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# A PROGRESS REPORT ON PULSEJETS

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## Introduction

At last year's Conference, the writer described the beginnings of a new engine cycle; the water pulsejet ship propulsor and its analogous water pump. The paper should logically have been assigned to the "Marine Power Systems" section of the conference, but was apparently deemed sufficiently far-out to end up in "New Engines and Novel Devices."

As is usual in a new technology, a retrospective reading a year later reveals severe shortcomings and errors in that earlier paper. But more than that, it discussed a very narrow part of a much wider field; that of pulsejet engines and pumps. In the present paper, we attempt to rectify this situation, for propulsive engines at least, by proceeding from the general to the particular, rather than the reverse.

In order to do useful work, an engine needs to perform the following functions:

> Raise the pressure of the working fluid.
>
> Then add heat to it.
>
> Then expand the fluid, doing useful work in the process.
>
> Reject heat from the fluid when it is at a lower pressure <u>or</u> have access to a fresh change of working fluid; the steam engine is an example of the first; the internal combustion engine and the air ramjet are examples of the second alternative.

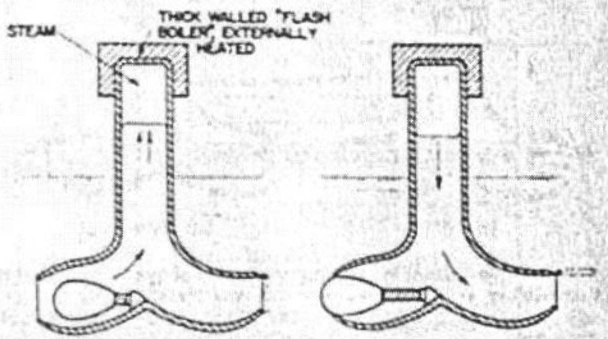
In order to efficiently convert heat to mechanical work, the "compression ratio" must be high; typically between 6:1 and 20:1 for an air-breathing engine. We usually achieve this compression by pistons or continuous flow "compressors" (axial or centrifugal) except in the special case of the ramjet.* An exception is the much misunderstood pulsejet family of engines. In a sense, these use a "piston" to raise the pressure of the working fluid, but the "piston" is the fluid itself, so that there is no need for any moving mechanical parts. The pulsejet can achieve very high compression ratios even under static thrust conditions; possibly higher pressures than are achievable in any other practical way. Thus, it offers the possibility of being an efficient engine, despite the fact that it can clearly be the lightest and the cheapest as well. This seems too good to be true. And why do we have no pulsejets now, or any work proceeding on them if they are so promising?

The answer must be a complex and fascinating illustration of what can happen in technologies which are not properly understood by workers involved in the developmental process; unfortunately, an attempt to analyze the reasons for this lack of basic research would require a separate paper in itself, which probably needs to be written by another author!

## Steam Water Pulsejets (SWPJ)

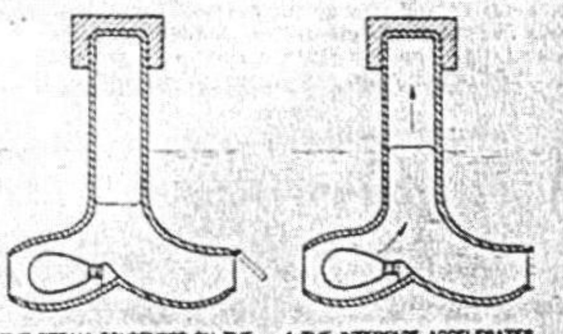
The SWPJ was unequivocally invented by McHugh in 1916. At the time he was trying to invent something else, and it (not unnaturally) took him some time to realize precisely what he had accomplished. His engine could be built only in toy sizes because (we now know) it required surface tension to stabilize the interface between the steam and the water.

Hundreds of thousands of toy "putt-putt" boats were built and sold in the twenties and thirties. A great deal of money was wasted in attempting to scale these "putt-putt" engines up to larger sizes; wasted because (presumably) no one really knew how the engine worked, let alone had a good math model of its operation. Even if they had been given the equations of motion, their solution would have been unbearably tedious in that pre-computer age.



1. WATER INTERFACE ENTERS THE "BOILER" AND STEAM IS MADE AT HIGH PRESSURE

2 STEAM PRESSURE DRIVES INTERFACE DOWNWARDS FROM THE BOILER



3. THE STEAM CONDENSES ON THE COLD WALLS, AND THE LOW INTERNAL PRESSURE ARRESTS THE DOWNWARDS MOTION OF THE INTERFACE.

4. THE INTERFACE ACCELERATES TOWARD THE "BOILER" TO REPEAT THE CYCLE

FIG. 1. A STEAM CYCLE WATER PULSEJET. THE EXIT VALVE (SHOWN DOTTED) IS HELPFUL IN VISUALIZING THE CYCLE, BUT IS UNNECESSARY IN PRACTICE.

