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No. 358

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Summary

This report describes a model water tunnel built in 1928 by the National Advisory Committee for Aeronautics to investigate the possibility of using water tunnels for aerodynamic investigations at large scales. The model tunnel is similar to an open-throat wind tunnel, but uses water for the working fluid. Results are given of tests of the tunnel and also of some observations made with model airfoils in the tunnel to study the phenomena of cavitation. It is concluded that a water tunnel does not offer a convenient method of making aerodynamic investigations at large scales. A large water tunnel would be of value chiefly for use in the study of cavitation.

Introduction

In aerodynamic model testing it is possible to obtain an air flow similar to that at full scale by conducting the tests at large values of the Reynolds Number. Since the Reynolds Number $\left(\frac{Vl}{\nu}\right)$ varies directly as the scale of the model (expressed by the characteristic length l), directly as the velocity (V), and inversely as the kinematic viscosity (ν), large values of

the Reynolds Number may be obtained by increasing V or decreasing ν. In the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics (Reference 1), tests are made in air compressed to 20 atmospheres. The kinematic viscosity is thus reduced to approximately 1/20 of its normal value, and the Reynolds Number at a given velocity is correspondingly increased. As another means of securing high Reynolds Numbers, the use of water for the working fluid has been considered. At normal temperatures the kinematic viscosity of water is between 1/8 and 1/15 that of air, but if the water is heated to a temperature of 90°C, the kinematic viscosity is reduced to 1/47 that of air at standard conditions.

An investigation of the possibility of using water for the working fluid in conducting aerodynamic tests at large values of the Reynolds Number was begun in January, 1928. Some preliminary designs of a water tunnel were made, and later a model water tunnel was designed and constructed. The experimental investigation was begun in August, 1928, when tests of the model tunnel were started. A number of special problems were encountered in connection with the investigation, the most important of which was that of dealing with cavitation. In the model tunnel, as first constructed, the water was circulated by a propeller, as is customary in wind-tunnel testing. However, it was found that the water was churned by the propeller, probably because of cavitation on the blades, until it became milky in ap-

pearance. The milky appearance was undoubtedly due to the presence of a large number of small air bubbles. Since this condition was considered very undesirable, a specially designed five-stage turbine type pump was substituted for the propeller. It was then possible to keep the water clear until a velocity was reached that was sufficiently high to produce cavitation on a model airfoil placed in the test section at any angle of attack. A brief investigation was then made on airfoil models mounted in the completed tunnel to study cavitation.

General Description

The model water tunnel of the National Advisory Committee for Aeronautics is of the open-throat type with a single return passage. A jet of water is discharged from a nozzle-shaped entrance cone through a glass-enclosed, water-filled test chamber into a flare-mouthed exit cone. As shown in Figures 1 and 2, a comparatively large chamber is provided, just ahead of the entrance cone, to equalize and stabilize the flow. The cross-sectional area of this chamber is nine times the area of the mouth of the entrance cone.

A marine type propeller proved unsatisfactory for circulating the water because of cavitation on the propeller blades, so a specially designed turbine type pump was substituted. This pump has five stages to reduce the pressure gain through each

set of blades. The pressure distribution through the pump is shown in Figure 3. Power is supplied through a belt drive by a variable speed electric motor.

A mercury manometer with water-filled leads is connected between the test chamber and the large chamber ahead of the entrance cone to indicate the average dynamic pressure. Another manometer indicates the static head in the test chamber.

In order to control the temperature of the water, two electrical-resistance heater elements are installed in the large chamber. Since the energy supplied to circulate the water increases its temperature, provision is made for cooling it by the introduction of cold water into the large chamber, the surplus being discharged from the test chamber. By regulation of the heads on the ingoing and outgoing streams the static pressure is controlled.

The diameter of the entrance cone is $2\frac{1}{2}$ inches. Three exit cones, with different minimum diameters, were tried, and a cone with a minimum diameter of 2-3/4 inches, or 10 per cent greater than that of the entrance cone, was selected as better than either of the smaller ones. The distance from the mouth of the entrance cone to the flare of the exit cone is 3-9/16 inches.

No attempt was made to measure forces on models in this tunnel, but a model mounting is provided by means of which airfoil or marine propeller section models with $1\frac{1}{2}$-inch chords can be mounted in the jet in such a manner as to permit the angle of

attack to be changed during operation. The model extends clear across the jet.

