REVIEW OF RING -BAFFLE PRESSURE DISTRIBUTION PROCEDURES IN VERTICAL SYLINDRICAL TANKS

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ABSTRACT

In this article a review on the various pressure distribution procedures on the ring baffle in Storage tanks is investigated. In this research 5 most common procedures in determining pressure loads on ring baffles is investigated. Radial and circumferential distribution of pressure on ring baffles in a 284 cm tank is tested. Some effective parameters on pressure distribution are: nondimensional liquid velocity$U_{max}T/2W$, liquid amplitude ξ/r, baffle depth d/r, radial position on the baffle y/W,circumferential position β, and baffle spacing s/W.

The dependence of the pressure loads on each of these variables is illustrated with representative data obtained with one and two baffles mounted in the tank. These data are compared with available theories where applicable. Results suggest that pressure distributions can be determined from available theories for the design of single and multiple baffle configurations.

INTRODUCTION

Sloshing is defined as the periodic motion of the free surface of a liquid in a partially filled tanks. If the liquid is allowed to slosh freely, it can produce additional forces. High amplitude fluid sloshing is one of the widespread causes of steel oil storage tanks during strong earthquakes addressed as an important failure mode (NASA SP-8031, 1969). This phenomenon generates additional forces impacting the wall and roof of the tanks. Since the damping provided by the wiping action of the fluid against the tank wall is small, free oscillations may persist for long periods, and forced oscillations may produce long free-surface waves unless suitable damping device are provided (Hosseinzadeh et al., 2014).

The undesirable sloshing phenomenon may be controlled by the proper geometrical design of the tank and by the addition of baffles. Tank geometry influences the natural sloshing frequencies and sloshing modes, forced response, resultant pressure forces and moments acting on the tank. Baffles increase the effective fluid damping and thereby reduce the duration of free oscillation and the magnitude of forced oscillations (NASA SP-8009, 1968).

The selection and design of suppression systems require quantitative knowledge of the slosh characteristics. Anti-slosh baffles are usually required in liquid-propellant space vehicles to minimize propellant oscillations. The most common configuration consists of rigid rings fitted around the internal periphery of the tank. Annular ring baffles in cylindrical tanks have been designed as integral parts of the structure to provide structural stability for the thin tank shell (Structural baffles) and as separate devices that are independent of the primary tank structure (Non-structural baffles). Efficient design of both rigid and flexible baffles requires a detailed understanding of the hydrodynamic loads as well as the damping associated with the baffle configuration. An annular ring baffle configuration is shown in Figure a(NASA SP-8031, 1969).Numerous studies have been conducted to investigate and develop anti-slosh devices. Most of these studies have concentrated on the damping provided by various baffle configurations, with much less attention directed toward baffle loads. Semi-empirical theories are presented in reference 6 for the maximum pressure on submerged baffles subjected to oscillatory slosh, as well as for baffles which are uncovered during the slosh cycle and subjected to a slapping or impact action (Scholl et al., 1972).

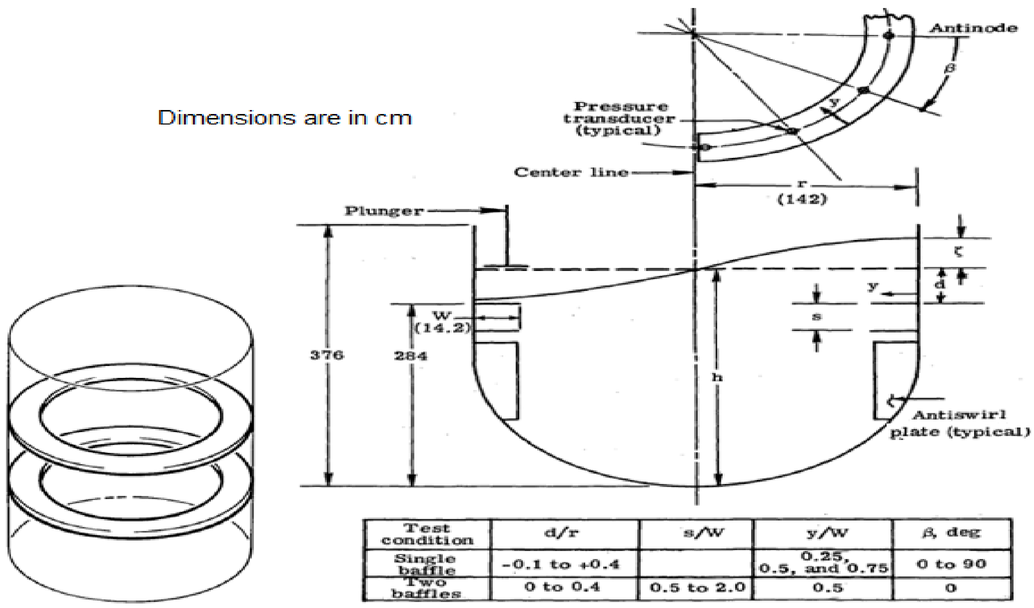
In this article 5 important theories on pressure loads and pressure distribution on ring-baffle are introduced. The loads experienced by a ring baffle while submerged and partially submerged in a relatively large tank of oscillatory liquid are examined in this study via the results obtained by a test which is conducted in a 284 cm diameter rigid tank and compared with available theories. Experimental and analytical data are presented as a function of slosh velocity or amplitude, baffle spacing, and baffle locations both above and below the liquid surface. Results suggest that pressure distributions and damping values can be determined from available theories for the design of single and multiple baffle configurations.

