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A PRELIMINARY INVESTIGATION OF THE BEHAVIOR OF CONDENSABLE JETS DISCHARGED INTO WATER

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CONTENTS

ABSTRACT

Preliminary observations of the behavior of submerged steam nozzles discharging into stationary and moving water are described, and photographs are presented to show the changes in appearance of the steam jet due to changes in chamber pressure and/or water velocity.

The measured static pressure distributions along the longitudinal axis of both a converging nozzle and one of the de Laval type have been plotted showing the contrast between the operation of a steam nozzle discharging into air and that of one submerged in water.

A missile running in an air-supported cavity was studied to determine the effect of the discharge of a condensable-jet propulsion unit upon the over-all size and shape on the cavity sheath surrounding the missile; a comparison was made with former experiments in which the propulsion unit used a noncondensing gas for the propellant.

The appendix presents the results of a preliminary study of the thrust augmentation effect suggested by Gongwer which is intended as a means for reducing the depth sensitivity of rocket propulsion units operating at high speeds.

INTRODUCTION

Recent emphasis on the feasibility of using high-velocity gas jets as a method for propelling underwater vehicles has created a demand for information about the behavior of these jets when submerged in still and moving water.

Preliminary work in this field was done by Sage and others in the Department of Chemical Engineering of the California Institute of Technology, using heated compressed air as a propellant.[1,2,3,4,5] In these investigations stationary nozzles were employed, no effort having been made to study the effect of the jet on the external flow. Subsequent work performed at this Laboratory[6,7] was aimed at the study of problems arising from the use of a jet-propulsion system for a cavity-sheathed underwater vehicle. Compressed air at room temperature was used as the propellant, but no attempt was made to study the nozzle itself or the behavior of a fully wetted vehicle using a jet-propulsion device. The primary interest lay in observing the influence of the jet upon the air-supported cavity. Having secured information about the performance of a jet-propulsion system using a noncondensing fluid as the working substance, the question arose as to what effect could be expected if a totally condensing vapor was used. The present investigation was therefore directed towards a study of the factors affecting the practicability of using such a condensable propellant and towards an examination of operational features peculiar to submerged operation of a nozzle using it. Neither the apparatus nor experimental procedures employed were intended to yield precise final results. Instead, existing facilities were used, often with no modifications, in an attempt to secure general summary data in a short time and with a minimum expenditure of resources.

Specific questions borne in mind during the course of the investigation were the following:

(a) In what way, if any, does submerging a nozzle in water affect the behavior of a condensing jet issuing from it?

(b) Does the condensability of the jet constitute an asset or a liability when the jet is used for underwater propulsion?

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(c) What happens when a vehicle running in an air-supported cavity is propelled by a condensing-jet motor, especially in relation to effects on the cavity and cavity-wake configurations?

(d) What type of test installation can best be used to study the problems of submerged condensing jets?

Measurements of thrust or of the hydrodynamic forces acting on the vehicle were not attempted in this study since it was believed that more extended investigation should be deferred until this report is published and requests for specific information are received. Instead, the method of Stodola[8] was used to compare the action of the submerged nozzle with that of one discharging into air. Thus, by measuring the static pressure distribution along the axis of symmetry of the nozzle under varying conditions of operation, changes in the performance of the propulsion unit could be evaluated which would be of help in the design of a condensable-jet propulsion system, and which also might uncover phenomena demanding further investigation.

APPARATUS

These experiments were carried out using two nozzles (Fig. 1) designated as nozzle No. S-1 and nozzle No. S-2, the former of the converging-diverging type (de Laval) and the latter a simple converging one. The throat area of the former is equal to the exit area of the latter, so that at equal chamber and back pressures the mass rate of flow from the two nozzles is the same. The external shapes of each were made reasonably similar so that hydrodynamic effects resulting from the flow of the water past the model would be the same for each and thereby obviate differences in the appearance of the jets not attributable to the characteristics of the nozzle itself.

The nozzles were mounted on a cylindrical body with an external diameter of 1 in. and a total length of 11.5 in., including the nozzle and the cone-shaped nose (Fig. 2). For the studies of cavity-running vehicles, the streamlined nose was replaced by a disc supported on a short sting and incorporating an air supply with which to maintain the cavity during operation. These simulated vehicles were in turn supported from the top of the Free-Surface Water Tunnel[9] by a streamlined strut which broke through

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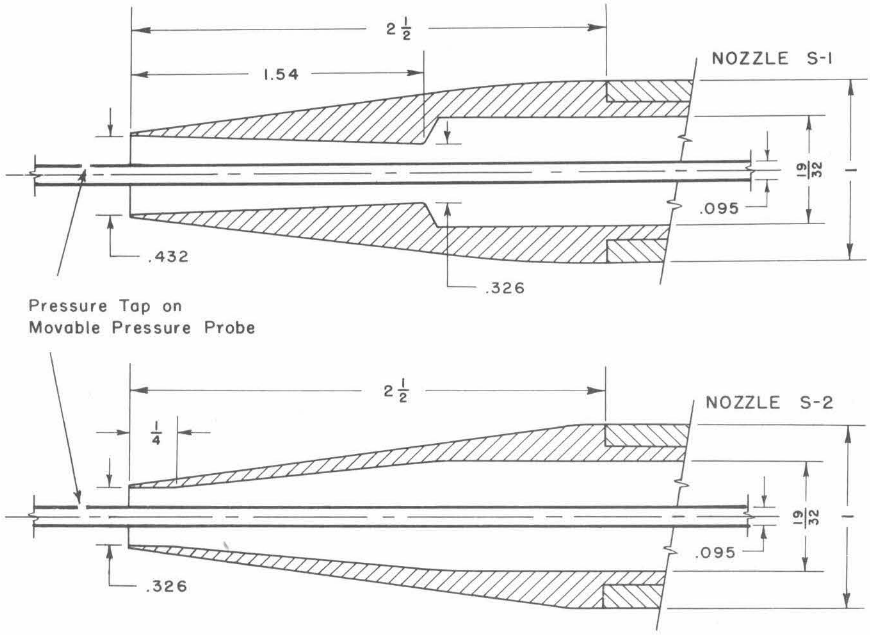

Fig. 1 - Scale drawings of steam nozzles S-1 and S-2 used in this investigation showing movable static pressure probe in place.

