Hot-Water Ejectors for Engine Test Facilities

O. Frenzl*
Societe Nationale D'Etude et de Construction de Moteurs D'Aviation, Paris, France

Hot water, at 700–1300 psia, can be used in ejectors to provide facility exhaust capabilities similar to those achieved by the more familiar steam-ejector systems. In fact, such hot-water drives may make larger facilities feasible in some cases, because the size and capital cost of the hot-water accumulator should be considerably smaller, and the operating cost is roughly half as great. (However, it should be noted that, in most cases, a hot-water ejector needs a simple water separator.) Another advantage is greatly reduced noise. The pressure drop in the accumulator during a run is low and can be eliminated if desired. With a wind tunnel using an atmospheric-pressure inlet, a single-stage, single-nozzle ejector can provide for Mach 0–3 testing; efficiency can be improved by using two or more ejector nozzles aligned parallel for the supersonic part of this regime. Various existing and planned installations in Europe for Mach numbers up to 5 (and even 20 for a three-stage ejector) are mentioned.

Introduction

FOR wind tunnels and for high-altitude test facilities with operating times up to several minutes, a hot-water-accumulator, hot-water-ejector system can offer advantages over the well-known steam-accumulator, steam-ejector system. Despite the higher accumulator pressures required, the equipment costs of the hot-water system are considerably lower, and, therefore, larger-scale facilities may become practicable. Because of the high water content of the driving jet, its speed and, consequently, the loss, is lower. This results in a significant reduction of the operating costs, as will be shown. The combustion confinement and noise reduction effects of the water droplets are further advantages. The accumulator pressure drop is low and may be reduced or completely eliminated at sufficient heat capacity.

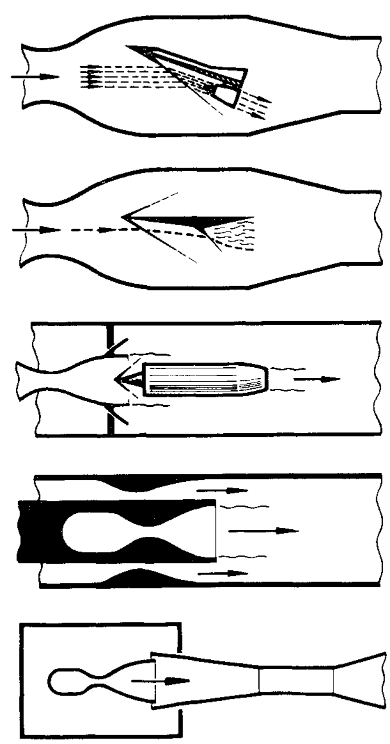
Figure 1 illustrates various testing arrangements with which a hot-water-ejector system might be employed to provide the necessary exhausting capability. If an engine is investigated while attached either to an aircraft or to a section of an aircraft (Figs. 1a and 1b), a special, very large tunnel (or expensive flight tests) is required. However, if an engine is tested alone (Fig. 1c), it is possible to reduce considerably the area of the stream passing around the engine which leads to a simplification and reduction in size of the tunnel. By the latter means, turbojet or ramjet engines can be tested at stream conditions corresponding to those experienced during flight. The arrangement according to Fig. 1d serves for the development of rockets and for the testing of nozzles or jet control. The simulation of the external flow around the tail end is obtained by means of an annular nozzle, so that the interaction between the external flow and the stream passing out of the engine may be investigated to a certain extent. Many rocket tests may also be executed with the arrangement shown in Fig. 1e, provided that sufficient pressure is produced at the nozzle exit plane to prevent any flow separation in the nozzle.

