
Valveless Pulsejet Engines 1.5

-- a historical review of valveless pulsejet designs --

by Bruno Ogorelec



The idea that the simplest engine an enthusiast can make at home is a jet engine will sound strange to most people -- we perceive jet engines as big complex contraptions pushing multi-million dollar aircraft through the skies. Yet, this is completely true. In its most basic form – the valveless pulsejet -- the jet engine can be just an empty metal tube shaped in a proper way. Everyone able to cut sheet metal and join metal parts can build one in a garage or basement workshop.

Due to peculiar historical circumstances, this interesting fact has escaped popular attention. It is not familiar even to enthusiasts of jet propulsion. You are not very likely to see or hear jet engines roaring in people's back yards on Sunday afternoon. Few if any people can be seen flying aircraft powered by jet engines they have built themselves.

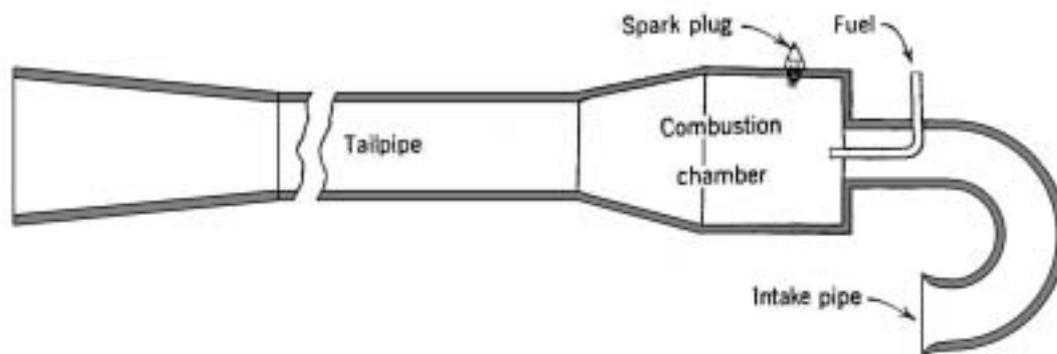
This document aims to help change that.

However, it is not a how-to primer. It is an attempt to describe and explain the valveless pulsejet in principle. It also offers a rough sketch of the amazing variety of layouts the inventors and developers have tried during the long but obscure history of this device.

My aim is to inspire, rather than teach. My goal is to demonstrate that jet power is accessible to everyone in a great variety of simple ways. Should you find the inspiration, plenty of information on the practical steps towards jet power will be available elsewhere.

HOW DOES A VALVELESS PULSEJET WORK?

The picture below shows one of the many possible layouts of a valveless pulsejet engine. It has a chamber with two tubular ports of unequal length and diameter. The port on the right, curved backwards, is the intake pipe. The bigger, flared one on the left is the exhaust, or tailpipe. In some other engines, it is the exhaust pipe that is bent into the U-shape, but the important thing is that the ends of both ports point in the same direction.



When the fuel-air mixture combusts in the chamber, the process generates a great amount of hot gas very quickly. This happens so fast that it resembles an explosion. The immediate, explosive rise in internal pressure first compresses the gas inside and then pushes it forcefully out of the chamber.

Two powerful spurts of hot expanding gas are created – a big one that blows through the tailpipe and a smaller one blowing through the intake. Leaving the engine, the two jets exert a pulse of thrust – they push the engine in the opposite direction.

As the gas expands and the combustion chamber empties, the pressure inside the engine drops. Due to inertia of the moving gas, this drop continues for some time even after the pressure falls back to atmospheric. The expansion stops only when the momentum of the gas pulse is completely spent. At that point, there is a partial vacuum inside the engine.

The process now reverses itself. The outside (atmospheric) pressure is now higher than the pressure inside the engine and fresh air starts rushing into the ends of the two ports. At the intake side, it quickly passes through the short tube, enters the chamber and mixes with fuel. The tailpipe, however, is rather longer, so that the incoming air does not even get as far as the chamber before the engine is refilled and the pressure peaks.

One of the prime reasons for the extra length of the tailpipe is to retain enough of the hot exhaust gas within the engine at the moment the suction starts. This gas is greatly rarified by the expansion, but the outside pressure will push it back and increase its density again. Back in the chamber, this remnant of previous combustion mixes vigorously with the fresh fuel/air mixture that enters from the other side. The heat of the chamber and the free radicals in the retained gas will cause ignition and the process will repeat itself.

The spark plug shown on the picture is needed only at start-up. Once the engine fires, the retained hot gas provides self-ignition and the spark plug becomes unnecessary. Indeed, if spark ignition is left on, it can interfere with the normal functioning of the engine.

It took me more than 300 words to describe it, but this cycle is actually very brief. In a small (flying model-sized) pulsejet, it happens more than 250 times a second.

The cycle is similar to that of a conventional flap-valve pulsejet engine, like the big Argus (which powered the V-1 flying bomb) or the small Dynajet used to power flying models. There, the rising pressure makes the valve flaps snap shut, leaving only one way for the hot gas to go -- into the exhaust tube. In the J-shaped and U-shaped valveless engines, gas spews out of two ports. It does not matter, because they both face in the same direction.

Some valveless pulsejet designers have developed engines that are not bent backwards, but employ various tricks that work in a similar fashion to valves -- i.e. they allow fresh air to come in but prevent the hot gas from getting out through the intake. We shall describe some

of those tricks at a later point.

You may wonder about the sharp transition from the intake tract into the chamber. It is necessary to generate strong turbulence in the incoming air, so that it mixes with injected fuel properly. A gentler, more gradual entry would not generate the necessary swirling of gases. In addition, turbulence increases the intensity of combustion and the rate of the heat release.

THE BEGINNINGS

The idea of using the elastic properties of air to generate power pulses is very old. The first pulsejet engines were built in France at the very beginning of the 20th century. They found only very limited use at the time and were soon forgotten for all practical purposes.

In the 1930s, however, German engineer Paul Schmidt rediscovered the principle by accident while trying to develop a detonation engine. He built a series of impressive pulsejets with valves. At roughly the same time and in the same country, engineers at the Argus engine company were working on a valveless device that used compressed air.

The circumstances were much more propitious now. The world was preparing for a big war and the war machines were gearing up. The German War Ministry brought Schmidt and Argus together, which resulted in the development of the first mass produced jet engine. Like the Schmidt engines, it used valves and natural aspiration, but its mechanisms were greatly modified by Argus.

Thus, while the opposed sides in World War II were still trying to put together their first jet-powered fighter aircraft in 1944, the *Vergeltungswaffe 1* (or V-1 for short) was regularly buzzing its way to England with a 1,870-lb load of explosives. Its Fieseler airframe was powered by the Argus As 109-014 pulsejet engine. You can see one flying over the English countryside on the photo on the right.

The utter simplicity, low cost and demonstrated effectiveness of the pulsejet impressed the Allies so much that they badly wanted to have something similar. It looked amazing to everyone that a device that simple could power a serious flying machine. Captured examples of the Argus were carefully studied and copies built and tested.

It soon became obvious that the pulsejet had certain drawbacks and limitations, but the basic principle still looked very attractive and ideas for improvement abounded. Various uses for the device were contemplated. Ford Motor Company built a proper assembly line to manufacture Argus copies. With the end of the war, some of the projects were scuttled, but the Cold War started soon and the quest for a better pulsejet continued.

Unfortunately, progress was very slow and purely incremental. In the mid 1950s, after a decade of effort, developers were not that much better off than their wartime German predecessors. In total contrast, the advances in turbojet design over the same period were



tremendous. By that time, turbojet-powered fighters already had the Korean War behind them. Turbojet strategic bombers were carrying nuclear weapons in their bomb bays and turbojet airliners were getting ready to earn their money carrying businessmen and the idle rich from continent to continent.

It was becoming completely clear to everyone that the turbojet was the jet engine of the future. Engineers were still excited by the promise of the pulsejet, but the reality was not to be denied. During the 1950s and 1960s, most pulsejet researchers gradually abandoned their efforts and turned to other things.

THE ADVANTAGES

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

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

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

The pulsejet is different. Here, the exhaust pressure is higher than the intake pressure. There is pressure gain across the combustor, rather than loss. Moreover, the pulsejet does it without wasting the power generated by combustion. This is very important. According to some rough figures, a 5-percent gain in combustion pressure achieved by this method gives about the same improvement in overall efficiency as the 85-percent gain produced by a compressor, all other things being equal. Now, that's rather impressive.

Personally, I am interested in the pulsejet for another reason -- because it brings the jet engine back to the people. It is a back-to-basics kind of machine, so simple to be accessible even to enthusiasts with rudimentary skills and simple tools. Turbojets and fanjets are at the opposite end of the complexity scale. In most cases they employ inaccessible, cutting-edge technology.

Just look at the collection of pulsejets on the picture on the right. They were built by Stephen Bukowsky, a high-school student, purely out of fun.



If I remember it right, the three valveless engines (second, third and fifth from left) each took him about a couple of days to make. This is just a part of Steve's collection!

Cost is another advantage. Pulsejets are cheaper than even the simplest piston engines of comparable output. In contrast, turbojets are frighteningly expensive.

THE DISADVANTAGES

So, given the advantages, why did the pulsejet disappear from view? There are several reasons.

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

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

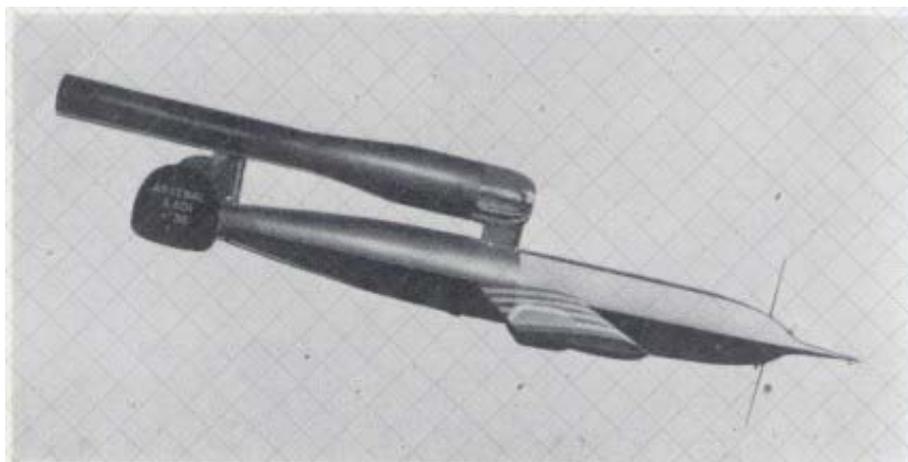
Alas, a turbine demands steady flows to function efficiently. Unsteadiness generates loss. Also, pulsations are dangerous for the brittle axial turbine blades. Radial turbines are tougher in that respect, but they are less efficient, especially so with intermittent flow. They are mostly used to exploit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

But, how about simplicity? In a manner of speaking, a pulsejet is what remains when you remove all the complex and expensive parts from a turbojet and leave only the simple and cheap combustor that is hidden in the middle.

Well, yes, simplicity is attractive, but it also has its disadvantages. The promise of the pulsejet on its own, outside a turbojet, is less significant. The pressure gain is still there, but in the atmospheric pressure environment, without the multiplication offered by the compressor, it does not amount to very much. The average pressure in the working cycle is low, the specific power unimpressive and fuel efficiency poor. The power 'density' is much lower too. For the same engine bulk, you get less thrust than with the competing jet engines.

Pushing the pulsejet further down the scale of desirability in the postwar era was the fact that even with the improvements arrived at in the 1950s and 60s; the pulsations still produced horrible noise and mad vibration. Pulsejets depending on reed valves were also short-lived and unreliable. OK, they were cheap, but in the Cold War era that was certainly not a prime consideration.

Finally, there was little that pulsejets were really good for. For a while, it looked like they would power small helicopters. Some spectacular-looking prototypes were built, especially in France. In the end, however, they never made the grade, mostly for aerodynamic reasons.



The French briefly used pulsejet power on motor gliders and flying drones, too. Cheap flying drones and missiles were built in several countries, including the US, Russia and China. The picture above shows the French Arsenal 501 target drone, powered by a valved engine. The color picture on the first page of this document shows a Chinese target drone with a valveless engine.

That was about it. Given the ample defense budgets, most of the real-life applications that required a jet engine were better satisfied with a turbojet or with rocket power.

Civilian industry did not look upon the pulsejet with any greater kindness. Turbojet development was intense and engineers had little time for the exotic pulsating things that few people understood properly anyway. The difficulty of defining the processes inside the pulsejet mathematically was a major problem for most researchers and engineers. Modeling the semi-chaotic pulsating combustion was far too much for the computing abilities of the time. It meant that pulsejet design was unpredictable -- part science and part black art. Industry tries hard to avoid such tricky propositions.

By the mid-1960s only a few isolated enthusiasts still considered the pulsejet as a potential aircraft powerplant. The noisy tube was in a blind alley and relegated to the role of model aircraft engine and such humdrum applications as an efficient combustor for central heating systems, a power unit for agricultural spray dusters and a blower and shaker for industrial slurry drying machinery.

CHANGE OF CIRCUMSTANCES

So, why look at pulsejets now? Well, my reason is the change of circumstances.

Sometime in the early 1980s, ultralight fun flying started getting increasingly popular due to the availability of good, simple and affordable flying platforms – hang gliders and paragliders. When provided with motor power, these machines offered unprecedented freedom of flight to anyone interested. In addition, with the fantastic development of modern electronics, a whole new class of unmanned flying machines appeared, designed as utility platforms for a variety of telecommunications, surveillance, measuring and sensing devices.

All those new flying machines, whether designed for fun or utility, are powered by piston engines that drive propellers. Jet engines only appear at the very top end of the price scale – on machines costing several hundred thousand dollars apiece.

All the piston engines currently used in ultralight flying are relatively heavy and cumbersome, even in their simplest form. They also require much ancillary equipment, like reducers, prop shafts, propellers etc. etc. Having all that gear mounted on a lightweight flying machine almost defeats the original purpose. A simple lightweight pulsejet seems much more appropriate.

Turbojets, on the other hand, are terribly expensive – far out of enthusiasts' reach. Things are not likely to get much better in the near future, either. Because of the very high technological requirements, the cost of turbojet engines has always remained high. Only the small turbojets based on old turbocharger parts are relatively inexpensive, because their most precious parts are taken off scrapped truck engines, but even their prices are not pleasant.

