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# INVESTIGATION OF TWO-PHASE HYDROGEN FLOW IN PUMP INLET LINE

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## ABSTRACT

An investigation was conducted to evaluate the vapor- to mixture-volume ratio present in the inlet line of a pump when liquid hydrogen is pumped in a boiling condition from a sealed tank. Both an experimental and an analytical approach were used. The good agreement obtained between the experimental and analytical results indicated that the vapor- to mixture-volume ratio can be predicted with reasonable accuracy. These estimated values of vapor- to mixture-volume ratio, when used with previously reported results, may be useful in predicting pump inducer performance with two-phase flow.

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## SUMMARY

An investigation was conducted to evaluate the vapor- to mixture-volume ratio present in the inlet line to a pump when the fluid is pumped at or near zero net positive suction head. One-dimensional flow, thermodynamic equilibrium, and a homogeneous mixture of liquid and vapor were assumed to exist in the pump inlet line. Analytical results were compared with those obtained from experimental studies in liquid hydrogen using a "workhorse" pump to generate flow in the test annulus. Tests were made at two mass flow rates and over a temperature range of $36^{\circ}$ to $42^{\circ}$ R (20.0 to 23.3 K). Reasonable agreement between the results from the experimental and analytical methods indicated that the vapor- to mixture-volume ratio can be predicted with reasonable accuracy and that it is dependent upon the temperature of the fluid, the mass flow rate, and the margin of total pressure above vapor pressure at the entrance to the inlet line.

The estimated values of vapor- to mixture-volume ratio, when used with previously reported results, may be useful in predicting pump inducer performance with two-phase flow.

## INTRODUCTION

Because of the large volume tanks required in liquid-hydrogen-fueled rocket vehicles, the weight and payload capacities of these vehicles are sensitive to required tank pressure. It is thus desirable to maintain the lowest tank pressure that will satisfy the net positive suction head (NPSH) requirements of the pump. The NPSH defined herein refers to the total pressure above the vapor pressure of the liquid at the pump inlet. Tests of cavitating inducers have shown that the required NPSH at a given operating point is much lower for operation in liquid hydrogen compared with that required for room-temperature water (ref. 1). This reduction in the required NPSH is attributed to local reductions in the temperature and pressure caused by the vaporization process within the cavitated region on the inducer blading. This reduced cavity pressure permits an equal reduction in NPSH for a given set of operating conditions and level of inducer performance. Because of the unique physical properties of liquid hydrogen, the reduction may be sufficient to allow pump operation at NPSH values sufficiently low that two-phase flow at the inducer inlet is obtained.

When the liquid being pumped is at zero NPSH, the total pressure is equal to the vapor pressure of the bulk liquid. The flow velocity in the inducer inlet will cause the local static pressure to fall below the vapor pressure of the bulk liquid. At this condition, the liquid will boil, and the fluid entering the pump will be a mixture of liquid and vapor.

Studies reported in reference 2 indicate that the inducer with two-phase flow in the inlet line can be predicted, provided that the cavitation performance (with no vapor in the inlet line) is known. The method involves an adjustment of the inducer flow coefficient to account for the higher volume flow rate through the inducer when two-phase flow is present in the inlet line. The method of reference 2 requires that the vapor- to mixture-volume ratio be known or that it can be estimated.

The purpose of this report is to evaluate by experiment an analytical method for estimating the vapor- to mixture-volume ratio for two-phase hydrogen flow in a pump inlet annulus over a range of temperatures and flow rates. The analytical prediction method is presented. The predicted results are compared with those obtained experimentally.

The volume of vapor formed is dependent on the physical properties of the fluid and the local static pressure which in turn is a function of the local fluid velocity. The vapor- to mixture-volume ratio in the inlet line upstream of an inducer can be calculated using a heat balance and one-dimensional flow relations if thermodynamic equilibrium and a homogeneous mixture of liquid and vapor are assumed. Similarly, the velocity of the liquid-vapor mixture and the static pressure in the inlet annulus can be estimated if the static pressure in the inlet line is assumed equal to the local vapor pressure.

The volume ratio can also be evaluated experimentally from measurements of the static pressure in the inlet annulus.