RING-BAFFLE PRESSURE DISTRIBUTION PROCEDURES

The designer of a baffle system is interested in finding the pressure history of the fluid acting on the baffles because after the spacing and width of the baffles have been optimized, integration of the pressure will give the moments to be expected. Thus, with the forces and moments acting on the baffle determined, the baffle material and its thickness can be chosen to withstand the load exerted on the baffles by the oscillating fluid (Roberts et al., 1966).

APPARATUS AND TEST PROCEDURE

A vertical cylindrical steel tank with a circular cross section and an ellipsoidal bottom was used in the investigation. The tank had an inside diameter of 284 command a wall thickness of 1.58 cm. Two relatively long, narrow anti-swirl plates were mounted vertically along the tank wall at the desired anti-node locations of the fundamental mode to minimize rotational drift of the slosh plane. The pertinent dimensions of the tank are given in Figure 1b (Scholl et al., 1972).



Test condition	d/r	s/W	y/W	β, deg
Single baffle	-0.1 to +0.4		0.25, 0.5, and 0.75	0 to 90
Two baffles	0 to 0.4	0.5 to 2.0	0.5	0

(a) (b)

Figure 1.(a) Ring baffles configuration in cylindrical tank; (b) Slosh-tank dimensions and test variables.(Scholl et al., 1972).

The measured pressure data are presented in terms of a reduced velocity parameter$U_{max}T/2W$which is a nondimensional parameter (often referred to as the period parameter) describing the relative velocity conditions of the liquid in the vicinity of the baffle. Where$U_{max}$is the maximum liquid velocity at baffle location? T is the natural period of the oscillation and W is the baffle width. The maximum vertical velocity in a cylindrical tank at the baffle location due to the antisymmetric mode, may be written (Scholl et al., 1972).:

$$U_{max} = \omega \xi_{max} \sinh\left(1.84\frac{h-d}{r}\right) / \sinh\left(1.84\frac{h}{r}\right) \tag{1}$$

where ω is the natural slosh frequency, ξ_{max} is the maximum displacement amplitudeat the surface, d is the distance of the baffle below the quiescent surface, r is the tankradius, and h is the liquid depth.When the baffle is located at or below the quiescent surface, the value of U_{max}obtained from equation(1) at the baffle depth may be used to obtain the value of the reduced velocity parameter. When the baffle is above the quiescent surface, the velocity U_{max}at the baffle isless than the velocity $\omega\xi_{max}$ at the liquid surface, and may be written as (Scholl et al., 1972):

$$U_{max} = \omega \xi_{max} cos\omega t \tag{2}$$

The angular displacement ωt is obtained from the relationship:

$$d = \xi_{max} sin\omega t \tag{3}$$

where d is the distance of the baffle above the liquid surface. The relationship between the actual wave height and the reduced velocity parameter $U_{max}T/2W$ for the exposedand the submerged baffle is shown inFigure 2(a).

