CAVITATION ANALYSIS OF WESTFALL'S 2800 AND 3050 MIXERS

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By

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INTRODUCTION

Alden Research Laboratory Inc. (Alden) was contracted by Westfall Manufacturing Inc. (Westfall) to develop an equation that will calculate the maximum flow rate in each of their mixers to preclude cavitation. Cavitation occurs when the local static pressure drops below the fluid's vapor pressure, resulting in the rapid formation and collapse of vapor bubbles within the liquid. The pressure waves caused by the rapid collapse of vapor bubbles are known to cause significant damage to structures submerged in the flow, and is generally to be avoided during typical operation. This report will describe the analysis and results of the calculations used to determine the maximum velocities for Westfall's 2800 mixer (Beta = 0.7, 0.8, and 0.9) and 3050 mixer (1, 2, and 3 stages) so that cavitation is avoided.

COMPUTATIONAL MODEL DESCRIPTION

The model geometry was developed using the commercially available three-dimensional CAD and mesh generation software, GAMBIT V2.4.6. The computational domains generated for the model consisted of between 1 - 3 million hexahedral and tetrahedral cells.

Numerical simulations were performed using the CFD software package FLUENT 13.1, a state-of-the-art, finite volume-based fluid flow simulation package including program modules for boundary condition specification, problem setup, and solution phases of a flow analysis. Advanced turbulence modeling techniques, improved solution convergence rates and special techniques for simulating species transport makes FLUENT particularly well suited for this study.

Alden used FLUENT to calculate the full-scale, three-dimensional, incompressible, turbulent flow through the pipe and flow conditioner. A stochastic, two-equation k-ε model was used to simulate the turbulence. Detailed descriptions of the physical models employed in each of the Fluent modules are available from Ansys/Fluent, the developer of Fluent V13.1.

MODEL BOUNDARY CONDITIONS

The tests were conducted in a 6-inch ID pipe. It has been determined through previous testing that the mixers performs similarly at different flow rates, provided the flow is turbulent (Re > 4600), so only one water flow rate was tested, corresponding to a velocity of 1-m/s at ambient pressure and temperature. The resulting pressures were then used to determine the maximum mixer velocity using well known scaling laws. A uniform velocity inlet was imposed at the model inlet, which was placed 5 pipe diameters upstream of the mixer inlet, and a uniform static pressure boundary was imposed at the model outlet, which was placed at least 5 pipe diameters downstream of the mixer outlet. On all surfaces, no-slip impermeable adiabatic wall boundary conditions were applied with roughness heights set to 0.00015-ft as appropriate for steel pipe. A turbulence intensity of 5% was imposed at the model inlet, which is consistent with fully developed pipe flow.

BACKGROUND ON CAVITATION

Cavitation occurs when the local static pressure at any point in a flow drops below the liquid's vapor pressure. This is very similar to boiling, except boiling generally refers to increasing the vapor pressure due to heating; and cavitation is the lowering of the local static pressure due to acceleration of the flow. Inception of cavitation is generally defined by the cavitation index, defined by the equation:

$$\sigma_i = \frac{\left(P_0 - P_{vap}\right)}{{}^{1}\!/_{2}\,\rho U_0^{\,2}}$$

Where, P_0 and U_0 are a characteristic pressure and velocity of the flow. In this case, they will be taken to be the static pressure in the pipe several diameters downstream of the mixer, and the average velocity in the pipe.

Turbulence plays a key role in the inception of cavitation. In any given steady-state, turbulent flow field, there is a constant, time averaged static pressure distribution across the flow field, on which a fluctuating turbulent static pressure distribution is superimposed. The sum of these gives the actual static pressure distribution, which is the important factor for cavitation. When this static pressure drops below the vapor pressure (given sufficient nucleation sites) cavitation will occur. This is shown in a more general form of the cavitation index, given by:

$$\sigma_i = \frac{\left(P_0 - P_{vap}\right)}{{}^1\!/_2\, \rho {U_0}^2} + K \frac{P_{turb}}{{}^1\!/_2\, \rho {U_0}^2}$$

Where K is an empirical factor that determines the relative importance of the turbulent fluctuations on the inception of cavitation. K is known to be on the order of 10 for a wide variety of flows.

In order to validate the model, and to benchmark the CFD results, an orifice plate was tested, which has a well know cavitation index of 3.0; however it is important to note that the characteristic velocity for an orifice is taken at the orifice throat, not the average velocity in the pipe. This convention allows a constant cavitation index to be used across all orifice sizes, but is a cumbersome method of calculation for the Westfall mixers, so for the mixers, the average pipe velocity will be used.

The turbulent pressure is calculated using the turbulent kinetic energy (k) in the flow field, where:

$$P_{turb} = 0.39 \rho k$$

In the orifice validation testing, the value K was found to be 24.0 in order to reach a cavitation coefficient of 3.0. This same value of K was used in the determination of the cavitation coefficient of the Westfall mixers. Since a cavitation number of 3.0 provides some safety margin in the operation of orifice plates to allow for some flow maldistribution at the orifice inlet, it is believed that the calculated K value is a bit higher than necessary, and so is conservative.