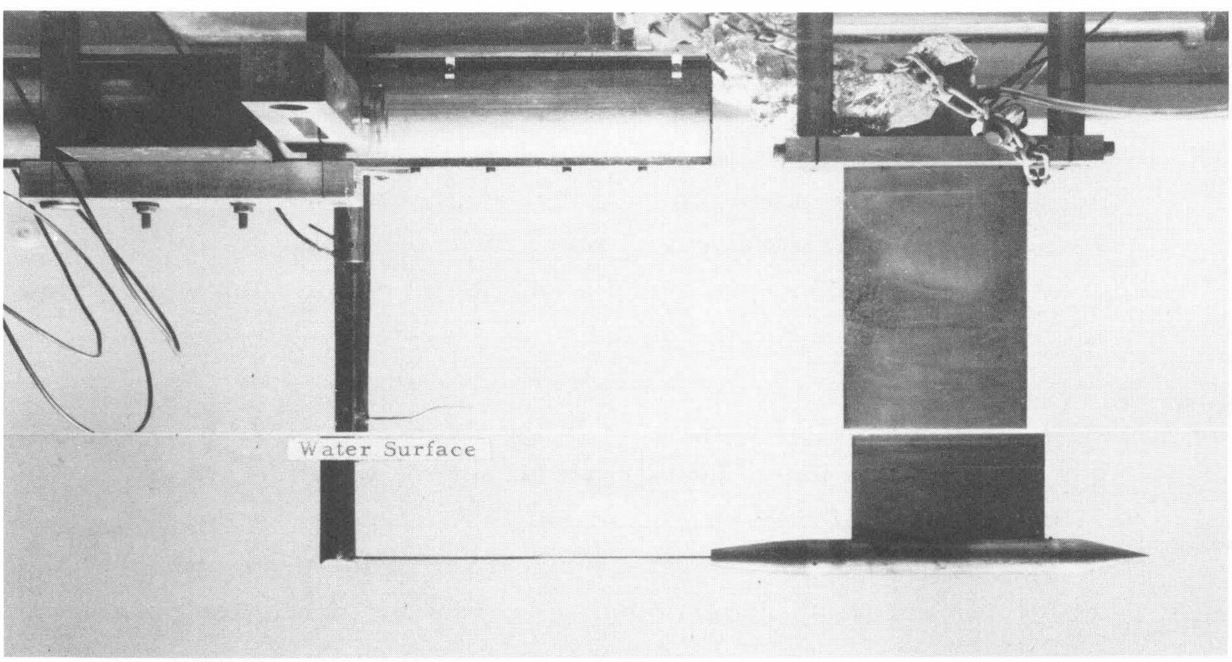

Fig. 2 - Photograph of test setup showing streamlined strut downstream from the nozzle exit and movable static pressure probe within the nozzle. Steam enters strut by way of the aluminum foil-covered steam hose above the strut.

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the air-water interface of the tunnel and which located the model 4 in. below the water surface.

In choosing a suitable propellant, several important considerations were kept in mind, those uppermost being availability and inability to contaminate the tunnel water. These factors, as well as the existence of a vast quantity of literature, resulted in the choice of steam as the working fluid. Continuous operation of the unit was secured by using steam supplied from the campus boiler room instead of generating it within the vehicle. The strut supporting the model incorporated built-in steam lines which connected to a flexible rubber steam hose about 5 ft long and covered with aluminum foil to shield it from possible water spray. The hose, in turn, joined with the end of the permanent steam line above the tunnel working section. Line pressures of 150 psig were available at the tunnel, but pressure drop through the strut placed an upper limit of about 90 psig for the chamber pressure at the higher flow rates used. Lower pressures were obtained by use of a throttle valve located near the end of the permanent line installation. Pressure was read on "Heise" precision pressure gauges mounted above the tunnel.

A static pressure probe mounted on a streamlined strut downstream from the model support strut was moved fore and aft within and behind the nozzle to measure the static pressure distribution along its longitudinal axis. To minimize vibration or misalignment of this probe, the upstream end was positioned centrally by a piece of brass tubing located within the nozzle chamber. This probe and a chamber pressure tap were connected to their respective precision gauges, each system incorporating a compressed air clearing system which permitted the pressure lines to be blown free of water which had condensed in the lines. During the course of the experiments it was found undesirable to permit water to accumulate in the lines because of the subsequent sluggish response of the gauges. Also, the unknown level of water in the vertical leg of the pressure lines could introduce an error of several pounds per square inch in the pressure reading.

OBSERVATIONS AND ANALYSIS OF DATA

Nozzle No. S-1 (de Laval type), Vehicle Fully Wetted

Nozzle No. S-1 was installed in the tunnel, mounted on the streamlined strut as described under the section on "APPARATUS". The 0.095-in. diameter probe was placed in position and the complete unit, the nozzle-probe combination, was submerged 4 in. below the water surface. Because the presence of the pressure probe had the effect of changing the original nozzle into one of different geometry, the photographs were taken of the combined unit, thereby permitting the measured pressure data to be correlated with the shape of the jet, as revealed by subsequent photographs. Trial runs were performed without the probe in place, however, and it was observed that the presence of the probe did not produce any noticeable change in appearance of any part of the jet.

The first runs made with the de Laval nozzle were of a qualitative nature. For very low chamber pressures and at zero water velocity, (10 psig, Fig. 3), detachment of the steam flow at the nozzle exit was observed, this being accompanied by a "crackling" sound similar to that which occurs during incipient cavitation of a rapidly moving body in water. The noise continued until a chamber pressure of 30 psig was reached, at which time the unit became very silent and remained silent for all subsequent higher chamber pressures. The appearance of the jet might be likened to that of an acetylene flame in external shape, and the color to that of a very frothy mixture of air and water, except for a narrow transparent band at the nozzle exit through which the pressure probe may be seen. The chamber pressure was varied through arbitrarily selected values from 10 psig to 80 psig and flashbulb photographs were taken of each (Fig. 3). The separation of the jet from the nozzle wall at subsonic throat velocities and for the low chamber pressures is apparent in the photographs, as is the continued expansion of the jet outside the nozzle for the highest chamber pressures used.

Several nozzle diameters downstream from the nozzle exit, only a trail of minute bubbles of air remained, their diameters being so small that they did not rise to the surface within the 8-ft length of working section. These air bubbles may have originated at either one or two sources: air may have been originally present as a contaminant in the steam supplied from the central steam plant, or air originally dissolved in the tunnel water was released as a gas because of the higher temperatures at the jet boundary. Of interest is the fact that although the tunnel motor was off, the thrust of the steam issuing from the nozzle caused the water in the working section (20 in. x 21 in. in cross section) to move at a velocity of several feet per second. Also, the temperature of the water in the vicinity of the jet was raised very slightly by the condensing steam.

The heat transfer from the nozzle to the surrounding water was considerable, as is evidenced by the air bubbles which are shown in Fig. 3. These bubbles, consisting of air originally dissolved in the tunnel water, formed on the nozzle then broke away and moved upward, later to be carried in a downward-curving trajectory back into the steam jet.

It was hoped to determine the effect of surrounding a de Laval nozzle with water by selecting a given chamber pressure and making a static-pressure survey along the axis of the nozzle. Since the efficiency of the nozzle and the quality of the steam passing through it were not known (calorimeter tests showed it to be 95% quality when the strut was not surrounded by water), the design chamber pressure was assumed to be that value at which the smoothest transition from nozzle exit pressure to ambient pressure occurred. This was quickly determined by the method of trial and error to be approximately 72.5 psig, no serious attempt having been made to determine this value with greater accuracy because the point of interest was the comparison between the behavior of the steam nozzle in water and with that of one in air. Pressure surveys were made at this design chamber pressure, then at values above and below it. The results of these surveys are shown in Fig. 4.

A plot of pressure measurements made at this same chamber pressure, but with the nozzle exhausting into air is shown on this same figure. Since the jet was submerged to a depth of only 4 in., no correction was made for the difference in back pressure between the water runs and the air run.