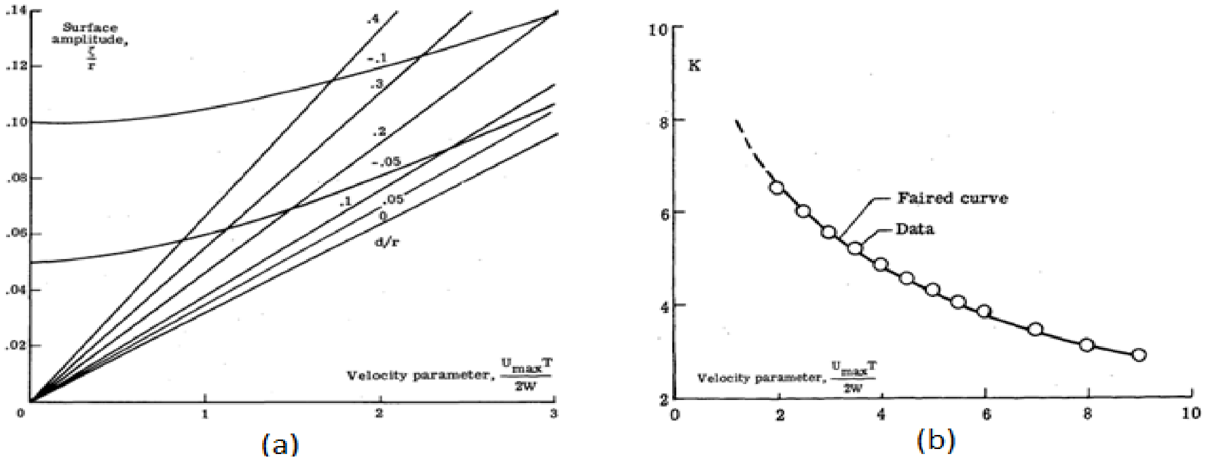


Figure 2. (a)Variation of surface amplitude with velocity parameter for various baffle depths (b) Value of K for oscillating plates(Scholl et al., 1972).

Procedure1. NASA SP-8009(NASA SP-8009, 1968)

The measured pressure data are nondimensionalized by dividing by the theoretical dynamic pressure $1/2\rho U_m^2$and are compared with the theories presented in the NASA monograph (NASA SP-8009,1968).The maximum pressure acting on a submerged baffle subjected to the oscillatory velocity of sloshing liquid can be computed from the expression

$$P = K\rho U_m^2 \tag{4}$$

Where K is the non-dimensional parameter shown in figure 2(b). When the baffle is above the quiescent liquid surface and subjected to the slapping action of the sloshing wave, an expression for the pressure of the form:

$$P = 2\rho U_m^2 \quad (5)$$

This expression is based on impulse momentum and assumes that the velocity of the liquid is completely reversed when it strikes the baffle.

Procedure2. Liu's Theory (Scholl et al., 1972)

Frank C. Liu developed a theory for pressure of the form:

$$P = 2\omega^2 \rho \xi e^{-3.68d/2r} W \sqrt{1-(y/w)^2} sin\omega t cos\beta \quad (6)$$

Which is based on liquid acceleration about the baffle? The expression also includes terms for radial and circumferential loading, y andβ respectively.

Procedure 3. Davis's Theory (Scholl et al., 1972)

The Davis derived a semi theoretical expression for pressure which includes both the liquid acceleration (as does Liu's expression) and liquid velocity. The expression, which is based upon an irrational flow analysis and the experimental results of Keulegan and Carpenter, is:

$$P = 2\omega^2 \rho \xi \frac{\sinh\left(3.68\frac{h-d}{2r}\right)}{\sinh\left(3.68\frac{h}{2r}\right)} \sqrt{W^2 - y^2} sin\omega t cos\beta$$
$$-\frac{3}{4} C_d \rho \left[\frac{\sinh\,(3.68\frac{h-d}{2r})}{\sinh\,(3.68\frac{h}{2r})}\right]^2 \omega^2 \xi^2 (1-\frac{y^2}{W^2}) |cos\omega t| cos\omega t cos^2\beta \quad (7)$$

The analysis also includes the terms for radial and circumferential loading. The drag coefficient $C_d$is discussed in the appendix and is assumed to be:

$$\mathrm{C_d} = 15(\mathrm{U_{max}T/W})^{-1/2} \quad (8)$$

Procedure 4. NASA SP-106 (Silverman and Abramson, 1966)

The dynamic pressure at any point on the baffle resulting from liquid sloshing in its fundamental mode in a cylindrical tank is given by:

$$\frac{P}{\theta_1 R\rho cos\theta} = \frac{2ng}{(\varepsilon_1^2 - 1)} \frac{J_1\left(\varepsilon_1 \frac{r}{R}\right)}{J_1(\varepsilon_1)} e^{-\varepsilon_1 \frac{ds}{Ry}} \quad (9)$$

