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SUBMERGED OPERATION OF THE FIXED-CONE VALVE

BY

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ABSTRACT

The flow field and cavitation characteristics downstream of a submerged fixed-cone valve were studied. The flow field was investigated using an air model. Laser measurements were obtained at a series of radial cross-sections within the flow field. Streamlines and values of turbulent intensity were computed from the velocities measured. Empirically determined relationships for the prediction of centerline jet velocities are presented. Cavitation in the turbulent shear flow downstream of the valve was investigated in a vacuum chamber. Cavitation inception was identified using spectral analysis techniques. Cavitation index values defining flow conditions corresponding to desinence and maximum noise are given.

INTRODUCTION

Fixed-cone (Howell-Bunger) valves have been in wide use for many years for flow control. Their simple design often affords less expensive initial costs than other types of valves. The valve opens by retracting an exterior sleeve. As the sleeve retracts water passes through the valve between the sleeve and a 45° cone at the end of the valve. The cone is supported by radial vanes projecting from the inner cylindrical body of the valve, figure 1. Under free flow conditions the valve creates a thin annular jet that spreads conically. To limit the spread of the discharging jet, an oversized cylindrical hood is often placed over the valve. Although the valve is generally used for free discharge applications, fixed cone valves have been operated submerged in many hydraulic structures. The most common submerged application is for pressure surge relief and bypass in turbines. Submergence, without air admission to the flow, dramatically changes the geometry of the jet downstream of the valve. The jet no longer continues to spread in its original annular form. Instead, the jet closes into a cylindricial form similar to a submerged jet originating from an orifice.

The history of fixed-cone valves operating submerged tells of both success and failure. Discussions by Mercer (7), Nag (8), and Parmakian (9), provide a review of prototype installations. Although little design information is available, air admission to the center of the jet downstream of the valve is generally recommended to reduce cavitation noise and vibration often associated with submerged operation (4, 8).

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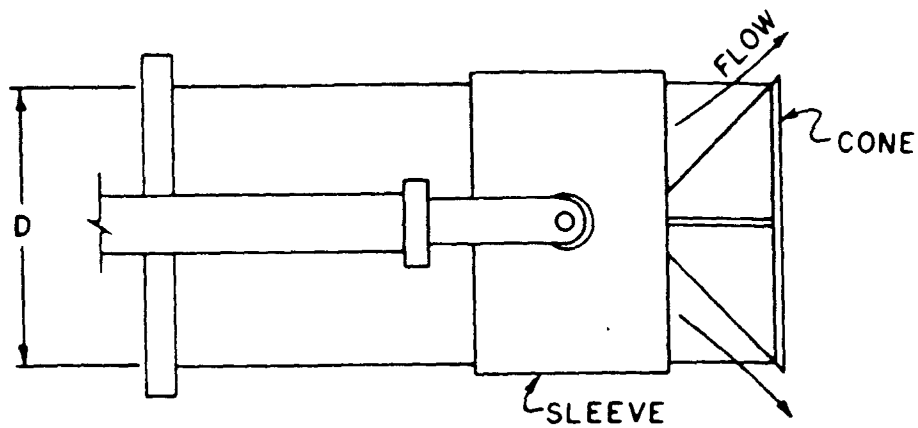

Figure 1. - Fixed-cone valve.

At the Bureau of Reclamation's Buffalo Bill project near Cody, Wyoming, the implementation of fixed-cone valves for pressure relief was reviewed. A 24-in (0.6-m) valve placed on the end of a bypass pipe branching off the scroll case was proposed for each turbine. The valves were sized to relieve upsurge pressures created by the rapid closure of the turbine wicket gates during power load rejections. Tailwater conditions required that the valves operate under a submergence of up to 10 diameters. Operating the valves submerged offered both advantages and disadvantages at Buffalo Bill. Submerging the valves reduces potential spray and icing problems normally associated with cold weather operation of a free jet. On the other hand, submering the valves increases the potential for cavitation damage and higher levels of structural vibration. To better understand the requirement for successful operation of submerged fixed-cone valves, a laboratory study was conducted to investigate the flow field and cavitation within the jet exiting the valve.