If a rocket jet discharges into an axisymmetric second throat diffuser as illustrated, the momentum of the jet can lower the pressure at the output end of the nozzle sufficiently such that an equivalent altitude of 65,000 ft or more can be obtained, depending upon nozzle and diffuser configurations.[1]

An exhausting system is required to obtain altitude conditions with such arrangements. Also, the starting of the second throat diffuser (often used with arrangements 1a–1d, as well as the case illustrated by 1e) is made easier, and the vibrations produced by large changes in pressure in the test section or the nozzle of the rocket and in the inlet of the second throat diffuser during the starting of the supersonic flow are reduced. In cases 1b and 1c, even if the peripheral stream is reduced in size, testing can be quite expensive.[2, 3] For plants that are frequently used, with operating periods of about 30 min (i.e., hypersonic wind tunnels), steam ejectors with conventional steam boilers are considered; for seldom-used plants, steam may be generated (less economically) in steam generators similar to rocket engines with water injection[4] (the hydrogen peroxide decomposition reaction is sometimes used). If the required test time is only a few minutes, a steam accumulator may be used to store steam for a blowdown operation. (Both the capital cost of the accumulator and the cost of operation of such a system are substantially lower than that of a compressed-air-accumulator, air-ejector combination.)

However, the steam accumulator (that was used for the first time by the author 25 years ago for a sonic wind tunnel) shows two major disadvantages:

1) It can be filled with water only to about 75–85% of its



a) Model aircraft with air-breathing engine

b) Wing with external combustion area

c) Ramjet engine

d) Rocket with external flow around the tail

e) Rocket without external flow

Fig. 1 Various testing arrangements.

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* Chief, Wind Tunnel Department.

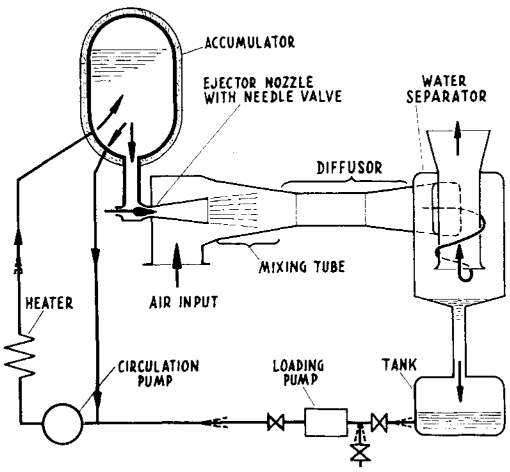

Fig. 2 Hot-water drive.

volume, if water entrainment or water-hammering effects are to be avoided during discharge. The lower value applies for a 15 atm loading pressure, the higher for 40 atm. If the period of discharge is shorter than 3 min, the filling percentage should be further reduced.

2) According to the quoted loading pressures, only approximately 5–12% of the water is vaporized during discharge, so that the discharged accumulator always contains a large mass of water at a high temperature (energy).

For these two reasons the steam accumulator results in a poor efficiency. However, if hot water were used as the driving medium for an ejector, the accumulator could be completely filled with water and could be almost completely emptied during the blowdown, which would lead to a substantial reduction in cost.

Hot-Water Drive

Figure 2 shows the diagram of such a hot-water drive, including means for recovering hot water and one of the various possibilities of loading the accumulator. The central plug or needle in the ejector nozzle controls the hot-water flow, and it also serves as a shutoff valve. For economy of operation, it is necessary for the pressure in the accumulator to be above 50 atm. The hot water is only partly vaporized in the ejector nozzle, but the remainder, say 70%, is finally atomized.[5] The discharge velocity from the nozzle, which is about 2000–2600 fps, is lower than in steam ejectors because of the large water content. Consequently, the mixture of the comparatively compact driving jet with the induced gas is performed with lower losses. The same is the case for the losses that arise after mixing upon deceleration. All this and the hot-water recuperation[6] at about 160°–200°F lead to a favorable economical operation of the hot-water drive system.

If no energy is added during discharge (i.e., the loading system is inoperative or infinitely small), the pressure will drop during the test run illustrated in Fig. 3. The volume of water flowing out is replaced by steam that is being formed. The sharp bend in the curve at unit run time corresponds to the exhaustion of liquid water; there remains only residual steam flowing out which is of no interest for the drive and causes a very large increase in noise. When this point, called the discharge pressure point, is reached, the run is terminated. Figure 4 shows how this discharge pressure and other parameters vary with the loading pressure of the accumulator. It is possible to compensate for the action of the drop in pressure by the use of the needle valve.