In contrast, the humble low-technology pulsejet is laughingly cheap by any standard.

Besides, in the engine sizes likely to be used by enthusiasts, the best pulsejets can compete in performance with the other jet engines, especially in the power-to-weight stakes.



I am often told that a jet engine will never be good for recreational purposes. Jet propulsion is really efficient only at relatively high airspeeds, seemingly making it unsuitable for low-speed devices such as hang gliders. However, maybe a niche for a simple jet engine

can be found at the top end of hang-glider performance – possibly with rigid wings.

Also, the rule does not seem to be very strict. For instance, a British Doodlebug harness powered by a Microjet turbojet engine has been tested with delightful results with a regular foot-launched hang glider (see the picture).

This bodes well for pulsejets. When equipped with a thrust augments, a good pulsejet can be optimized for speeds much lower than those of other jet engines. It can hardly fail to perform at least as well as the Microjet in a similar application. In terms of thrust to weight it is already superior.

Tote up those points and the lightweight, simple, cheap low-speed pulsejet engine suddenly starts making a lot of sense. Its admittedly high fuel consumption, noise and vibration need not be of major importance for the applications I have in mind -- or may perhaps be alleviated or designed out of the concept.

The enormous advances in computing power over the past few decades have made modeling of pulsating combustion more realistic, too. It is still not easy even for the supercomputers, but it can now be done. This can cut down development time drastically and make it much more straightforward.

Finally, our understanding of pulsating combustion has advanced to the point where these engines can be designed on paper with performance predictability much closer to that of the other engine types.

It is perhaps time to blow the dust off the old tube.

WHY VALVELESS?

The ordinary pulsejet is already a very simple engine. It is just a piece of tube cut to the required dimensions, with a few small flaps and a fuel jet at one end. So, one might ask, why go that one small step further and eliminate the valves?

The prime reason is that the use of flap valves limits the reliability and longevity of the engine. The valves of the As 109-014 lasted for only about 30 minutes of continuous use. Given that its role was to destroy itself in the end anyway, this was not a big fault, but today you might have a flying model that is your pride and joy up in the air, or you may even want to fly yourself. You really need your engine to last a bit longer.

Admittedly, development has improved the design in many ways and stretched its working life from minutes into hours, but the fundamental problem remains. In fact, it looks well nigh insoluble, given that the valves are supposed to satisfy conflicting demands.

In the interest of combustion efficiency, they should not impose their own timing on the flows. This is very important, as the combustion process is not only intermittent but also somewhat erratic and highly dependent on feedback. If we want to avoid disturbing the natural progress of the pulsation as much as possible, the valves must respond to changes of pressure almost instantaneously. To do that, they have to be as light as possible.

At the same time, however, they have to endure great mechanical stress (bending open and slamming shut at high-speed) and do it in a high-temperature environment. They have to be very tough. If something has to be light, yet exposed to great abuse, it either spells short life or exotic technology. The former is impractical and the latter is expensive.

Finally, there is a question of elegance. I find the idea of a jet engine that is actually just a cheap empty metal tube without moving parts very appealing. Making the various gases jump through hoops and produce useful tricks without resorting to any mechanical complexity is a nifty thing that will be appreciated by all lovers of simplicity and elegance. (I am talking of elegance in the mathematical sense -- desired result achieved with minimal complication.)

KADENACY OSCILLATION, THERMAL BREATHING AND ACOUSTIC RESONANCE

Before getting into details of actual engine designs, let's get some important theory out of

the way. People who hate theory may skip this part, but my advice is to skip it only if you are already reasonably familiar with the laws of acoustics and fluid mechanics and aware of how they pertain to pulsejets. On the other hand, people who like theory should be warned that the following is a greatly simplified description of very complex mechanisms.

Kadenacy Effect

In the explanation of the working cycle, I described how inertia keeps driving the expanding gas out of the engine all the way until the pressure in the chamber falls below atmospheric. The opposite thing happens in the next part of the cycle, when the outside air pushes its way in to fill the vacuum. The combined momentum of the gases rushing in through the two opposed ports causes the chamber briefly to be pressurized above atmospheric before ignition.

There is thus an oscillation of pressure in the engine caused by inertia. The gases involved in the process (air and gaseous products of combustion) are stretched and compressed between the inside and outside pressures. In effect, those fluids behave like an elastic medium, like a piece of rubber. This is called the Kadenacy Effect.

The elastic character of gas is used to store some of the energy created in one combustion cycle and use it in the next. The energy stored in the pressure differential (partial vacuum) makes the aspiration (replacement of the burned gas with fresh fuel-air mixture) possible. Without it, pulsejets would not work.

Some observers have noticed another, additional facet of the process, akin to breathing. Swiss pulsating combustion wizard Francois H. Reynst called it 'thermal breathing' – heating the gas causes it to expand (and the engine to 'exhale') while the cooling of the gas due to convection of heat to the cooler chamber walls leads to contraction, and the engine 'inhales'.

Acoustics

Other people studying the process came up with the acoustic explanation of the same process. They detected acoustic resonance behind the pressure swings.

Namely, the explosion in the chamber generates a pressure wave that strikes the engine tube and the air within it, making them 'ring' like a bell hit by a hammer. The pressure wave travels up and down the tube. When the wave front reaches an end of the tube, part of it reflects back. Reflections from opposed ends meet and form the so-called 'standing wave'.

Everyone who has heard a pulsejet roar knows that it is a sound generator. The fact needs no amplification – the noise is... well, not just deafening; it is an *über*-sound that shakes all things around you seriously. What the establishment of the standing wave means is that this 'sound', just like its lesser brethren, will obey the laws of resonance.

Graphically, the standing wave is best represented by a double sine curve. The same is true for the pulsejet cycle. The undulations of a single sine curve depict the changes of gas pressure and gas speed inside a pulsejet engine very well. The doubling of the curve – the addition of a mirror image, so to say – shows that the places where the pressure and speed are the highest in one part of the cycle will be the places where they are the lowest in the opposite part.

The changes of pressure and the changes of gas speed do not coincide. They follow the same curve but are offset from each other. One trails (or leads) the other by a quarter of the cycle. If the whole cycle is depicted as a circle – 360 degrees – the speed curve will be offset from the pressure curve by 90 degrees.

The resonance establishes a pattern of gas pressures and speeds in the engine duct that is peculiar to the pulsejet and not found in the other jet engines. In some ways it resembles a 2-stroke piston engine resonant exhaust system more than in does a conventional jet engine. Understanding this pattern is very important, for it helps determine the way the events in the engine unfold.

When considering a pulsejet design, it is always good to remember that those machines are governed by a complex interaction of fluid thermodynamics and acoustics.

Elements of Resonance

In acoustic terms, the combustion chamber is the place of the greatest impedance, meaning that the movement of gas is the most restricted. However, the pressure swings are the greatest. The chamber is thus a speed node but a pressure antinode.

The outer ends of the intake and exhaust ports are the places of the lowest impedance. They are the places where the gas movement is at the maximum and the speed changes are the greatest – in other words, they are speed antinodes. The pressure swings are minimal, so that the port ends are pressure nodes.

The pressure outside the engine is constant (atmospheric). The pressure in the combustion chamber seesaws regularly above and below atmospheric. The pressure changes make the gases accelerate through the ports in one direction or another, depending on whether the pressure in the chamber is above or below atmospheric.

The distance between a node and an antinode is a quarter of the wavelength. This is the smallest section of a standing wave that a resonating vessel can accommodate. In a valveless pulsejet, this is the distance between the combustion chamber (pressure antinode) and the end of the tailpipe (pressure node). This length will determine the fundamental wavelength of the standing wave that will govern the engine operation.

The distance between the chamber and the end of the intake is rather shorter. It will accommodate a quarter of a wave of a shorter wavelength. This secondary wavelength must be an odd harmonic of the fundamental.

Given that a valveless pulsejet is a tube open at both ends, you may wonder at the above statements. Namely, an open tube is not a quarter-wave resonator. It normally has a pressure antinode in the center and a node at each end – which comprises half a wavelength. Nevertheless, it is much closer to reality to look at a valveless engine as two different quarter-wave oscillators mounted back to back than as a single half-wave oscillator. The underlying half-wave character of the resonance of the entire duct is still there, of course, but its effects are completely drowned by everything else that is happening inside.

So, the tailpipe length must be an odd multiple of intake pipe lengths for the engine to work properly. However, please note that we are talking of acoustic length. The required physical length is somewhat different. It changes with the temperature (which changes the local speed of sound). Thus, it will not be the same in all parts of the engine. It will not be the same with the engine cold (e.g. at the startup) and when it is hot, either. This is the source of much frustration for experimenters and the reason why a new pulsejet invariably requires some tuning and fiddling to achieve proper working resonance.

Waves and Flows

Both the 'Kadenacy' and the 'acoustic' approaches to the definition of the pulsejet cycle are correct. In a roundabout way, both may be considered just different manifestations of the same thing. However, they are not the same thing. This should not be forgotten.

The classical acoustical phenomena take place at small pressure changes, low gas velocities and little gas displacement. Sound waves are vibrations -- roughly speaking, elastic, reversible disturbances in the medium. In pulsejets, we see great pressure variations, high gas velocities and great gas displacement. The forces involved are stronger than the elastic forces keeping the molecules of the medium together, meaning that the medium (gas) is not just made to vibrate, but is irreversibly displaced. It is made to flow.

It is difficult to see the difference between the wave and the flow, but it can be done. A wave is not a material phenomenon, but an energy phenomenon. It is a moving disturbance in a force field. That is why it will easily turn any corner, including doubling back 180 degrees. A fluid flow, which has mass and inertia, will not. So, the two can be made to separate, which demonstrates that they are in fact two, rather than one.

You can see pressure waves separated from flow in the valveless pulsejet designs that feature ports with irreversible flows (e.g. an intake that does not also serve as an auxiliary exhaust). In such ports, pressure waves will move with the flow in one direction and without the flow in the opposite direction.

To recapitulate, pulsejets follow their own, distinctive, Kadenacy-like cycle of compression and rarefaction powered by the self-excited explosive combustion process and helped along by the heat convection pattern. The genesis of the cycle has nothing to do with acoustics and everything to do with thermodynamics. There is no doubt, however, that the scenario of events resembles acoustical phenomena very closely. As a consequence, the laws of acoustics can and do apply. They superimpose themselves over the thermodynamic events and modify the inflow and outflow of gas, often significantly so.

Because of that, one should watch out for acoustic resonance, knowing that the regular pressure impulses will inevitably set up standing waves, which will influence the timing and

distribution of gas pressure, the speed and intensity of combustion, the speed and intensity of gas flows etc. The negative influence of resonance must be avoided and – if possible – the positive influence harnessed to help the engine along.

This is a very complex task and some designs do this better than others. Some have been brilliant at the task, using a hugely complex concatenation of wave reflections, reversals, mergers and collisions to boost the efficiency of aspiration and combustion appreciably. Others have taken only the roughest note of the possibility. I cannot deal with the issue in great detail because of inadequate knowledge, and will mention it as we go along only in a superficial manner.

What I am really interested in are the practical results of pulsejet design.

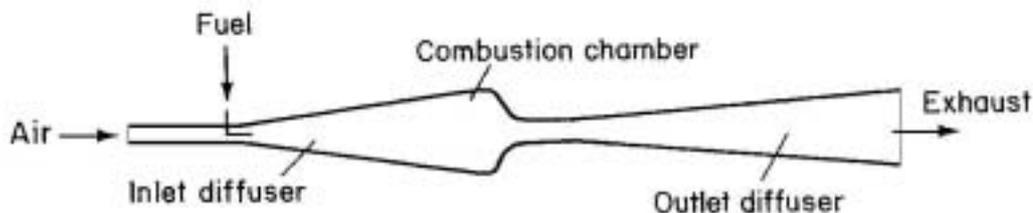
ENGINE DESIGNS

Marconnet

The world may have been shocked into awareness of the pulsejet by the German flying bomb in the 1940s, but the history of that curious engine goes much further back, to the very beginning of the 20th century and the efforts of French engineers to develop a gas turbine.

Steam turbine was a fine machine but needed a huge burner, boiler and condenser apparatus to handle the water vapor cycle. It looked to the innovative French as if hot gas generated by combustion of fuel might power the turbine wheel just as well as steam did, but with much less complication, bulk and cost. Pulsating combustion occurred to them because it provided automatic aspiration. The pulses not only drove hot gas forward to power the turbine, but also sucked in fresh charge in the condensation part of the cycle. No special machinery was needed, just a couple of spring-loaded poppet valves.

In 1909, Georges Marconnet went a step further and developed the first pulsating combustor without valves. It was the grandfather of all valveless pulsejets.



Marconnet figured that a blast inside a chamber would prefer to go through a bigger exhaust opening, rather than squeezing through a relatively narrow intake. In addition, a longish diffuser between the intake and the combustion chamber proper would direct the charge strongly towards the exhaust, the way a trumpet directs sound. He tolerated what hot gas did escape from the intake.

In their descriptions of the Marconnet engine, F. H. Reynst and J. G. Foa (each in his time a noted expert on pulsating combustion) agreed that it could not have worked very well, really requiring forced air at the intake (by a fan or a similar device) if the blowback was to be avoided. Foa actually called the Marconnet “a bad ramjet” on account of the need for some ram pressure at the intake. In principle, it does resemble ramjets of a few decades later rather closely.

To my eyes, the combustion chamber of the Marconnet ‘engine’ lacks a notable means of creating turbulence in the incoming flow, meaning that the mixing of fuel with air may have been problematic and the combustion was of a relatively low intensity. Later practitioners of the art introduced much more pronounced cut-offs between the intake and the combustion chamber.

While it may not have been very practical either as a jet engine or as a turbine combustor, the basic idea behind the Marconnet design was good. It just needed development.

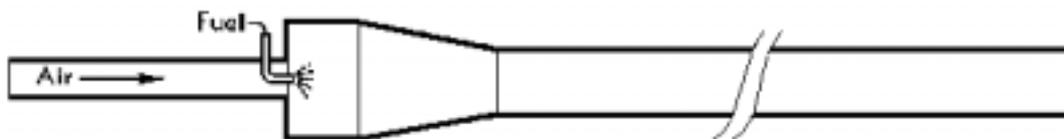
However, it was not destined to receive it. Even in France, the valveless combustor soon became just a footnote in history. Outside France, few people were even aware of the idea. Instead of developing valveless pulsating combustors, most experimenters of Marconnet's era concentrated on various layouts incorporating poppet valves.