Tests

A series of calibration tests were made on the water tunnel to determine its operating characteristics. These tests showed satisfactory total head distributions across the jet. Curves of jet velocity, power consumption and energy ratio were obtained (Fig. 4).

Velocities up to about 45 feet per second are obtained without excessive power absorption. The energy ratio of the tunnel alone is approximately 0.77 throughout most of the operating range, but decreases at velocities above about 42 feet per second. This energy ratio is probably somewhat lower than would be obtained in a larger tunnel because of the excessive friction losses in the small turbine pump, and because the pump was too small to permit accurate forming of the cast bronze blades.

Flow characteristics.- Velocities up to about 45 feet per second are obtainable without objectionable surges or pulsations. The flow through the test chamber is marked, however, by large eddies in the water surrounding the jet. These eddies were studied by means of fine pieces of coal in the water, and their maximum velocity was estimated to be about 1/10 to 1/6 that of the average jet velocity. At high speeds, these eddies are so pronounced as to cause cavitation at the flare of the exit cone.

The model, which extends clear across the jet, deflects the flow so that an increased amount of water is spilled out around the bottom of the exit cone.

Free surface operation.- The use of a free surface, that is, a water to free air surface on the test chamber would facilitate the installation, maintenance, and operation of a force balance and other testing equipment. It would also offer advantages in photographing flow formation and in observing the model during tests. Tests were made, therefore, with the glass top removed from the test chamber. The water level under these conditions is lower than it would normally be in a tunnel of this type, consequently the static pressure in the jet is very small. Several runs were made to determine the jet speeds at which the free surface became noticeably disturbed. With the model set at -6°, this speed was found to be 2.2 feet per second. With the angle of attack increased to $+24^{\circ}$, this velocity increased to 3.6 feet per second. Runs were also made to determine the speeds at which the surface entirely broke down and let air bubbles into the exit cone. This speed was found to be 7.6 feet per second with the model at an angle of attack of -6°, and 11.0 feet per second with the model at $+24^{\circ}$. It is noteworthy that the jet speed with a free surface can be greater when there is a wing across the jet. From these tests it is concluded that free surface operation at reasonably high speeds is practicable only with a much larger tunnel.

Cavitation tests.- A series of comparative cavitation tests was made by means of visual observation on models of several marine propeller sections and one airfoil section (a Clark Y section reduced to a thickness of 10 per cent of the chord). An attempt was made to correlate the results of these tests with the results of pressure-distribution tests.

The visual cavitation tests were made at constant water temperature and static pressure. The cavitation on the different models was compared at angles of attack corresponding to certain computed lift coefficients. At jet speeds above about 30 feet per second, cavitation began with the appearance of a small, rapidly fluctuating, and occasionally disappearing cavity near the leading edge of the section. The cavity was located on either the upper or lower surface, depending upon the form of the section and the angle of attack.

Table I gives the conditions under which cavitation first appeared on the airfoil. At higher jet speeds the cavity varied very rapidly in size but never disappeared. At the highest jet speeds obtainable, the cavity streamed off the surface of the section and formed a milky region extending into the exit cone (Fig. 5). With the different models there were noticeable differences in the jet speeds at which cavitation began, in the appearance and location of the cavity, and in the rate at which the cavitation increased with jet speeds, but these differences were not so pronounced as to make any section markedly superior in

these respects.

In order to investigate the local conditions under which cavitation appeared, measurements of the pressures near the point of formation of the cavity were attempted. The results of these tests were not satisfactory, owing to difficulties encountered because of the small size of the model. Peak negative pressures occur on a very small area. It was impossible to know whether this maximum negative pressure was measured because: only one orifice could be used at a time, difficulties were encountered in locating this orifice in this small area, and the smallest practicable orifice was too large in comparison with the size of the section. The peak pressures on the airfoil section, however, were calculated from wind-tunnel tests (Reference 2). The peak negative pressures on the sharp-nosed marine propeller sections were too problematic and too sensitive to small changes in angle of attack to allow an estimate of their magnitudes to be made.