If energy is added during discharge, by a heating plant or other auxiliary means, the drop in accumulator pressure is reduced or eliminated. This can simplify the hot-water control and make the accumulator cheaper.

For wind tunnels with a large range of Mach numbers between about 0.5 and 3 which were of interest in Europe at the beginning of the development of the hot-water drive, it is possible to produce a single-stage, single-nozzle ejector (Fig. 5) that allows operation throughout the whole Mach range without any modification in the shape of the ejector. Better matching (efficiency) can be obtained by means of an ejector with a plurality of driving nozzles which are used one, two, or more at a time, depending on the Mach number, as illustrated in Fig. 6.

For altitude tests of rockets (Fig. 1e), which are nowadays the focus of interest, there is generally only one predetermined induced-flow requirement for a given rocket nozzle. When operating, such rockets can themselves act as ejector drives to reduce the pressure in the test cabin. However, if the ignition of the rocket engine is also to be done under altitude conditions, it is necessary, when there is no exhaust from the rocket, to provide the desired altitude pressure by means of an auxiliary single- or multi-stage ejector. With wind-tunnel tests of rockets (Fig. 1a or 1d), ejectors can be used to provide test Mach numbers up to 3 or more, whether or not the rocket is being fired.

Driving Nozzle

The driving nozzle accelerates and partially vaporizes the water. The steam content and output velocity may be de-

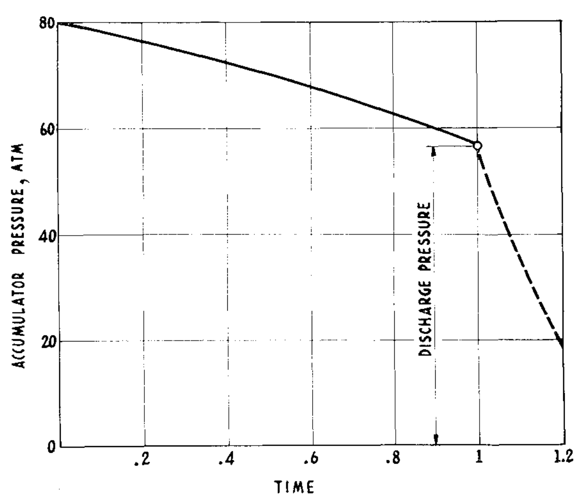

Fig. 3 Modification of pressure in a hot-water accumulator to which no energy is added during discharge.

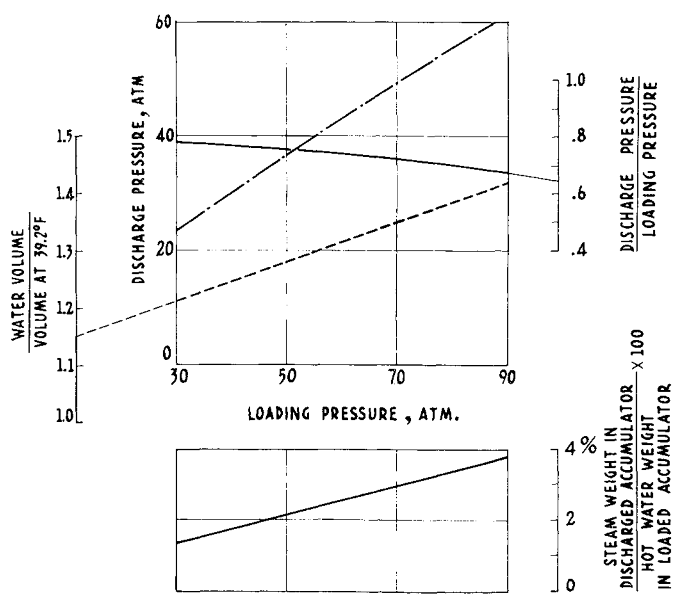

Fig 4 Effect of the loading pressure.