Locations where cavitation is most likely to occur downstream of an orifice are shown in blue in Figure 1. In the figure, the flow is from left to right, and the orifice (Beta = 0.67) is seen towards the left of the picture. Red represents the highest pressures, and blue represents the lowest pressure, including the effect of turbulence, where cavitation is most likely to occur.

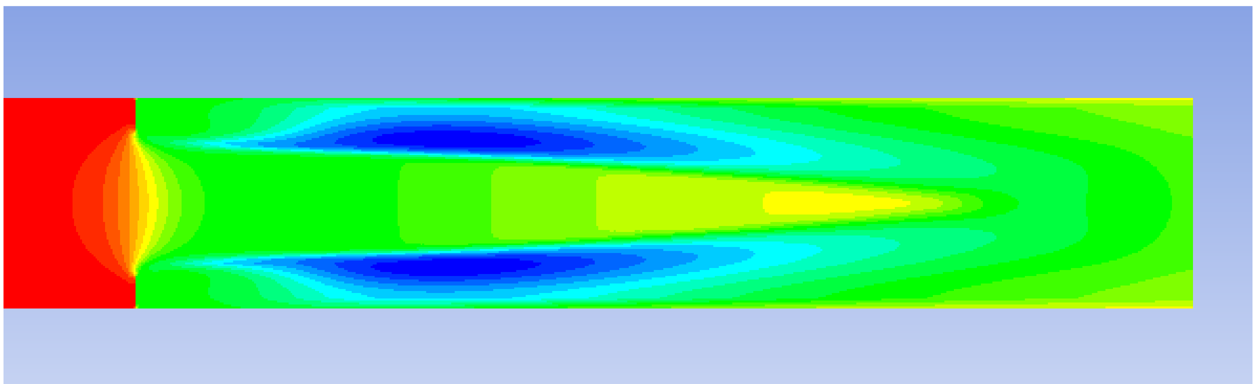

Figure 1 - Cavitation Pressure Downstream of an Orifice (Beta = 0.67)

The cavitation will occur on the edges of the jet where the static pressures are low, and the shear rate, and thus turbulent kinetic energy is high. Not that the cavitation inception is displaced downstream of the orifice by a short distance, as the turbulence has not fully developed at short distances from the plate. This agrees very well with experimental data of cavitation downstream of an orifice.

The presence of non-condensable gas in the flow field can also has an impact on the rate and inception of cavitation. As the fluid pressure drops, dissolved gasses may also come out of solution at nucleation points, in a somewhat similar manner to cavitation. The main difference however, is that as the pressure rises again, the non-condensable gas will not return to the liquid very quickly, and instead an air bubble is formed. The rapid collapse of vapor pockets and resulting shock wave is what causes damage in cavitation, as it creates extremely high pressures. The presence of non-condensable gas acts as a shock absorber, and prevents complete collapse of the vapor pocket. Though high fractions of dissolved gas may cause bubbles to persist downstream of the mixer, it will generally help to protect the equipment from cavitation damage.

RESULTS AND DISCUSSION

Each of the six mixers tested were evaluated for the minimum pressure present in the flow field (both static and turbulent), and from the minimum pressure value, a cavitation coefficient was developed. In all cases, the maximum advisable velocity through the mixer can be calculated using the specified cavitation coefficient, and the following equation:

$$U_{max} = \sqrt{\frac{(P_0 - P_{vap})}{\frac{1}{2}\rho\sigma_i}}$$

Where P_0 is the static pressure several pipe diameters downstream of the mixer, P_{vap} is the vapor pressure of the liquid, ρ is the liquid density, and σ_i is the mixer-specific cavitation coefficient.

The cavitation coefficients for the six mixers tested were found to be:

Table 1 – Westfall Manufacturing Mixer Cavitation Coefficients:

Model:		σi
2800	0.7 Beta	79.0
	0.8 Beta	46.3
	0.9 Beta	28.9
3050	Single	4.0
	Double	4.4
	Triple	5.3

In the 2800 series mixer, the cavitation coefficient intuitively decreases with increasing open area, allowing a higher velocity to be reached before the onset of cavitation. If the same convention of using the throat velocity is used to determine the cavitation coefficient as is typically used for an orifice, the cavitation coefficient for the Westfall mixer would be 5.0

(compared to 3.0 for an orifice). The reason for the higher cavitation coefficient is the increased turbulence in the corners of the hourglass shape hole in the mixer, which also contributes to better mixing performance. The areas where cavitation is likely to initiate are shown in blue in Figure 2 downstream of a 2800 0.8 Beta mixer.