Where p is the pressure, $\varepsilon_1 = 1.84$is the firstroot of $\mathrm{J}_1'(\varepsilon) = 0$, and d,$a_0$, r, R, θ, θ_1, are relatedto tank geometry and coordinates as shown in Figure 3. It is seen that the pressure distribution varies with the $cos\theta$ aroundthe circumference of the baffle and varies onlyslightly with the coordinate r for values ofw/R. Thetotal moment $M_b$acting to overturn the baffle is obtained by integration of this pressure baffle is therefore distribution over the baffle. Thus:

$$\frac{M_b}{\theta_1 R^4 \rho} = \frac{\pi}{4} n g e^{-\epsilon_1 \frac{d_s}{R}} \left[1 - \frac{a_0}{R} \frac{J_1\left(\epsilon_1 \frac{a_0}{R}\right)}{J_1(\epsilon_1)} + \left(\frac{a_0}{R}\right)^2 \varepsilon_1 \frac{J_1{}'\left(\epsilon_1 \frac{a_0}{R}\right)}{J_1(\epsilon_1)}\right] \quad (10)$$

It can readily be determined by integration of the force per unit length of baffle over the circumference of the baffle that:

$$M_b = \pi \bar{R}^2 F_b \tag{11}$$

and that the total force acting on one-half the baffle is therefore:

$$F = 2F_b\bar{R} = \frac{2M_b}{\pi\bar{R}} \tag{12}$$

Figure 4. shows a plot of the left-hand side of equation as a function of h/R for various values of a_0/R, valid for fluid depths. For lower depths, a correction factor CF is given as:

$$CF = \frac{e^{\epsilon_1 \frac{d_s}{R}}}{cosh\left(\epsilon_1 \frac{d_s}{R}\right) + sinh\left(\epsilon_1 \frac{d_s}{R}\right) tanh\left(\epsilon_1 \frac{d_s}{R}\right)} \tag{13}$$

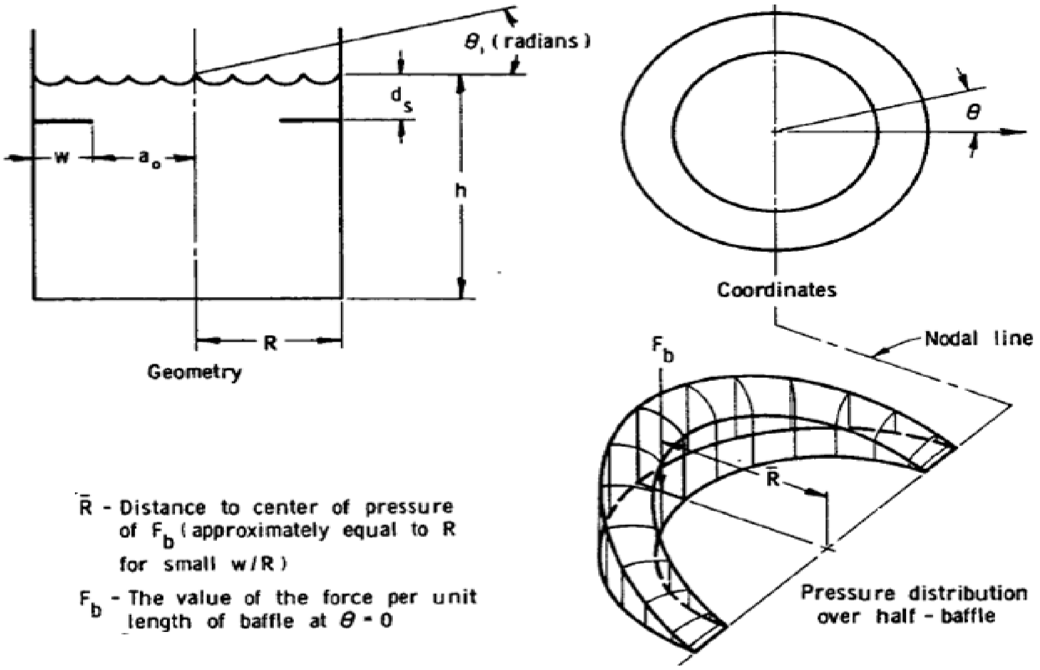


Figure 3. Geometry, coordinates, and pressure distribution for ring pressure calculations (Silverman and Abramson, 1966)

to be applied such that:

$$M_b(true) = M_b(eq.13) \times CF \tag{14}$$

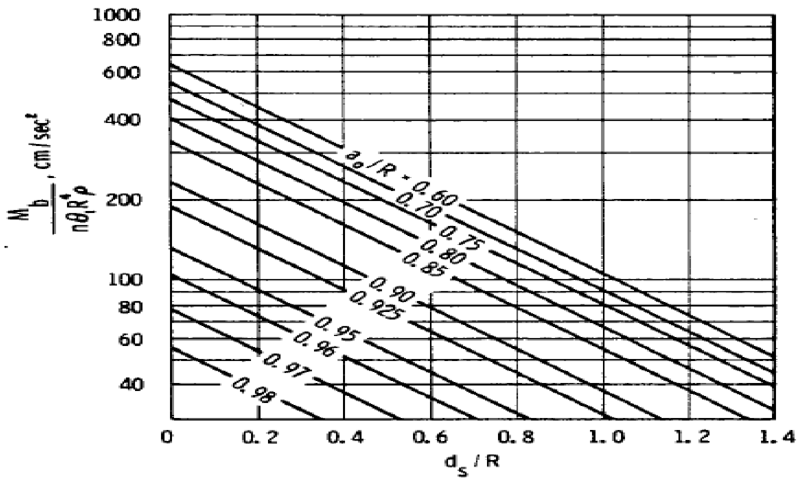


Figure 4. Moments acting on an annular ring baffle as a function of baffle depth and width (Silverman and Abramson, 1966)

Procedure5. Mile's Theory (Scholl et al., 1972)

Theforce per unit area on the ring is given by:

$$p(\theta,t) = C_D \frac{\rho}{2} f^2 \omega^2(-d) cos^2\theta sin^2(\omega t) \quad (15)$$

where w is the vertical component of the fluid velocity, f (z) = sinh k(z+h)/sinh(kh) and C_D is the local drag coefficient. Its value may be obtained from the empirical relation:

$$\begin{aligned} C_D &= 15\sqrt{\frac{U_m T}{D}} \quad , \qquad 2 \le \frac{U_m T}{D} \le 20 \\ C_D &= 2 \quad , \qquad \frac{U_m T}{D} \ge 100 \end{aligned} \quad (16)$$

Where$U_m T$/D is the "period-parameter"U_m denotes the time wise maximum velocity, T the period, D the plat width and:

$$\frac{U_m T}{D} = \frac{[\omega \xi_1 f(-d) cos\theta](2\pi/\omega)}{\alpha a} = \frac{2\pi f(-d)}{\alpha}\left(\frac{\xi_1}{a}\right) cos\theta \quad (17)$$

Substituting$\omega^2 = kgtanh(kh)$into Eq. and expressing the maximum pressure on the baffle as an equivalent head of the liquid, we have:

$$Z_{max} = \frac{P_{max}}{\rho g} = \frac{1}{2} katanh(kh) f^2(-d)(C_D)_{max}(\frac{\xi_1^2}{a}) \quad (18)$$

CONCLUSIONS

In this Article the various procedures on determining pressure loads and pressure distribution over the ring baffles are investigated. Some results are :

1. The test program consisted of the isolation and examination of the baffle pressure loads and slosh damping, with the following as variables: nondimensional liquid velocity$U_{max}T/2W$, liquid amplitude ξ/r, baffle depth d/r, radial position on the baffle y/W,circumferential position β, and baffle spacing s/W. The dependence of the pressureloads on each of these variables is illustrated with representative data obtained with one and two baffles mounted in the tank, followed by damping data obtained with single and multiple baffles. These data are compared with available theories where applicable.

2. Effect of amplitude: sample data and available theories for comparison are presented in figure 5to illustrate the effect of slosh amplitude, in terms of the nondimensional velocity parameter ont he baffle pressure P.Theoretical values derived from Liu's equation (eq.(6)) are considerably lower than those of Davis for the range of depths and liquid velocities examined during these tests and therefore are not presented. As might be expected, the pressure on the baffle increases with increasing values of the velocity parameter. Furthermore, there appears to be good agreement between theoretical and experimental results for the submerged baffle and fair agreement when the baffle is exposed.

3. Figure 6 shows that the theoretical values for the submerged case are dependent on $U_{max}T/2W$ but independent of d/r, whereas thesplash theory (eq.(5)) when nondimensionalized is independent of $U_{max}T/2W$. The measured values of the pressure parameter decrease with increasing values of the velocity parameter in both submerged and exposed cases and also vary with baffle depth d/r between 0.1 and -0.1.