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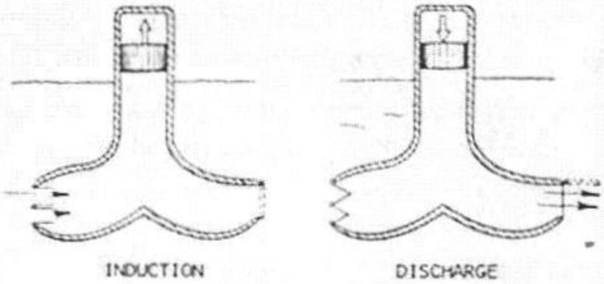
* The air breathing ramjet, as its name implies, obtains most of the ram-air pressure rise $\frac{1}{2}\rho u_o^2[f(M)]$ by slowing the air down prior to combustion of fuel in it, subsequently expanding the air through a nozzle to obtain a positive thrust. It cannot produce a static thrust; its subsonic thrust is low and its specific fuel consumption high. The water ramjet is not a heat engine, but a propulsor which requires a supply of compressed gas.

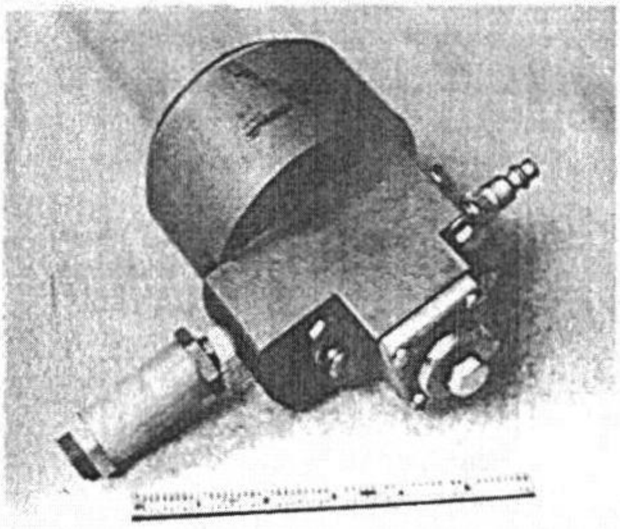
Quite fortuitously, we were able to pick up the ball again in 1971, and as a result of modern developments in fluid mechanics and computers, were successful in breaking the size barrier. Some of our early results were described in last year's paper. Some of our later work is being funded by the Office of Naval Research, and we feel reasonably confident that the SWPJ will have a future in marine propulsion.

By way of recapitulation, the operation of a bifurcated steam pulsejet is indicated in Figure 1. The figure is self-explanatory, but it should be remarked that the "boiler" is nothing like a conventional boiler, and that the term may give rise to misconceptions. The steam water pulsejet (SWPJ) boiler is a compact block of metal - usually copper or brass - which has demonstrated heat transfer rates as high as 25,000 Btu/ft$^2$hr°F and $5 \times 10^6$ Btu/ft$^2$hr. These figures are orders of magnitude better than a conventional "pool boiling" or superheating boiler. Additionally, the steam energy is sufficient for only one stroke, so that conventional boiler safety hazards are not involved.

### The Piston Pulsejet (PPJ)



This piston pulsejet (PPJ), sketched above* for a water propulsion application, may use any "piston engine cycle" to drive it, since the driving cycle is separated from the working fluid by a piston. So far we have only built one driven by compressed air (Figures 2 and 3) and paradoxically, it turns out that, for this particular motive power, the piston is not actually needed. The water itself acts as the piston. Relying on "Humphrey Gas Pump" experience, we anticipate that the same will be true for PPJ's operating on the Otto cycle.