SUBMERGED FLOW PATTERN

The velocity distribution downstream of the valve was studied using an air model. The test facility consisted of a 6-in (152-mm), 4-vane, fixed-cone valve placed on the end of a plenum chamber. The mean flow pattern downstream of the valve was determined with a laser doppler velocimeter. Velocity componets in the axial and radial direction were measured at several radial cross sections along the axis of the jet, figure 2A. Radial symmetry about the axial centerline was assumed within the flow field. Streamlines were computed from the axial velocity components, figure 2B. As the jet emerges from the gate, viscous shear initiates lateral mixing of the jet and the surrounding fluid. The shear force along the inner surface of the annular jet creates a stationary ring vortex downstream of the cone. The resulting pressure differential across the jet draws the main flow back toward the axial centerline of the valve creating a stagnation point on the flow centerline. The entire flow field was mapped at 45 percent gate opening for only one discharge. The location of the stagnation point was measured to define changes in the eddy form due to valve opening and Reynolds number. The eddy length,

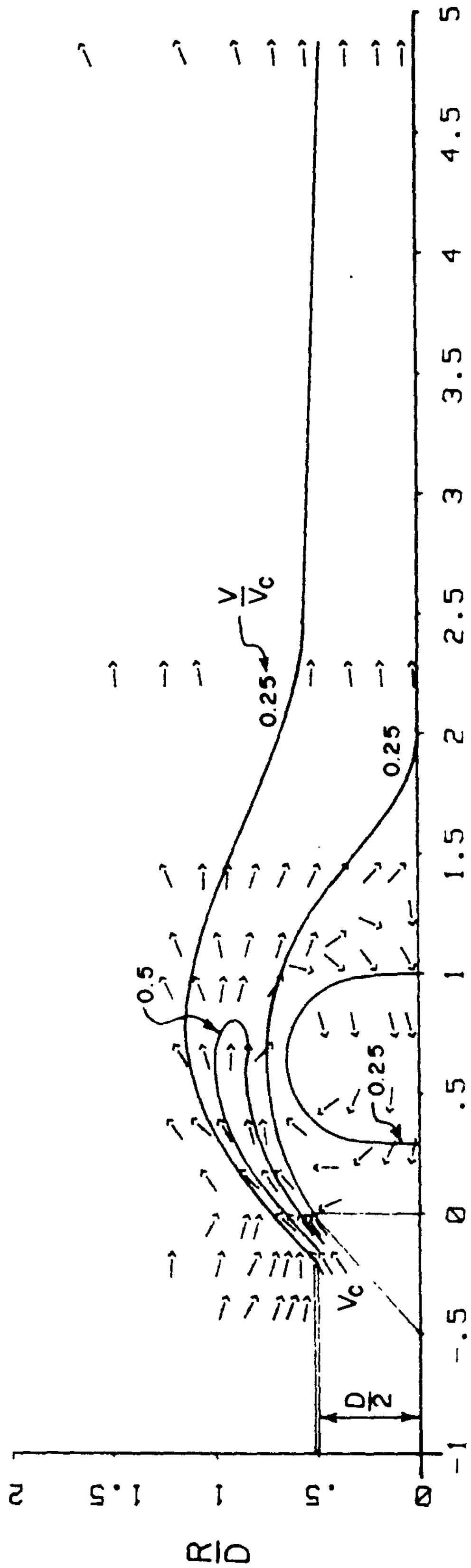

Figure 2A. - Measured flow profile at 45 percent opening.