4. Effect of radial position: The distribution of the pressure in terms of y/W is presented for liquid depths d/r of 0.2 and 0.4in figure 7. The experimental distributions are compared with the theory of Davis, which includes the pressure distribution across the baffle, and with the theoretical values from (eq.(5)), which does not include y/W effects. Davis's prediction of the magnitude of the pressure across the baffle is somewhat low for a low value of $U_{max}T/2W$, but does follow the trend of thedata.

5. Effect of circumferential position: The effect of circumferential position β onthe baffle pressure parameter is presented in terms of the nondimensional velocityparameter in figure 8. The theory of Davis is shown for comparison with the data taken at d/r = 0.4. Agreement appears to be good ford/r = 0.4 and (β = 30°, but as β increases the agreement is not as good. Although thetheory predicts zero pressure at the nodal point (β = 90°), the liquid in fact exhibits a verticaloscillatory component at the nodal point during antisymmetric slosh.

6. Effect of baffle spacing: The effect of baffle spacing s/W on the baffle pressure parameter is presented in figure 9. For comparison, faired curves based on the data for the single baffle are also presented. With the possible exception of the spacing s/W of 0.5, the addition of a second baffle provided little or no attenuation of the baffle pressures. In fact, under certain conditions the pressures were higher in the case of the multiple baffles.

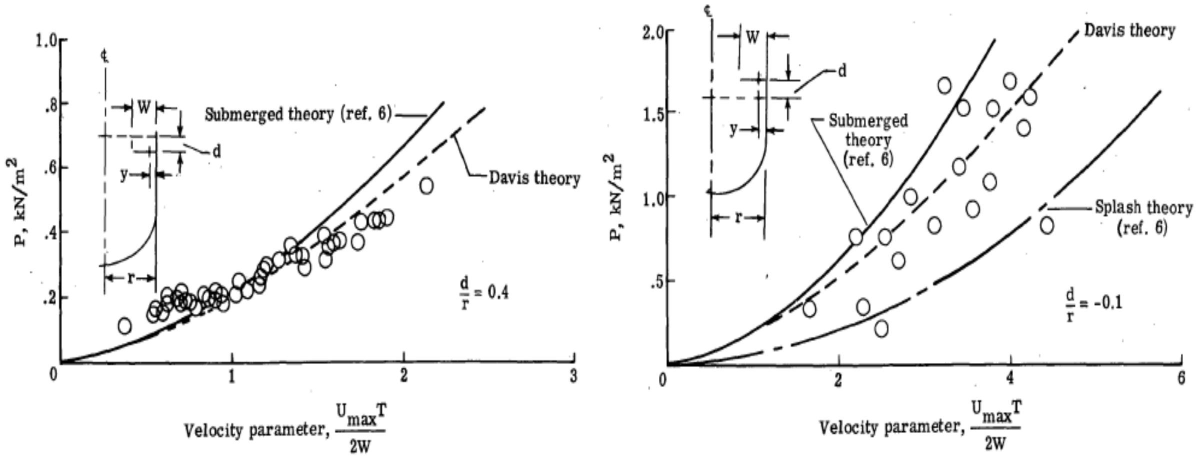


Figure 5. Effect of velocity parameter on baffle pressure for two baffle depths. Single baffle; β= 0°; y/W = 0.25(Harland F. Scholl et al., 1972).