Cavitation might be expected to occur when the absolute local pressure is reduced to the vapor pressure of the water. The calculations made for the Clark Y airfoil reduced to a thickness of 10 per cent of the chord indicate that the local reduction in pressure below the static pressure would not exceed 1.2q at the angles of attack used. If this reduction was reached, visible cavitation began when the pressure reduction was 48 per cent of the total absolute static pressure minus the vapor pressure of the water. If it were assumed that pressures approach-

ing the vapor pressure of the water were reached when visible cavitation first began, pressure reductions of 2.44q would be required in the flow, nearly $2\frac{1}{2}$ times the dynamic pressure. This seems hardly possible in the range of angles of attack investigated, although at the highest speeds at which tests were made, a local pressure reduction of only 1.29q would be required to reduce the local absolute pressure to the vapor pressure of the water, and this pressure reduction would undoubtedly be reached on the surface of an airfoil at moderate angles of attack. These results indicate that visible cavitation probably begins before the absolute local pressure is reduced to the vapor pressure of the water because of dissolved air coming out of solution. It is also probable that visible cavitation has become very pronounced before the vapor pressure of the water is reached.

Conclusion

This investigation has led to the conclusion that aerodynamic tests at high Reynolds Numbers cannot be made as conveniently by use of a water tunnel as by other methods, but the experiments suggest that such apparatus may be of great value for investigating the phenomena of cavitation in water.

Langley Memorial Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., November 28, 1930.

References

1. Munk, Max M. and Miller, Elton W. : The Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. N.A.C.A. Technical Report No. 227, 1926.

2. Jacobs, Eastman N. Stack, John, and Pinkerton, Robert M. : Airfoil Pressure Distribution Investigation in the Variable Density Wind Tunnel. N.A.C.A. Technical Report No. 353, 1930.

TABLE I

Cavitation on Clark Y airfoil (10 per cent thick)
Temperature 28°C
Static pressure (absolute) 2200 lb./sq.ft.

Angle of attack	Dynamic pressure at which cavitation appeared lb. per sq.ft.	Location of cavitation
-35'	877	Below leading edge
+1° 25'	1162	" " "
+2° 25	1136	" " "
+4° 25'	1291	Above and below leading edge.