The nozzle discharging into air at 72.5 psig chamber pressure (Fig. 4) exhibits pressure waves which decrease in amplitude as measured by the probe as it was moved downstream from the nozzle exit. That these pressure waves exist at all, proves that the nozzle is not operating at its exact design pressure ratio, but there is no indication of either serious underexpansion or overexpansion. The air runs, unlike those performed on

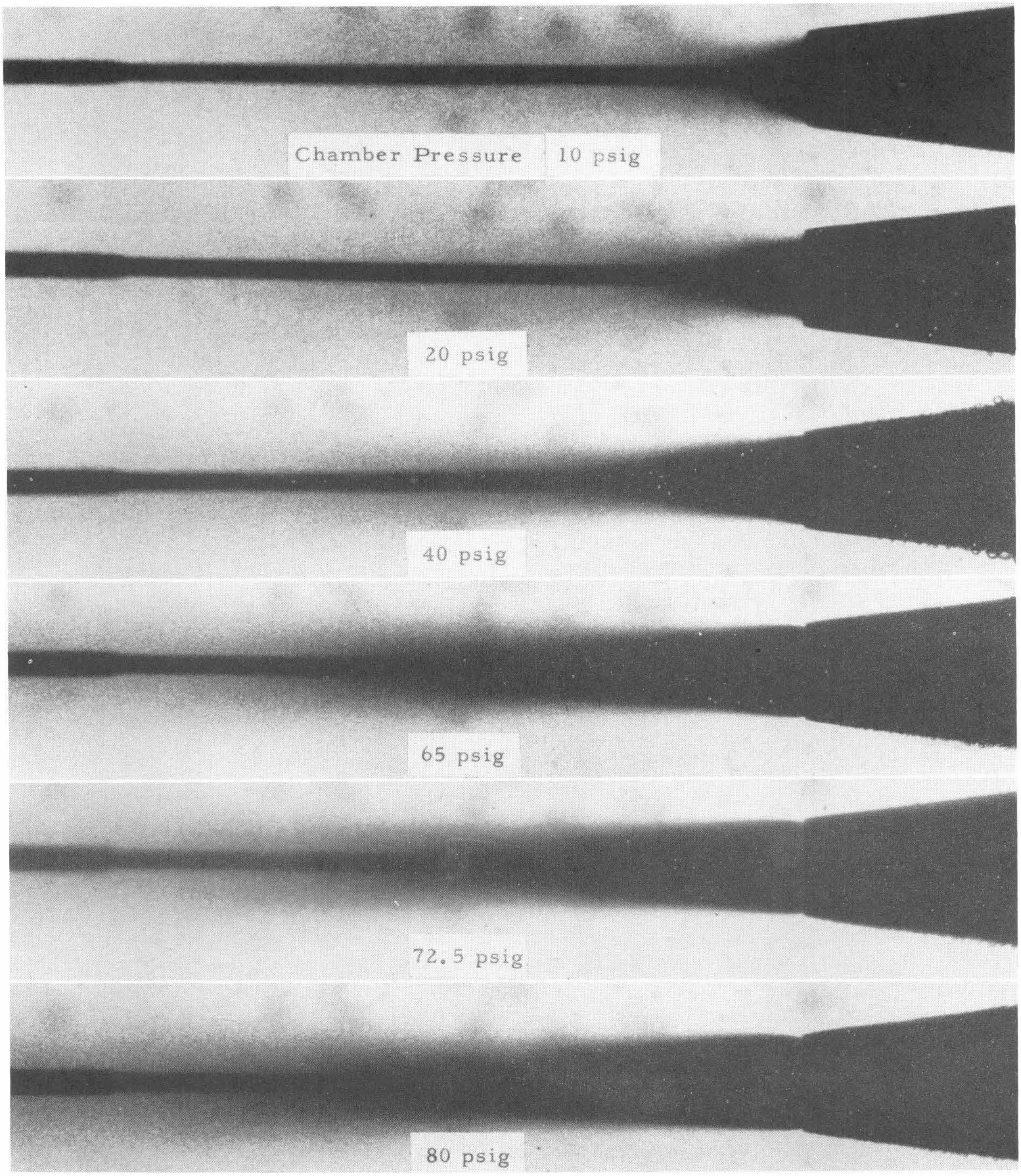

Fig. 3 - Flashbulb photographs of steam nozzle No. S-1 (de Laval type) discharging into still water at various chamber pressures. The static pressure probe can be seen to the left of the nozzle. (Velocity = 0 fps)

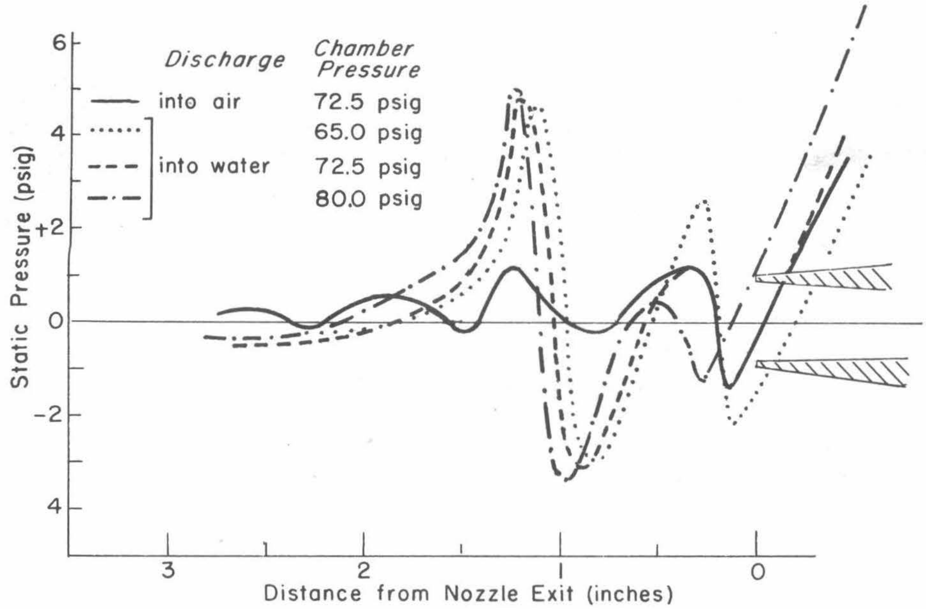

Fig. 4 - The effect of variations in chamber pressure upon the static pressure variation beyond the exit of a de Laval steam nozzle submerged in still water. Also shown is the static pressure distribution for the same nozzle discharging into air.

