blow air through the air orifice. This air draws gasoline level is below the fuel orifice at an amount of 1/2 inch or smaller. The fuel air mixture is directed toward the spring valves, since the pressure is large the valves open and permit the mixture to the combustion chamber.

We provide a spark through the spark plug. This spark ignites the mixture and the jet starts functioning according to the principles explained in the first part of the thesis.

The instructions that we followed during starting are the following:

- 1) Mount the engine firmly with a sheet metal strap to a stand (test-stand).
- 2) Install a fuel tank so that the surface of the fuel sits at about 1/2 inch lower than the tip of the engine's nozzle. Regular automobile gasoline should be used.
- 3) Choke a small amount of gas into the venturi or through the tail.
- 4) Connect the plug cap to (+) side of a battery, and (-) side plug respectively.
- 5) Connect a regular bicycle tire pump hose to the blowpipe and supply a few strokes of air.
- 6) As soon as the engine starts disconnect the air supply and electric supply.

WHEN DIFFICULTIES ARE ENCOUNTERED WHILE STARTING

- 1) Check the fuel tank for sufficient fuel.
- 2) Check the fuel systems to see if any dust has lodged in the metal systems.
- 3) Check the glow plug system for sufficiently current.
- 4) Check if there are any air leaks in the combustion tube assembly.
- 5) Check whether the position of the gas tank is properly.

"If nothing is found wrong, choke again and try all over

"If it makes dull POP and fire comes from tail pipe as soon as you start pumping there is no trouble in ignition systems but only flood therefore it will start properly if you keep pumping. It will also be a good idea to lower the tank's position. (If the tank and the engine is mounted on the plane, swing the head parts up and down calmly while starting).

"If the jet backfires through the air intake venturi, check the valve position for proper alignment.

"If the engine does not make even a faint 'POP', check the electrical system.

"If everything is properly arranged the jet engine should start very easily with large explosion noise as soon as a few strokes of air is

supplied. In case it makes a faint 'POP' try to pour more gas into the tank or raise its situation.

'The proper mixing proportion of the air, pressure and amount of is very important to start the jet engine, therefore the gas level and position of fuel tank combined with a proper ignition system should always be maintained in accordance with the above instructions.

'Never peep into the exhaust tube or stand behind it while starting. it must be noted that intense heat is generated in operation and it is only properly cooled while flying, therefore it should not be statically run over 15 seconds.

Though we followed the instructions word by word at the beginning we were unsuccessful. We tried many changes. We changed the fuel level, from 1-inch below the pulsejet tip up to a level almost equal to the tip level, but still the engine did not start. Then we thought that the pump was insufficient and changed it by another stronger one but still the engine did not run. Then we took out the cover of the engine and checked the spring valves for air leakage. One valve was a bit open in the equilibrium position. We closed the valve so that no air leakage occurred and tried it again using the stronger pump. After some strong strokes the engine started to operate making a terrible noise. After few seconds it became red hot so we stopped the engine by cutting off the fuel. We tried again using the smaller pump, though the engine started after too many strokes it was obvious then that a much more stronger pump would start it very easily. We then used a car-tire pump, and fortunately we managed to start the engine even with one single stroke. After trying many times and being thus able to start the engine very easily at once we set up the apparatus to measure the thrust. The apparatus set-up diagram was given in the previous page.

Since the strain indicator was too sensitive to forces applied to the strain gage we first run several times the engine and adjust the sensitivity of the strain indicator. After doing so we measured the thrust as follows:

We first turn the dials so that we locate the bright line of the screen to a horizontal position. At this time the engine was not in operation. We noted the reading of dials. Let it be R_1 . Then we run the engine. The bright line deflected from the horizontal position and took a new position so that it makes a certain angle with the horizontal.

