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WAVE ENERGY EXCHANGER FOR HYBRID PROPULSION SYSTEM

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WAVE ENERGY EXCHANGER FOR HYBRID PROPULSION SYSTEM*

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Summary

An experimental investigation was carried out of a new concept of momentum transfer from a fluid of high specific momentum to a fluid of low specific momentum in ducts by means of pressure waves. This mode of direct momentum exchange can be implemented in a wave energy exchanger which is a very attractive alternative to the ejector. Such a device can be used in ramjet-type engines that incorporate a rocket-type gas generator to entrain ambient air under static and low flight speed conditions to generate thrust under these conditions.

Tests with a device that achieves the proposed process under conditions that are typical for such an application showed that its efficiency exceeds that of an equivalent ejector by factors of 5 and 9 when laid out for maximum compression and entrainment, respectively. Compression ratios between 2.5 and 2.6 were measured with the wave energy exchanger, while an equivalent ejector was found to have a compression ratio of about 1.4 at vanishing entrainment ratios.

An evaluation was made of the static performance of a hybrid airbreathing-rocket propulsion system incorporating a gas generator and a wave energy exchanger featuring a single rotating component of relatively small dimensions and complexity. Its thrust-augmentation ratio was estimated to be 1.6 at take-off, while the ejector-ramjet incorporating the same gas generator was found to have a thrust-augmentation ratio well below 1.

I. Introduction

At the Seventh ICAS Congress in Rome we have reported on preliminary work on new methods of aerodynamic energy exchange [1]. These methods are based on direct interactions between a flow of initially high specific momentum (primary flow) and a flow of initially low specific momentum (secondary flow). One well-known scheme for the direct interaction between flows of initially dissimilar momenta is realized in ejectors: The momentum exchange is solely due to shear stresses and it is coupled with the mixing of the fluids. Due to these strictly viscous effects the efficiency of ejectors is known to be very low, particularly if the primary fluid has a lower density than the secondary fluid. In the interaction scheme investigated by us the exchange of mechanical energy between flows is basically due to moving pressure fields and as such it could be, in the ideal limit, essentially nondissipative like the processes in conventional turbo-machines and piston devices. Indeed, the basic idea of the investigated concepts is the replacement of ordinary compressor blades and pistons or solid moving elements in positive displacement pumps by the primary fluid. However, the primary fluid being in direct contact with the secondary fluid, shear stresses and possibly unstable contact surfaces cannot be avoided so that significant energy dissipation and mixing of the fluids will occur during the momentum exchange and will tend to reduce the efficiency. It is reasonable, therefore, to expect that the efficiency of properly operating energy exchangers utilizing the proposed forms of momentum transfer will be somewhere between the efficiencies of conventional compressors and ordinary ejectors.

Unfortunately the experimental results published earlier [1] were rather disappointing. We had obtained efficiencies that barely exceeded those of equivalent ejectors. Some of the reasons for the unattractive performance were given in our previous paper. On the basis of a theoretical analysis we have concluded that the exchange of mechanical energy by means of replacing solid turbo-compressor blades with primary fluid, the so-called crypto-steady energy exchange, cannot be made attractive if the primary fluid has a very high momentum. Since it is planned to apply the novel momentum exchange concept to hybrid airbreathing-rocket propulsion systems, where the primary fluid is supplied by a rocket-type gas generator and consequently does have a very high momentum per unit mass, we have abandoned the crypto-steady energy exchange concept. The other energy exchange scheme under investigation involves nonsteady flows in ducts: A high-energy jet of primary fluid is directed temporarily toward the entrance section of a duct and acts as a gaseous piston on the gas column in the duct, compressing it and causing it to flow toward and through the exit into a receiving chamber. Due to their inertia, the media in the duct keep moving toward the exit even after

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*) This work was carried out at the Federal Aircraft Factory, Research Dept., Emmen, Switzerland

the driving jet is no longer directed into the duct, thereby causing a zone of low pressure to appear in the front portion of the duct. Thus, fresh secondary fluid is aspirated from the surroundings through the entrance section. Then another high-energy jet is directed into the duct and the pumping cycle is repeated. Our analysis has shown that in order to avoid spillage of primary gas across the inlet lips and to create significant inflow of secondary fluid during the time intervals of stopped primary fluid inflow the Mach number of the undisturbed primary flow in front of the duct must exceed a certain level that is determined by the fluid properties by the geometry, and by the flow conditions in the duct. This requirement had not been met during our preliminary experimental work.