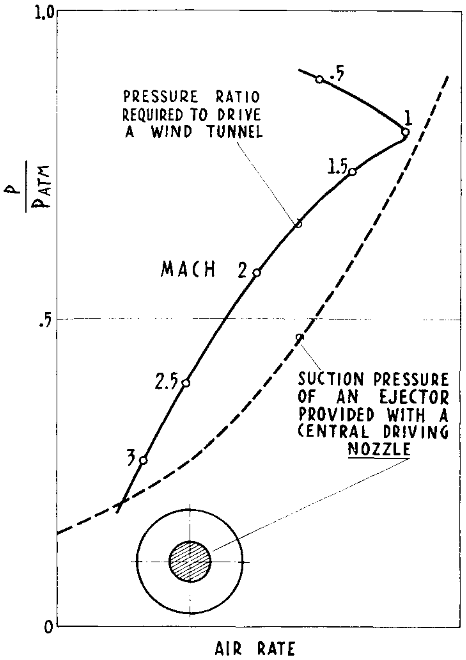

Fig. 5 Matching of one-nozzle ejector with a wind tunnel with atmospheric intake.

fined for an isentropic (no-loss) stream by means of a Mollier diagram. Thrust tests performed with nozzle models of different sizes have shown output velocities equal to 82–92% of the theoretical isentropic values. Efficiency increased with size; hence, still higher values may be achieved with large units. The loss can be divided into that due to the heterogeneous system (droplet drag) and that due to friction against the wall. The former is proportional to the square of the radius of the water drops and inversely proportional to the length of the nozzle.[5] These losses have not yet been distinguished experimentally.

When no delay in the boiling of the water occurs, a froth is produced which has a velocity of about 160 fps at the throat of the nozzle. The corresponding throughput (weight flow per unit area) is illustrated by the heavy solid line in Fig. 7.

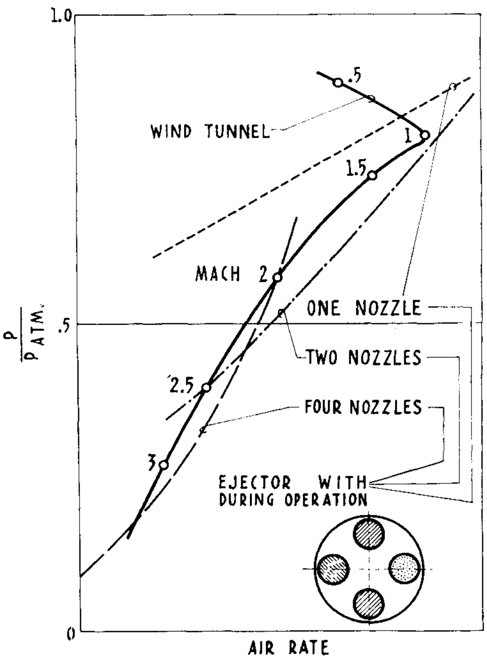

Fig. 6 Matching of a four-nozzle ejector with a wind tunnel with atmospheric intake.

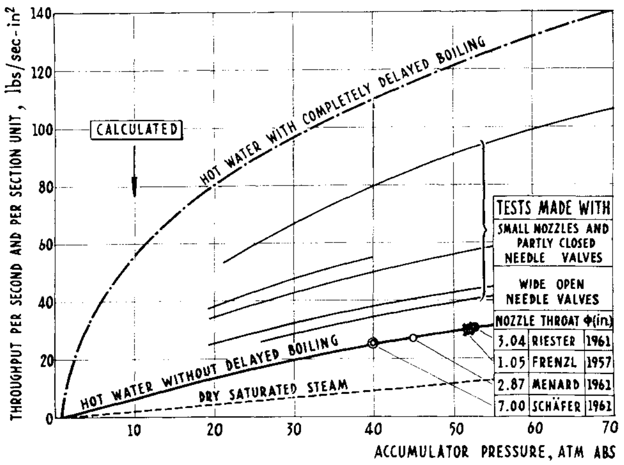

Fig. 7 Flow rate per unit of throat cross-sectional area.