The previous assumptions of thermodynamic equilibrium, homogeneous mixture, and vapor pressure equal to the local measured static pressure are used to calculate the liquid temperature drop between the bulk liquid in the tank and the liquid in the annulus. On the basis of this temperature difference, the volume ratio is then calculated.

Measurements were made in an instrumented inlet annulus that was submerged in a large tank of boiling liquid hydrogen. The tests were conducted over a range of bulk fluid temperatures of $42^{\circ}$ to $36^{\circ}$ R (23.3 to 20 K) and flow rates of 170 and 112 pounds per second per square foot (830 and 547 kg/(sec)/($m^2$)). The experimental studies were conducted at the Plum Brook Station of the NASA Lewis Research Center.

## ANALYSIS

The model used in the one-dimensional analysis of the flow from station 1 in the tank to station 2 in the inlet line is illustrated in figure 1. For two-phase flow at station 2, the mixture is assumed to be homogeneous and in thermodynamic equilibrium. That is, when the velocity head in the line (station 2) becomes greater than the margin of total head above the head corresponding to vapor pressure at station 1, it is assumed that the fluid in the line (station 2) will boil until the local vapor pressure is reduced to the local static pressure.

The Bernoulli equation for incompressible flow, together with a simple heat balance equation, is used to determine the amount of vapor formed in the line (station 2). The static pressure in the line (station 2) for a homogeneous vapor-liquid mixture in the line is

$$p_2 = P_1 - \frac{\rho_{m,2}(V_{m,2})^2}{(2g)(144)} (1 + C_D) \tag{1}$$

(Symbols are defined in the appendix.) Since

$$V_m = \frac{W}{A\rho_m}$$

Equation (1) can then be written

$$p_2 = P_1 - \frac{\left(\frac{W}{A}\right)^2}{(\rho_{m,2})(2g)(144)} (1 + C_D) \tag{2}$$

When vapor is present in the line, both the static pressure $p_2$ and the mixture density $\rho_{m,2}$ are unknown, and additional relations are required to obtain the conditions at station 2. A heat balance for the vaporization process may be written

$$M_{v,2}L_2 = (1 - M_{v,2})C_{P,2}(T_1 - T_2) \tag{3}$$

and

$$\mathcal{V}_{m,2} = \mathcal{V}_{l,2} + \mathcal{V}_{v,2}$$

or

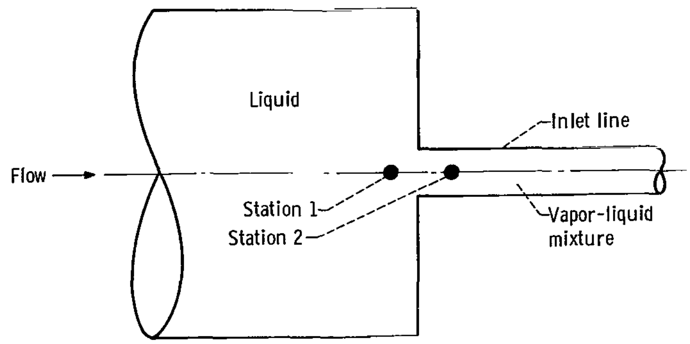



Figure 1. - Model used for inlet line analysis.

$$\frac{1}{\rho_{m,2}} = \frac{1 - M_{v,2}}{\rho_{l,2}} + \frac{M_{v,2}}{\rho_{v,2}} \tag{4}$$

Equations (2) to (4) are solved simultaneously through the use of an iterative procedure. A first approximation of the static pressure $p_2$ is obtained from equation (2) by assuming all liquid flow ($\rho_{m,2} = \rho_{l,1}$). If the computed static pressure is less than the vapor pressure in the tank (station 1), vapor is assumed to be present and the vapor pressure in the line equal to the calculated static pressure. The corresponding saturation temperature $T_2$ is used in the heat balance relation (eq. (3)) to evaluate the mass of vapor formed $M_{v,2}$. The corresponding mixture density from equation (4) is then used in equation (2) to obtain a closer approximation to the static pressure. The procedure is repeated until the mixture density $\rho_{m,2}$ in equations (2) and (4) converges to the desired accuracy.