II. Intermittent Flow of a Jet into a Duct: "Guillotine" Tests

To substantiate the theoretical result just mentioned, a simple experimental device was built and tested. It comprised a tube with a deLaval nozzle at one extremity and a bearing at the other extremity so that it could rotate about an axis normal to the tube axis. During a test the tube would sweep a certain angle and the nozzle would move past the entrance section of a stationary tube that was positioned so that its axis would go through the point of rotation of the movable tube. Means were provided to impulsively introduce the motion of the first tube and to stop the motion once the nozzle had swept past the inlet of the second tube. The installation allowed only one sweep of the nozzle during a test, in sort of a guillotine fashion. The stationary wave tube being open to the atmosphere at both ends, it was occupied by a column of quiscent air at the beginning of a test. The movable tube was fed with compressed and moderately preheated air through a flexible hose near the position of the bearing. Then, as the nozzle would sweep across the inlet of the stationary tube, a slug of high-energy air would enter the tube and the process briefly mentioned before would start.

A device for the pumping of a secondary fluid by such a process apparently works properly only if a sufficiently pronounced under-pressure zone of reasonable duration is created in the front portion of the wave tube after the driving jet has been directed away from the tube entrance. Thus, the purpose of the experimental work was to investigate how some of the most important parameters would influence the under-pressure zone. Specifically we varied the flow Mach number and sweeping speed of the driving jet and the wave tube geometry. The static pressure was recorded as a function of time at four positions in the wave tube with the aid of fast-response pressure transducers. Fig. 1 shows the pressure VS time history whereby the traces correspond, in ascending order, to positions in the tube from front to rear with the lowest trace recorded at a position 10 cm from the entrance section. It can be seen that, as expected, the jet Mach number Mp has to exceed a value of 2 and that, at the same time, the sweeping speed u should be rather low, i.e., about 2 % of the jet velocity or less in order that conditions for the aspiration of a reasonably large charge of secondary fluid are obtained. It should be noted, however, that this conclusion may have to be altered when there is still strong inflow of secondary fluid into a tube at the instant when a new jet is directed toward the entrance. The trough in the lowest pressure trace in the lower right corner has a length corresponding to about 6 msec and the pressure level during this time is well below 0.5 atm., so that sonic inflow of secondary fluid must have occured. Not shown in Fig. 1 is the influence of the wave tube geometry. We have found that it does not influence significantly the pressure level but that the duration of pronounced under-pressures can, for the same wave tube length, be extended by increasing the cross sectional area toward the exit section.

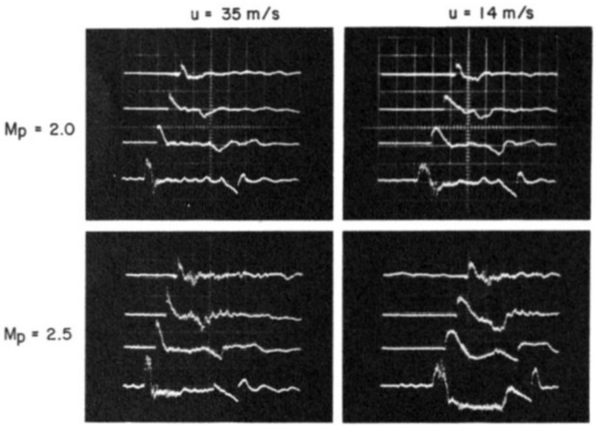


Fig. 1. Pressure VS time recordings at different positions in a wave tube

III. Intermittent Flow of a Jet into a Duct: Continous Operation

The conditions during the "guillotine" tests differed in several important ways from those that are present in an actual wave energy exchanger. As conceived by us, the latter will consist of a stationary gas generator that supplies high-energy gas to a rotor that divides the gas flow into a series of jets which, upon leaving the rotor, sweep across the entrance sections of a circumferentially arranged series of wave tubes. The wave tubes lead to a plenum chamber in which the pressure is maintained above the static pressure in front of the wave tubes. Thus, not only will a wave tube entrance intermittently be exposed to driving jets, the frequency of this process being dependent on the rotational speed of the rotating gas divider, but a pressure difference must be maintained across the tube during the entire operation of the device. After they have mixed in the plenum chamber primary and secondary fluid are released to the atmosphere through a nozzle, the size of which is selected so that a desired pressure level is obtained in the plenum chamber.

To allow quick changes of the wave tubes we have not actually built up an entire wave energy exchanger but only one single wave tube. However, we believe that with a single tube the operating condtions are not more favorable than with a series of ducts. In fact, there is reason to believe that the strength of upstream travelling compression waves and shocks, which are generated when downstream propagating rarefaction waves have reached the tube exit section, will be weaker when a series of ducts is used, due to induction effects caused by fluid leaving adjacent ducts[2]. Since any upstream propagating pressure pulse has an adverse effect on the operation of the device it would appear that the test results obtained with a single wave tube can safely be used to predict the performance of an entire wave energy exchanger.