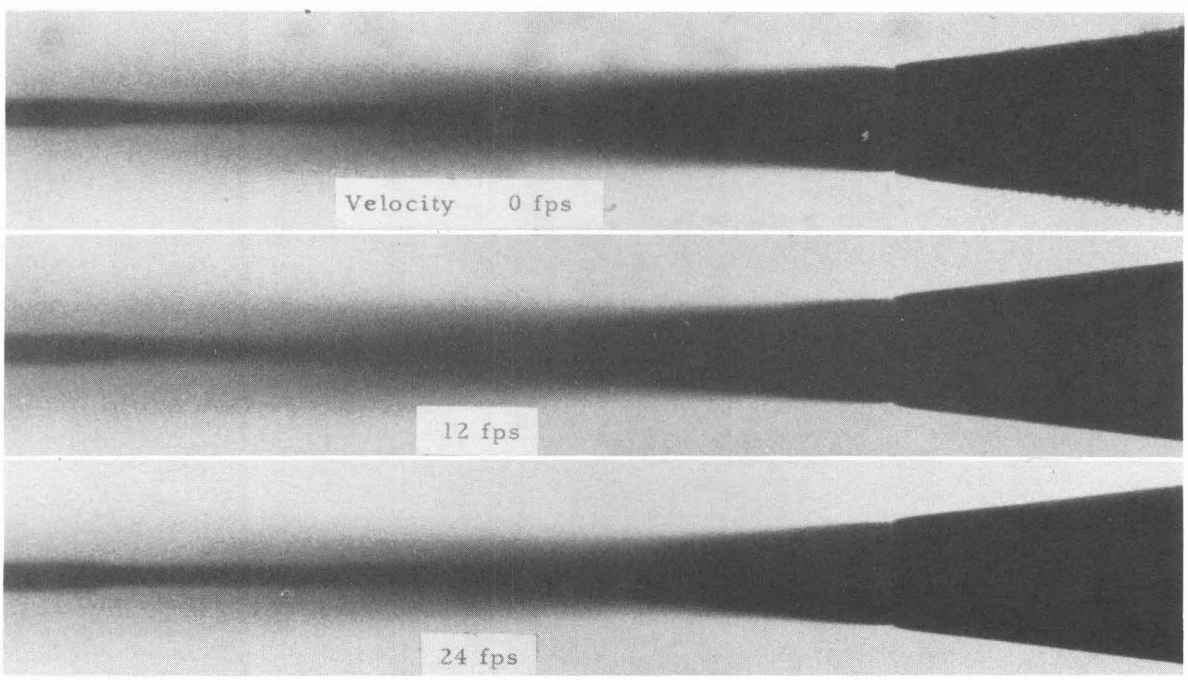

Fig. 5 - Nozzle No. S-1 (de Laval type) discharging into water moving at different velocities, chamber pressure being held constant. Direction of water flow is from right to left. (Chamber pressure 72.5 psig)

submerged nozzles, were quite troublesome to execute, being accompanied by a deafening roar and clouds of condensed steam, even though a duct had been installed to carry the exhaust steam into the diffuser and air separator of the tunnel. Hence the chamber pressure was made equal to that for the reference water run (72.5 psig) without trying to secure more favorable operation of the nozzle in air. In any case, the pressure waves for the air run are similar to those of the submerged runs for a distance of one exit diameter downstream. Farther downstream the water runs show a large drop in pressure, followed by a larger rise above ambient, with the position of the maximum and minimum points corresponding to the much smaller ones exhibited during the air run. Although not obvious from the flashbulb photographs, the region from two to three diameters aft of the nozzle was at least partly filled with water. This was deduced on the basis of the slow response of the pressure gauge for points farther away from the nozzle than the second minimum point. Indications are that in these after regions the pressure fluctuated greatly with time, and that the pressure tap was located in steam at one instant and in water the next. Electronic-flash photographs, (Fig. 6f), taken of the second nozzle show this phenomenon more clearly.

The effect of increasing the chamber pressure for the submerged runs (chamber pressures 65 psig, 72.5 psig, 80 psig) was to displace the large pressure variations rearward, a result which seems to be correlated with the change in size of the jet.

Running the tunnel first at 12 fps and then at 24 fps produces no large change in the jet configuration when a constant chamber pressure of 72.5 psig is maintained (Fig. 5). Close examination of the photographs reveals that the jet may "bulge" slightly more when the water is stationary and that the trail of bubbles behind the principal region of the jet flares less as the velocity is increased.

Pressure surveys were made at velocities of 12 fps and 24 fps, but experimental difficulties made the measurements for the 24-fps run unreliable. The refinement of apparatus which would be required in order to make an accurate pressure survey at this higher velocity would involve an expenditure of time and resources not deemed commensurate with the purpose of this preliminary study. The plot of the pressure survey for the 12 fps run shows no significant difference from that at 0 fps, and has not, therefore, been included in this report.

Nozzle No. S-2 (convergent type), Vehicle Fully Wetted

The procedure with nozzle No. S-2 was similar to that for S-1, except that a more complete set of data was taken. Greater emphasis was placed on the converging nozzle than on the de Laval type because it could be operated under extreme underexpanded conditions with very moderate chamber pressures. Since a vehicle using this type of propulsion might be designed to operate against considerable back pressure, it is of interest to study the effects of greatly reduced ambient pressure (shallow submergence) on the behavior of the propulsion system.

Figure 6 shows the jet operating at different chamber pressures. This series of photographs, taken at zero water velocity shows the increasing bulge of the steam jet as underexpansion becomes more severe.

A comparison of the photograph in Fig. 6e with that of Fig. 6f shows that the clean regular outline of the steam jet is due in part to the long exposure of the flashbulb (20 millisecs). The shorter exposure (15 microsecs) electronic flash lighting reveals that the outline of the steam jet is by no means smooth, but consists rather of a series of puffs of varying intensity. This lighting technique was not used through the experiment because it was thought that the longer exposure gave a better comparison of the average jet shape for different operating conditions.

Pressure surveys were made at two different chamber pressures, with the nozzle discharging both in air and water. At the higher chamber pressure a survey was also made at a water velocity of 20 fps, the highest velocity at which reliable pressure readings could be made. The record of pressure measurements at the lower chamber pressure is presented in Fig. 7 and those at the higher pressure in Fig. 8. Each will be discussed in turn.

At a chamber pressure of 12 psig and exhausting into a back pressure of one atmosphere, the simple converging nozzle should operate very nearly at its design point. This supposition is borne out by the pressure measurements for that part of Fig. 7 showing the air run. When the nozzle was submerged in water the measurements indicated a steeper pressure gradient outside the nozzle exit, with slightly higher pressures measured at the nozzle exit. After reaching ambient pressure, one nozzle exit diameter downstream, however, the pressure increased again for a distance of