[A historical note: One of the earliest valve-equipped pulsating combustors to be devised actually made commercial history. The first gas turbine ever to be marketed commercially was designed by Hans Holzwarth in 1905 and developed for practical applications by the Swiss Brown Boveri Corporation. It enjoyed some commercial success between 1908 and 1938, the bulky drum-shaped devices reportedly operating faultlessly (if not particularly economically) for ages. There are indications that the Holzwarth combustor, which features intake and exhaust valves, is being re-evaluated for modern use in low cost turbine engines.]

Schubert

The principle of the valveless pulsating combustor was rediscovered -- by all accounts independently from Marconnet -- by Lt. William Schubert of the US Navy in the early 1940s. (It was patented in 1944.) His design, called the "resojet" at the time, on account of its dependence on resonance, is one of the simplest successful valveless designs of all.

The most probable reason for the scant interest in valveless combustors early in the 20th century was the lack of good means to prevent the wasteful and unpleasant blowback through the intake. At first sight, the Schubert engine does not look better in that respect than the Marconnet, just more angular. However, the appearance is deceiving.



First, Schubert's sharp cutoff at the entrance of the intake port into the chamber provided strong turbulence for better mixing of fuel and air, as well as more vigorous combustion. Second, and more interesting, Schubert carefully calculated the geometry of the intake tube so that the exhaust gas could not exit by the time the pressure inside fell below atmospheric.

The resistance of a tube to the passage of gas depends steeply on the gas temperature. Thus, the same tube will offer a much greater resistance to outgoing hot gas than to the incoming cold air. The impedance is inversely proportional to the square root of the gas temperature. This degree of irreversibility seems to offer the possibility for the cool air necessary for combustion to get in during the intake part of the cycle, but for the hot gas to encounter too much resistance to get out during the expansion part.

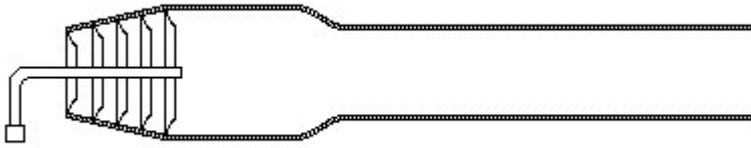
In practice, it worked less well. For a number of reasons ignored by the simple general theory, the Schubert engine still displayed a bit of blowback when stationary. It needed to move forward at some speed (or to have air blown in by a fan) to prevent it. The intake tract long enough to prevent the blowback completely would choke the air supply too much for good performance. Nevertheless, the Schubert was a notable step forward from the Marconnet.

Trick Intakes, Baffles, Serrated Tubes, Convoluted Passages...

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

Paul Schmidt and Jean Henri Bertin (among others) tested a number of designs featuring concave ring baffles in the intake tract, which offered great resistance to back flow but let fresh air in easily. A simple version of the Bertin baffle intake is pictured below. Fresh air coming in from the left encounters a series baffles, but flows easily past them. The baffles

have increasingly broader openings, forming a diffuser.



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

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

Alas, that is the sad story of almost every valveless pulsejet that employs some kind of asymmetry of resistance. Such devices never work as well as their designers hope for. They mostly pitch in only at high gas speeds, meaning that the engine will suffer from at least some blowback at the beginning of each cycle.

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

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



Few people will be surprised to hear that the amazingly prolific and spectacularly inventive researcher of things electrical, Nikola Tesla, also turned his mind to the problem of pulsating combustion. He wanted to have a good gas generator for his neat smooth-disk rotor turbine that used the viscosity of the working fluid to transfer energy to a rotating shaft. He immediately saw that mechanical valves would not offer the simplicity and reliability he had sought. So, he studied the ways to rectify the gas flow aerodynamically. Eventually he came up with arguably the best aerodynamic 'valve' ever. Its cross section is shown below.



At first glance, it looks like another serrated passage, but if you take a closer look, you can see that it does not really employ either baffles or dead air pockets. Instead, it just changes the direction of the gas and turns it upon itself. At each turn, a side blast of gas will push the main flow towards the side passage that eventually turns backwards. The harder you blow into that tube, the harder it will resist.

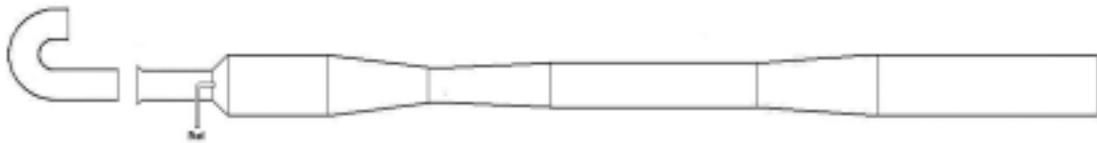
While undoubtedly ingenious, the 'valvular conduit', as Tesla called it, never found practical application to the best of my knowledge. Tesla himself probably did not have time or

inclination to pursue its development after applying for patent, being busy with his experiments in electromagnetism, and the patent was mostly forgotten. As the inventor has recently become the center of a cult following, his modern disciples have revived the idea. A few have been built, but I have not been able to find data on their performance.

Escopette

In 1950, dissatisfied with the baffled intake designs, Bertin and his fellow engineers at the French SNECMA (*Societe Nationale d'Etude et de Construction de Moteurs d'Aviation*) corporation simply turned the intake tract backwards. That way, blowback contributed to thrust. To its designers, the machine looked like one of the old-fashioned musket guns and they called it *Escopette* (which is French for musket).

It looks very similar to the picture we used in the introduction. However, the intake does not curve backwards directly from the combustion chamber. Its first part points straight ahead. What turns the hot exhaust gases backwards is a separate curved tube mounted at some distance from the mouth of the intake proper. So, the engine breathes through the gap between the intake and the 'recuperator', as the designers called the curved tubular deflector.



This neat design deftly exploits the resonance in several different ways.

The functioning of the split intake is subject to some controversy, but simply put, it may be said that it allows the engine to behave as if its length were variable – long during the expansion part of the cycle and short during the suction part. During expansion, it treats the recuperator as a part of the effective length of the engine and uses it to turn the escaping gas around and increase thrust. In the intake part of the cycle, however, the effective front end is at the gap between the intake and the recuperator. This reduces the effective length of the intake and lets the *Escopette* inhale more easily.

Next, the tailpipe, instead of being just a straight pipe, is in fact a series of steps of increasing section. Each transition from a straight section into a diffusing section (flaring cone) represents a point from which the pressure waves traveling up and down the tube will reflect in the opposite direction and with the opposed sign. A compression (high pressure) wave passing a step will reflect back as a rarefaction (low pressure) wave and vice versa.

Just glancing at the picture will give you an idea of how many different compression and rarefaction waves are generated by each blast of the charge in the chamber as it tries to exit the engine. Remember also that each step of the pipe works at a different temperature from the preceding or succeeding steps, meaning that the wave will travel at different speeds.



The tracing of the events is not for the faint of heart and is certainly too complex for me to attempt to describe here. Bertin *et al.* harnessed all those waves very carefully, tuning them to produce the maximum possible aid to aspiration. What seems to be happening is that the engine 'skips a beat', so to say. It inhales twice for each expansion cycle, with the second inhalation topping up the first.

The next trick Bertin employed on the *Escopette* – for the first time ever in a pulsejet -- was the utilization of surplus heat in the exhaust stream to increase thrust. The effect is sometimes called 'primary thrust augmentation'. It requires some explanation.

The problem starts with the amount of air available for propulsion. Basically, a jet engine is a device that employs heat to accelerate air. Ambient air is made to pass through the engine duct and absorb the heat generated inside by combustion. However, air does not flow through the pulsejet duct the way it does through other jet engines.

In a turbojet, a little hot gas pushes along a great quantity of cool air. In pulsejets, a small amount of air is sucked into the combustion chamber and used for combustion and a slightly larger amount is sucked back into the exhaust tube between explosions. That is all. There is no through-flow.

At the same time, the exhaust gas produced by a pulsejet is much hotter than in a turbojet. Combustion takes place at similar temperatures -- between 2000 and 2500°C -- but the exhaust gas in a turbojet is immediately mixed with a lot of cool air, so that the temperature is lowered to between 800 and 1200°C before it enters the turbine. The main reason is to keep the turbine from damage. In the pulsejet, which has no moving parts, the exhaust gas does not need to be cooled. It travels towards the end of the engine at very close to its initial temperature – two to three times hotter than in a turbojet.

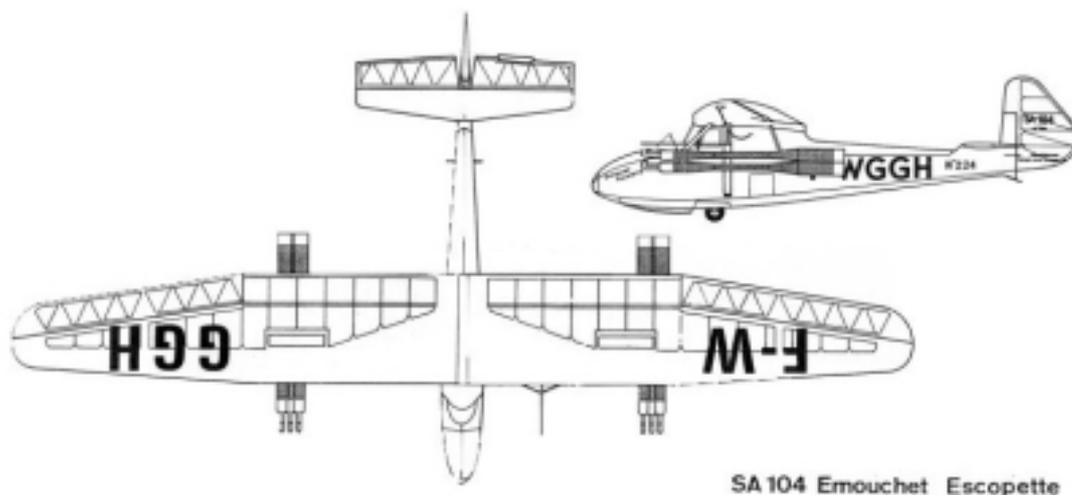
Because there is no through-flow of air, however, there is very little propulsion mass for this considerable thermal energy to act on. This generates problems. The small mass of exhaust gas and fresh air is propelled to the maximum speed possible under the circumstances (the local speed of sound) and no further. The sonic choking of the duct prevents the gas speed from rising further, despite the fact that there is sufficient energy for further acceleration. A 'de Laval' nozzle would probably push the speed beyond the Mach barrier, but it does not work at all well with a pulsating flow, so pulsejet designers avoid them.

So, only a small part of the heat liberated by the process of combustion is converted into useful kinetic energy. Much of the available energy has nowhere to go. At sonic speed, gas is not capable of absorbing more heat. This generates compression waves that travel up and down the engine, disrupting the cycle.

In other words, the energy-mass transfer ratio is low and the resulting thrust is lower than it could be. So, the super-hot exhaust of the pulsejet simply cries out for additional propulsion mass to heat up and accelerate.

Enter Bertin. He made the exhaust tube on the *Escopette* progressively larger towards the end, so that the final section is a veritable bustle. This increased the volume of the exhaust duct considerably as well as gave the duct a shape that promoted the intake of fresh air during the suction part of the cycle. The result was an exhaust filled with a large amount of fresh air, which the engine could use as additional propulsion mass.

Each blast from the combustion chamber pushes the fresh air 'plug' mechanically, but the engine also transfers a lot of its heat to the air, both from the hot tube walls and from the pushing hot gas. Heating increases static pressure, which increases the speed at which fresh air is expelled backwards. Much additional thrust is exerted.



The version intended for commercial applications, model 3340, developed static thrust of about 22 lbs, operating at the frequency of between 90 and 100 Hz. The weight with the ancillaries was about 11 lbs. At the widest part, the *Escopette* was only about 4 inches wide, but the length was a somewhat unwieldy 9 feet plus.

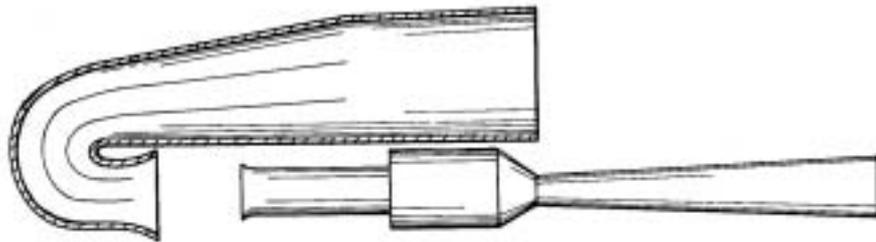
The *Escopette* is one of the few pulsejets to have carried people aloft. It was extensively tested on the French *Emouchet* SA 104 sailplane in various configurations. The first trials were with a single engine under each wing, but later models carried two and three engines on each underwing pylon. While the test results were positive – the auxiliary power enabled the

pilot to take off and achieve soaring altitude without a tow plane or a winch, it seems that it was never offered commercially.