The preceding guillotine tests showed that it might be of interest to vary the operating frequency independently of the sweeping speed. Hence several rotating gas dividers were built, all with identical channels laid out for a primary flow Mach number of 2.75 and with exit cross sections of 12 x 20 mm^2 but with different numbers of channels. We have tested rotors with 12, 8 and 6 channels. It is planned too to test different wave tubes. However, so far we have conducted most tests with one tube with an entrance cross section of 15 x 22 mm^2, an exit cross section of 127.5 x 22 mm^2, and a length of 1 m. No fairing was provided at the inlet and consequently fairly large losses must have occured during secondary fluid inflow due to flow separation from the sharp-edged walls. In subsequent tests we intend to investigate other types of inlets, e.g., inlets with those walls outwardly curved that are positioned parallel to the sweep velocity vector.

For the purpose of comparison the performance of an equivalent ejector was calculated for each test carried out. To compute the ratio of mixing-tube channel area A_1 (at the entrance) to the driving-fluid nozzle exit area A_{1p} of the equivalent ejector, we have integrated over time the area formed by the normal projection of the exit sections of the gas divider channels on the entrance section of the wave tube. This calculation is based on the assumption that the driving flow remains supersonic right down to the sharp lips of the wave tube inlet and that the jet cross section is fully preserved over the distance of approximately 1 cm between the exit section of the rotating gas divider and the entrance section of the wave tube. For the three rotors with 12, 8 and 6 channels the area ratio A_1/A_{1p} was found to be 3.6, 5.4 and 7.2, respectively, thus covering the range of values that are selected in typical ejector designs. In addition, the ejector calculations are based on the same fluid properties that have been determined during the tests in front of the wave tube. One difference between the wave energy exchange tests and the ejector calculations should be mentioned. It was found that reverse flow through the mixing duct of the ejector would have occured in all instances if the calculations had been carried out for the same nozzle exit area of the plenum chamber as was used in the wave energy tests. Therefore, while most of the tests were conducted with one and the same exit nozzle, the calculations of the equivalent ejectors were carried out for a range of exit nozzle cross sections that result in secondary flow Mach numbers at the mixing duct entrance ranging from 1 all the way down to 0, or, conversely, compression ratios from 1 up to the maximum possible value.

It was found that the rotational speed of the gas divider and hence, for a given test configuration, the ratio of operating frequency f to the natural frequency f_n of the gas column in the duct had an influence on the performance of the wave energy exchanger.

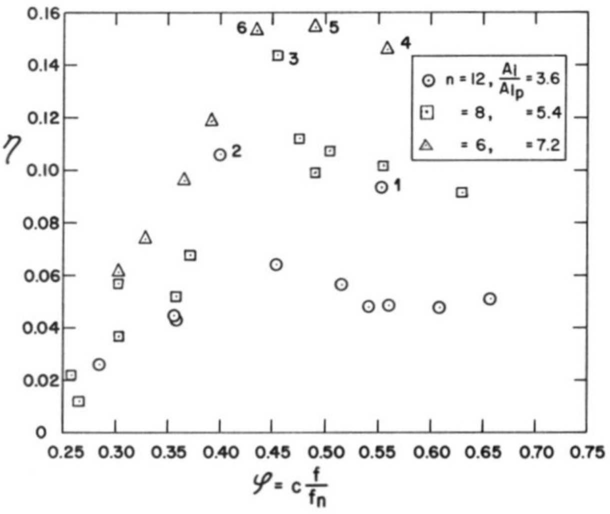


Fig. 2. Wave energy exchange efficiency VS φ

Fig. 2 shows the efficiency η as a function of φ, which is proportional to the frequency ratio. The efficiency is expressed by

$$\eta = \mu \frac{h_{3s} - h_{1s}}{h_{1p} - h_{3p}}$$

whereby μ is the entrainment ratio, defined as the ratio of time-averaged secondary fluid mass flow rate to time-averaged primary fluid mass flow rate, $h_{3s} - h_{1s}$ is the isentropic enthalpy rise of unit mass of secondary fluid (ambient air), and $h_{1p} - h_{3p}$ is the isentropic enthalpy drop of unit mass of primary fluid (air-kerosene combustion gas with a stagnation temperature of about 1200° K and an initial stagnation pressure of about 25 at.). It should be noted that this definition ignores the fact that the fluids reaching the plenum chamber through the wave tube are partially mixed. The computed efficiencies depend only on initial and final states and are independent of the mixing process. Assuming that the media can be considered as calorically ideal gases within the range their state is changing, one can write