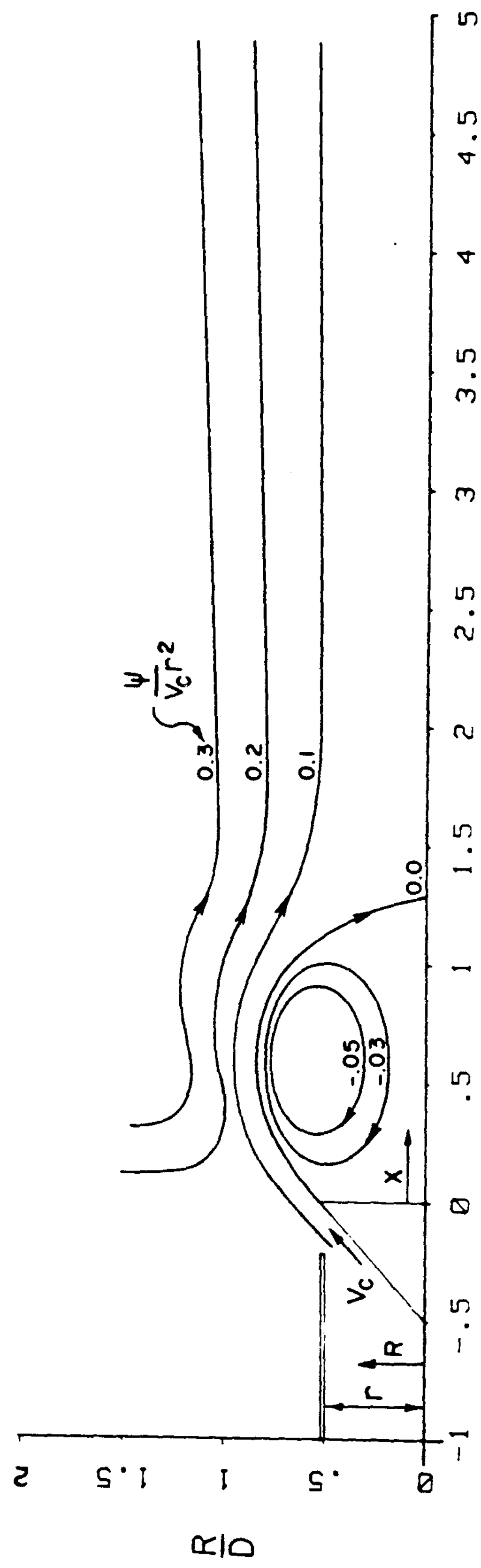

Figure 2B. - Computed strealines at 45 percent opening.

distance between the valve and stagnation point, increased from 0.77 diameters at 10 percent to 1.34 diameters at 60 percent opening. At larger valve openings the eddy length remains nearly constant. The length of the eddy did not change as a function of Reynolds number within the 50 thousand to 500 thousand range tested in the model. Studies by Arie, et al., (1) investigating the eddy flow behind a normal wall found the form of the standing eddy remained nearly constant for Reynolds numbers above a few thousand. Some change in the form of the eddy zone would be expected if cavitation was predominant in the flow field. Downstream of the eddy zone the annular jet merges reforming a solid core jet with the maximum velocity at the centerline.

To facilitate the design of submerged fixed-cone basins the decay of the jet's centerline velocity was also measured as a function of valve opening, figure 3. Velocities are given as a ratio of centerline velocity, V, to average velocity at the control section of the valve, Vc. Velocities within the eddy zone were measured for only 45 percent gate opening. Negative velocities near the valve indicate the area of reverse flow along the interior of the circular eddy. Centerline velocities increase sharply as the annular jet converges downstream of the stagnation point. The centerline velocity peaks between the stagnation point and about 7 diameters downstream of the valve. Beyond the peak, the drop in the velocity can be predicted using empirically determined power law relationships, figure 3.

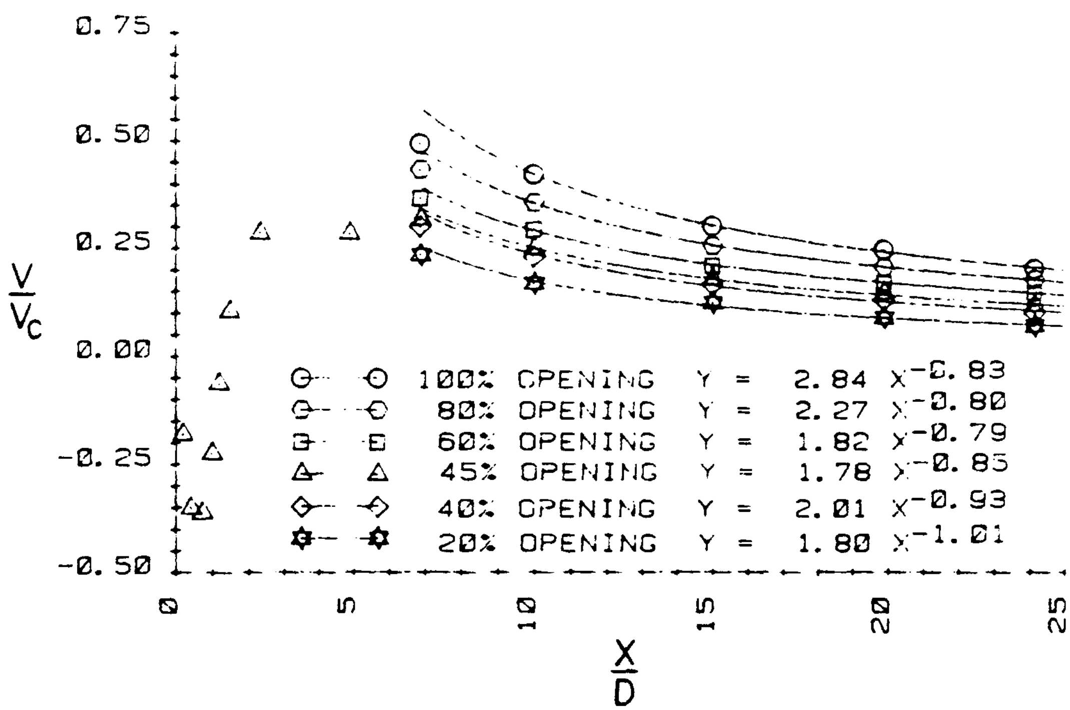

Figure 3. - Centerline velocity distribution.