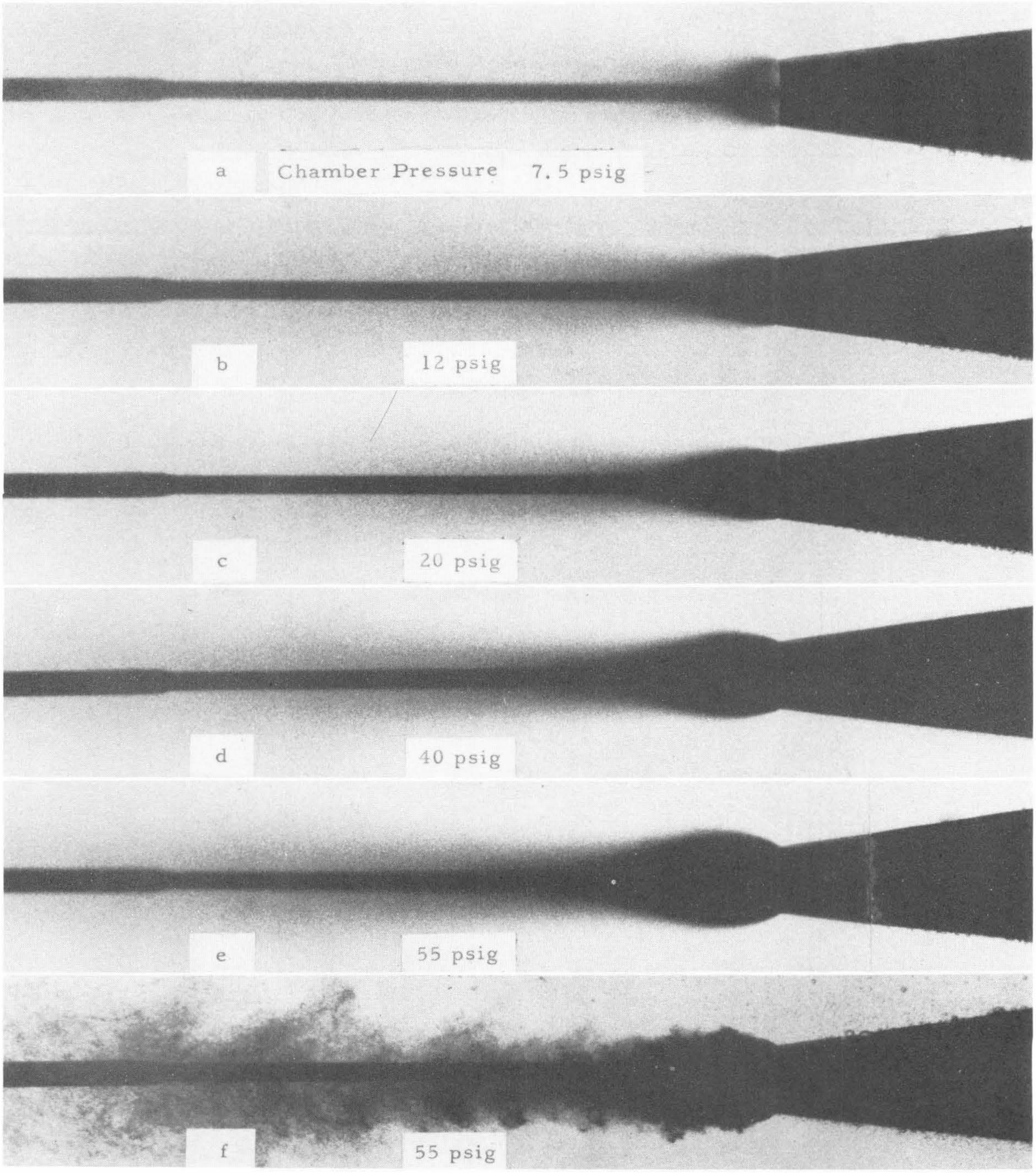

Fig. 6 - Photographs of steam nozzle No. S-2 (converging type) discharging into stationary water at various chamber pressures. The pressure probe can be seen to the left of the nozzle. Figures a to e were taken with flashbulb illumination, whereas Fig. f was made using electronic flash techniques. (Velocity = 0 fps)

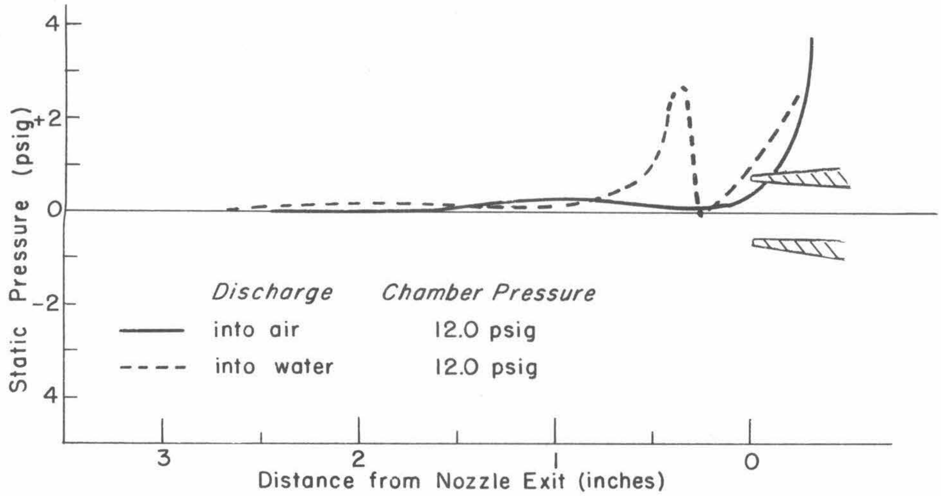

Fig. 7 - Comparison of static pressure distribution beyond the exit of a converging steam nozzle when discharging into air and into water. Chamber pressure near design value.

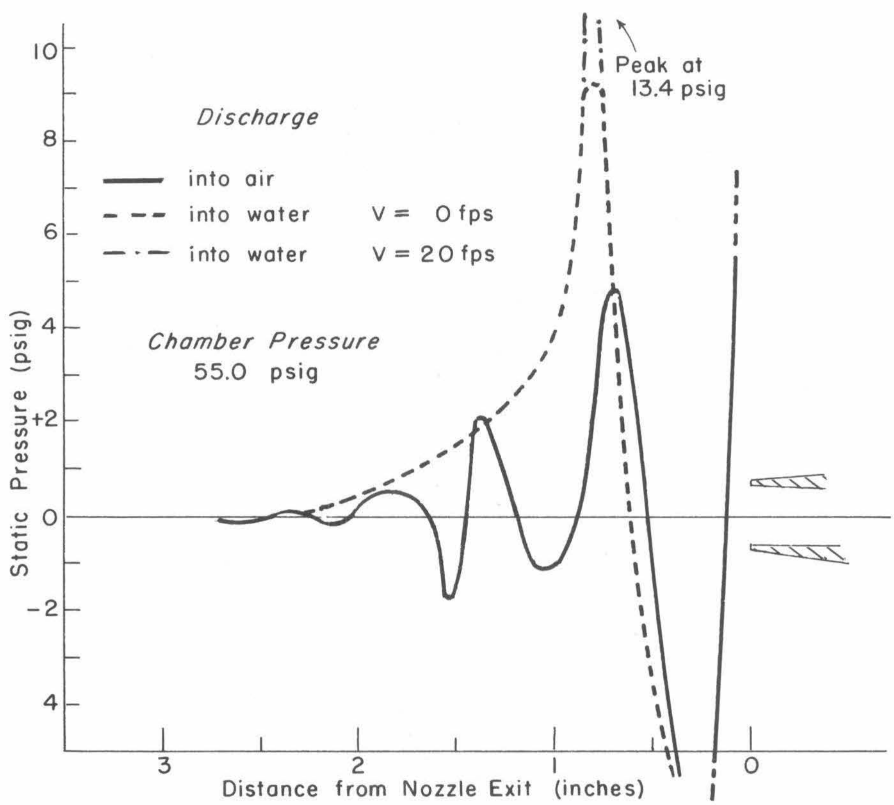

Fig. 8 - Static pressure distribution beyond the exit of a converging steam nozzle when discharging into air and into still and moving water. Chamber pressure higher than design value.

one-half diameter, then decreased smoothly farther downstream. The response characteristics of the pressure gauge for that region corresponding to the sharp rise in pressure suggested that water was at times striking the pressure tap. The photograph in Fig. 6b also indicates that the pressure rise took place in the region where the steam jet was condensing. The reason for the presence of pressures higher than those measured during the air run within, and at the exit of the submerged nozzle, has not been adequately explained, since the existance of supersonic exit velocities (which are assured for chamber pressures greater than critical) should have precluded the possibility of downstream disturbances causing changes in the upstream pressure distribution.