Tests with small nozzles and partly closed needle valves (the 5 bracketed curves of Fig. 7) show larger densities of the stream from which it may be concluded that a considerable delay occurs in the boiling of the water ahead of the throat. However, all of the measured values lie between the dot-and-dash line corresponding to completely delayed boiling (with constant temperature and atmospheric pressure prevailing in the throat) and the no-delay curve. Tests made with large nozzles (throat diam >1.0 in., throat length >4 in.) show throughputs that agree exactly with the cross section of the hot-water needle valves for large-scale applications.

Since the weight flow per unit area for hot water is substantially larger than that for dry saturated steam (the dashed curve), whereas the driving-medium requirement is only 20–30% larger than for the steam system, the needle valve may be substantially smaller and lighter than the equivalent valve needed to regulate steam pressure.

Mixing and Deceleration

For the theoretical case of mixing and kinetic energy exchange in a frictionless cylindrical tube to a final state of thermodynamic equilibrium between steam, water, and air, it is possible to obtain a system of equations[8] which allows the prediction of that final state from the known conditions before mixing. Thus the pressure, speed, density, temperature, steam content, partial pressure, and enthalpy after mixing can be computed. Generally speaking, this leads to two solutions, corresponding, respectively, to a supersonic and to a subsonic stream. Both types of streams can be obtained simultaneously, and they may be separated by a shock-wave system. The pressure rises accordingly, but the temperature rises only slightly by reason of the high water content. This being the case, the rise in pressure which is assumed to

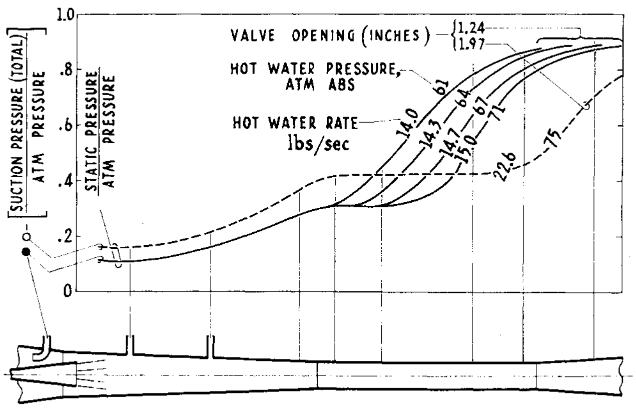

Fig. 8 Distribution of static pressure along the mixing tube and diffuser for constant air rate.

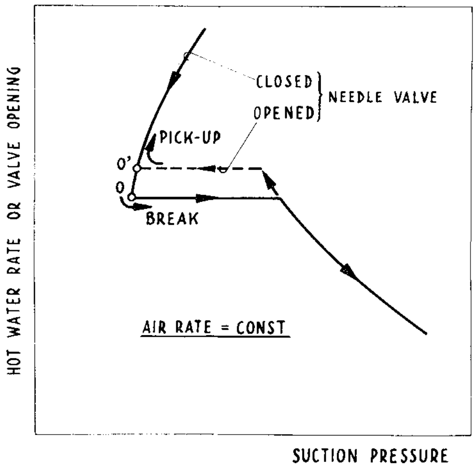

Fig. 9 Effect of the needle valve opening on the suction pressure.

be obtained without any loss can be defined only in a stepwise manner during the delay in the subsonic diffusor, since no simple adiabatic equation is known for a mixture of air, water, and steam.

It is preferable to use, instead of a plain cylindrical mixing tube, a mixing tube with a convergent inlet, particularly for production of low suction pressures. If this convergent shape is such that the mixing occurs at constant pressure, the calculation of performance is also simple. It is assumed that mixing is completed prior to compression in a supersonic diffusor. (Actually, the mixing and compression processes are continuously intermingled, of course.) Figure 8 shows the static pressure distribution on the tube wall; in the convergent part, the mixture decelerated to a lower supersonic speed. The pressure increase in the cylindrical section (curves drawn in thick lines) is very important, because the shock-wave system (at the end of which the flow is subsonic) can be deduced from it.