JET CAVITATION

Cavitation studies of the jet discharged from the valve were conducted by mounting a 6-in (152-mm) diameter valve inside a closed loop cavitation test facility. The facility contained a 4-ft by 15-ft by 12-ft (1.2-m by 4.6-m by 3.7-m) chamber which allowed the valve to be tested from free discharge to 10 diameters of submergence. Ambient pressure within the chamber could be reduced from atmospheric to .1 atmospheres.

Different degrees of cavitation in the shear zone of the jet were created by regulating the ambient pressure and the discharge through the valve. Cavitation was detected by placing four dynamic pressure transducers spaced 1.5 inches (38 mm) apart along the axial centerline of the jet. The transducers were mounted to a narrow rod tapped into the center of the downstream face of the valve. A single triaxial accelerometer was mounted to the downstream face of the valve to record the vibrational response of the valve. The output from the transducers were measured in the frequency domain using FFT spectrum analyzers.

Tests were conducted to determine relative levels of vaporous cavitation noise intensity and desinent cavitation indexes for the model. To minimize the effect of gas concentration on cavitation desinence the chamber was operated at a low ambient pressure (high vacuum) for 12 hrs prior to data collection. Maintaining a low ambient pressure over the 12-hr period allowed gas concentrations to approach saturation at the reduced pressure. Tests were conducted by increasing the ambient pressure in stages to maintain low levels of free gas content. Cavitation noise levels and the lower limit of cavitatiaon were defined by summing the normalized mean square spectral density per frequency band width as discussed by Martin, et al., (6). The frequency spectrum was normalized using the background noise response of the noncavitating jet. The measured lower limit of cavitation referred to as the desinent cavitation index was expressed as,

$$\sigma_d = (Pc - Pv)/\tfrac{1}{2}\rho V_c^2 \qquad (1)$$

where σ_d = desinent cavitation index, sigma
Pc = reference pressure
Pv = vapor pressure
Vc = reference velocity
ρ = fluid density

Pressures and velocities used to calculate the index were referenced to the minimum cross sectional area of the valve opening. Reference pressures were measured at the entrance to the valve and transferred to the valve control section using Bernoulli's equation. Cavitation noise measurements were taken at valve openings of 20, 40, 45, 60, 80, and 100 percent. Measurements were obtained at each valve opening to define the noise output as a function of sigma, starting with heavy cavitation and progressing toward noncavitating flow conditions.

At low sigma values the eddy downstream of the valve formed a solid, ring shaped, cavitation cloud. Starting just downstream of the valve, cavitation bubbles appeared in the high shear zones along both surfaces of the annular jet. A sharp increase in the cavitation noise occurred at higher sigma values as cavitation within the eddy zone began to decay into fractured pockets of vapor bubbles. By continuing to increase the ambient pressure in the chamber the cavitation noise peaked and then decreased sharply as the flow approached noncavitating conditions. Measurements of cavitation noise in shear flows by other investigators (10, 11) have shown a similar progression in the noise levels as a function of sigma. Visual observations indicated that high noise levels occurred when flow conditions supported the rapid growth and collapse of large isolated vapor pockets. The pockets formed in the shear zone along the outer radius of the large scale eddy. Vibration levels measured on the downstream face of the valve corresponded directly to changes in the cavitation noise level. Sigma values defining flow conditions at which maximum noise and vibration levels were recorded are given in Table 1 along with sigma values for cavitation desinence.