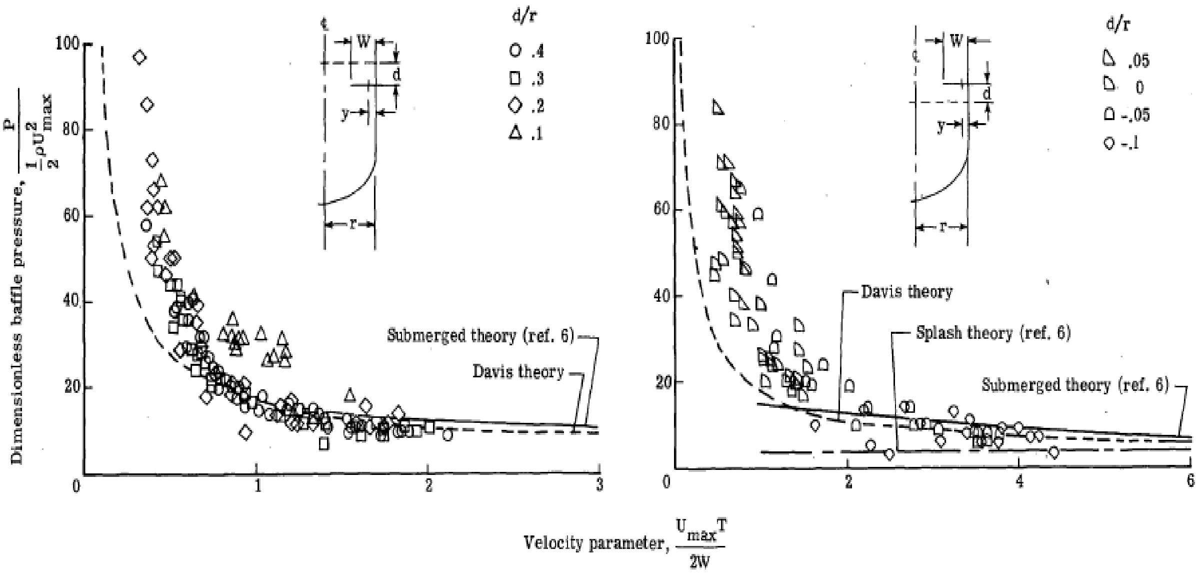


Figure 6. Effect of velocity parameter on baffle pressure parameter for a range of baffle depths. Single baffle; ; β= 0°; y/W = 0.25(Harland F. Scholl et al., 1972).

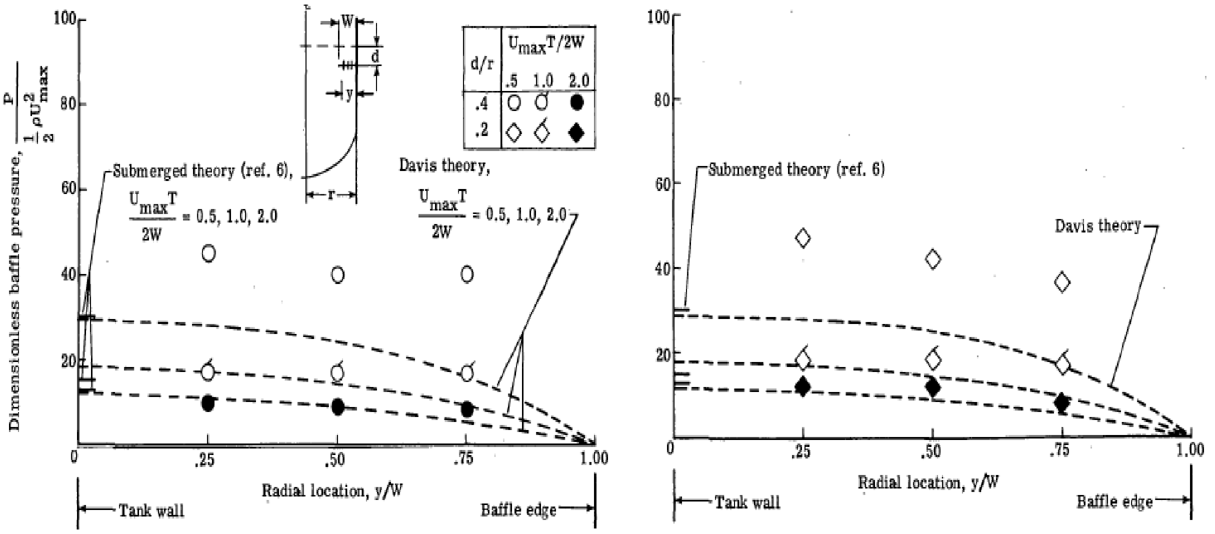


Figure 7. Effect of radial location on baffle pressure parameter for various velocity parameters at two baffle depths. Single baffle; β= 0°(Harland F. Scholl et al., 1972).