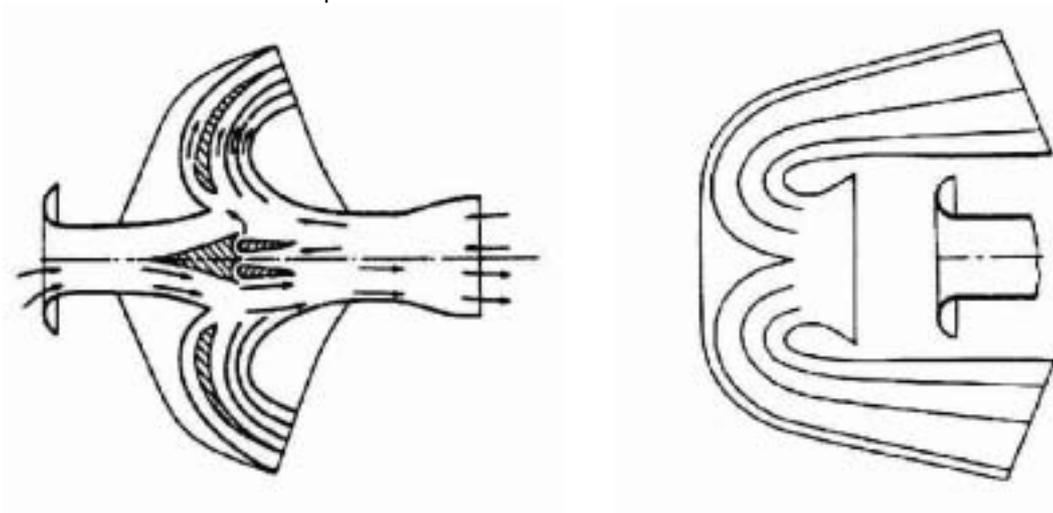
Kentfield's Recuperator

The idea of a recuperator or deflector found several adherents who produced variations on the theme, some simple and others complex. J. A. C. Kentfield, one of the most recent scientific researchers in the pulsejet field, tried to make up for the energy lost in turning the gas flow around by introducing thrust augmentation to the recuperator.



Instead of a simple tube bent backwards, he employed a gently flaring curved cone, which let fresh air be sucked in by the hot gas stream as extra reaction mass. (This is often called secondary thrust augmentation, to make it distinct from the kind used in the *Escopette*. I will talk about it in more detail in a later chapter.) According to Kentfield, who patented the idea, the gain more than offset the drag and turbulence losses incurred by the 180-degree turn.

He experimented with variations on the theme a lot. Most recuperators were symmetrical and used internal vanes to help control the flow and lower the turbulence. Two such designs are shown on the next two pictures.



The one on the left looks more ambitious. It attempts to harness ram pressure of the incoming air. Ram pressure would seem to give a welcome boost to the power output at no

cost. The J-shaped and U-shaped engines as well as most engines with recuperators up front must forgo that advantage, as their intake ports are either turned in the wrong direction or masked by the recuperator structure.

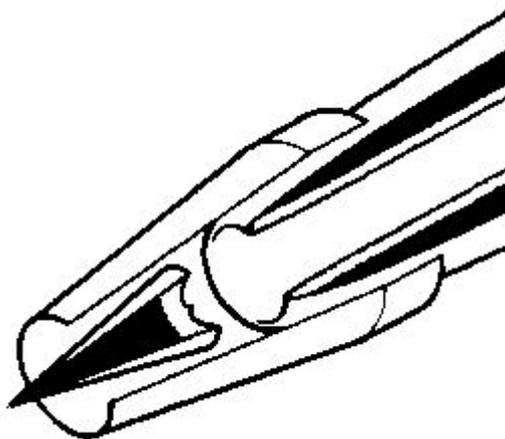
This one has an almost straight path for fresh air from the front intake to the combustion chamber (see the lower half of the picture). The trick that prevents the exhaust gas from escaping through the same route may have been borrowed from Tesla, but similar methods are also used in various other pneumatic flow control devices.

Note the two small airfoil-section vanes in the central passage, right behind the intake wedge. When the hot exhaust gas is pushed forward by the blast, the part blowing into the gap between the vanes is divided into two flows, one going upwards and the other going downwards. Each flow forms a kind of a gas curtain that cuts across the path of the main flow (see the upper half of the picture). The curtain deflects exhaust gas flow towards the curved passages that turn the flow around and eventually eject it backwards. As a result, almost all the exhaust gas that would normally be blown out of the intake port gets deflected and contributes to the thrust.

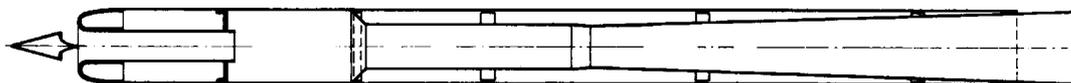
According to Kentfield, the simple one on the right outperformed the more complex one on the left in laboratory testing. I am not surprised. Due to intermittent operation, a pulsejet is not very good at tapping ram pressure, most of which goes to waste. Providing a straight path for fresh air is simply not as important as in the other jet engines. A pulsejet will happily suck air from the side or even from the rear, because it has to accelerate it from standstill anyway. Its direction matters very little. The only thing that matters is pressure.

Messerschmitt

One of the best practical recuperators I have seen is the one developed by the German Messerschmitt company in the early 1970s. The intention of its engineers was to build an engine that would segue from pulsating combustion at low speeds at which ram pressure is poor, to constant combustion at high speeds, at which the ram pressure is sufficient to contain combustion. The task required a deflector that would be efficient in redirecting the reverse flow coming from the intake, but would not represent too much of an obstacle to the entry of fresh air.



I will disregard the ramjet part or the Messerschmitt engine in this explanation, as it is not the subject of this paper. However, the recuperator is a different story, as it is eminently usable on 'ordinary' pulsejets. It is simple and elegant -- and easy to make even for an enthusiast of average skill. As you can see, it consists of a simple sharp cone whose rear is shaped to deflect the blast from behind at the right angle to the engine axis. When stationary, this did not do much for thrust, but even at relatively gentle forward speed the deflected gas stream bent backwards, around the engine, helped by the Coanda effect.



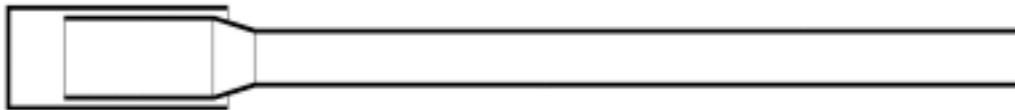
For low speeds, Messerschmitt designers provided a nose cawling to help entrain the flow. As the speed rose, the cawling became less necessary. At a considerable fraction of the speed of sound, the incoming air stream is so strong that even the deflector is not strictly necessary anymore, as the hot gas is entrained tightly between the air stream and the outer engine surface.

Capped Tubes

Gas deflectors need not be ancillaries tacked onto the engine. They can be an integral part of its structure. For instance, if you put a loose cap over the end of a tube, so that a gap

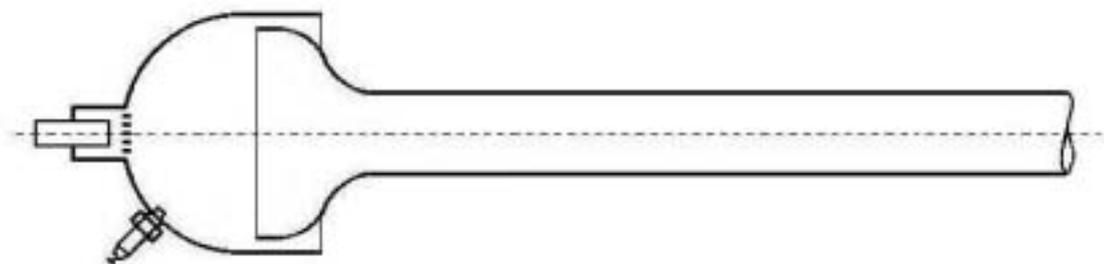
is left between the cap and the tube, you get a kind of deflector that will turn your exhaust gases backwards. Unlike a separate recuperator, however, this one also serves as the intake tract. Arguably, this is the simplest valveless pulsejet design of all.

Possibly the most prominent among pulsejet developers to tackle a capped tube design



were none other than the Argus engine company, best known for their reed-valve engine that powered the V-1 flying bomb. They tested a number of layouts, some of which appear to be useful only for stationary applications.

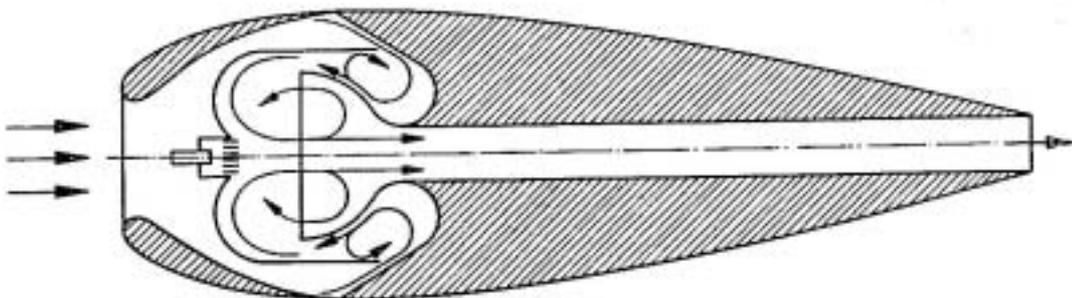
The sketch below shows the central part of their valveless engine. The 'combustion chamber' is formed between the bottle shape we know from many other pulsejet designs and a cap with hemispherical top. Fuel is injected through a nozzle situated on the tip of the cap and protected from the chamber by a metal grid. The grid functions as a heat sink and prevents gas from burning at the nozzle itself.



In the first tests, this central core engine was enveloped in a plenum chamber into which air was forced at pressure by a compressor. Only the exhaust was sticking out. This meant that the pressure of forced air prevented hot gas from getting out into the plenum chamber and almost all of it went into the exhaust. (If it were designed to work without the pressurized shroud, the chamber and the exhaust passage would probably have to be longer than on the above picture, to provide the necessary resonant properties.)

Argus engineers were apparently delighted with their valveless machine and were about to develop it for aircraft purposes, but were ordered to halt the work and concentrate on the valve-equipped engine inspired by Paul Schmidt's ideas.

One can only wonder how far they would have gone if not rudely interrupted by the authorities. The next sketch shows the layout they developed to work without forced air. The outer streamlining is the most obvious difference, but a subtler one is the annular chamber through which fresh air must pass before it is drawn into the combustion chamber. Curved arrows on the sketch show the gas paths inside the engine.



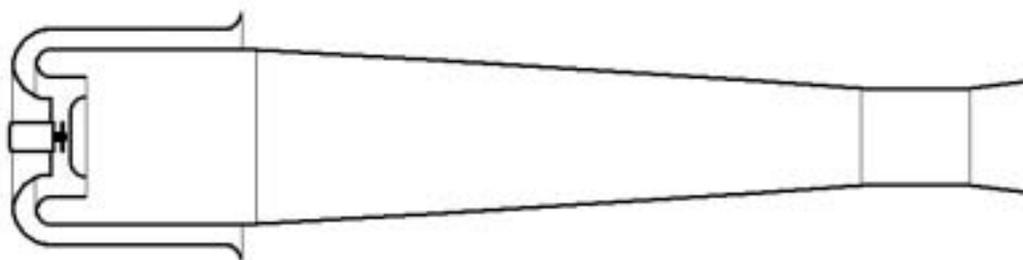
It is obvious that the incoming air will swirl in a toroidal vortex that will allow outside layers of the vortex to detach and slip into the combustion chamber. However, the hot gas exiting between the chamber and the mantle will also swirl in a vortex – one whose direction of rotation will be opposite to the direction of the exit from the annular chamber. In addition, the

slit through which the annular chamber communicates with the outside is very narrow. It might let sufficient fresh air in, but will choke when hot gas tries to pass.

The engineers at Argus were almost certainly unaware of the work of F. H. Reynst, whose pulsating combustors will be described later in this review. Reynst's machine also utilizes the special properties of the toroidal vortex. It was first patented in 1933, while Argus developed its jet almost a decade later. A decade was hardly enough for the relatively obscure Dutch patent to percolate to German engineers dabbling in jet propulsion. One can only wonder what influence, if any, Reynst's idea would have had on engine development had the contact between the two been made.

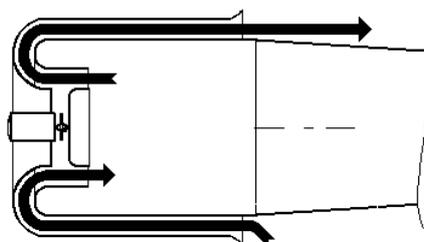
As it is, the toroidal vortices must have helped the Argus engine work well, but they are not central to its operation. The Argus is not essentially different from the bent intake engine whose sketch – the very first in this paper -- we used to explain the workings of a valveless pulsejet. The only difference is that a narrow annular gap between the combustion chamber and the cap is used for intake instead of a bent tube.

Saunders Roe



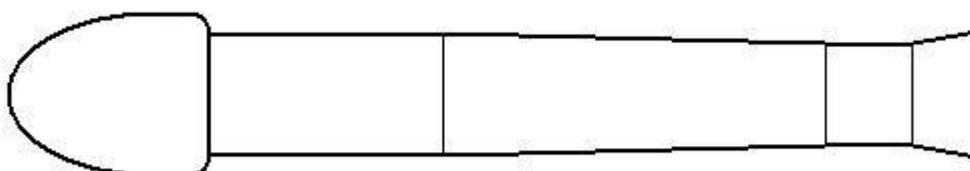
The next to exploit a similar configuration was C. E. Tharratt, a British researcher working on pulsejets for the Saunders Roe aircraft company in the early 1950s. I have no idea whether he was familiar with the Argus layout or not, but the principle he employed is similar. Here is the simplified longitudinal cross-section of one of his valveless engines.

The 'cap' is no longer a simple cap but a mantle that curves inwards and backwards, following the curvature of the front part of the combustion chamber. Again, the annular gap between the mantle and the chamber wall serves as the auxiliary exhaust. During expansion, most of the hot gas escapes through the exhaust proper, at the rear end of the engine, but a portion is driven forward, into this auxiliary exhaust. The device in the center of the front plate is the fuel injector. Its fuel jets are disposed radially, injecting fuel at the right angle to the fresh air flow.



Tharratt apparently cared little for the effectiveness of the cap as the exhaust, only really devoting attention to its properties as the intake port. There have been several versions, with rather different internal arrangements, but they all offered a smooth passage to fresh air towards the chamber and an indifferently shaped path for the hot gas out.