When equations (2) and (4) are satisfied, the vapor- to mixture-volume ratio can be calculated from the following equation:

$$\left(\frac{\mathcal{V}_v}{\mathcal{V}_m}\right)_2 = \frac{\dfrac{M_{v,2}}{\rho_{v,2}}}{\dfrac{1 - M_{v,2}}{\rho_{l,2}} + \dfrac{M_{v,2}}{\rho_{v,2}}}$$

$$= \frac{1}{\dfrac{\rho_{v,2}}{\rho_{l,2}}\left(\dfrac{1}{M_{v,2}} - 1\right) + 1} \tag{5}$$

Values of vapor- to mixture-volume ratio were calculated over a range of bulk fluid temperature at station 1 for the condition where the total pressure was set equal to the vapor pressure of the liquid. The results are presented in figure 2, which shows vapor-

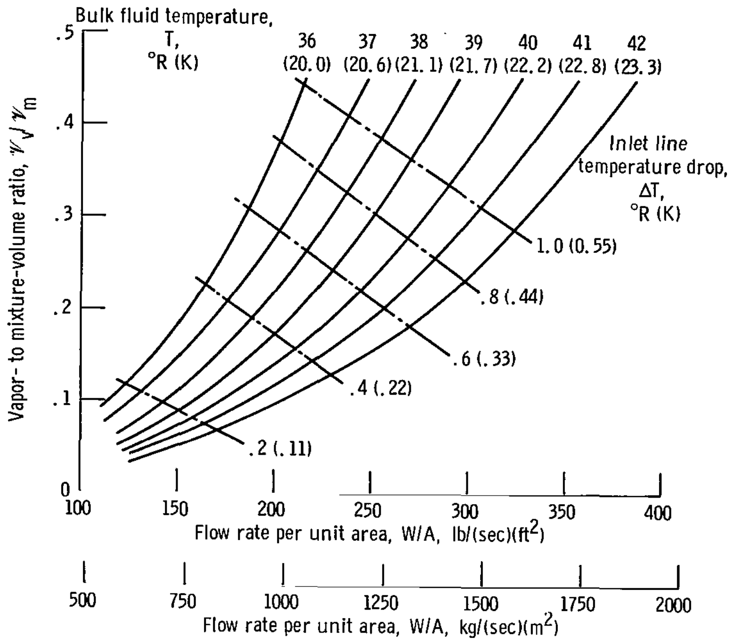



Figure 2. - Computed values of vapor- to mixture-volume ratio as function of flow rate for liquid hydrogen. Entrance loss coefficient, 0.11; net positive suction head, 0 feet (0 m).

to mixture-volume ratio as a function of weight flow rate per unit area. Curves for several values of temperature drop of the vapor-liquid mixture in the inlet line are also shown. An entrance loss coefficient value $C_D$ of 0.11 was selected to correspond with the value for the experimental inlet annulus described in the Apparatus section of this report.

To illustrate the use of the curve, consider the bulk liquid temperature to be 37$^\circ$ R (20.6 K) and the flow rate to be 200 pounds per second per square foot (976 kg/(sec)/(m$^2$)). Under these conditions, the temperature of the liquid will drop 0.6$^\circ$ R (0.3 K) to 36.4$^\circ$ R (20.3 K), and the vapor- to mixture-volume ratio will be 0.285. This vapor- to mixture-volume ratio may be useful in predicting the performance of a pump operating with two-phase flow present in the inlet by the method described in reference 2. Because of the drop in local fluid temperature caused by two-phase flow in the inlet line, it may be also necessary to adjust the cavitation performance, as described in reference 3.

## PROCEDURE FOR EVALUATION OF ANALYSIS

The conditions in the inlet line to a pump were experimentally evaluated by measuring the static pressure in the inlet line and the fluid temperature in the tank in a liquid-hydrogen pump test facility. Thermodynamic equilibrium is assumed; that is, the vapor pressure of the liquid in the inlet annulus is assumed equal to the measured static pressure. The inlet line temperature is thus assumed to correspond to the vapor pressure of the saturated liquid in the inlet annulus. These measurements and assumptions together with equations (3) and (5) were used to evaluate the volume ratio experimentally. The iteration procedure was not required because the static pressure in the inlet annulus could be measured directly.