Scale of drawing in inches

0 3 6

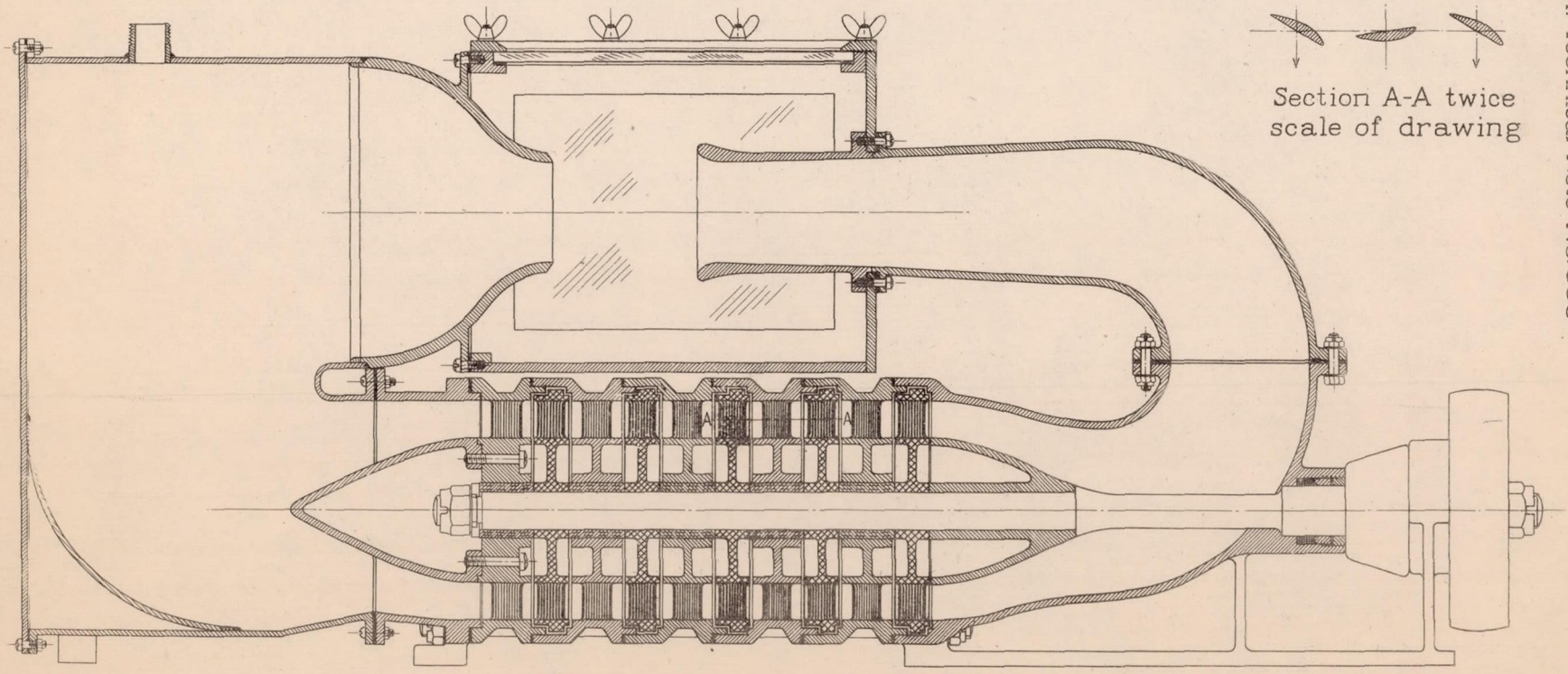

Fig.1 Model water tunnel section

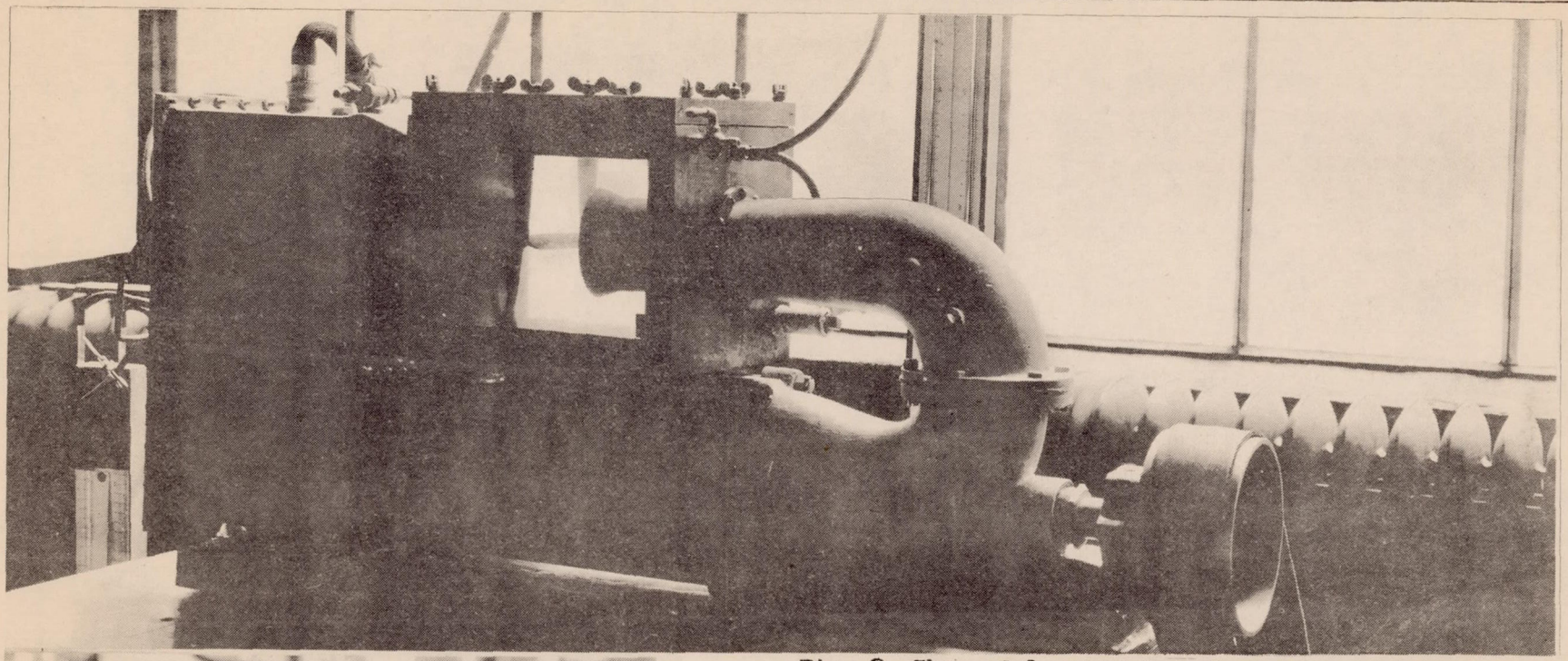

Fig. 2 The model water tunnel showing airfoil mounted in test chamber.