When the pressure and flow rate of the hot water decrease, the shock-wave system moves upstream. If the cylindrical-section inlet is nearly reached (which in our example is the case for a hot-water flow rate of 14 lb/sec), optimum conditions prevail; following this, a supersonic flow breakdown occurs in the diffusor, and the induction pressure increases suddenly.

If the needle valve is closed down at constant hot-water pressure and constant air flow, thereby reducing the hot-water rate (Fig. 9), the suction pressure diminishes. At point O, the ejector operates optimally; then the suction pressure increases suddenly, and the flow becomes unstable. If the valve opens up again, the pickup generally occurs not at the optimum point (O) but at one that is somewhat higher (O′). This is simply the well-known supersonic diffusor hysteresis effect that may also occur with other driving means. In practical operation, an operating point is chosen (set by the needle valve) which lies somewhat above the point O.

Figure 10 shows the variation of the optimum point with the hot-water pressure and the air flow for one particular ejector (No. 170/207).[9] If the accumulator pressure decreases during operation (as in Fig. 3), the ejector is sized for the discharge pressure. The ejector is then able to generate a lower suction pressure at the beginning of operation which is very desirable for the starting process of the wind tunnel's supersonic diffusor that is located upstream of the ejector. Tests were performed to examine the influence of the shape of the ejector mixing tube and its inlet diffusor on its operation. For example, Fig. 11 shows the effect of the diffusor throat diameter on the optimum point. In order to obtain steady and efficient diffusor operation, the throat length should be about eight times its diameter; an extension to 12 times its diameter is not prejudicial.

If cold air flows through a supersonic tunnel, a certain suction pressure builds up at the ejector. If air is heated for another run in the same tunnel, without any other modification, the suction pressure will be slightly lower which results in better reliability (i.e., margin) for the wind-tunnel driving system. The air-flow change is proportional to $T_t^{-1/2}$ because of the wind-tunnel throat. If, instead of air, water-steam is induced at the same or slightly higher temperature, the same suction pressure is obtained when the steam rate is about 20–30% lower than the air rate.

The continuation of this development work will aim at achieving optimum mixing-tube shapes and determining more accurately, by trials, the influence of the temperature and molecular weight of the induced medium.

Applications

At the SNECMA plant at Villaroche, France, a hot-water system with a heater of 46 ft³ under a maximum pressure of 100 atm serves primarily for the development of model-size ejectors. This provides a good possibility of application of the results on large-scale models. The accumulator with simple electrode heating[7] has proved its reliability through several thousand loadings. It has been used to examine one-stage ejectors with one and four driving nozzles, to drive wind tunnels of 6- × 6-in. cross section, and as a jet deviation test bench for Mach numbers below 4.5. Recently, two-stage ejectors were also tested under a minimum suction pressure of $\frac{1}{150}$ atm.

A four-nozzle, one-stage, hot-water ejector at the Aerotechnical Institute at Saint-Cyr (near Paris) serves for operating a 2.8- × 2.8-ft wind tunnel in which the Mach number may be continuously adjusted between 0 and 3. Conditions corresponding to $M = 3$ at 76,000 ft may be simulated for 5–15 min. The loading of the four hot-water accumulators with a total capacity of 4240 ft³ is performed chiefly by means of waste steam fed out of a turbine through a heat exchanger. The accumulator loading pressure is relatively low (65 atm) for this first, large-scale facility.