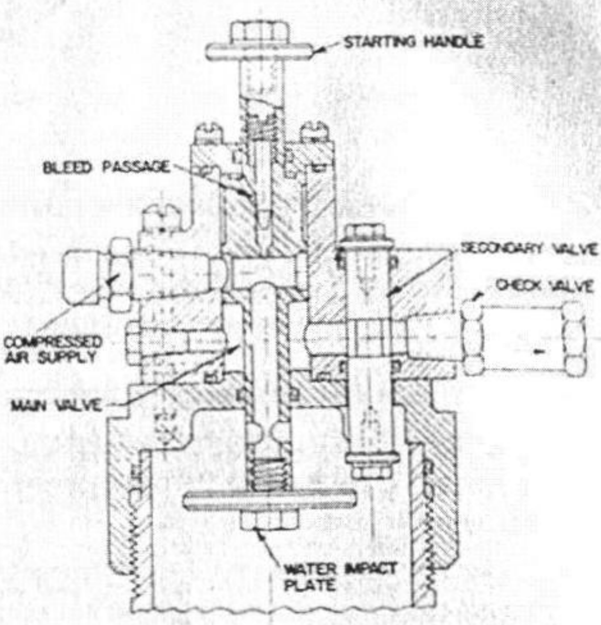


FIG. 2. CROSS-SECTION OF THE PAYNE, INC. THREE-INCH COMPRESSED AIR DRIVEN WATER PULSEJET.

Initially charged with water, downwards motion of the piston results in a pressure build-up which closes the intake valve and expels a propulsive jet to the rear. When the pressure above the piston has fallen to a sufficiently low value, the downwards motion is arrested and the piston starts to rise, allowing a fresh charge of water to enter the intake valve.

The water charge in the engine acts like a "linear flywheel"; analogous to the familiar rotating flywheel of

FIG. 3. TWO VIEWS OF THE PROTOTYPE PAYNE, INC. COMPRESSED AIR-DRIVEN WATER PULSEJET.

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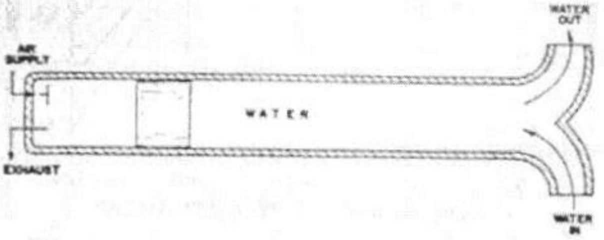
* The exit valve (shown dotted) is helpful in visualizing the cycle, but unnecessary in practice.

a rotary shaft piston engine. The piston is driven by pressure changes above it, like any conventional engine, and these pressure changes can be induced in any of the conventional ways, i.e.

| | |
|---|---|
| Internal Combustion | - Diesel cycle |
| | - Otto cycle |
| Vapor | - Rankine cycle |
| Gas Pressure Change | - Stirling cycle |
| | - Ericsson cycle |
| | - Roesel cycle |



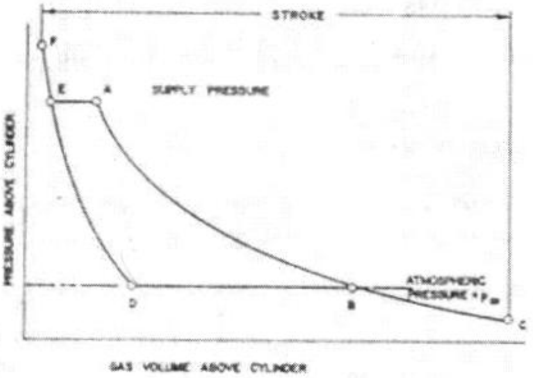


FIG. 4. P-V DIAGRAM FOR A COMPRESSED-AIR-POWERED PULSEJET.

The compressed-air-driven pulsejet of Figures 2 and 3 is the easiest to understand, and of course its performance is a basic analog to any of the above cycles. Referring to Figure 4, the cylinder is charged with compressed air between points E and A and the air valve closes at position A. The air continues to expand, and the downward velocity of the "piston" increases. At position B, the internal air pressure has fallen to ambient, and the piston starts to slow down, stopping and reversing its motion at C. It returns to B along the same adiabatic, at which point a valve opens to vent the cylinder to atmosphere until point D is reached, when the valve closes. The remaining air is compressed by the upward motion of the piston until it stops at point F and bounces back. The air supply valve opens at E, the space above the piston is again charged with compressed air, and the cycle repeats itself.

Such a cycle is modelled in Payne, Inc.'s computer program "ADPJ$," which is based on the equations given in the last section of this paper, and some outputs for an engine of randomly selected geometry (Table 1) are given in Figures 5 through 14.

In Figures 5 through 9, the supply pressure is held at the fairly low value of 450 psi, while the ship speed and exhaust nozzle area are varied. Maximum propulsive efficiency (Figure 8) for the arbitrarily selected geometry is seen to be 0.62 at 80 ft/sec (47.4 knots) when the thrust level is 288 lb.