# APPARATUS AND INSTRUMENTATION

## Apparatus

The liquid-hydrogen facility used in the study of two-phase flow in the pump inlet line is shown schematically in figure 3. A detailed description of the facility is presented in reference 1. A 5-inch-(12.7-cm-) diameter inducer rotor was submerged in liquid hydrogen near the bottom of the 2500-gallon (9.46 cu m) vacuum-jacketed tank. A 5-inch-(12.7-cm-) outside diameter, 2.5-inch-(6.3-cm-) inside diameter constant-area inlet annulus extended 30 inches (76.2 cm) upstream of the inducer, the inlet annulus had a bellmouth entrance.

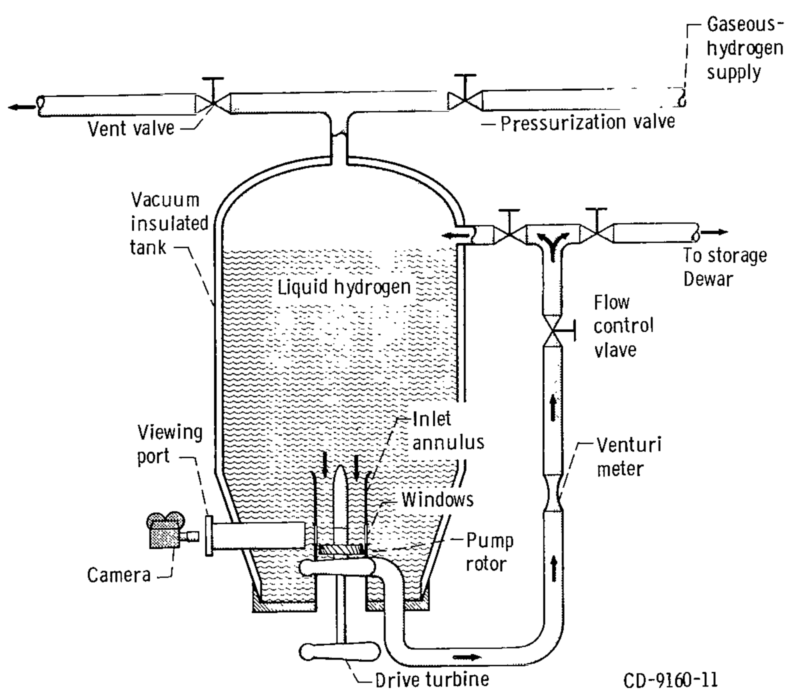
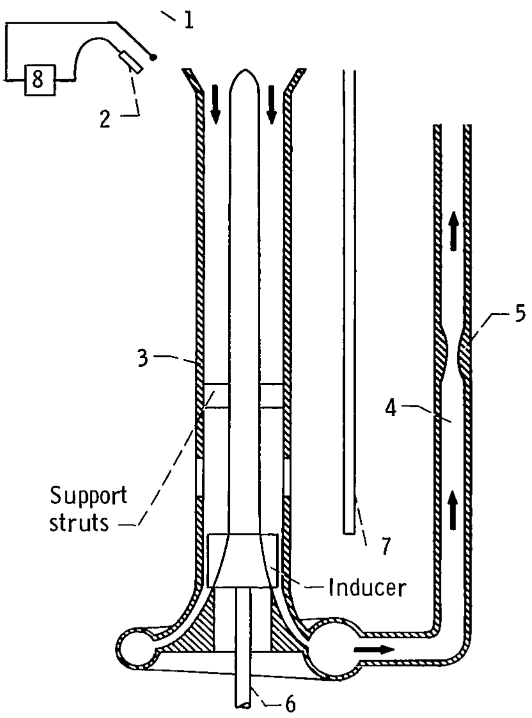



Figure 3. - Liquid-hydrogen test facility.