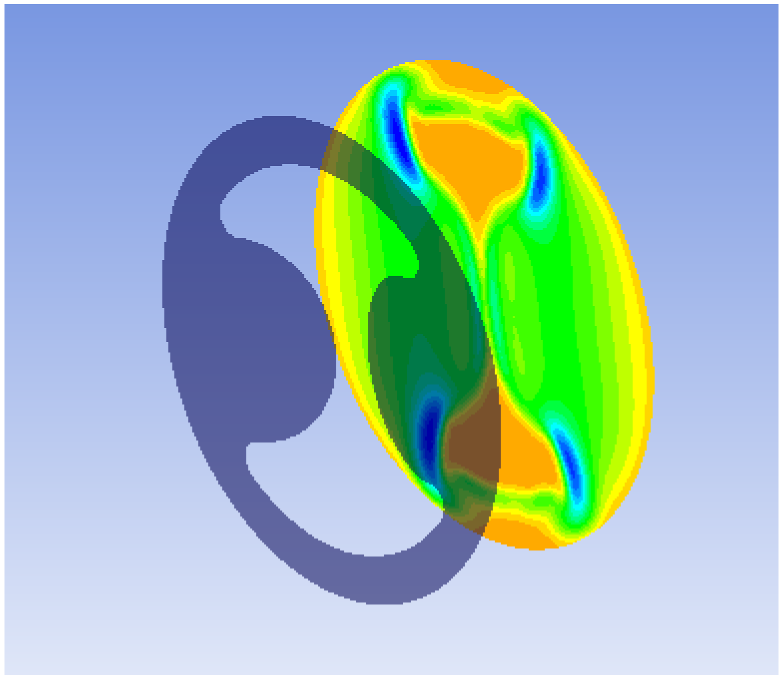

Figure 2 - Cavitation Pressure 0.4D Downstream of a 2800 0.8 Beta Mixer

As with an orifice plate, the cavitation is likely to be displaced downstream of the mixer and carried downstream by the flow, so the damage due to cavitation is not likely to be found on the mixer itself. Rather, especially for the high beta mixers, any damage due to cavitation is likely to be found on the pipe wall within a few pipe diameters downstream of the mixer.

It is notable that the cavitation coefficients for the 3050 mixer are significantly lower than for the 2800 mixer. This is due to the fact that the peak turbulent kinetic energy is nearly an order of magnitude lower than for a 2800 mixers at the same flow rate. Also, with a lower area blockage, the peak velocity is lower in the 3050 mixer than in the 2800 mixer, both of which enable higher velocities and lower pressure loss, with less risk of cavitation.

Unlike the 2800 mixer, the lowest cavitation pressures for the 3050 mixer are located near the downstream surface of the last stage of forward-leaning tabs (Figure 3), so any damage from cavitation is likely to occur to the last stage vanes as well the pipe wall directly downstream of the mixer. Perhaps an additional safety factor should be used if there is a flange located in this area.

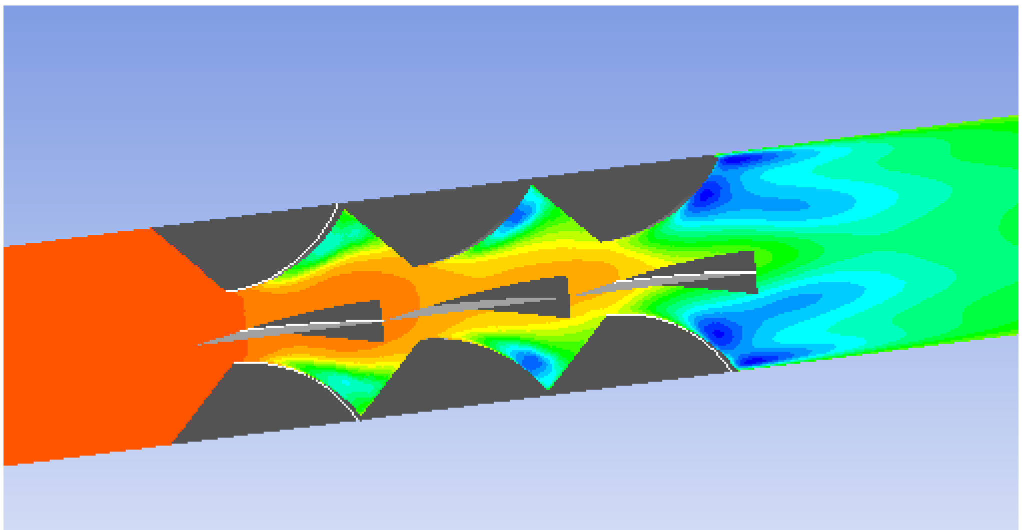

Figure 3 - Cavitation Pressure in Westfall 3050 Triple Mixer

CONCLUSIONS

A cavitation coefficient was developed for Westfall's range of pipe mixers, with an equation provided for determining the maximum velocity recommended for each mixer based on the liquid's properties. The 3050 mixers can withstand a higher velocity before cavitation occurs than the 2800 mixers due to the relatively lower turbulence levels and lower relative peak velocities. Should cavitation occur, areas where the damage would be located have been highlighted.