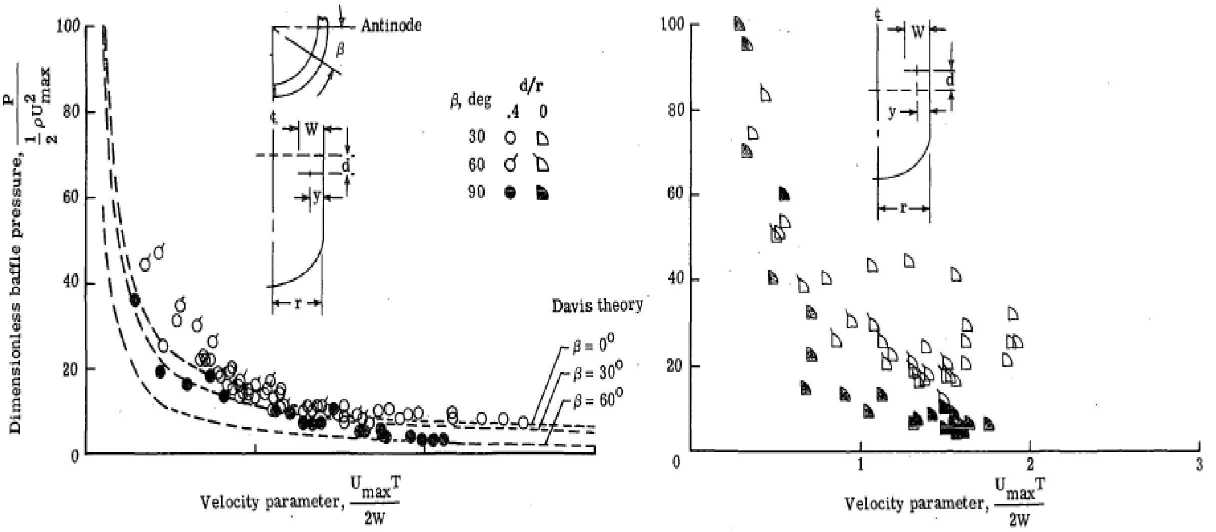


Figure 8. Effect of velocity parameter on baffle pressure parameter for a range of circumferential locations at two baffle depths. Single baffle; y/W = 0.50(Harland F. Scholl et al., 1972).

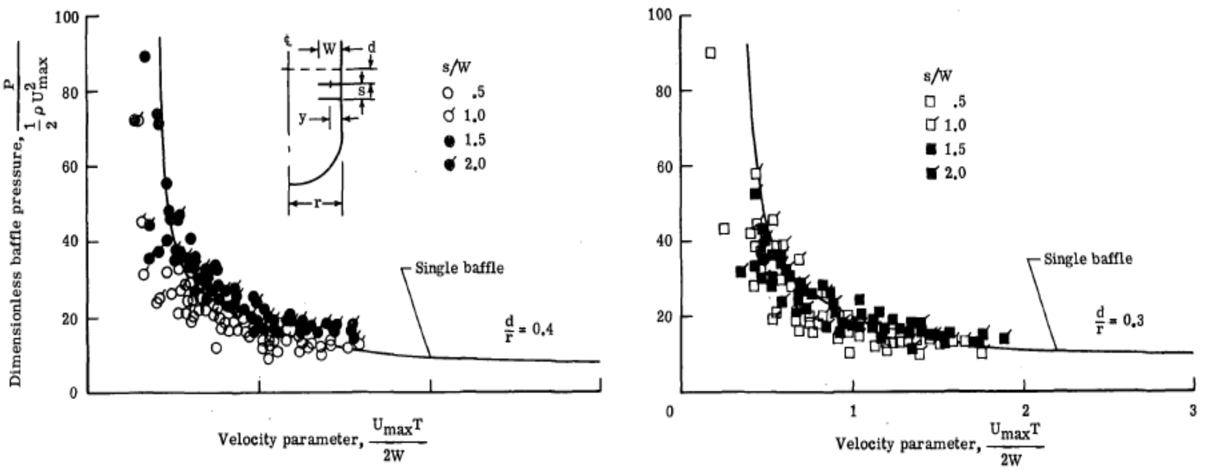


Figure 9. Effect of velocity parameter on baffle pressure parameter for a range of baffle spacing and depths β= 0°; y/W = 0.50(Harland F. Scholl et al., 1972).

REFERENCES

Anon.: Propellant Slosh Loads (1968) NASA Space Vehicle Design Criteria (Structures).NASA SP-8009

Anon.: Slosh Suppression (1969) NASA Space Vehicle Design Criteria (Structures). NASASP-8031

Scholl HF, David G, Stephens and Phillip K Davis (1972) RING-BAFFLE PRESSURE DISTRIBUTION AND SLOSH DAMPING IN LARGE CYLINDRICAL TANKS, NASA TN D-6870

Hosseinzadeh N, Sangsari MK and Tavakolian Ferdosiyeh H (2014) Shake table study of annular baffles in steel storage tanks as sloshingdependent variable dampers, Journal of Loss Prevention in the Process Industries 32, 299-31

Roberts JR, Edzcdrdo RB and Pei-Ying C (1966) SLOSH DESIGN HANDBOOK I, NASA CR-406

Silverman S and Abramson HN (1966) Damping of Liquid Motions and Lateral Sloshing. Ch. 4 of The Dynamic Behavior of Liquids in Moving Containers, NASA SP-106, pp. 105-143