| Parameter | Accuracy | Remarks |
|---|---|---|
| 1 Tank pressure | ±0.5 psi ($\pm 0.35\ N/cm^2$) | Total pressure at inlet |
| 2 Vapor pressure | ±0.25 psi ($\pm 0.17\ N/cm^2$) | Vapor bulb charged with hydrogen from research tank |
| 3 Wall static pressure | ±0.01 psi ($\pm 0.007\ N/cm^2$) | Wall static tap in inlet annulus |
| 4 Venturi inlet temperature | ±0.1° R (±0.06 K) | Carbon resistor probe |
| 5 Venturi differential pressure | ±0.1 psi ($\pm 0.07\ N/cm^2$) | Venturi calibrated in air and water |
| 6 Rotative speed | ±100 rpm | Magnetic pickup in conjunction with gear on turbine drive shaft |
| 7 Liquid level | ±0.5 ft (±0.15 m) | Capacitance gage |
| 8 Net positive suction head | ±0.05 psi ($\pm 0.035\ N/cm^2$) | Measured as differential pressure between vapor bulb and total pressure at inlet |

Figure 4. - Instrumentation for liquid-hydrogen inlet line studies.

In each test run, liquid hydrogen was pumped from the tank through the annulus and pump and was collected in a storage Dewar. Visual observation of the fluid in the inlet annulus was possible through a viewing port and a transparent plastic section in the inlet line.

The annulus entrance loss coefficient $C_D$ of 0.11 was based on experimental measurements in air at Reynolds numbers greater than the critical; that is, in the range where $C_D$ was constant as Reynolds number was varied. Since experimental tests in liquid hydrogen were conducted at Reynolds numbers greater than the critical, a constant $C_D$ value of 0.11 was used.

## Instrumentation

The instrumentation used in this investigation is shown schematically in figure 4 together with a listing of the measured parameters and the estimated system accuracies. The temperature measurements made within the inlet annulus were not used; flow of the saturated fluid around the thermocouple caused the fluid to cavitate, and the resulting cooling produced temperature readings below the free-stream values.

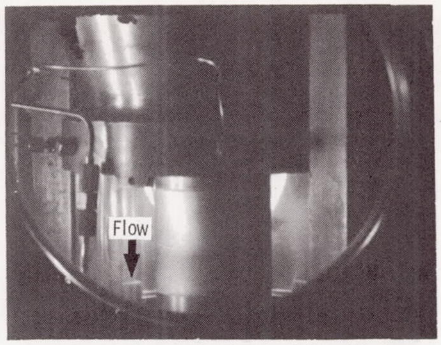
# RESULTS AND DISCUSSION

## Photographic Study

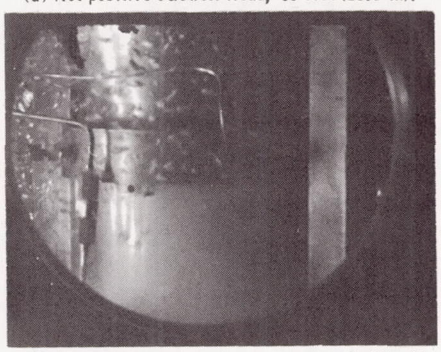
In the experimental and theoretical methods used for the determination of the volume ratio, it was assumed that the vapor-liquid mixture in the inlet line is homogeneous. Photographs of fluid conditions in the inlet line during the test tend to validate this assumption (fig. 5). At an NPSH of 60 feet (18.3 m), as measured in the tank, the line is vapor free (fig. 5(a)), while at an NPSH of zero, (vented tank), the line is apparently completely filled with a homogeneous mixture of liquid and vapor (fig. 5(b)). For the zero NPSH condition, the liquid in the tank between the viewing port and the inlet line has started to boil. When the liquid is pumped from the sealed tank (NPSH $<$ zero), the liq-in the tank boils violently (fig. 5(c)).

## Experimental Data

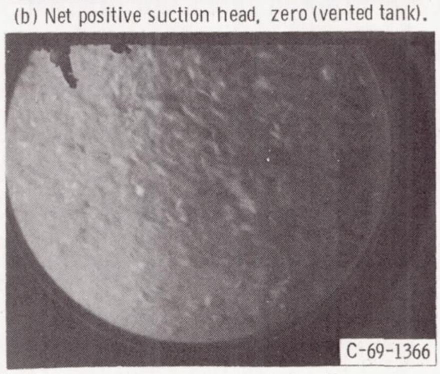
The variation in significant parameters throughout the course of a typical test run is plotted in figure 6. The net positive suction head in the tank at the entrance to the inlet




(a) Net positive suction head, 60 feet (18.3 m).