On the first two diagrams, the engine looks like having a bluff front end, but that is because it is shown without the streamlined nose. With it in place, the engine looked like this:



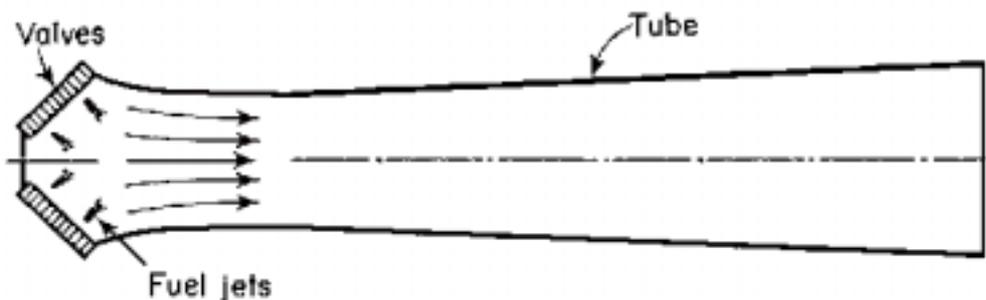
Like Hiller and some others, Saunders Roe was trying to develop a small helicopter with pulsejets at rotor tips. I have seen no records on the success of the project, but it could not have been great, given that most helicopter history books neglect to mention it even in

passing. Of course, it does not necessarily mean that Tharratt's engine was not good. The problem here lies with the helicopter concept, rather than the engine. Rotor-tip jet helicopters are just not a very sound idea, regardless of the kind of engine that is mounted on the rotor.

A detail that makes Tharratt's designs particularly interesting is the move away from the chamber-and-tube configuration found in most pulsejets, valved or valveless. It does not have the traditional 'tulip' or 'bottle' shape but tapers gently down, somewhat like a baseball bat or a bowling pin, having no pronounced bulge where the combustion chamber is situated. Its narrowest point is all the way back, just before the end of the tailpipe.

The tulip shape has been inherited from the petal-valve designs like the popular Dynajet, and has created a lot of misdirection among enthusiasts. Namely, according to a number of experts, it does not necessarily have great relevance to what is going on in the engine. The broad front part is not the combustion chamber and the narrower pipe is not a tailpipe.

In a well-designed pulsejet, Tharratt says, combustion will be going on through most of the tube interior and there will be no functional difference between the 'combustion chamber' and the 'tailpipe'. Look at the engines that Paul Schmidt, the father of the modern valved pulsejet, designed for his own purposes and you will see either a straight, constant-section tube or the one that broadens (flares) gently towards the exhaust end. The latter layout is shown in the next picture. The objective is to provide the least possible obstruction to the gas flow and the propagation of pressure waves.



The reason Dynajet-style pulsejets are broad up front is because the petal valves and air passages are inefficiently packaged and take up a lot of room. So, to provide an adequate amount of valve area, the valve head must be disproportionately broad. The tulip 'waist' is nothing but a gentle transition from broad section to narrower.

That may well be true in theory, but in practice, the tulip shape is difficult to do without. Kadenacy breathing will not take place unless (a) the pressure differential between the chamber and the ambient is high enough and (b) the differential can be maintained over a sufficient minimum period. Gas must be pushed forward by sufficient pressure and given sufficient time to accelerate to a great enough speed. It must gain at least the minimum momentum necessary for the Kadenacy effect. This requires a certain amount of confinement.

Generally speaking, the openings through which the combustion chamber is evacuated and refilled must not be too big, or gas speeds will be too low, the gas momentum will be too small, and there will be no Kadenacy effect. The engine will not work.

We know that Paul Schmidt achieved exceptional filling ratios of his pulse tubes and quite probably exceptional rates of flame propagation due to very careful design. That gave him pressure peaks so high that he could get away with relatively poor confinement of the burning gases in the tube. Few designers after him have managed to duplicate his results reliably. Those results simply cannot be taken as a reasonable yardstick.

Tharratt tried to combine the conflicting demands -- providing confinement to the gases, yet producing the least amount of harmful obstruction -- by having the chamber narrow down towards the exhaust in a very gentle slope, so that the narrowest part was situated almost at the very end of the engine. He argued that the shape conformed to the natural shape of accelerating gas flow. Only the very end of the pipe exhibited a short outward flare, to enable the fresh air sucked back into the exhaust to enter more easily.

Interestingly, F. Schultz-Grunow, a noted German pulsejet researcher, pronounced this shape highly unsatisfactory in his landmark comparative study of pulsejet duct shapes. Yet, it

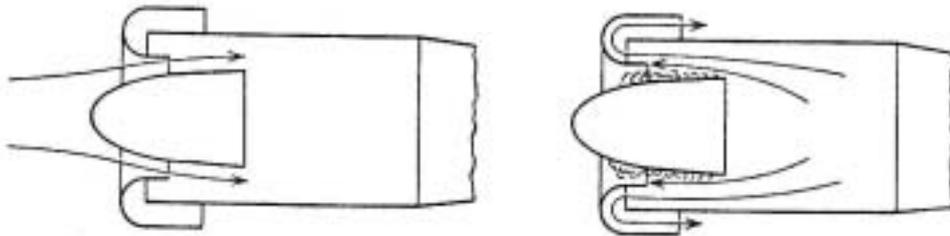
obviously worked for Saunders Roe, as more or less the same shape was employed on their engines with valves, which saw greater use than the valveless ones.

The design remains unusual. No other designer I know of has chosen to emulate it. Yet, a very basic pulsejet of this kind would be extremely easy for an enthusiast to build. It would consist just of a kind of a tin can capping the chamber and exhaust pipe of a conventional pulsejet, like a Bailey, or Atom jet, or any other of a score of small flying-model pulsejets. Spacers – possibly just simple screws – could hold the cap centered, keep it at a set distance from the chamber wall and prevent its fore-and-aft movement. An advantage of the design is the relatively easy altering of the cap placement. Moving the position of the cap slightly forward or backward will give the builder a way to fine tune the configuration and find the ‘sweet spot’ at which it works best.

The problem will be the same as in any annular design – how to provide the fuel supply that will allow good mixing. Looking at the Argus engine, perhaps having the propane supply right at the center of the chamber front plate would work well.

Foa

Joseph G. Foa, another well-known pulsejet researcher, investigated a capped-tube layout with a very interesting twist. He added the front entry of fresh air. It is shown on the next diagram.



Such a direct entry reduces the pumping loss and allows the Foa to benefit from ram pressure (to the extent that a pulsejet can benefit). This is a very elegant flow rectifier and has reportedly worked well. Perhaps worth noting here is the fact – not mentioned in the literature that I have seen -- that it is no different in principle from the *Escopette* ‘recuperator’, even though its shape looks very different.

Given the simplicity of the layout, I am surprised that something similar has not gained popularity among amateur enthusiasts. One is truly tempted to consider such an engine as a DIY project, as the only real difficulty seems to be presented by the semi-toroidal surfaces.

However, as pulsejet enthusiast Mike Kunz has noted, those can be made relatively easily by cutting sections of bent tube lengthwise to get semicircular-section channels. Such channel segments (say, four 90-degree ones) are joined by welding the ends together and form a nice half-torus. Some people I know have looked at old torque converter casings with a spark in their eyes, too, but I have not heard of anyone actually using it for this purpose.

[Please note that most diagrams in this book are not at all useful as engineering drawings. Some of them have been constructed from bits and pieces of information and represent only a rough representation of what the actual engine layouts were like. Dimensions shown on the sketches are approximate at the very best. If you build an engine based on any of those, do not expect it to work right away! In fact, it is almost certain that a great amount of tinkering will be required before success.]

The Sidewinders -- Logan and NRL

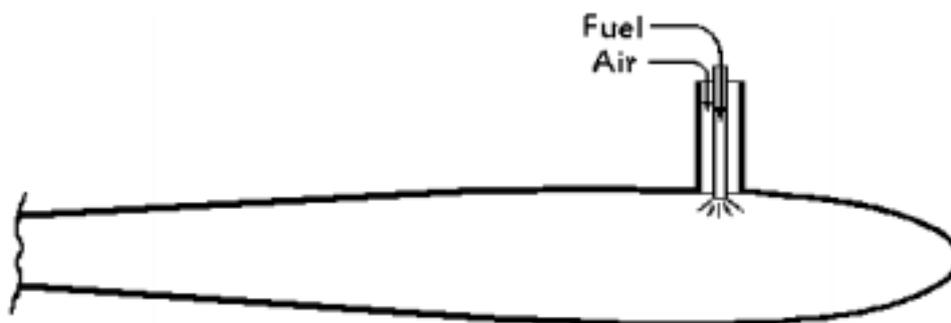
As we have seen before, the direction a pulsejet intake points at matters very little. The engine ingests stalled air anyway and can just as easily suck it from the front, the sides or the rear. This has given rise to a number of interesting layouts. Two particularly successful ones have the intake sticking from the side of the combustion chamber. Why this should be a good place for the intake is a matter of some controversy.

I have not found a really good explanation anywhere, but there is a considerable body of evidence from practical tests saying that it works well. Some recent computer simulations done by enthusiasts have also shown this to work well. Unfortunately, they do not tell you

why something works; only that it does.

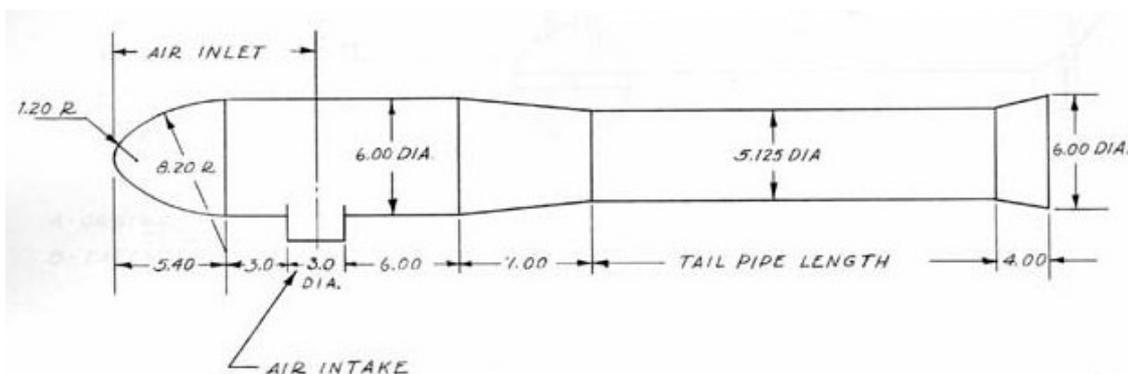
I have seen two pulsejet designers of the past argue the merits of intake position -- Reynst and Albert G. Bodine, Jr. After cutting through their hemming and hawing, both can be said to favor the inner end of the intake positioned at the pressure antinode. In practice, however, both ended up positioning it at about a third down from the antinode towards the node.

So, two serious men with very firm ideas finally arrived at the same practical solution, which was not quite in line with the ideas they put on paper. Neither really explained the reason for the disparity. In the pulsejet world, this is far from uncommon. Look at a sufficient number of pulsejet research reports and you will find an amazing number of obfuscations, finessing of dubious claims etc. etc. It is not a good field for the scientifically rigorous.



Whatever the theoretical merit of the side draft, the first engine to employ it with notable success was the Logan. The reason for the layout was simple – the engine was meant to be mounted on helicopter rotor tip, perpendicular to the rotor span, and its air and fuel were fed through the rotor.

The designer, Joseph G. Logan, was a prominent pulsejet researcher – one of the big names in the famous US government-funded Project Squid – and later a wave engine designer. He left behind a legacy of other notable designs (e.g. the Hertzberg-Logan pulsating combustor with rotary intake and exhaust valves). The above configuration appears to be a later version, made to self-sustain without help of pressurized air. The next picture shows the configuration developed within Project Squid. It was fed with fresh air at above atmospheric pressure.



At first glance, its principle of operation should be identical to the Schubert engine, yet some sources say that it worked substantially better than the Schubert in practice. The fact that the fresh mixture enters at the right angle and hits the opposite wall of the chamber must be playing a role.

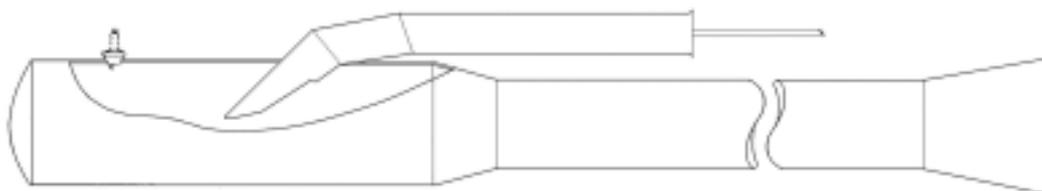
I can speculate that, guided by the curvature, the stream splits into two regular and opposed vortices around the longitudinal axis of the engine. It is a very good way to mix fuel with air. In addition, the paired vortices give the charge momentum in the direction away from the intake. Some of this motion away from the intake may be retained through the process of combustion and offer slight relief from full combustion pressure. Maybe the slight relief is sufficient to help the sonic choking of the intake work as Schubert had hoped it would.

There may also be an acoustical reason for the effectiveness of the layout. There is a possibility that the intake tube pointing at the sidewall of the chamber may actually 'see' the

sidewall as the chamber bottom and thus the pressure antinode. This juxtaposition of the intake and the chamber 'bottom' not too far across the chamber seems to be a positive thing. It works well on a number of engines.

[The same kind of side intake is found in an unrelated -- but also acoustically tuned -- engine, the Gluhareff 'pressure jet'. Gluhareff claimed that the layout produced a 'sonic lock' necessary for the proper operation. This is peculiar Gluhareff terminology but does sound rather apt. There are strong indications that the Gluhareff is in fact just a species of pulsejet, but I do not have enough data at hand to present the case and will leave it out of this review.]

Whatever the truth, it is almost certain that the Logan layout was a product of happy coincidence. The designing team was not guided by the nature of the intake but dictated by the need to make a rotor-tip engine. Good combustion arrived as a bonus.



A superficially similar design, but one that did not use the Schubert trick of the choking intake, came out of the Naval Research Laboratory (NRL) at Chesapeake Beach, MD, in 1957 and '58. A team led by Carroll D. Porter developed a device somewhat resembling the Logan to produce pressurized gas for a gas turbine (see the above picture).

They also developed a complex system of ducts and baffles to turn the pulsating stream emanating from the engine into a steady one, more suitable for turbine-driving purposes. According to their findings it worked. However, it was not taken up by any turboshaft or turbojet engine manufacturer I know of. It is quite possible that the ducting the design required was simply too bulky to be very practical.

The combustor itself, however, appears to have performed quite well. It seems to be relying less on the direction imparted to fresh charge than on the shielding of the intake tube from the combustion blast. See the way the inside end of the stack is cut so that only a relatively small part of the exhaust gas takes this route out, while the greatest part escapes through the exhaust.



