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by Nelson L. Sanger
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at Fluids Engineering Conference sponsored by the American Society of Mechanical Engineers Philadelphia, Pennsylvania, May 6, 1968

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by Nelson L. Sanger*

Lewis Research Center
National Aeronautics and Space Administration
Cleveland, Ohio

Introduction: Future space vehicles will require large quantities of electric power. One means of meeting these requirements is through the use of a Rankine cycle system having a liquid metal as the working fluid. The application of jet pumps in such systems [1] requires that the pumps have low ratios of nozzle exit area to throat area, R (see Fig. 1).

Low area ratio jet pump design considerations for non-cavitation operation were explored analytically and experimentally [2]. In the high temperature Rankine cycle systems considered, cavitation represents a serious problem, and thus a knowledge of jet pump cavitation performance is necessary to optimize system weight and performance. Several investigations of cavitation in jet pumps have been reported [3, 4, 5], but no single method of predicting the cavitation-imposed operating limits of jet pumps has yet been accepted. It is the purpose of this commentary to present a parameter which predicts jet pump headrise deterioration due to cavitation and to compare it to existing methods of prediction.

Cavitation Investigations: When considering the literature on jet pump cavitation it is important to distinguish between conditions at cavitation inception and conditions at the point when headrise breakdown occurs. Gosline and O'Brien [3] dealt with the latter case. They derived an expression for the maximum attainable secondary (pumped) flowrate, for a given secondary inlet pressure and flow area, using a one-dimensional analysis and assumed that the static pressure in the exit plane of the nozzle was equivalent to vapor pressure at the point of cavitation-induced headrise breakdown.

Rouse [6] conducted an experimental investigation of cavitation inception in a free jet, using water as the test fluid. A conventional cavitation number of 0.6 correlated audible incipient cavitation.

Bonnington [4] modified the Rouse parameter to account for the influence of the bounding walls of a jet pump. His experimental results did not correlate with the modified parameter. The transformation from free to ducted jets would appear to be more complex than was indicated in [4]. Furthermore, the direct application of Rouse's 0.6 value for incipient cavitation to conditions of cavitation-induced head breakdown in a jet pump is not valid. Mueller [5], however, obtained data for the point of performance breakdown which correlated closely with the modified Rouse parameter. There is thus a direct contradiction between the experimental results of Refs. [4] and [5].

In the NASA investigation, a cavitation prediction parameter ω has been developed [7] which combines the analyses from Refs. [3] and [4]. The energy and continuity relations are applied to the secondary fluid, and the resulting expressions are made dimensionless by dividing by the velocity head of the primary fluid at the nozzle exit.

$$\omega = \frac{p_2 - p_v}{(\gamma\, V_N^2/2g)} = \left(\frac{MR}{1-R}\right)^2 (1 + K_s) = \left(\frac{V_3}{V_N}\right)^2 (1 + K_s) \qquad (1)$$

where K_s, the friction loss coefficient [2] is defined by:

$$K_s = \frac{p_2 - p_3}{(\gamma\, V_3^2/2g)} \qquad (2)$$

The nomenclature is defined in Fig. 1; γ is the specific weight of the fluid, p_v is the vapor pressure of the fluid, and primary and secondary fluids have the same temperature. It is assumed that at the condition of total head-rise breakdown the pressure in the plane of the nozzle exit p_3 will be equal to vapor pressure.

At the point of cavitation inception local pressures in the mixing layer are equal to vapor pressure. But when cavitation becomes so extensive that the head-rise deteriorates, the assumption that static pressure in the plane of the nozzle exit is equal to vapor pressure, if not precise, is nevertheless a good approximation.

Discussion of Results: An experimental investigation of two jet pumps having area ratios of 0.066 and 0.197 was conducted at NASA Lewis Research Center using 80° F water as the test fluid [7]. Experimental values of ω obtained at points of performance dropoff are compared with theoretical values (eq. (1)) in Fig. 2(a). The curves for $K_s = 0.09$ ($R = 0.066$) and $K_s = 0.14$ ($R = 0.197$) correspond to measured values of K_s. Curves that correspond to arbitrarily selected values for K_s of 0 and 0.30 are also plotted for comparison.

In general, ω correlates the data well. Two effects should be noted, however. At the fully inserted nozzle positions ($s/dt = 0$) the data fall slightly above the respective theoretical curves. It is believed that this reflects the effect of a finite nozzle thickness ($4\frac{1}{2}$% of d_n for $R = 0.197$, and 8% of d_n for $R = 0.066$). The thickness of the nozzle wall produces a wake which increases the turbulence in the mixing layer. The increased turbulence intensifies the cavitation and results in a premature deterioration in headrise.

*Member ASME.