(b) Net positive suction head, zero (vented tank).




(c) Net positive suction head, less than zero (sealed tank).

Figure 5. - Effect of net positive suction head on hydrogen in inlet annulus and tank.

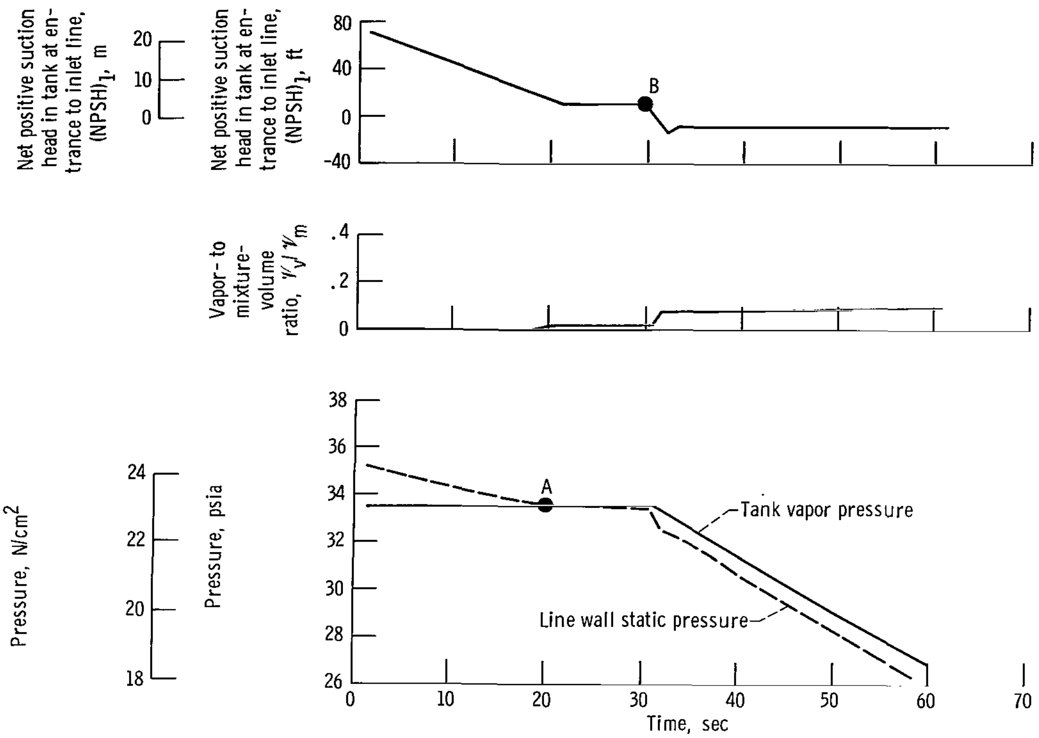



Figure 6. - Variation of inlet line parameters during pumpout vapor test in hydrogen. Initial temperature, 42° R (23.3 K); flow rate per unit area, 112 pounds per second per square foot (547 kg/(sec)(m$^2$)).

line $(NPSH)_1$, the volume ratio computed from the measured wall static pressure in the inlet annulus, the inlet annulus wall static pressure, and the tank vapor pressure at the entrance to the inlet annulus are plotted as a function of run time. For each test run, the pump was operated at a constant rotative speed, and the mass flow rate through the inlet annulus was held constant. The value of $(NPSH)_1$ was initially set to be positive, and no vapor formed in the inlet annulus. The value of $(NPSH)_1$ was then gradually decreased by lowering the tank total pressure at a constant rate to the lowest value obtainable with the venting system.

In figure 6 at a run time of 20 seconds (point A), the inlet annulus wall static pressure is equal to the tank vapor pressure, and vapor starts to form in the inlet annulus. At this point, the net positive suction head is equal to the velocity head in the inlet annulus. At a run time of 30 seconds (point B), the tank is sealed and continued pumping causes a sharp negative spike in the tank NPSH measurement. The NPSH then settles out to a negative value for the remainder of the test run. The measured negative values of $(NPSH)_1$ are attributed to lag in the instrumentation system. As the tank is sealed, there is a step increase in the vapor- to mixture-volume ratio. The test run was stopped when the liquid level in the tank approached the bellmouth of the inlet annulus.