The NRL report made the rounds and apparently impressed somebody at the Low Temperature Laboratory at the National Research Council of Canada. Low temperature research is not easily associated with pulsejets, but that is what happened. Taking a good look at the NRL engine, the guys in Canada developed the above 3'6" machine that developed 3.5 lbs thrust.

It does not sound like much, but it was not the point. Optimized for propulsion purposes, it would probably have developed much more than that. But, it was actually a hot-air blower, not a propulsion engine. In winter, such pulsejets blew into large underground diffusers and produced a huge amount of hot air that slipped among the tracks, rods and bell cranks of remote railway switching stations, keeping the vital parts clear of snow and ice.

A paper describing the development of the blower makes some interesting points, one of them being the impossibility of starting such a device without forced air. Tricks just do not help, it seems. The initial conditions necessary for pulsation cannot be created by the stationary fuel-air mixture.

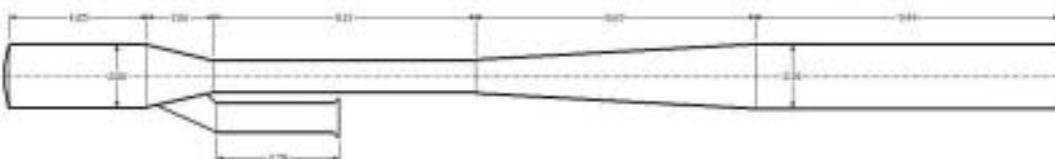
This point has been successfully disputed by some enthusiasts -- in Florida, Mark 'Thixis'

actually starts some of his home-brewed pulsejets with a spray of methanol and a match and they roar away, never even getting close to compressed air. Bruce Simpson in New Zealand has discovered that a sufficiently big valveless pulsejet will not need forced air either. His very big Lockwood-style engine just needs propane and spark to start roaring. It just goes to show how questionable all the theoretical knowledge about pulsejets really is.

Right or wrong, the NRC team developed a forced air-and-fuel jet you can see on the above photo, mounted on the elbow of the bent intake/exhaust tube. Compressed air was blown through the jet, picking up propane on the way. Once the engine caught on, compressed air was disconnected and the jet would work with normal aspiration. A neat design detail worth noting.

Chinese CS

Thanks to Don Laird who made a drawing according to a factory-built example in 1993 and Kenneth Moller, who published the plans on his website at the end of the 1990s, a Chinese-manufactured engine has become a popular design among amateur engine builders.



Though legend says that it was designed in Europe, there is little evidence to support the story. In the 1950s and early 60s, it was produced by CS of Shanghai, until very recently a notable manufacturer of conventional 2-stroke piston engines for model aircraft. The company no longer exists – or at least does not manufacture model engines anymore.

Two models were available on the US market – the SJP-1 (22" long, rated at 2.6 lbs static thrust) and SJP-2 (34" long, rated at 5.1 lbs static thrust). Both were designed to use liquid fuel (regular car gasoline). Today, most run on propane, but that is a later, amateur development.

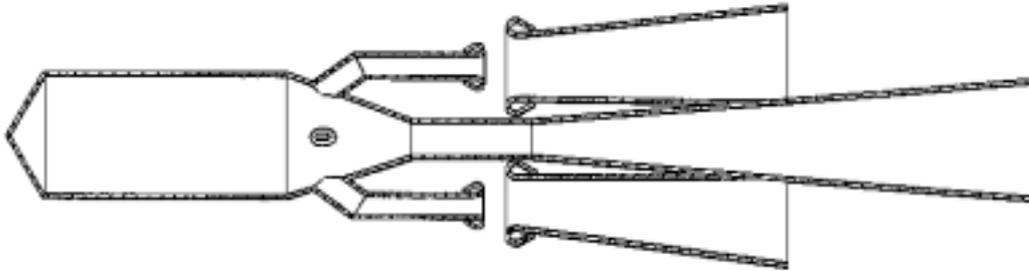


The engine is back in production, after a fashion. You can order stainless steel parts from Conception GLC Inc, a Canadian company run by pulsejet enthusiasts and involved in several interesting engine designs. The picture above shows the engine put together from their parts kit.

It is a very interesting and very controversial engine. Unlike the Logan, the intake port (which also serves as the auxiliary exhaust) branches out from the chamber very close to the exhaust proper. Instead of fresh mixture entering the chamber on one side and hot gas on

the other, they enter virtually from the same side, in streams that impinge on each other at an angle of approximately 45 degrees.

Some designers have been quite taken by the layout, sometimes to extremes. The mid-1960s effort of a Frenchman, Rene Malroux, on the next picture is a case in point. I have no data on its performance, but it would have to be extraordinary to justify the forbidding bulk.



On a more reasonable level, Larry Cottrill of Iowa, a tireless inventor of practical designs accessible to the amateur, has developed his Focused wave Engine (FWE) as a slightly simpler to build and entirely valveless kind of 'Chinese'. The picture shows an example built by Eric Beck roaring away on the snowy background. One of its notable features is a very short length by valveless pulsejet standards – just 26 in.



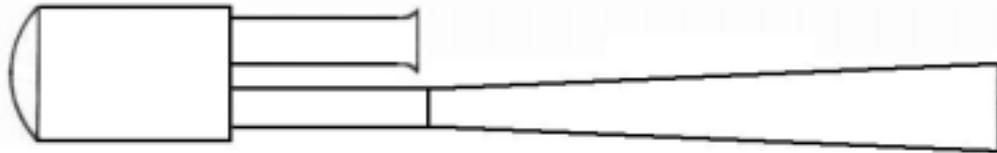
Opinions on the effectiveness of the Chinese engine vary. Some builders have found it a waste of time. One builder I know, who built his example after a few successful Lockwood engines, described the output of his 'Chinese' as "a hamster blowing through a straw". It has to be noted, however, that his version had a straight, constant section tailpipe and did not have flared lips either on the intake or the tailpipe ends. Both details would tend to reduce performance.

Other people say the Chinese produces an adequate amount of thrust for its size and mass. One expert even claims it is one of the best designs around. It is possible that the poor-performing engines were built to wrong proportions, however. That would account for the unusual discrepancy among the performance accounts.

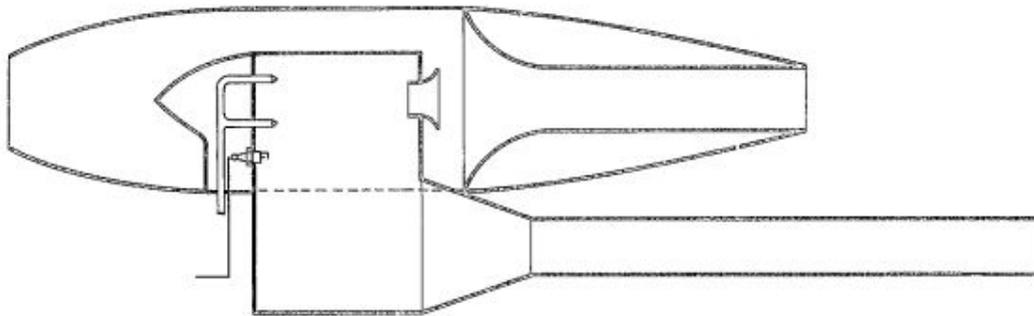
My personal experience with the Chinese is very positive. At a May 2005 meeting of pulsejet enthusiasts at the Babcock vineyard near Lompoc, California, two different-sized CS-style engines had their thrust measured under the same circumstances and both turned out impressive figures – the smaller one built by Mikhail Jones of Oregon produced 4.6 lbs static thrust and the larger one by Ed Knessl of Arizona did 5.3 lbs. Given the engine size, the figures impressed everyone present.

More can probably be expected soon, as Knessl, for one, continues to develop the concept in various directions.

The Back-Enders – Bohanon and Thermojet



As the above sketch shows, the intake does not even have to be on the side and bent backwards. One can simply have it stick out of the rear end of the combustion chamber. The slight disadvantage of this layout is the same as for the bent-back exhausts -- it has to suck fresh air against the stream if the engine powers a moving vehicle. However, unless the forward speed is really high, this does not appear to be a great problem.

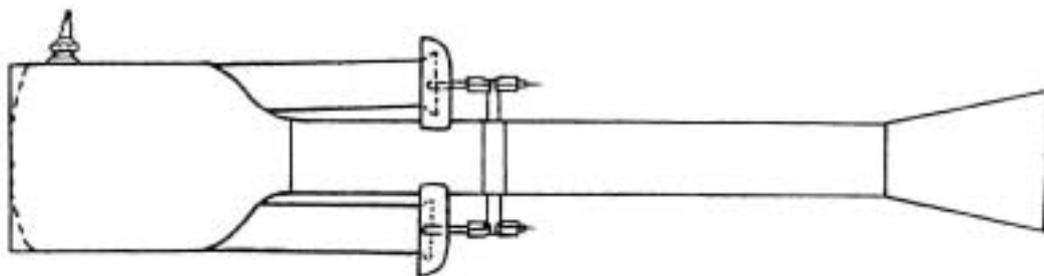


One of the most sophisticated efforts in this direction was the work of Robert H. Bohanon, an engineer with the NACA in the 1940s and 50s who seems to have done most of his work with ramjets and thrust augmentation. The above sketch shows his "valveless intermittent ramjet" engine, as he called it. I have no idea why he avoided using the 'pulsejet' tag.

It is a very interesting layout. Seemingly, the combustor 'intake' is given greater attention than the exhaust, which appears to be there mostly for the purposes of providing proper resonance. The use of multiple injectors spraying fuel into the incoming fresh air is also unusual. Most other engine designers spray their fuel downstream into the incoming air or at right angles across the stream. The Bohanon inlet must have produced very strong turbulence for this layout to work.

What seems likely is that the cowled ejector idea of the Bohanon would also work on the Chinese CS.

At about the same time as the Chinese CS engine was marketed in the US, model aircraft builders could also purchase the so-called Thermojet from selected model shops. It was among the best-known and most successful commercially available pulsejets of the time.



Designed by John A. Melenric and manufactured by his Thermo-Jet Standard Inc. of Kerrville, Texas, this device had between two and four short parallel intakes flanking a long exhaust. Splitting the intake tube into several smaller ones increases the impedance, allowing the intakes to be shorter. The most common model, J-3 200, drawn above, had two.

The Thermojet endeared with its simplicity but reportedly disappointed with its

effectiveness. The 3-foot 3-lb engine (counting the weight of the propane plumbing but not the fuel tank and fuel) generated 3 lbs thrust under the best circumstances, but this often degenerated to something like 1 lb.

People who tried it on flying models reportedly found out that it consumed vast amounts of the propane fuel – over 16 lbs per hour at full thrust -- while often failing to push their models to a successful take-off. I can offer no obvious explanation for the poor performance. I could not find the Thermojet described in any serious research paper and have had to rely on modelers' lore and some contemporary tests performed by modelers' magazines.

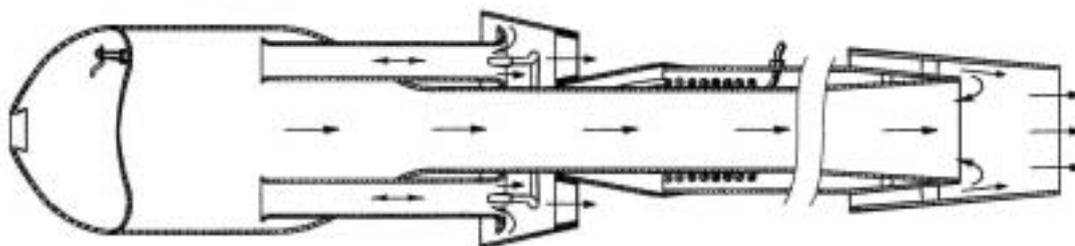


It may be that the Thermojet only really works well in larger sizes. That would account for its poor record with flying model builders but reports of successful exploits in the world of 'real' flying. For instance, a big version is said to have powered man-carrying sailplanes, just like the *Escopette* did. Here's a photograph of a big one -- a man-sized engine -- on which I have no hard data on it. I have never seen a picture of a sailplane with a Thermojet.

The most ambitious Thermojet by far seems to have been the engine on the

picture below – apparently the final flowering of Melenric efforts – dating from the early 1970s. It was almost certainly built to power a flying drone. The designer claimed his engine was good not only in the speed range normally achieved by pulsejets (i.e. under Mach 0.5) but almost up to sonic speeds. This was achieved by careful streamlining and ducting of fresh air. (Melenric is not the only one to claim successful high-speed application – a specially streamlined *Escopette* is said to have achieved Mach 0.85 powering a drone.)

From the simplified cross section shown below, one can see that the basic layout follows that of the model-sized Thermojet. It is also clear, however, that the intake tracts (three of them, radially disposed around the central exhaust tube) project well into the combustion chamber in order to deliver the fresh charge at a precisely (acoustically) determined place. The same feature can be seen on the larger flying-model Thermojets, too. One might argue that the inboard-projecting intake of the NRL engine is but a variant of this layout.



According to the inventor, the front wall of the combustion chamber was profiled to resist pressure shocks, rather than to offer any aid to the mixing of the incoming charge. The front dome is empty (it is there solely to provide streamlining) and is cooled by air passing through an intake and several small outlets in the dome wall.

The second notable feature of the Melenric engine is the fresh air scoops around the intake and exhaust ends. The scoops and ducts serve to provide extra fresh air near the ends which allows the engine to ingest it more easily in the intake part of the cycle. It is less of a struggle for the engine to suck fresh air against the stream.

In the expansion part of the cycle, this extra air gets blown rearwards through the back

ends of the scoops, pushed by exhaust gas. The scoops and ducts serve to provide some thrust augmentation. To some extent, the benefit of augmentation of intake and exhaust is negated by the increased drag, but at very high speeds, this is probably the only way such an engine will function at all.

The third notable feature is the effort to utilize the waste heat of the engine to gasify the liquid fuel and inject it into the engine as gas. Fuel is led to the engine through a metal pipe coiled around the exhaust (see the central part of the engine on the picture). Exhaust heat boils and vaporizes the fuel, and the vapor is led to injectors that poke into each intake tube.