$$\eta = \mu \frac{h_{1s}}{h_{1p}} \frac{\left(\frac{p_3}{p_{1s}}\right)^{\frac{\gamma_s-1}{\gamma_s}} - 1}{1 - \left(\frac{p_3}{p_{1p}}\right)^{\frac{\gamma_p-1}{\gamma_p}}}$$

where h and p are the total enthalpies and pressures, respectively, and γ is the ratio of the specific heats. Subscripts 1 and 3 indicate initial and final states, respectively, and subscripts p and s indicate primary and secondary fluid, respectively. Of course, this definition of η can be used also for the equivalent ejectors. The natural frequency f_n is assumed to be inversely proportional to the length of the wave tube and proportional to some average speed of sound of the fluids in the tube which itself is assumed to be proportional to the speed of sound of the fully mixed fluids in the plenum chamber. It can be observed that, under the conditions present during our tests, the efficiencies are generally highest for values of φ between 0.40 and 0.55. The points representing the highest efficiencies have been numbered for identification in other graphs.

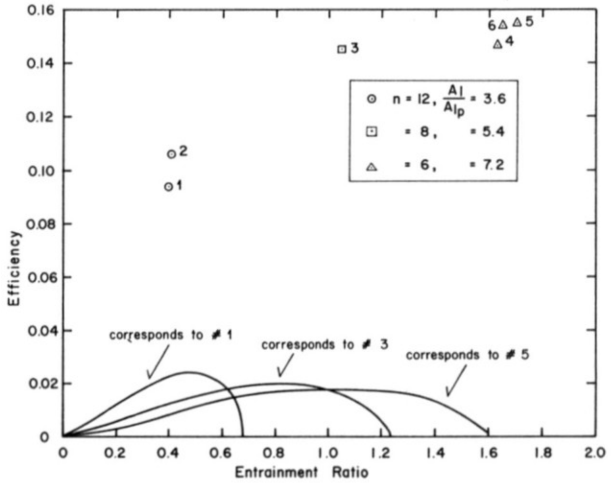


Fig. 3. Efficiency VS entrainment ratio

Fig. 3 shows the highest efficiencies attained to date as a function of the entrainment ratio. Since we have not yet varied some of the most important parameters, such as wave tube geometry, the efficiencies shown can hardly be considered as the highest attainable ones. Moreover, in the tests with $A_1/A_{1p} = 3.6$ that yielded points no. 1 and 2 we had operated the primary gas generator about 200° C below the design stagnation temperature, which may explain the relatively low values of η of around 10 % as opposed to the values of around 15 % for $A_1/A_{1p} = 5.4$ and 7.2. Also shown are the efficiencies of the equivalent ejectors, whereby each curve was determined for the conditions of one particular test. It can be seen that the best efficiencies of the wave energy exchange process are about 7 to 8 times higher than the best ejector efficiencies.

The compression ratio. defined as the ratio of the stagnation pressure in the plenum chamber to the stagnation pressure of the air in front of the wave tube, is shown in Fig. 4 as a function of the entrainment ratio.