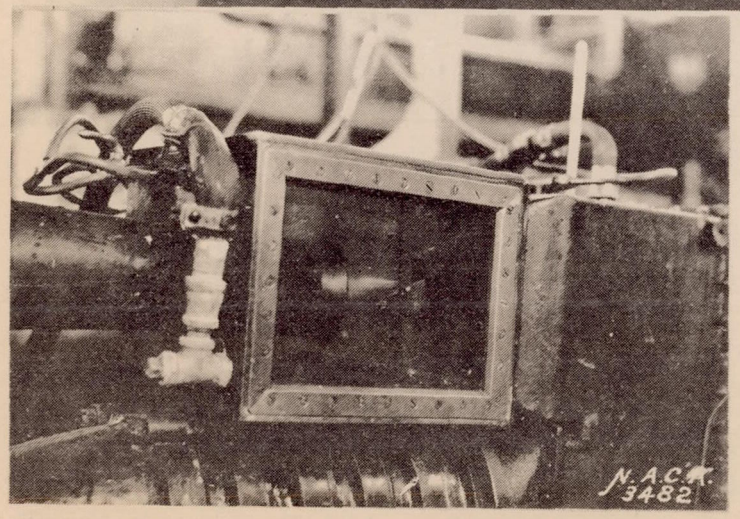

Fig. 5 Cavitation on wing model.

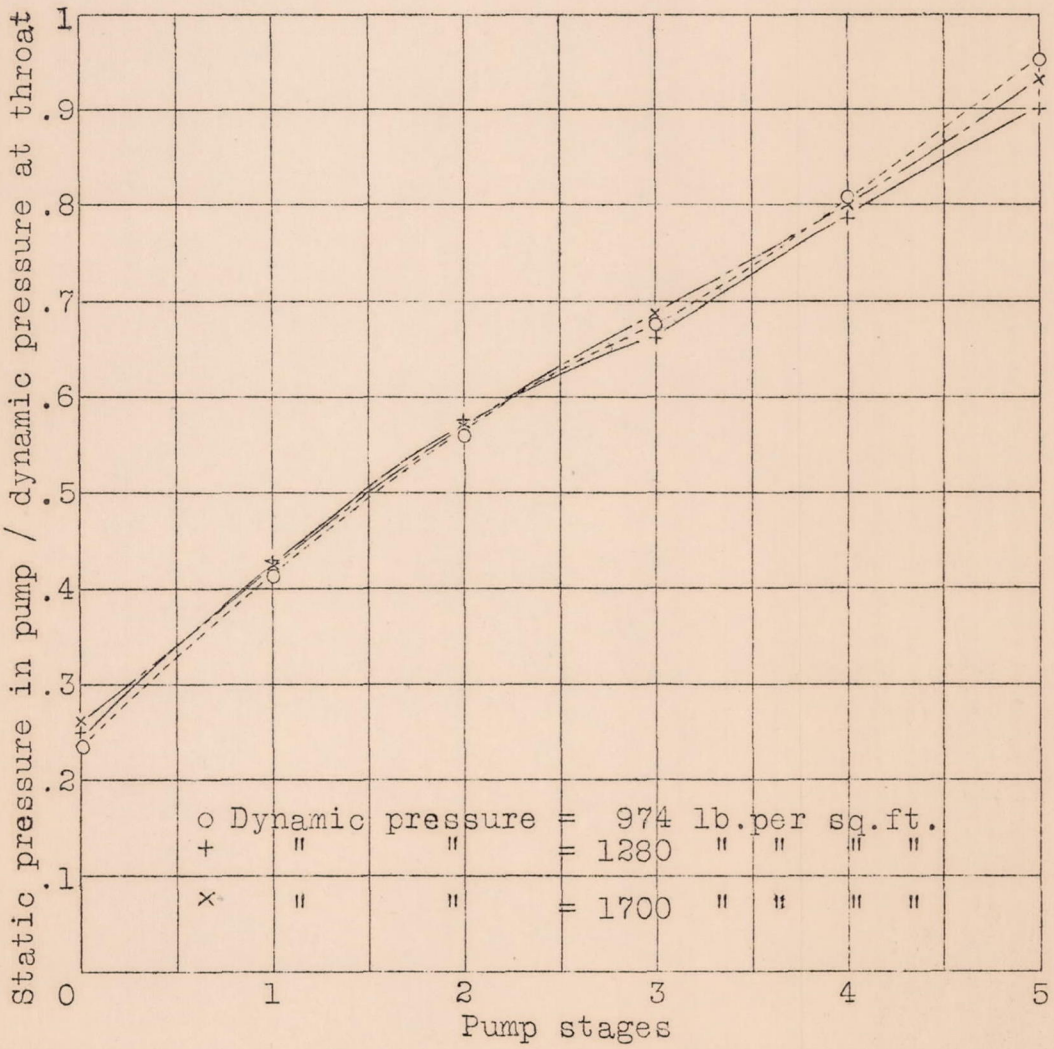

Fig. 3 Pressure in pump stages.