We took a new reading R2 And then we stopped the engine. We again brought the bright line to horizontal position at which the reading was R1 To measure the thrust we started putting weights on the scale and the same time watching the deflection of the bright line in the screen of the strain indicator. At a deflection corresponding to the reading R2 we stopped putting weights. The amount of weights present on the scale at this moment was 3 KG. Then from the moment equation we calculated the thrust

$$3 \times 16.5 = 38.7 \times T$$

$$T = \frac{3 \times 16.5}{38.7} = 1.28 \text{ kg} = 1280 \text{ gram}$$

$$T = 1280 \text{ GRAMS}$$

$$T = 2.82 \text{ Lp}$$

So it is seen that the calculated static thrust is 2.82 pound whereas the static thrust given in the specifications is 3.25 lb.

$$\text{There is a deviation of } \frac{3.25 - 2.82}{3.25} = 13.2 \%$$

This deviation may be due to the fact that the experimenting conditions in both cases is not the same as well as to some unavoidable friction appearing in the pinned connections.

6-----

THEORETICAL DETERMINATION OF THE THRUST

Consider the following pulsejet diagram:

We can write the following equation:

$$T_1 + p_m (A_1 - A_2) = Q (V_3 - 0) \quad \text{where: } T_1: \text{Temperature internal thrust}$$

p: pressure
A: Area
Q: Rate of mass flow

$$T_2 = P_{ex} (A_1 - A_2) \quad T_2: \text{External thrust}$$

$$T(\text{net}) = Q V_3 + p_m (A_1 - A_2) + P_{ex} (A_1 - A_2)$$

Assuming steady polytropic flow we write:

$$V_3 = \sqrt{\frac{2n}{n-1} \frac{R}{M} T_m \left(1 - \left[\frac{p_2}{p_m} \right]^{\frac{n-1}{n}} \right)} \quad \text{where } p_m: \text{Max. pressure}$$

n: 1.3
 T_m : Max. temperature

We can determine the max. temperature of the pulsejet as follows:

1) Since after the pulsejet starts to operate the combustion chamber region becomes red hot we can approximately guess the temperature inside the combustion chamber. the combustion chamber is made of stainless steel which becomes red hot in 2500- 3000° F..

2) There is an empirical relation which relates the sonic velocity inside the pulsejet to the frequency of pulsation.

$$\text{Frequency} = \frac{\text{velocity of sound}}{4 \times \text{tailpipe length}}$$

$$f = \frac{a}{4 \times L} = \frac{\sqrt{\frac{2n}{n-1} \frac{R}{M} T_m}}{4 \times L}$$

$$T_m = \frac{4 \times f \times L^2}{g n R}$$

Having calculated T_m we can find v_m

$$P_m \times v_m = \bar{R} \times T_m \text{ hence } v_m = \frac{\bar{R} T_m}{P_m}$$

Also $p_m v_m^n = p_3 v_3^n$ hence

$$v_3 = \sqrt[n]{\frac{p_m v_m^n}{p_3}}, \quad \rho_3 = \frac{I}{v_3}$$

Then the term $Q V_3 = \rho_3 A V_3^2$

We had the relation giving the net thrust

$$T(\text{net}) = Q V_3 + p_m (A_2 - A_1) + p_a (A_1 - A_2)$$

P_m : Assumed $3 \times P_a = 3 \times 14.7 = 44.1$ psia

A_2 : πx

A_1 :

P_a : 14.7 psia

$Q V_3$: As found above

To find the frequency of pulsation we make use of an instrument which measures vibrations (amplitude, frequency) Making use of this instrument we found that the frequency is $f =$

Then $T_M =$

$v_3 =$

$v_m =$

$\times \times V_3 =$

$Q V_3 =$

$T(\text{net}) =$

It is readily that to the simplified assumptions that we made there a deviation of between the calculated and measured thrust. The major trouble is the irregular combustion. Schults-Grunow recommends to use in calculations as maximum temperature $3 \times P_{\text{atm}}$.

Bibliography :

1 - An extension of the Chapman Jouguet Gas Dynamics of Combustion, by D.F. Pangburn and J.V. Foa.

Rensselaer Polytechnic Institute Research Division.

2 - A Gas Dynamical Formulation for Waves and Combustion in Pulse - Jets.

New York University.

3 - Gas Dynamic investigation of the Pulse-Jet Tube, by F. Shultz Grunow.

NACA.

4 - A.F. Manual 52-5

Jet Propulsion Power Plants.

Departement of the Air Force.

5 - Jet Propulsion Engines , by Rudinger.

6 - Combustion in intermittent Jet Engines.

Rensselaer Polytechnic Institute.

- - - - -