Table 1

% Valve opening	Reynolds No. ($x10^5$)	Sigma desinent	Sigma maximum noise
20	2.14	2.24	0.75
40	4.34	2.45	1.30
45	5.56	2.58	1.56
60	6.24	2.51	1.74
80	8.30	3.01	2.10
100	9.29	3.25	1.92

The desinent cavitation index estimates the termination of cavitation in the shear flow of the jet. Neglecting hysteresis effects desinent cavitation and incipient cavitation are synonymous. The desinent cavitation index was found to increase as larger valve openings were tested. Increasing valve opening changed both the profile and Reynolds number of the flow. The effects of changing the flow profile or Reynolds number on cavitation inception could not be adequately studied with the single valve size available in the model. Studies by Kermeen, et al., (5) on incipient cavitation in the shear flow downstream of sharp-edged disks have shown inception in shear flow is largely a function of Reynolds number. The incipient cavitation index was found to increase with Reynolds number with no upper bound identified within the range of their data. Arndt (2, 3) in similar tests on disks also showed a strong dependence on Reynolds number. Arndt found at low Reynolds numbers the functional relationship between the parameters could be estimated by,

$$\text{Sigma} = 0.44+0.0036\ (VD/\nu)^{0.5} \qquad (2)$$

Equation 2 fits the data from Kermeen, et.al., for Reynolds numbers below about $2x10^5$. The equation overestimates much of the data at higher Reynolds numbers due to secondary effects which are not yet fully defined. Comparing equation 2 to the data from the valve study finds a similar result. Although more data are needed, the strong dependency shown by the disk studies would indicate a large part of the increase in the incipient cavitation index in valve data is likely due to Reynolds number effects.

A comparison of the output from the four pressure transducers spaced along the axial centerline indicated the highest noise was generated in the region from the centerline of the eddy to 0.25 diameters downstream. The location at which the maximum noise was measured remained nearly constant as sigma was varied. Values of turbulent intensity were obtained from laser velocimetery measurements of the flow profile in air, figure 4. The turbulent intensity values define the fluctuating axial velocity component as a ratio of average velocity referenced to the control section of the valve. Two areas of high turbulent intensity lie on either side of the core of the jet near the radial centerline of the eddy. The areas of high turbulent intensity measured correspond with both visual observations and the axial position of the major zone of cavitation determined from the transducer output.

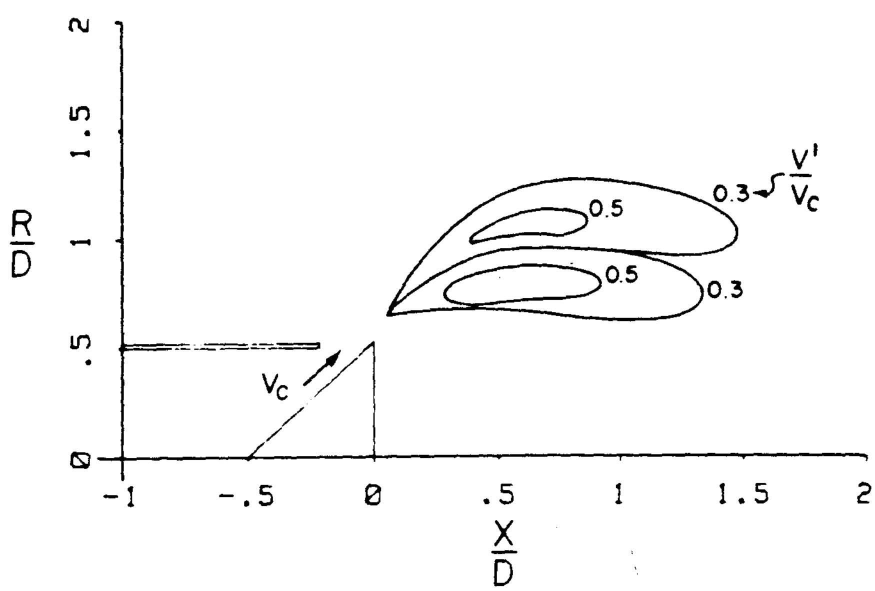

Figure 4. - Turbulent intensity measurements at 45 percent opening.

CONCLUSIONS

The experimental data presented from this study shows the submerged operation of a fixed-cone valve produces a complex flow pattern. As the annular jet penetrates the surrounding fluid a ring vortex fills the center cavity adjacent to the downstream face of the valve. Further downstream, the jet recombines with the maximum velocity occurring along the axial centerline of the valve. Centerline velocities well downstream of the valve were measured at several gate openings. Correlation of the data beyond approximately 7 diameters downstream of the valve indicates the maximum jet velocity can be estimated by a power function of distance.

Valve vibration levels were found to increase as cavitation formed in the turbulent shear flow downstream of the valve. Random vibration levels in the valve responded directly to changes in cavitation noise within the shear flow. Measurements of the maximum turbulent intensity in the flow field corresponded with the location of incipient cavitation as determined by visual observations and the location of maximum noise levels.

The information given allows for a better understanding of the basic flow conditions to be expected. Additional studies are needed to define the effect of air admission downstream of the valve and investigate the formation of cavitation internal to the valve.

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