The effect of submerging the converging nozzle in still and moving water at chamber pressures high above the design value (Fig. 8) was similar to that observed in the case of the de Laval nozzle. Fewer pressure waves were present than for the run made discharging into air, but pressure measurements made within one and one-half diameters of the nozzle exit duplicated the values obtained in air. The first pressure peak was greater in the case of the submerged nozzle than it was with the nozzle discharging into air, most likely due to the impact of water striking the pressure tap. At a water velocity of 20 fps, the only observed difference in the pressure survey was an increase in the peak reading. Figure 9 shows that there are no detectable changes in the size and shape of the steam jet for velocities up to 24 fps, that is, up to a dynamic pressure of 7% of the gauge chamber pressure.

Nozzle No. S-2, Cavity-Running Vehicle

Former experiments performed at this Laboratory[6, 7] with noncondensing jets discharging into an air-supported cavity, showed that discharge of a supersonic jet from the afterbody of a cavity-running vehicle collapsed the cavity so that its length was approximately equal to that of the vehicle. In this respect, there is no difference between the operation of the condensing jet and that of the noncondensing jet. The appearance of the wake differs in the two cases, however, because of the greater quantity of air being discharged in the case of the noncondensing jet. When the propulsion jet is condensable, the amount of air in the wake does not increase with chamber pressure since the visible wake consists only of the air supplied behind the disc nose to support the cavity[10]. Figure 10 shows the effect on the cavity configuration of increasing the chamber pressure of the steam nozzle. The values of chamber pressure used in this run were selected to demonstrate the dependence of the cavity size upon chamber pressure up to the point where the cavity collapses on the vehicle afterbody and the subsequent independence between the two after this takes place. In all cases the cavity-supporting air supply was held constant at a high flow rate. Increasing this flow rate did not alter the length or diameter of the cavity significantly, but only caused distortion of the cavity wall in the region of the cavity-supporting air supply. This behavior is to be expected, as was shown in reports previously issued by this Laboratory[11, 12].

The reader is cautioned to observe that the cavity-running vehicle experiments involved air-supported cavities and not vapor cavities. In the former case, the cavity pressure results from a supply of air injected behind the nose of the model, and any action tending to restrict this air flow or to increase the rate at which air is carried away from the cavity will result in a lower cavity pressure. This lowered cavity pressure implies a higher cavitation number and hence a shorter cavity, if velocity and ambient pressure remain constant[13]. This is not the case when the cavity is filled with water vapor supplied from the boundary of the cavity, where the cavity pressure is determined by the vapor pressure corresponding to the temperature of the water. Although no experimental verification exists, it is believed that the over-all size or shape of a vapor cavity will not be altered by a supersonic steam jet issuing into it.

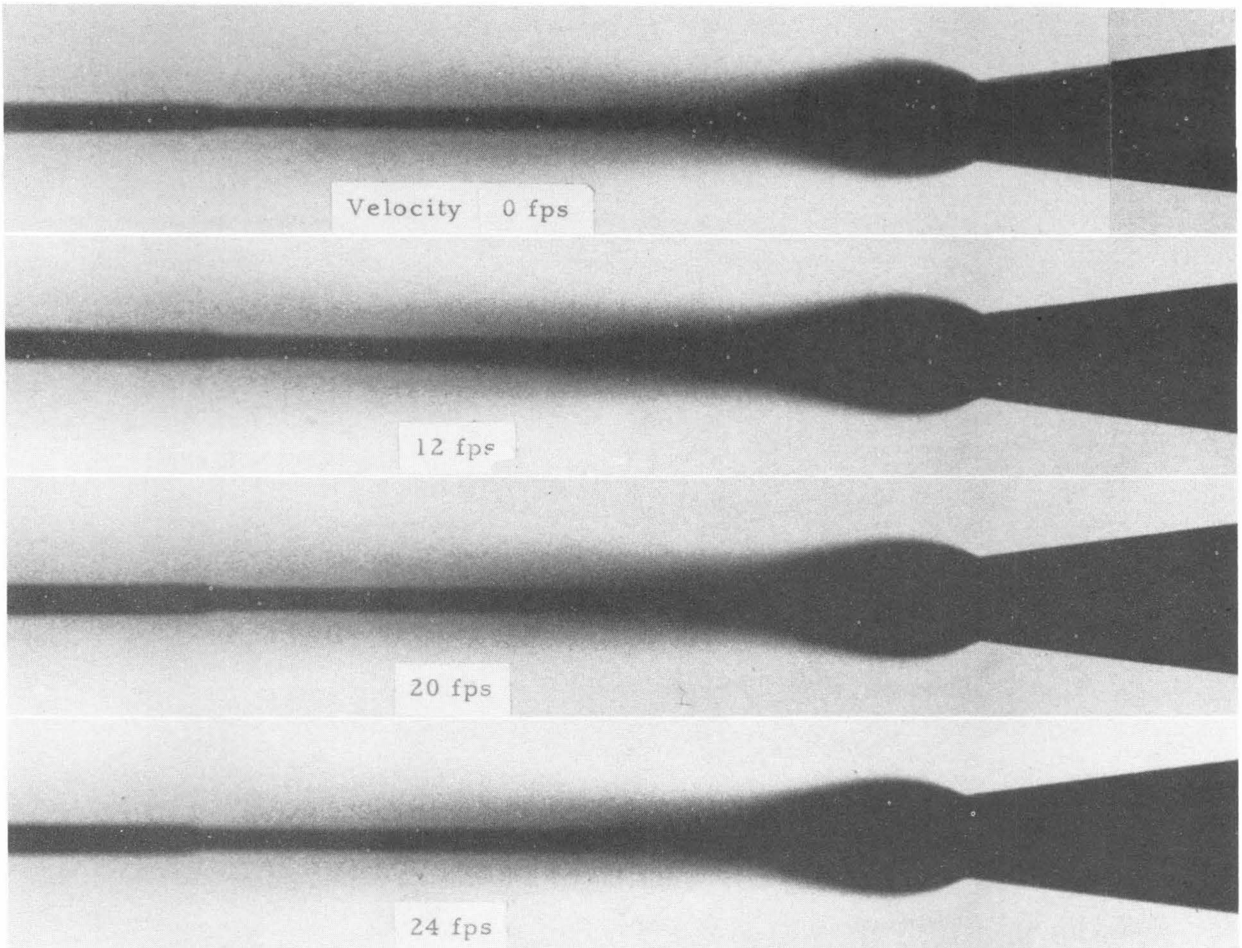

Fig. 9 - The above photographs, taken at the same chamber pressure but with varying water velocities, show no detectable change in the appearance of the steam jet but reveal a decrease in flare angle of the entrained air bubbles far downstream from the nozzle exit. (Chamber pressure 55 psig)