At the Deutsche Forschungsanstalt für Luftfahrt (DFL) plant at Braunschweig, tests of a hot-water jet apparatus have produced results consistent with those obtained with the model apparatus of SNECMA (which is three times smaller). The wind tunnel with a cross section of 16 × 16 in. serves for tests of air-breathing engines at Mach numbers up to 3, and it is to be equipped later with a two-stage ejector for Mach numbers up to 5. DFL also is erecting a 7000-ft³, 100-atm hot-water accumulation at Trauen. It is to be as-

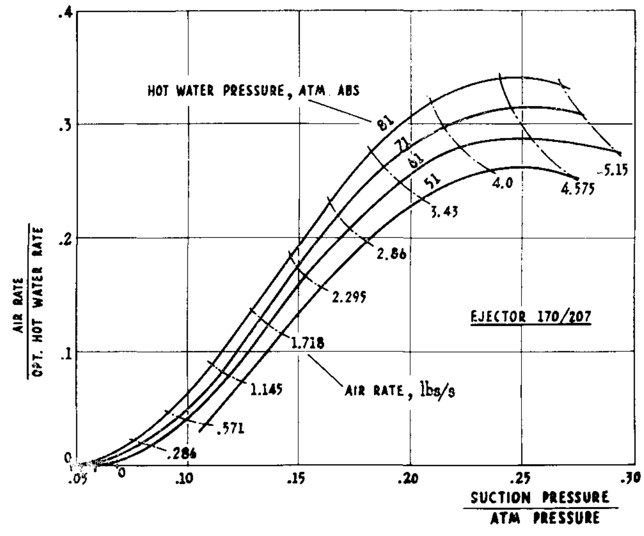

Fig. 10 Effect of the hot-water pressure and air rate on suction-pressure and optimum-mass ratio.

sociated with a Mach 5 wind tunnel for engine testing, with a cross section of 2.46 × 2.46 ft, and with a Mach 20 tunnel with a three-stage ejector. This facility can also be used for the further development of the hot-water ejector and rocket test facilities.

At the Technical University of Berlin, a single-stage, hot-water ejector provided with interchangeable driving and mixing tubes allows various flow experiments. It drives a 6- × 6-in. tunnel at $M = 0$–2.7, which later is to be increased to 4.3, still with a single-stage, hot-water ejector. Its noise of only 63 db, measured at a distance of 50 ft, does not disturb neighbors!

Comparison with Steam Accumulator/Ejector System

For this comparison, it will be assumed that relative accumulator costs (hardware requirement) are proportional to the product accumulator volume and loading pressure and that air at a stagnation temperature of 65°F is to be pumped to 0.2 atm absolute. The steam ejector [an RFL 1][4] is assumed to operate at a steam pressure of 8.0 atm absolute, which corresponds to an optimum loading pressure of 40 atm absolute, with steam rate/air rate = 2.7. The hot-water ejector is assumed to have the performance given in Fig. 10.

Figure 12a shows the relative accumulator costs,[10] and Fig. 12b shows the relative operating costs that are equal to the heat requirement relationship. In this case, it is assumed that loading water is available free of cost for the hot-water system (for instance, by recovery, Fig. 2). Since the pressure in the water heater is about twice that in the steam generator, the water-system heating costs are obviously lower than those of the steam system but not significantly so.

For facilities that are not used intensively, the water-heater cost for the hot-water system is about 10–20% of the accumulator cost, because a low loading rate is used. During the accumulator discharge the pressure drops, so that it is necessary to actuate the needle valve.† Intensively used facilities require conventional high-performance water heaters, at a cost equal to 50–80% of the accumulator cost.

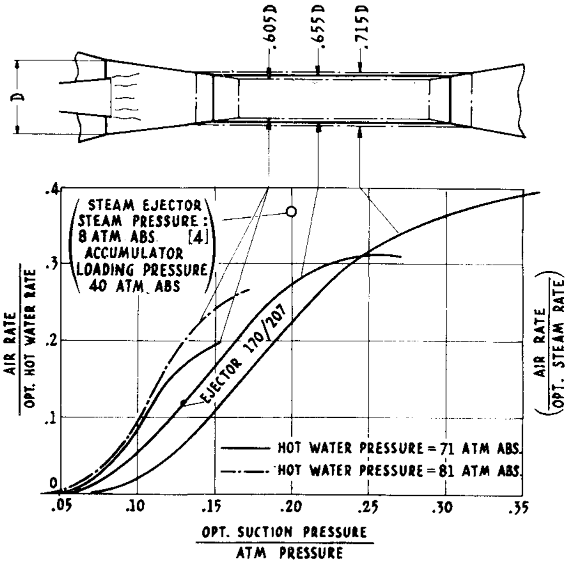

Fig. 11 Effect of the throat diameter on the optimum ejector characteristics.