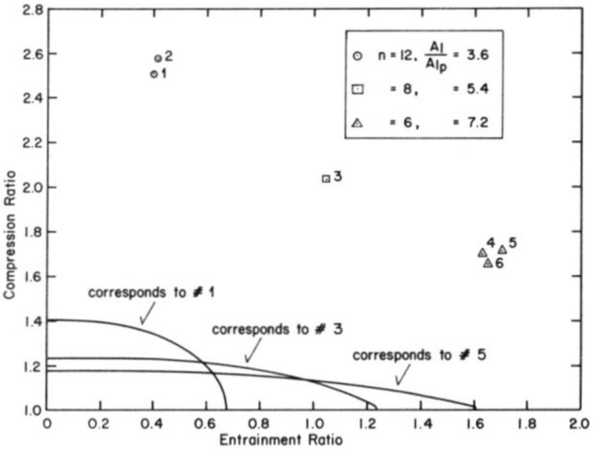
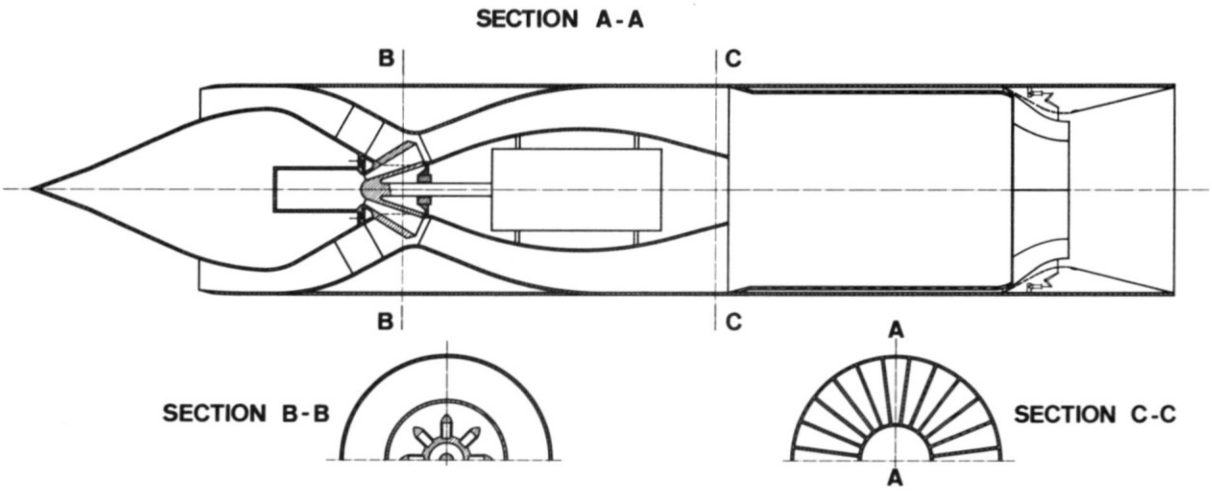


Fig. 4. Compression ratio VS entrainment ratio

Here again a rather large difference can be noticed between the values obtained with the wave energy exchange mode and those of the corresponding ejector operation. While the highest compression ratios attainable with an ejector (under conditions where little or no secondary fluid is entrained) are only slightly above 1.4 we have measured values between 2.5 and 2.6 in our experimental device, with a corresponding entrainment ratio of about 0.4. For an area ratio A_1/A_{1p} of 7.2 the wave energy exchange processes yielded compression ratios arround 1.7 at entrainment ratios that could not even be reached with the equivalent ejector.

IV. Application of the Wave Energy Exchanger to Hybrid Propulsion

The most interesting application of a wave energy exchanger is probably in hybrid airbreathing-rocket propulsion systems, i.e., in ramjet-type power plants that incorporate a rocket-type gas generator to achieve thrust at take-off and low flight speeds. Fig. 5 depicts schematically such an engine. The only major rotating component is the rotating gas divider whose flow channels would be slightly skewed so that it would be driven by the primary flow and could possibly provide the drive for the propellant pump, the electric generator, and other rotating equipment.



HYBRID AIRBREATHING-ROCKET PROPULSION SYSTEM
WITH WAVE ENERGY EXCHANGER

One of the most important parameters of any hybrid airbreathing-rocket propulsion system is the so-called thrust-augmentation ratio, i.e., the ratio of the thrust of the entire engine when operated in the hybrid mode to the thrust of its gas generator alone if it were operated as a pure rocket motor. Assuming that the gas generator is operated with the monopropellant ethylene oxide at a chamber pressure of 40 atm, that the efficiency and compression ratio of the wave energy exchanger are 10 % and 2.0, respectively, and applying typical stagnation pressure losses in the engine intake, in the rotating gas divider, and in the main combustion chamber downstream of the wave energy exchanger, a thrust-augmentation ratio of 1.6 was computed for the static case. The static thrust per unit frontal area was found to be about 0.66 kg/cm^2. If the wave energy exchanger in this engine would be replaced with an equivalent ejector the static thrust-augmentation ratio would be well below 1.

We conclude from this comparison and from the pumping characteristics - compression ratio VS entrainment ratio - shown in Fig. 4 that a hybrid airbreathing-rocket propulsion system with a wave energy exchanger is, in most applications, a much more attractive power plant than the somewhat simpler ejector-ramjet or ducted rocket.

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References

1. Felix Berner & Max Hermann: Aerodynamic Energy Exchanger for Hybrid Airbreathing-Rocket Propulsion Systems. Paper No. 70-61; ICAS Congress, Rome, Italy, Sept. 14-18, 1970.
2. Helge K. Heen & Robert W. Mann: The Hydraulic Analogy Applied to Nonsteady, Two-Dimensional Flow in the Partial-Admission Turbine. Trans. of the ASME, Sept. 1961, pp. 408-422.