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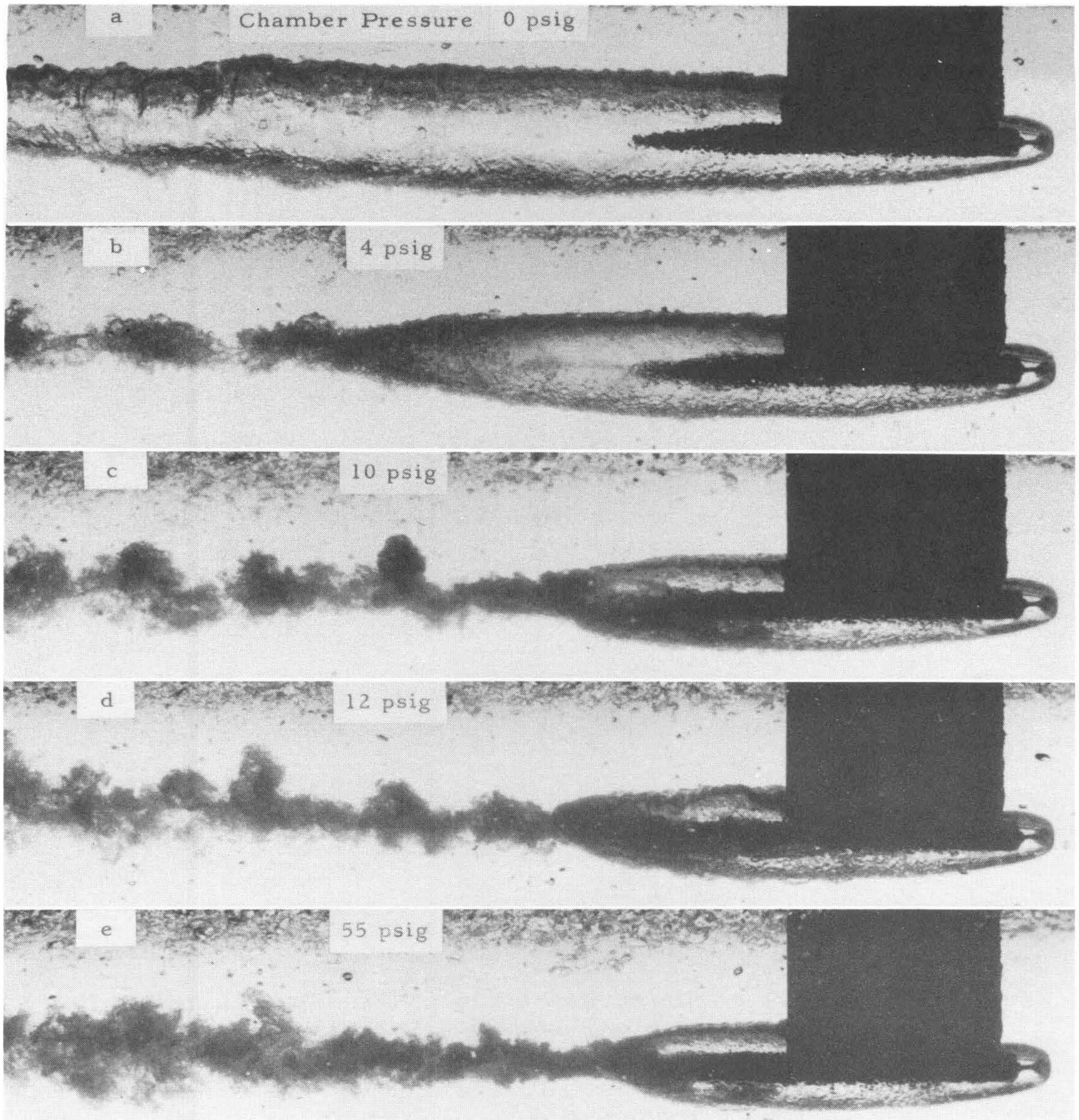

Fig. 10 - Air-supported cavity-running vehicle with steam nozzle (S-2) and propulsion system exhausting into the cavity. Water velocity and cavity support air supply constant, varying chamber pressure. (Velocity 24 fps)

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CONCLUSIONS

Steam nozzles of either the de Laval or simple converging type may be submerged in water without introducing any difficulties of operation so long as exit velocities are supersonic. At exit velocities lower than these, a loud crackling sound is heard and the steam leaves the nozzle in definite surges. It is also probable that water backs into the nozzle in the time period between surges so that slugs of water are intermittently expelled.

When sonic exit velocities are attained, the operation of the nozzle becomes smooth and quiet, much more so than a nozzle using noncondensable gases for the propellant. In this latter case, explosive expansions of the gas outside the nozzle are always present regardless of the chamber pressure used. Also, the visible wake of the vehicle using a condensing jet propulsion system consists only of the noncondensable gases present as impurities or of those coming out of solution in the surrounding water. All the steam condenses within five nozzle diameters, at most, behind the vehicle.

For supersonic exit velocities, the static pressure distribution along the axis of symmetry of the nozzle is identical for the nozzle discharging into either water or air for points within the nozzle or less than about one diameter beyond its exit. Farther downstream the submerged runs are characterized by waves of greater intensity, but fewer in number, than those observed during the runs made discharging into air. This condition holds true even when water flows past the nozzle at a velocity of 20 fps, at least so long as severe underexpansion is present. No measurements were made where the chamber pressure was near the design value and with the nozzle moving relative to the water. The design of a steam nozzle, therefore, does not seem to be altered by demands of underwater operation, excepting that heat transfer from a nozzle exposed to rapidly flowing cold water might cause appreciable reduction in performance.

All the observations made during the course of this investigation indicate that a propulsion system designed to use a condensable propellant is at least as practicable as one using a noncondensing gas. No difficulties in design or operation which can be attributed to the condensability of the exhaust have been encountered; in fact, from the viewpoint of silence and smoothness of operation, the condensing jet is far superior.

The effect of a supersonic jet of steam on the size and shape of an axially symmetric, air-supported cavity is identical with that of a similar jet of noncondensable gas. In both cases the jet sweeps away the air within the cavity and reduces its length by virtue of the increased cavitation number. This decrease in length continues until the cavity closes on the vehicle after-body ahead of the nozzle and seals the air (or gas) envelope so that further reduction in the cavity pressure due to the action of the nozzle is not possible.

Further work using facilities with greater range of operating velocity and/or ambient pressure may reveal characteristics hitherto unnoticed, but until more information or specific requirements of this type of propulsion system are demanded, development work on this type of propulsion system could probably be undertaken using the information on steam nozzles existing in the available literature.

Should further investigation of the effect of increasing the range of operation or pressure be required, profitable use can be made of water tunnels of the high-speed type such as exists at this Laboratory. These tunnels usually possess a greater range of velocity and pressure than is available in the Free-Surface Water Tunnel, although they are unable to cope with large quantities of entrained air, a feature shown in this report to be unnecessary for the study of totally condensing jets. The problem of the condensable jet exhausting into a vapor cavity can also be investigated with comparative ease.