Table 1. Example Compressed-Air-Powered Pulsejet

| | |
|---|---|
| Total length | 8 ft |
| Diameter | 6 in |
| Ram recovery efficiency | 1.0 |
| Vent valve closes at | 7.9 ft from nozzle |
| Compressed air valve closes at | 7.6 ft from nozzle |
| Supply pressure is | - 450 psi in Fig. 3-7<br>- Variable in Fig. 8-12 |
| Nozzle area ratio* is | - Variable in Fig. 3-7<br>- 2.0 in Fig. 8-12 |
| Ship velocity is | - Variable in Fig. 3-7<br>- 30 ft/sec in Fig. 8-12 |

* Nozzle area ratio is defined as being the ratio of "piston" area to water exhaust nozzle area.

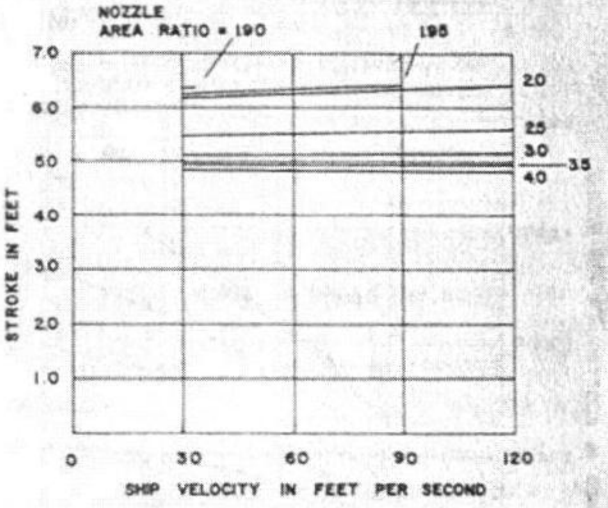


FIG. 5. PISTON STROKE FOR THE EXAMPLE PULSEJET.

In Figures 10 through 14, the nozzle area ratio was arbitrarily held constant at 2.0 and the ship speed at the relatively low value of 30 ft/sec, while the supply pressure was increased. As would be expected, the thrust increases rapidly with supply pressure, and the propulsive efficiency falls. At maximum pressure, the high thrust level of 1300 lb is quite remarkable for a six-inch-diameter engine.

These calculations assume a relatively sophisticated valving system, where the location of the piston (or water interface, if the engine has no piston) is sensed in some way and appropriate valves are opened and closed.

A simpler practical embodiment is that shown in Figures 2 and 3. In this engine, the rising water interface strikes the impact plate and pushes the main valve to the "up" position, allowing compressed air to flow into the space above the water. The water is pushed down by the air pressure, the main valve falls to a closed position because the force associated with the pressure above its bleed passage becomes greater than the force tending to hold it open. After it falls, it opens the cylinder to the secondary valve passage, but the secondary valve itself is held closed by the overpressure within the cylinder. As the air continues to expand by

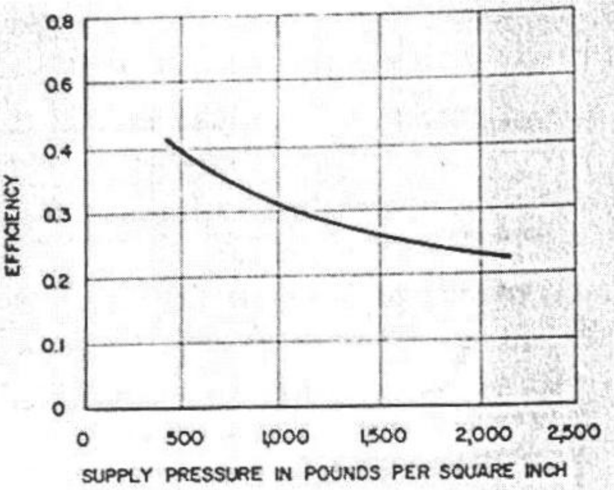


FIG. 13. EFFECT OF SUPPLY PRESSURE ON PROPULSIVE EFFICIENCY WHEN THE INTERFACE IS ALLOWED TO BLOW OUT OF THE NOZZLE.
NOZZLE AREA RATIO = 2.0
SHIP VELOCITY = 30 FT/SEC