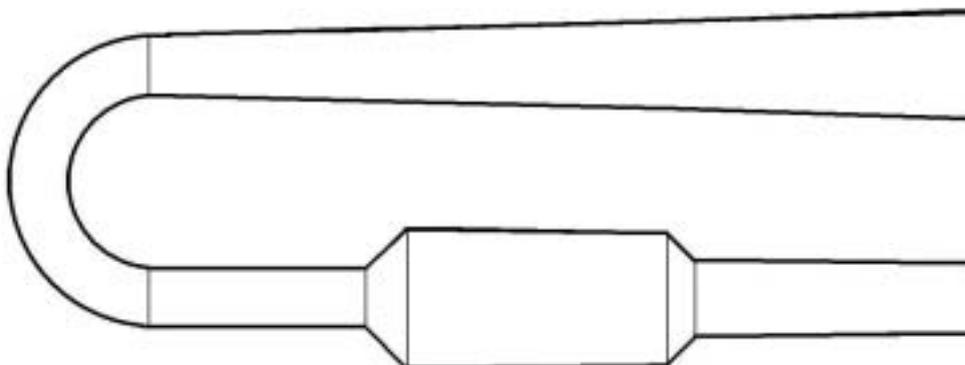
Pre-heating and vaporizing the fuel served several purposes. One was the possibility of using liquid fuel like Jet-A, with its greater energy content, but still do without a sophisticated injection system that required a separate power supply. Another good point was the steady delivery of fuel regardless of engine position. 'Ordinary' Thermojets, in contrast, only worked well when the engine was more or less level. Notable inclinations were likely to cause switches from liquid propane delivery to gaseous and back, as it sloshed in the tank.

The jets, optimized for liquid, could only deliver a poor amount of gaseous fuel, meaning that the power output fluctuated wildly. Also, the engine was optimized to work at a certain fuel pressure. With the tank more than half empty, the pressure dropped too low and the already poor performance declined to a uselessly low level. Finally, in a manner similar to the Gluhareff pressure jet, the strong flow of pressurized gaseous fuel helped boost the intake flow considerably, forcing the mixture into the chamber. It is a very good way to utilize the excess heat provided by the pulsejet engine.

The Thermojet layout looks attractive to the amateur builder and many have been made by enthusiasts, with varying success. At the moment, the most serious attempt at development I am aware of is that of Eric Beck's semi-pro engine outfit (<http://www.beck-technologies.com>).

[NOTE: Historically, the term 'thermojet' applies to a jet engine whose compressor is driven by an auxiliary engine, like the one powering the Campini Caproni CC-2 aircraft, officially the first jet aircraft ever (1940). Some historians give precedence to the essentially similar device built and flown 30 years earlier by Romanian Henri Coanda. Such engines later came to be called 'motor jets', so that we can probably be justified in using 'thermojet' as a generic name for this specific kind of a valveless pulsejet.]

Ecrevisse and Lockwood-Hiller



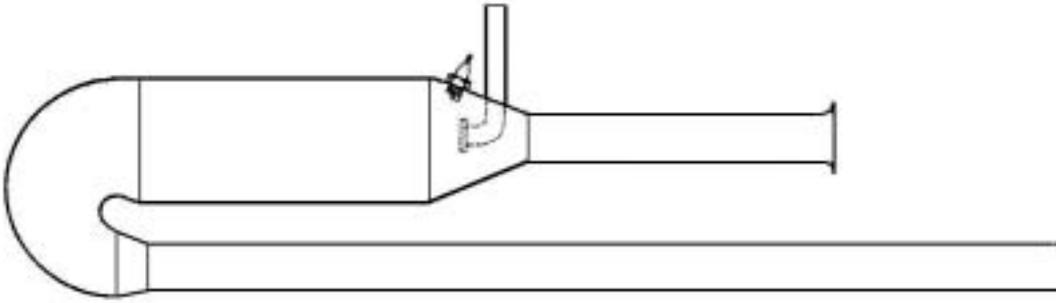
The U-shaped Lockwood-Hiller engine is arguably the most familiar valveless design by far. This is possibly due to the effort of Ed Lockwood, inventor Raymond Lockwood's son, to preserve his father's legacy and keep it in the public eye (not to mention selling copies of his papers), but there is no denying that the Lockwood is an effective valveless pulsejet engine, possibly among the best developed ever, despite its deceptively simple appearance.

The mixture was generated by the mixing of propane gas, which was injected through a jet either built into the side of the combustion chamber or on a strut projecting into the chamber, or on two crossed struts spanning the front part of the chamber. The chamber is the drum-like broad part of the engine. The short tube to the lower right is the intake. The flaring cone end is the exhaust.

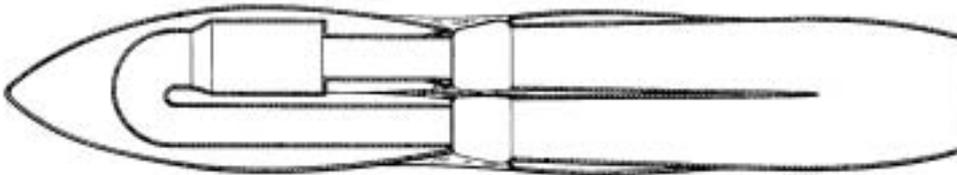
Later on, some researchers and enthusiasts successfully used liquid fuel injection, but propane remains the simplest and most popular.

Ray developed it in the early 1960s, partly at the Fairchild and Hiller companies and partly on his own, mostly on the basis of previous French designs, themselves based on the

Marconnet, to which Hiller had purchased rights. (In 1964, a patent for this engine was issued in Lockwood's name -- curiously, given that it is but a development of a French patent.)



The most notable of Lockwood predecessors was the *Ecrevisse* ('Crayfish') developed at SNECMA by Pierre Servanty and Bertin. The pictures above and below show two versions of the *Ecrevisse*. One (see above) is a basic early model and the other (below) a streamlined later version with thrust augmenters. I will not deal with it further, as the data on the *Ecrevisse* are still not easily available. The Lockwood is essentially the same design and much better known to enthusiasts.



Reportedly, the "standard" Lockwood/Hiller engine (Model HH 5.25-7) offered by Hiller pushed out 280 lbs of thrust. It weighed only 30 lbs. I believe the latter figure, for it is just an empty tube. However, judging by the efforts of enthusiasts building Lockwood-type engines, the former figure is somewhat suspect. It may have been available under laboratory conditions, or at a certain favorable flight speed, but no one else seems to be able to get anywhere near such high power outputs even when the layout was copied slavishly.

Some observers have opined that Lockwood/Hiller may have been intentionally optimistic with their figures at the time, as their efforts were obviously pitched at defense contracts. Higher figures were more likely to produce R&D grants. Kinder observers pointed out that critics may be comparing figures for augmented jets with those for un-augmented ones.

The way the Lockwood engine functions is outwardly simple and fits the explanation I have given at the beginning of this paper very closely. However, remember that it is among the most extensively developed valveless pulsejets ever (with the exception of the *Ecrevisse* and *Escopette*) and thus features some fine details that one can develop only after a lot of careful experimentation and testing. This is particularly true for the fuel supply system.

Some of the details evade simple explanation and have generated controversy in the circles of pulsejet enthusiasts. One of the more controversial features is the fact that the exhaust tube is very narrow where it exits the combustion chamber. Its area is only about a half of the intake tube area. In most other pulsejets (including valveless ones), the exhaust is bigger than the intake.

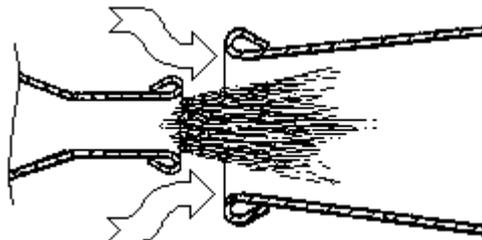
One reason I can see is that the rather large diameter of the intake tube is necessary to facilitate breathing. However, the total area of both apertures (front and rear) must be in certain relationship to the volume of the chamber in order for the chamber to work like a Kadenacy oscillator. If that area is too large, the Kadenacy effect will be lost. So, if the Lockwood is to have a big intake for good breathing, it must have a small exhaust aperture.

Bruce Simpson, a well-known New Zealand-based pulsejet developer, says that the megaphone shape of the exhaust -- a small hole at the chamber flaring out to a fairly large diameter rear end -- is a good "Kadenacy pump", which enhances the pressure swings in the chamber. Enthusiasts Graham Williams and Larry Cottrill have pointed out that it makes for good ignition, shooting a slug of retained hot gas deeply into the center of the chamber, from

where combustion can spread through the chamber easily and evenly. They may all be right.

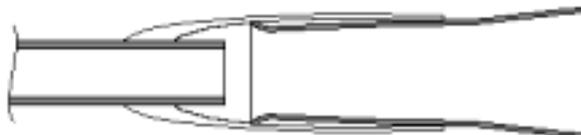
A curious detail is that the Lockwood engine, if built properly, does not have a single 'straight' (cylindrical) part. All its parts are tapered and its cross-section changes constantly from front to back. The reason here is probably the wish to escape the constraints of acoustic resonance. Such a shape will be willing to resonate in a fairly broad spread of frequencies. Among other things, this will allow the engine to be throttled up and down easily.

What Lockwood may well come to be remembered for in history will be the fact that he was a prominent champion of thrust augmentation. A thrust augmenter is a device that uses hot exhaust gas to suck additional fresh air into the exhaust jet gas stream. Though the device was known long before this application, it gained general attention in the field by increasing the thrust of the Lockwood engine very noticeably.



Hot gas streaming out of the end of the exhaust tube (on the left of the picture) enters a venturi-shaped duct on the right, sucks fresh air behind it and pushes fresh air before it. The result is a net increase in thrust.

The principle is very old and many a designer has tried to exploit it. The majority of those experiments were performed either with compressed air (notably by NACA) or with turbojet engines. The practical results never justified the added complexity and bulk (except apparently on some very special designs). Yet, when augmenters are used on a pulsejet, the gain is quite appreciable. If I am not mistaken, this was first done by our friend Bertin of SNECMA, and the patent on pulsejet augmentation is held in his name. Above is a sketch of an elegant-looking Bertin augmenter. Below is the picture of rather cruder but apparently very effective device on a homebuilt Lockwood engine of rather generous proportions, powering a gokart.



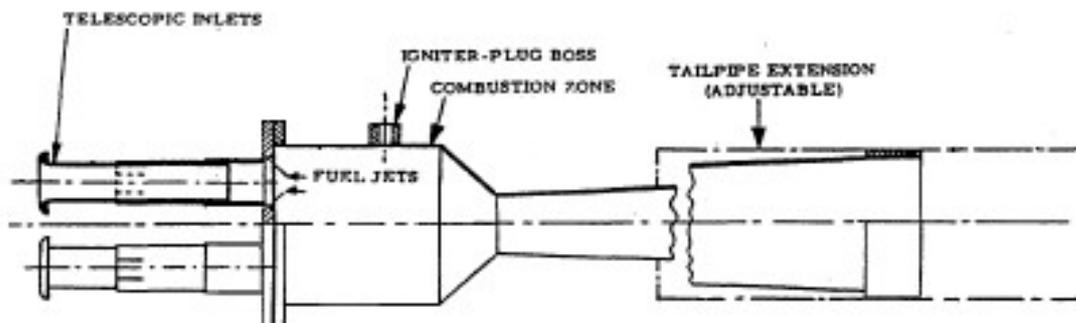
[As an aside -- the picture also shows the way a pulsejet can be bent. Unlike the steady-flow jet engines, pulsejets do not appear to be greatly affected by bends in their ducts. The reason is not quite clear. I think that the peculiar nature of the pulsejet flow -- part flow and part wave -- could be the reason. Unlike flows, waves are not bothered by turns and can

follow any change of direction of the duct easily. This property may be easing the fluid flow around the bend, lessening the turbulence that the same bend generates in steady flows.]

Ray Lockwood believed the gain in thrust came from a combination of aerodynamics of the augmenter and the pumping effect. The curved front lip of the duct generates forward 'lift' as air streams over it. Exhaust gas boosts the flow and generates extra lift (or perhaps extra 'pull' in this case). However, this does not explain the particular suitability for pulsejets. On other jet engines, thrust augmentation is of marginal use at best.

There are several reasons for this. First, ejectors in general are more effective with a pulsating, rather than steady, flow. In the case of the pulsejet, the mechanical pumping effect is greater due to the fact that the exhaust pulses create toroidal vortices, which expand to the walls of the augmenter and travel along as fluid pistons, pushing fresh air ahead and pulling more fresh air behind them. Such a 'piston' is more effective than a simple flat pressure front because it stays together over a much longer distance before degrading. In addition, its swirl also appears to act as a rotary pump, drawing even more air with it. All this air adds to the reaction mass and greatly increases thrust.

Second, the augmenter utilizes surplus heat in the exhaust stream – similar to the trick Bertin employed on the *Escopette*. Hot gas ejected into the conical duct mixes with the fresh air passing through and heats it up. Heating makes air expand, which increases static pressure on the walls of the augmenter. A component of that pressure is aimed forward, pushing the augmenter. Again, the toroidal swirl helps the process, as it is an efficient mechanism for blending the hot gas with cool air.



Claims of the effectiveness of thrust augmenters on pulsejets vary considerably. I have personally seen a hastily cobbled augmenter boost the thrust of a small Lockwood by 40 percent. That would seem to confirm the claims that well over 50 percent is available with careful design. However, one must also bear in mind that the augmenter presents extra aerodynamic drag. Over a certain speed limit, this will start outweighing the extra thrust.

An interesting variation on the Lockwood formula is an engine a team led by J.A.C. Kentfield developed in the search of lower fuel consumption and more compact dimensions. As we saw on the example of the Thermojet, splitting the intake area into several intake ports of smaller diameter increases the intake impedance and allows the tract to be shorter. This allows a proportional shortening of the rest of the engine. The Kentfield team developed a



very short straight engine with four intake pipes. The intakes and the exhaust were adjustable for length to allow variations in the testing program.