APPENDIX

Experimental Study of the Dynamic Recovery of Thrust Effect of Condensable Jets

During the course of investigation which culminated in this report, observations were made which are related to work being performed by C. A. Gongwer of the Aerojet Engineering Corporation. Gongwer shows[14] that the performance of a rocket nozzle is not reduced if the gases are under-expanded when leaving the nozzle, so long as the velocity of the missile, and hence the dynamic pressure of the oncoming water, is high. Under these conditions of operation Gongwer suggests that expansion of the exhaust gases continues in an orderly fashion beyond the nozzle exit. The mechanism whereby this is possible stems from the formation of a water nozzle wherein the exhaust gases are contained. The "stiffness" of the rapidly flowing water passing over the external surface of the well-formed body impinges on the exhaust gases and causes them to flair an amount commensurate with the nozzle area ratios required for correct expansion. Even though the continued expansion takes place beyond the nozzle, the thrust of the rocket is increased because of adjustments in the external flow which result in higher pressures acting upon the exterior surface of the nozzle and missile afterbody. Gongwer asserts that the use of a rocket nozzle cut off at the throat will result in a missile which is less depth sensitive than one incorporating a de Laval nozzle of fixed area ratio .

In spite of the limited maximum velocities which could be obtained in the Free-Surface Water Tunnel, the preliminary condensable jet study was amended to include investigation of this property of thrust augmentation. Not possessing adequate instrumentation to make direct thrust and drag measurements on the simulated rocket-propelled vehicle, an inferential technique was used. The static pressure distribution beyond the underexpanding nozzle should show less intense spatial pressure fluctuations when discharged into rapidly moving water than when discharged into water having no velocity relative to the nozzle. This would imply that the motion of the water did, in fact, create a water nozzle in which the pressure change from its value at the nozzle throat to that of the free stream took place more smoothly - a criterion for correct functioning of a steam nozzle. Figure 8 in the main body of the report shows that this was not the case, nor was there any significant change in the appearance of the jet which was due to the change in velocity. Whether these negative results are due to the insufficient velocity of the vehicle, or to other causes, is not yet known.

Future attempts to study this phenomenon in the Free-Surface Water Tunnel might employ more accurate instrumentation than was used here. By comparing a nozzle operating under conditions of very slight underexpansion and submerged first in stationary water, then in moving water, the anticipated continuation of orderly expansion outside the nozzle might be detected. Very slight underexpansion is required because the limited water velocities available in the Free-Surface Water Tunnel do not permit any other method of attaining the required high ratio of ram pressure to exit pressure.

The difference in appearance of the condensing jet as seen in the Free-Surface Water Tunnel and the one shown in the report by Gongwer was at first believed to be due to the tremendous difference in velocities of the two models. An attempt, therefore, was made to obviate conditions of operation not common to both models. The vehicle tested by Gongwer was not propelled by a rocket using totally condensing gases, but rather by one whose exhaust products contained 25% hydrogen. To simulate this condition for the Caltech model, compressed air from a metered supply line was bled into the steam supply far enough ahead of the model to insure complete heating and mixing of the air prior to its expulsion with the steam. Even with mass flow rate ratios of only 6% (air to steam) the appearance of the jet-wake combination changed radically. In place of the short jet and invisible wake which characterized the all steam operation, a jet appeared with a wake longer than the 8-ft length of the tunnel working section. Photographs showing the air-diluted steam run (Fig. 11) show a general similarity in appearance to that presented in the report by Gongwer except in the immediate vicinity of the nozzle exit, where the flare angle of the jet is essentially the same as it was without air dilution. Changes in water velocity produced large changes in the appearance of the wake but little or no change in the jet shape close to the nozzle exit where such a change would be most significant.

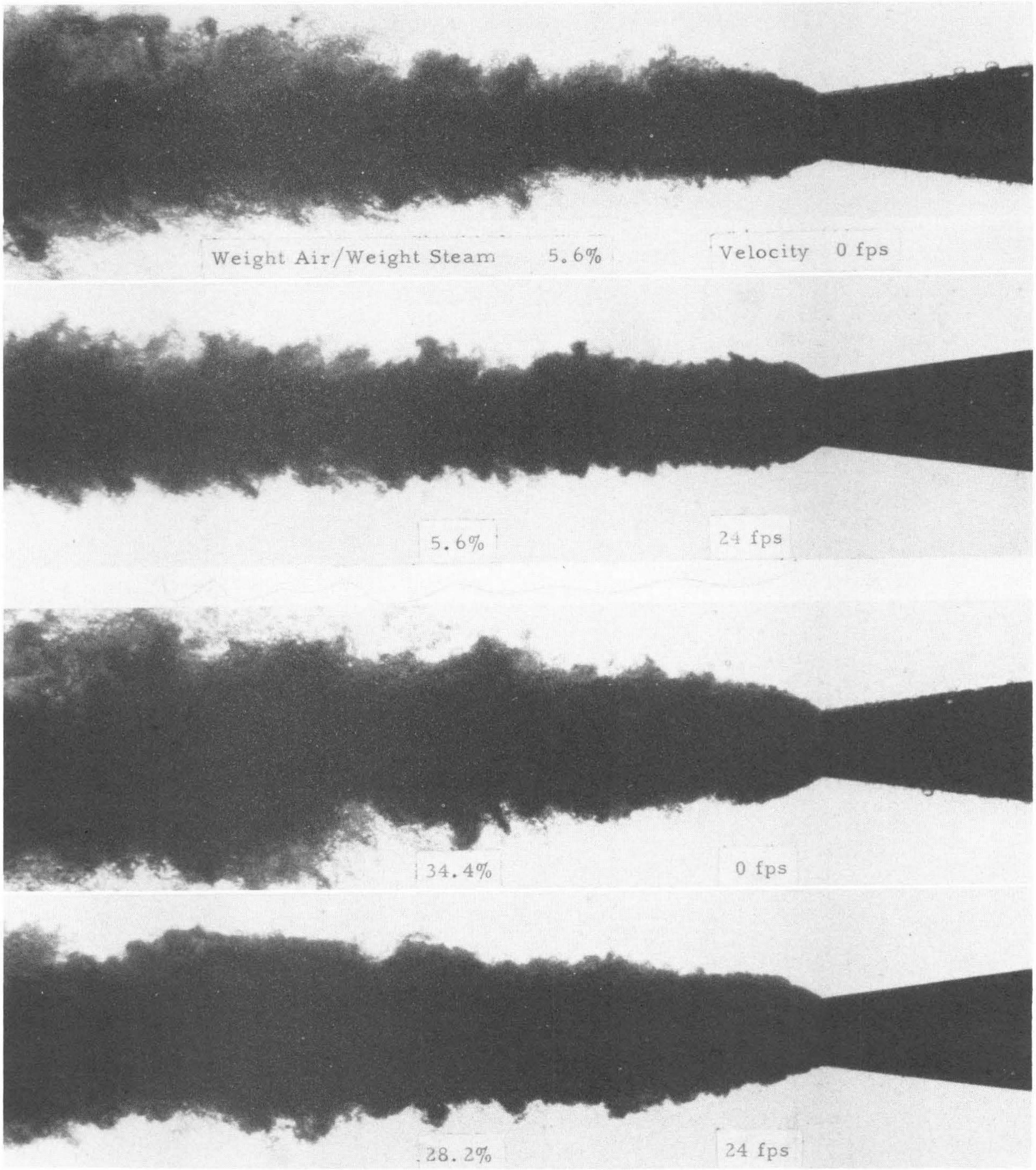

Fig. 11 - Electronic flash photographs showing the effect of air dilution upon the appearance of nozzle discharging steam into stationary and moving water. (Chamber pressure 55 psig)

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