At positive values of $(NPSH)_1$ the bulk liquid temperature in the tank is constant. However, when the tank is sealed and liquid is pumped from the tank, some of the bulk liquid must boil to fill the ullage space. The resulting evaporative cooling causes a decrease in the temperature and vapor pressure of the bulk fluid in the tank. The vapor-to mixture-volume ratio increases as the bulk liquid temperature in the tank is reduced.

The vapor pressure of the liquid in the tank shows essentially a constant slope after the tank is sealed. Other test runs show that with continued pumping from a sealed tank the slope of the tank vapor pressure curve is a function of the ratio of the volume of liquid in the tank to the total tank volume at any given time, the rate at which the liquid is removed from the tank, and the temperature of the liquid in the tank. Of these factors, temperature probably has the greatest effect on the slope of the tank vapor pressure curve. The slope is greater for higher temperature liquid because of the greater vapor density at saturated conditions. As the liquid is pumped from the tank at higher temperature, a greater mass of liquid must be vaporized to form a given volume of vapor, and thus increased cooling of the remaining liquid results.

During a run, the static pressure in the inlet annulus decreases as the bulk fluid temperature is decreased. The experimental values of volume ratio are based on this inlet annulus static-pressure reading.

## Comparison of Experimental and Theoretical Results

A comparison of the theoretical and experimental values of volume ratios for a range of bulk liquid temperatures and for two flow rates is shown in figure 7. Each of the five sets of data represents a single test run, one of which was presented in figure 6. The data presented in figure 7 are for the portions of each run for which the tank was sealed. The experimental values of volume ratio are based on the inlet annulus wall static-pressure measurement and the bulk fluid temperature as measured with the vapor bulb in the tank. The theoretical values of volume ratio were computed using measured values of bulk fluid temperature, $(NPSH)_1$, and weight flow rate. The reasonably good agreement between the two methods indicates that the analysis based on one-dimensional flow, thermodynamic equilibrium, and a homogeneous mixture in the inlet line is valid over the range of conditions tested. As expected, the volume ratio in the inlet line is smaller at the higher tank temperatures and lower flow rate. A low flow velocity in the inlet line and a relatively high tank fluid temperature is therefore desirable if liquid hydrogen is to be pumped from a sealed tank that would have very low or zero net positive suction head. However, since the liquid vapor pressure also increases with temperature, the maximum temperature is limited, of course, by tank structural considerations.

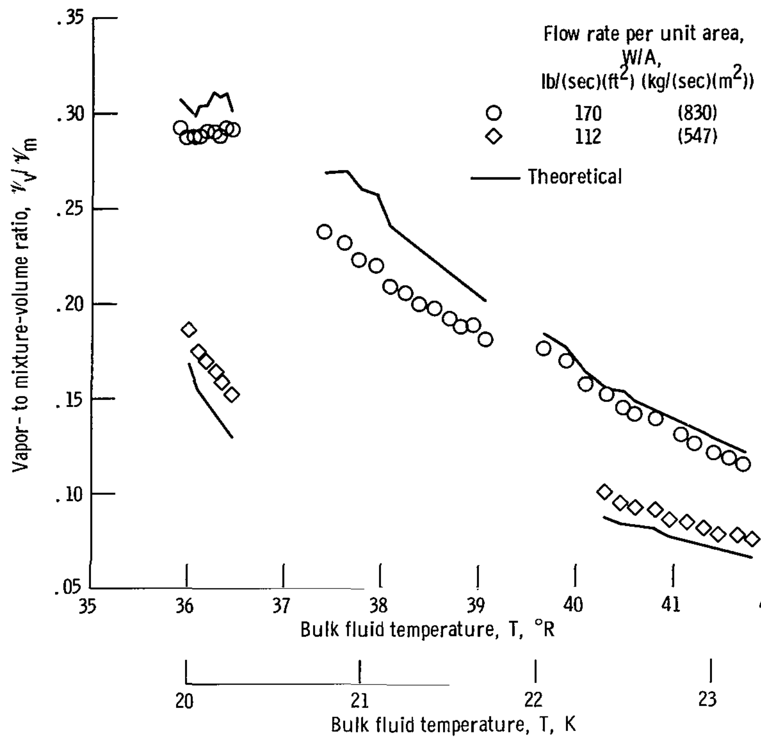



Figure 7. - Comparison of experimental and theoretical vapor volume ratios over range of bulk fluid temperatures (sealed tank).