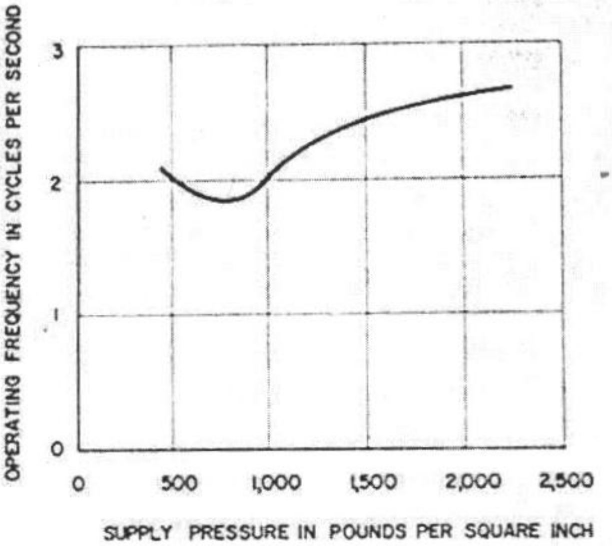


FIG. 14. EFFECT OF SUPPLY PRESSURE ON OPERATING FREQUENCY OF THE EXAMPLE PULSEJET.
NOZZLE AREA RATIO = 2.0
SHIP VELOCITY = 30 FT/SEC

his engine ran just as well! He failed to follow through on this discovery, for reasons now unknown. The French discovered that the "aerodynamic valves" of Figure 17b could be made to work rather well, but that significant "negative thrust" pulses were coming out of the "intake valve." So with fine Gallic logic, they bent their engine double, so that both "inlet" and "exhaust" were pointing aft. They too failed to perceive what their engine was trying to tell them; that the "intake" wasn't necessary at all.

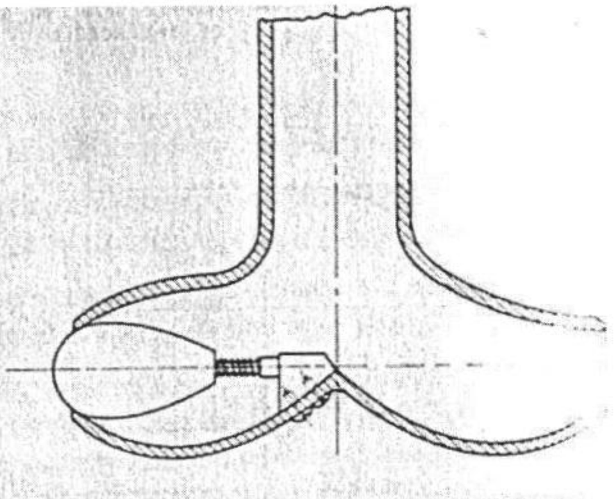


FIG. 15. THE LOWER END OF THE THREE-INCH COMPRESSE
AIR DRIVEN PULSEJET, SHOWN IN FIGURES 1 AND 2.

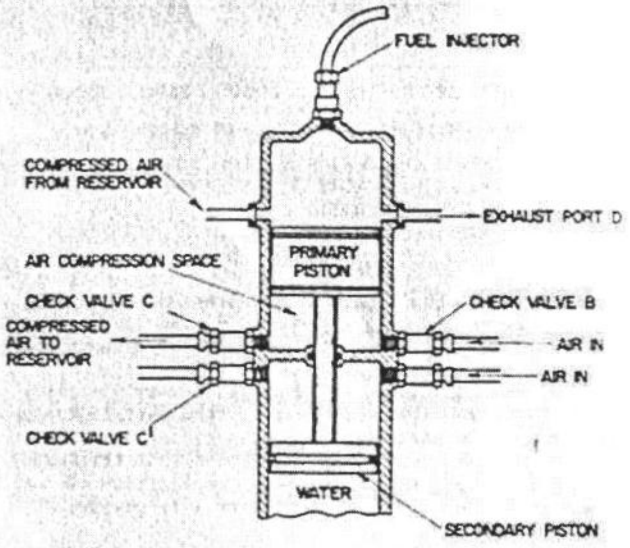


FIG. 16. A DOUBLE-PISTON DIESEL PULSEJET.

Based on our recent work with water pulsejets, we think that the ideal low speed configuration is probably that of Figure 17c; just a tube with a closed end. It could perhaps be used as the motive power for a subsonic ramjet as shown, for example, in Figure 18. Or it could be bifurcated (like the water pulsejets) as shown in Figure 19. Note that this separation of "inlet" and "exhaust" opens a new dimension in permissible geometric variations, and that if our water pulsejet work is anything to go on, one would expect to achieve performance improvements when the exhaust is constricted.

## The Ideal Propulsive Efficiency of a Pulsejet

Modern propulsors are more or less steady state, continuous flow devices, even though a detailed analysis reveals some small scale velocity variation in their wakes, due to vorticity and viscous effects.

In contrast, man's earliest mechanical propulsors -- paddles, oars and sweeps -- produced a pulsed wake. These were all man-powered. In ships, the transition to steam power was accomplished with the paddle wheel, itself a transition between discrete pulses in the water and the quasi-continuous flow of the modern propulsor.