Another effect evident from Fig. 2(a) is that of nozzle spacing. Although one of the premises of the analysis is that nozzle spacing is zero, variation of the nozzle spacing between s/dt of 0 and 2.7 did not have a large effect on ω. Retraction of the nozzle did, however, act to reduce ω slightly. Although there is no method for predicting the effect of nozzle spacing quantitatively, an empirical value of $K_s = 0$ appears justified for predicting the cavitation dropoff conditions for nozzle spacings of $s/d_t \geq 1.0$. At nozzle spacings less than one throat diameter a value of K_s equal to or slightly greater than the actual measured K_s is necessary.

The theoretical curves for $K_s = 0$ and $K_s = 0.30$ are repeated in Fig. 2(b) together with a plot of the modified parameter of Ref. [4], and data from Refs. [4,5,7]. Bonnington's data [4] agrees generally with the data obtained in the present investigation. There is, however, no agreement with the data reported by Mueller [5], except at velocity ratios greater than 0.5. It is not completely clear why the jet pumps of Ref. [5] cavitated at higher values of ω. But it appears that the performance dropoff was abnormally early and may be related to blockage of the secondary flow area by the primary nozzle external contour. The exterior contour of the nozzle tested in [5] created a converging-diverging secondary inlet area, thus presenting a greater than normal restriction to the secondary flow. Calibration of the secondary inlet region [5] resulted in extremely high losses ($K_s \sim 0.73$), which also suggests a restricted inlet region. Thus the apparent correlation between the data of Ref. [5] and the modified parameter of Ref. [4] may only have been coincidental.

Concluding Remarks: The cavitation prediction parameter ω has correlated jet pump cavitation data from two different experimental investigations. Its use appears justified over a wide range of spacings of the nozzle exit from the throat entrance.

[1] E. S. Chalpin, J. R. Pope, and C. L. Foss, "Development of a SNAP-8 Pump for Mercury Service," AIAA Specialists Conference on Rankine Space Power Systems, Vol. 1, AEC Report CONF-651026, October 26-28, 1965, pp. 171-185.

[2] N. L. Sanger, "Noncavitating Performance of Two Low-Area-Ratio Water Jet Pumps Having Throat Lengths of 7.25 Diameters," NASA Technical Note D-4445, March, 1968.

[3] J. E. Gosline and M. P. O'Brien, "The Water Jet Pump," University of California Publications in Engineering, Vol. 3, No. 3, 1934, pp. 167-190.

[4] S. T. Bonnington, "The Cavitation Limits of a Liquid-Liquid Jet Pump," British Hydromechanics Res. Assn., Harlow, Essex, England, RR-605, 1958.

[5] N. H. G. Mueller, "Water Jet Pump," Proceedings of the ASCE, Vol. 90, No. HY3, pt. 1, May, 1964, pp. 83-113.

[6] H. Rouse, "Cavitation in the Mixing Zone of a Submerged Jet," LaHouille Blanche, Vol. 8, January-February, 1953, pp. 9-19.

[7] N. L. Sanger, "Cavitation Performance of Two Low-Area-Ratio Water Jet Pumps Having Throat Lengths of 7.25 Diameters," Proposed NASA Technical Note.

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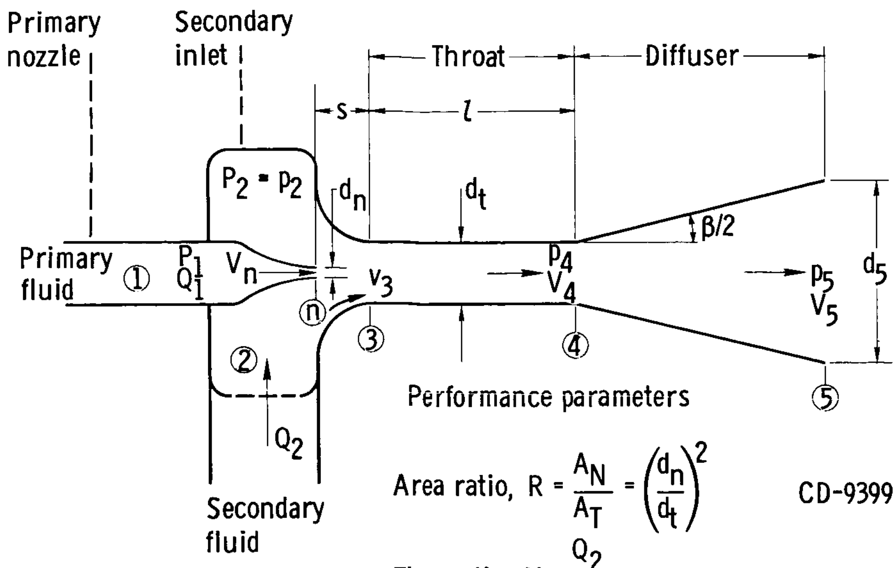

Area ratio, $R = \frac{A_N}{A_T} = \left(\frac{d_n}{d_t}\right)^2$

Flow ratio, $M = \frac{Q_2}{Q_1}$

Head ratio, $N = \frac{H_5 - H_2}{H_1 - H_5}$

Efficiency, $\eta = MN$

Figure 1. - Schematic representation of a jet pump.