Since the volume ratio can be estimated with reasonable accuracy by use of the method presented herein, the performance of a given inducer with two-phase flow in the inlet line may be predicted, provided that the cavitation performance of the inducer of interest, operating with a single-phase fluid in the inlet line, is known. The method for predicting the performance of a pump with two-phase flow is presented in references 2 and 3. The "workhorse" pump rotor of the present experimental program was used only to generate flow in the test annulus, and its performance was not determined.

## SUMMARY OF RESULTS

An investigation was conducted to evaluate a method for calculating the ratio of vapor- to mixture volume in the inlet line to a pump when the fluid in the storage tank is at or near zero net positive suction head. The predicted results, obtained by using an analytical method, were compared with those obtained in an experimental evaluation. The analysis assumes one-dimensional flow, thermodynamic equilibrium, and a homogeneous mixture of liquid and vapor at the pump inlet. In the experimental studies, two-phase liquid-hydrogen flow was formed in the inlet line over a range of temperatures and at two flow rates.

The reasonable agreement obtained between the analytical and experimental results indicates that the vapor- to mixture-volume ratio can be predicted with reasonable accuracy when the bulk fluid temperature in the tank, the weight flow rate, and the net positive suction head in the tank at the entrance to the inlet annulus are known. Apparently, the assumptions of the analytical method (i. e., one-dimensional flow, thermodynamic equilibrium, and homogeneous mixture in the inlet line) are valid over the range of conditions tested.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 22, 1969,
128-31-32-06-22.

# APPENDIX - SYMBOLS

| | |
|---|---|
| $A$ | cross-sectional flow area, $ft^2$; $m^2$ |
| $C_D$ | entrance loss coefficient |
| $C_P$ | specific heat, Btu/(lb)($^oR$); J/(kg)(K) |
| $g$ | gravitational constant, 32.2 (lbm/lbf)(ft/$sec^2$); 1.0 (kg/N)(m/$sec^2$) |
| $L$ | latent heat for vaporization, Btu/lb; J/kg |
| $M_v$ | mass of vapor formed per lb (kg) |
| NPSH | net positive suction head, ft; m |
| $P$ | total pressure, psi; N/$m^2$ |
| $p$ | static pressure, psi; N/$m^2$ |
| $T$ | temperature, $^oR$; K |
| $\Delta T$ | temperature drop, $^oR$; K |
| $V$ | velocity, ft/sec; m/sec |
| $\mathcal{V}$ | volume, $ft^3$; $m^3$ |
| $W$ | flow rate, lb/sec; kg/sec |
| $\rho$ | density, lb/$ft^3$; kg/$m^3$ |

Subscripts:

| | |
|---|---|
| $l$ | liquid (original nonvaporized liquid) |
| m | two-phase mixture |
| v | vapor portion of vapor-liquid mixture |
| 1 | entrance to inlet line |
| 2 | inside inlet line immediately downstream of entrance |

# REFERENCES


1. Ball, Calvin L.; Meng, Phillip R.; and Reid, Lonnie: Cavitation Performance of $84^{\circ}$ Helical Pump Inducer Operated in $37^{\circ}$ and $42^{\circ}$ R Liquid Hydrogen. NASA TM X-1360, 1967.
2. Meng, Phillip R.; and Connelly, Robert E.: Investigation of Effects of Simulated Nuclear Radiation Heating on Inducer Performance in Liquid Hydrogen. NASA TM X-1359, 1967.
3. Meng, Phillip R.: Change in Inducer Net Positive Suction Head Requirement with Flow Coefficient in Low Temperature Hydrogen ($27.9^{\circ}$ to $36.6^{\circ}$ R). NASA TN D-4423, 1968.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