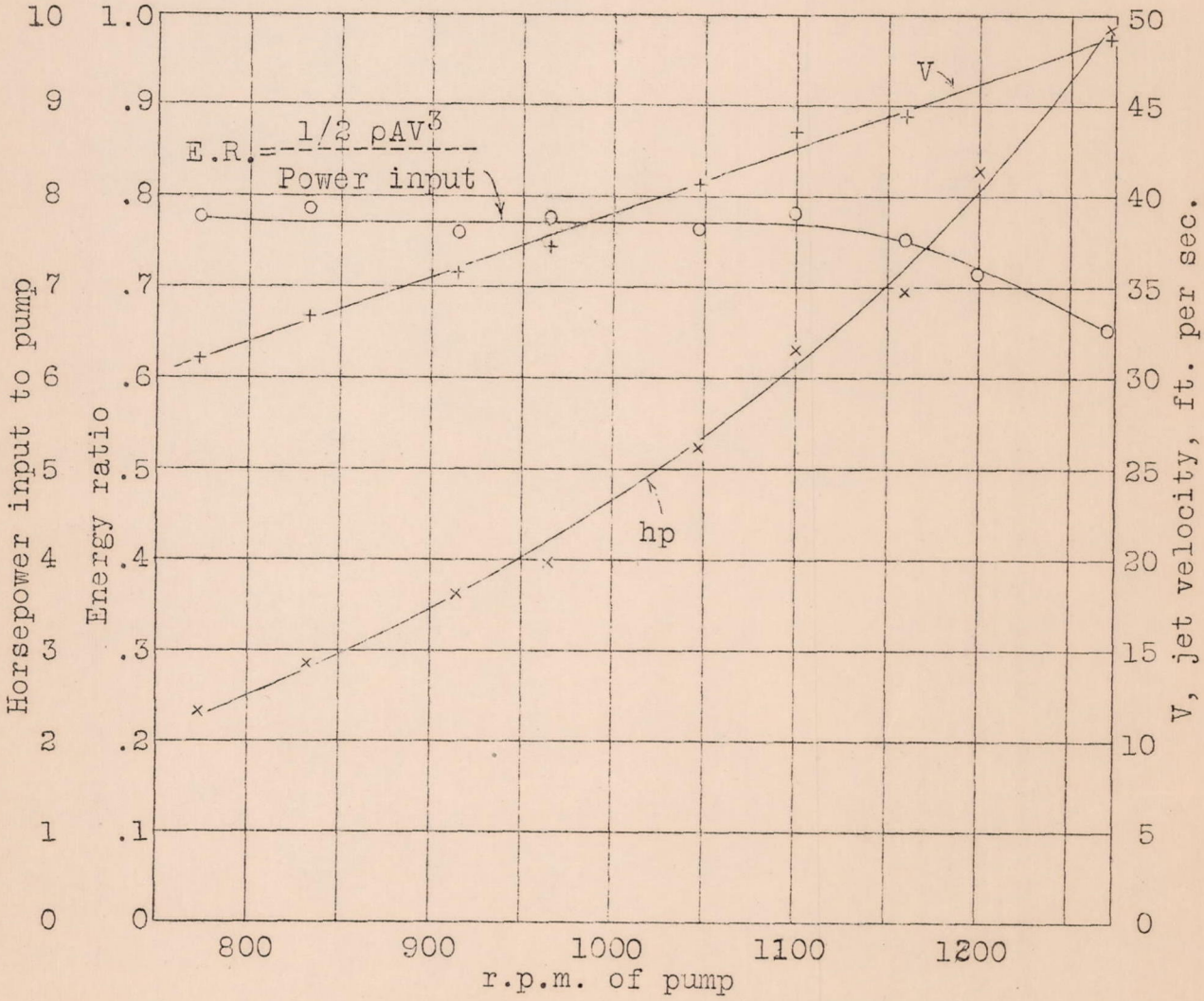

Fig. 4 Characteristics of model water tunnel.