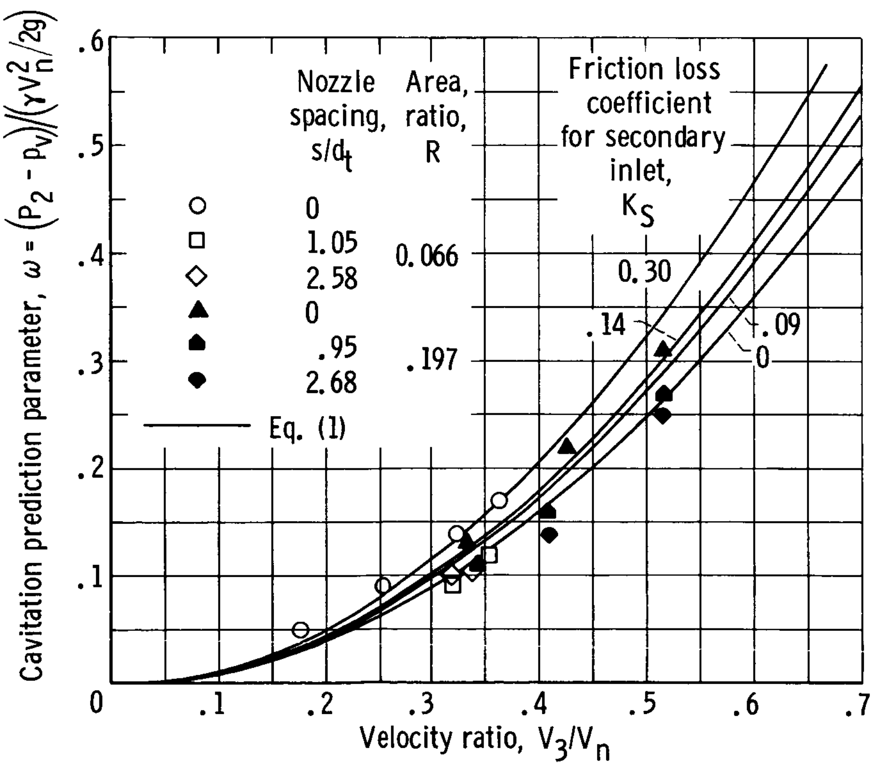

Figure 2(a). - Comparison of experimental and theoretical values of prediction parameter.

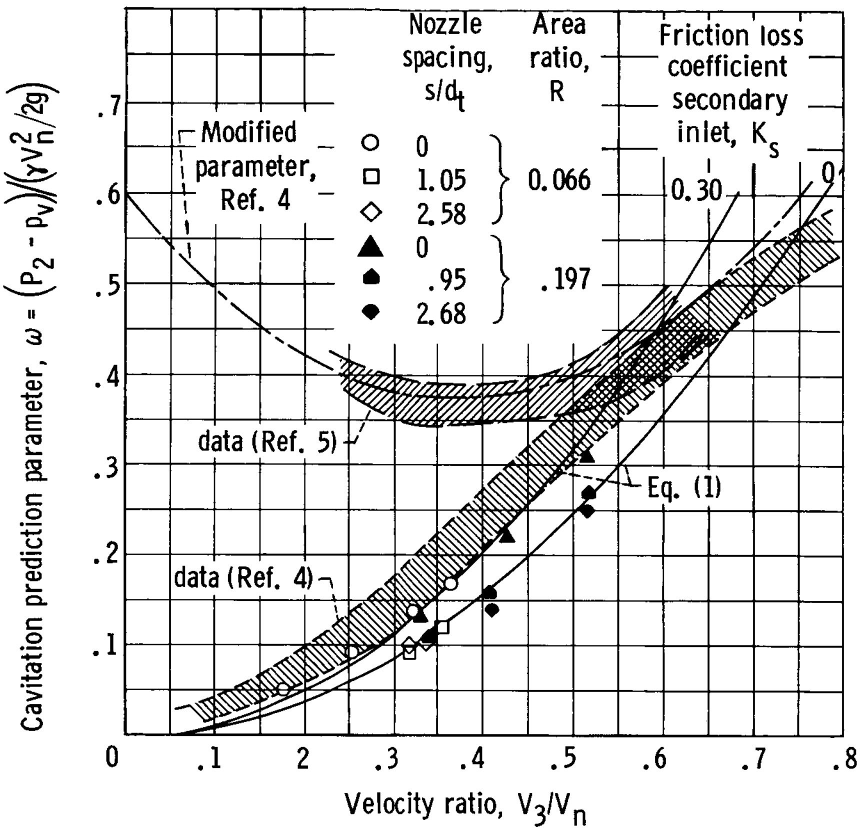

Figure 2(b). - Comparison of cavitation data with various analyses.