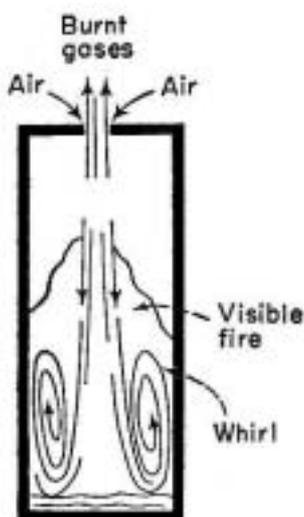
A version of that engine has been built by an enthusiast, too – Bill Hinote of California,

who went to the trouble of developing a special liquid fuel injection for the engine as well as building curved recuperators for all four intakes. An early photograph can be seen above. As you can see from the curious distribution of heat, at that point in the development, the flame front was still too far downstream from ideal.

Anyone interested in building a Lockwood is well advised to browse the Internet sources for more information on this engine. I will mention just a few -- the official Lockwood website (<http://www.blastwavejet.com>), Eric Beck's site I have already cited, Bruce Simpson's small jet engine site (<http://www.aardvark.co.nz/pjet>) and Paul Sherman's fire and thunder website (<http://www.brainvirus.org>), but there are many others.

The Lockwood site is rich in historical information and offers the possibility to purchase engine plans. This is not a snake-oil site but a genuinely enthusiastic effort, but one should be aware that the documents there date back to the cold-war era and contain some deliberate misinformation. Nothing that will hurt an amateur enthusiast, though.

The place to see the Lockwood in theatrical action -- perhaps not quite the use envisaged for it by Ray Lockwood -- is the Survival Research Laboratories (SRL). You can find about them at www.srl.org. This is a group of people devoted to mechanical mayhem for public entertainment, preferably involving heat, fire and noise. One of their most popular tools are pulsejet engines, Lockwoods as well as some others. Another strong recommendation; this time for the entertainment value.



Reynst

Diverse as the two dozen or so engines we have described so far may be, most have one feature in common: at least two openings. If there are two, one is the intake and the other the exhaust, with the intake most often serving also as an auxiliary exhaust. If there are more than two, there is one big main exhaust and several smaller intake/exhausts.

Enter a truly original thinker, Francois H. Reynst of Switzerland. Like most of us, he liked to play with fire as a youngster. While he tried burning alcohol in his mother's jam jars, he accidentally discovered an interesting phenomenon. If he put a little alcohol on the bottom of jar, closed it with a lid that had a small hole in it, and ignited the alcohol vapor at the hole, a curious pulsation ensued. Flame would shoot out of the hole, only to be sucked inwards and then ejected out again at a rapid pace. It looked as if the jar breathed fire. What Reynst discovered was a peculiar pulsating combustor he would later develop into a serious industrial product.

What was happening in the jar was a relaxational oscillation driven by the combustion of the mixture of air and alcohol vapor. Combustion would generate a great amount of hot gas (mostly carbon dioxide and water vapor). Pressure inside the jar would rise and the gases would expand out through the hole in the lid. Because of inertia, the gases would overexpand and the resulting partial vacuum would suck fresh air in. This fresh air would whirl inside the jar, mixing with alcohol vapor. The mixture was ignited by the remaining free radicals present in the hot gas that would remain clinging to the walls inside the jar.

This simple experiment is very easy for everyone to reproduce at home. Just make sure that the lid is sealed tight and preferably put the jar into some water, so that it gets cooled, or the heat will crack it within several seconds. Of course, various metal vessels can also be used. Reynst was fascinated by this and eventually published a research paper on the behavior of such a combustor. Later still, he developed an industrial combustor working on the same principle. A simplified layout is shown on the next sketch.

The chamber has a conical intake/exit nozzle that serves as the accelerating jet in the exhaust phase and a decelerating diffuser in the intake phase. A mixing chamber encloses the nozzle leaving only the mouth of the chamber free. Air flows into the mixing chamber from below and gas is added through a feed on the upper left. Fresh mixture is sucked into the pot through the narrow slit between the chamber mouth and the mixing chamber.

The chamber sucks in the mixture from the sides rather than air from above because of the distribution of pressures. When the suction starts, air that is straight above the mouth is

still moving away from the engine due to inertia, trailing the flow from the previous exhaust pulse. The pressure above the mouth is thus below atmospheric, while the pressure in the mixing chamber is higher -- at least atmospheric, possibly slightly higher. So, the flow that replenishes the chamber commences through the slit, rather than through the big intake aperture on the top.

The unusual conical item in the middle of the chamber is an additional intake diffuser that helps form the kind of flow that works the best. This is another peculiarity of the Reynst 'pot'. As the air is sucked from the sides into the chamber, it forms into doughnut-shaped (toroidal) vortex that travels towards the bottom of the chamber. The diffuser entrains it on its way, preventing it from expanding too early. When the vortex hits the bottom it rebounds and -- expanding to the walls of the chamber -- climbs back upwards.

The diffuser thus separates the downward part of the internal flow from the upward-moving part. Unlike most other pulsejet combustion chambers, this one has a tidy two-way flow, with the mixture traversing the entire chamber at least twice -- from the top down and from the bottom up. As it whirls all the time in the toroidal vortex, all of the mixture makes high-speed contact with the chamber wall at some point. No part remains isolated in the gas 'core' as happens in some other engines.

This makes for very reliable ignition by free radicals that remain in the thin boundary layer of hot gas clinging to the chamber wall. They are intimately and vigorously mixed into the flow. So, the ignition starts at about the moment the vortex touches the bottom and continues on the way towards the top. At some point of travel, internal pressure created by combustion makes the vortex explode. The internal pressure jumps steeply and the whirling mass of hot gas is ejected from the engine at the top.

The filling of the chamber is helped by vortex behavior. As ignition starts inside the vortex, the heat adds energy to the spin and the vortex accelerates its whirling and contracts. This lowers the volume of the ingested mixture and still more mixture is sucked in. The inventor also described a thermal side to the cycle, with contractions strengthened by the transfer of heat to the walls of the chamber. As a result of this complex process, the Reynst engine reportedly exhibits the most efficient Kadenacy pumping of all pulsejets.

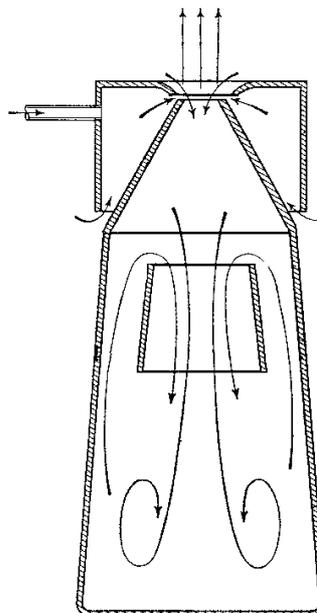
Young F. H. Reynst thus gave birth to a pulsejet engine that -- unlike any other -- only has one aperture. This is a logical layout -- after all, it is only with continuous combustion that intake and exhaust must be separate. With pulsating combustion the separation is not essential, as the intake and exhaust parts of the cycle are not simultaneous. The combustion chamber thus 'breathes' in and out through the 'mouth'.

The Reynst pot is not an acoustical resonator and its working cycle is much slower (by an order of magnitude) than the natural frequency of its chamber. However, by pure luck during testing, Reynst discovered a way to make it into an acoustical resonator and improve performance very notably.

He used a flue to take away the hot gas, as his tests were performed inside a building. One day, the flue split transversally at some distance from the pot. The lower part fell down, leaving only a small gap between the pot and the broken flue. The combustor suddenly switched into high gear, quadrupling the frequency and increasing the pulse amplitude notably. After that, Reynst instigated a program of development that perfected the resonator exhaust for practical applications.

The complete, fully developed Reynst combustor looked similar to the one drawn in a simplified manner on the next picture.

I can see a case of useful switching of the resonance modes between the intake and exhaust parts of the cycle. The fundamental mode is that of a single quarter wave resonator, with the antinode at the bottom of the chamber and the node right outside the end of the exhaust. At the same time, the vessel also resonates in the first odd harmonic of the fundamental, with the chamber being the quarter-wave resonator and the exhaust a half-wave

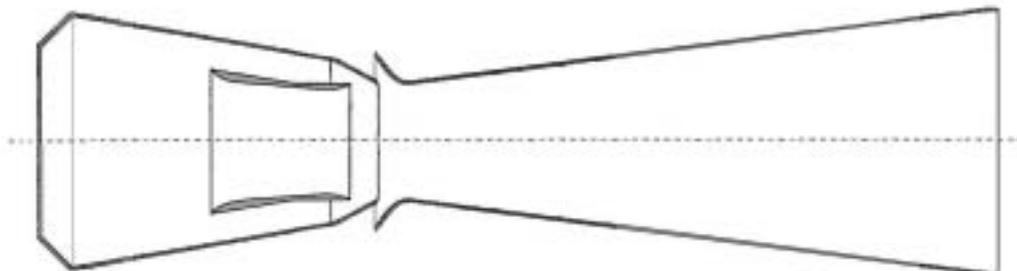


one. The antinodes are at the bottom of the chamber and in the middle of the exhaust. The nodes are at the intake slit and at the outer end of the exhaust.

The former mode is important in the expansion part of the cycle, when the chamber generates the peak pressure, which is relieved downstream, towards the end of the duct and into the atmosphere.

In the intake part of the cycle, the pressure is the lowest in the combustion chamber and in the middle of the exhaust. It is higher at the intake slit and at the end of the exhaust, so that fresh air rushes in at those two points, refilling both the chamber and the exhaust for the next cycle.

(This is a rather simplified explanation but close enough to the real events to be true for our immediate purpose.)



The whole thing was about a meter long. "The noise produced," wrote Reynst, "can be heard, depending on the wind, at about six miles." This appears to have been its undoing.

What must be remembered is that Reynst never intended his combustor to be a jet engine. It was an industrial device, designed to work as a blower furnace. The pesky noise and considerable vibration must have made it an unpleasant thing to work with. Its ability to produce a great volume of high-temperature gas while burning cheap fuels (it works well on heavy oils and even on coal dust!) never really saw practical application.

Reynst never tried optimizing it for thrust. At the time, jet engines were practically unheard of. However, there is no reason that I can see that would make it any worse than the more common valveless pulsejets. Indeed, it might easily be the best of them all, given its excellent pumping and mixing ability.

Just imagine the blunt bottom of the pot rounded into a more aerodynamic shape (closer to the teardrop form). Imagine also the exhaust resonator extended forward to enclose most of the chamber and serve as the annular fresh air duct. The resulting form gives a very nice jet engine shape, while remaining about as simple as any other valveless pulsejet.

Another thought that intrudes is a similarity to the Chinese CS engine. Look at the section of the CS and rotate it around the longitudinal axis. What you get is a Reynst 'pot' with a long tubular exhaust. In a manner of speaking, the Chinese engine is a Reynst with a tubular, rather than annular, intake.

WHAT NEXT?

The next step in the development of the valveless pulsejet is difficult to predict. As I noted in the paper, methods have been developed to make the design more predictable. This is pushing the pulsejet closer to practical applications. My guess is that those applications will only come if the problem of noise and vibration is addressed. No serious, long-term work in that direction has ever been done to the best of my knowledge.

The problem is considerable, but so are the means at one's disposal. Sound control technology has made enormous strides since the 1950s when pulsejets were last considered for everyday applications. In my opinion, however, those methods will really work well only if their basic task is eased, for the noise a pulsejet makes is enormous. As one enthusiast has noted, "pulsejets redefine noise".

The simplest way to cut at least some noise is to have it do some useful work. Theory says – and some experiments confirm – that having two identical pulsejets work out of phase will cancel some of the noise out. This is the kind of ‘easing the task’ I am hoping for. One should not be too optimistic, for pulsejet noise has many elements. Out-of-phase cancellation will be just one of the many steps required. But, it will be a good beginning. Experiments made so far (by Kentfield at the University of Calgary) indicate that some useful reduction in noise is indeed available by this method.

Making two pulsejets work as an opposed pair is easy. Theory says that they should help each other work more efficiently. One should theoretically be able to increase the mean effective pressure in the other and vice versa. In practice, this has not been achieved. Indeed, Kentfield reported a slight decrease in total thrust for the paired engines, compared to the sum of two singles.

However, his efforts were somewhat cursory. They were not aimed at “mutual supercharge” (as he called it), but simply at making the engines work in opposed pairs and reducing noise. Both aims were achieved in several different ways with apparent ease.

I have great hopes for a pairing of engines that will achieve not only the reduction of noise but also a boost of operating efficiency. One of the best side effects of the process – if the design is done right – will be the reduction of vibration. Like the opposed-twin piston engine, two pulsejets working together can be made to cancel the vibrations out.

A further reduction of noise and increase of efficiency probably hides in proper thrust augmentation. Mixing of fast hot gas with slow cool air has worked to lower the noise of turbojets. There is no reason why it should fail to do a similar job for pulsejets. More massive but slower exhaust flow will at the same time make the pulsejet more effective at low speeds.

Next, the use of surge chambers, sound-deadening materials etc. should be considered.

If we can make the pulsejet more acceptable, we can turn our attention towards some serious competition with the other jet engines. Advances are available in efficiency – from various ways to boost combustion pressure to the utilization of the great amount of waste heat.

Afterburning has only been tried in a cursory manner, yet it would offer a performance boost for safer takeoffs, while ‘regular’ and fuel-efficient power levels are used for cruising. Water injection has been mentioned by many and tried by very few.

Finally, with some careful design, pulsating combustors may come back to the heart of the turbine engine, where their French inventors thought they should be from the very start.

In short, there is a great array of methods and techniques at one’s disposal to make the pulsejet tamer, more suitable for everyday use and an even livelier performer. Few if any have been tried with any serious dedication. The field is still wide open. This is the last corner of jet propulsion practically neglected by the big industry and completely open and accessible to enthusiasts. I hope someone takes serious advantage of the situation and makes the breakthrough this amazing engine deserves.

The author of the document can be contacted by e-mail at bruno.ogorelec@gmail.com or by conventional mail at Terna Information Services, Kopernikova 10, 10020 Zagreb, Croatia.

Note on the use of illustrations.

The illustrations used in this document come from a broad spectrum of sources. Few are actually mine. For most, I do not even know the source anymore. Some have been modified by me to suit the purposes of this document better. This is not a commercial publication. I gain nothing from its publication but dubious reputation among pulsejet enthusiasts. If you see a picture in there that is yours, and you object to its use, please let me know. I will pull it out and replace with some other. If this is not sufficient and you are still irked about it, well, sue me.