† The accumulator pressure could be maintained constant during discharge only by means of an auxiliary steam generator, for instance, a rocket combustion chamber with water injection.

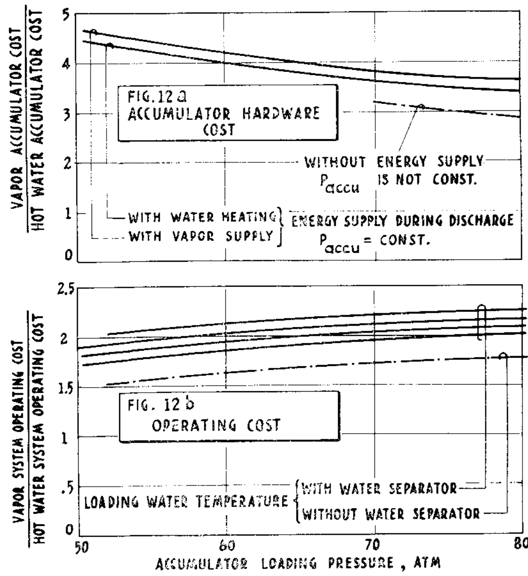

Fig. 12 Accumulator hardware and operating cost comparison.

These high-recovery-rate heaters enable the accumulator to be discharged with little or no pressure drop. When the loading performance increases, the loading time–discharge time ratio is reduced. For the time relationship quoted in Fig. 13, discharge under constant pressure is just possible.

In many cases, it is prudent to load the accumulator at constant maximum pressure by acting on the feeding water quantity. Even when the accumulator is nearly completely emptied, the facility is ready within a short time for a new operation of shorter duration.

According to the foregoing, the hot-water-accumulator, hot-water-ejector system is superior to a steam-accumulator, steam-ejector system with regard to the main structural parts and operating costs. Therefore, it can be considered suitable for driving very large wind-tunnel facilities for rockets or air-breathing engines for space vehicle boosters, which are becoming of interest in the flight corridor at Mach numbers up to 10. If several test cells are connected to a common single

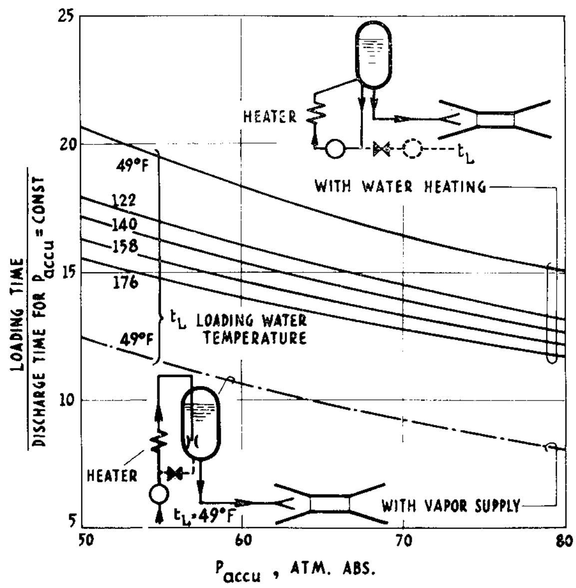

Fig. 13 Proportion of the loading and discharge times for a constant accumulator pressure during discharge; loading valve is closed during discharge period.

accumulator to obtain greater facility utilization, the hot-water accumulator investment becomes still more reasonable and the lower operating costs more evident. The presence of water droplets in the mixing tube tends to confine combustion and provide an excellent noise-reduction effect. However, it should be noted that, in most cases, the hot-water ejector needs a simple water separator.

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