July 1, 2011

Appendix A

Review of FAI/08-70, "Gas-Voids Pressure Pulsations Program" (Reference 16)

A-1 Summary

FAI/08-70 summarizes its contents as follows:

> "The results of this experimental program show that: (1) a Froude number in the piping highpoint of 0.54 is sufficient to sweepout an accumulated gas volume, (2) the gas void fraction for the initial stratified gas-water configuration is essentially preserved during the waterhammer event, (3) the peak waterhammer pressure is determined by the initial gas pressure and volume, the pump shutoff head and whether the system is flushed before the test conditions are established, (4) the peak force generated by the gas-water waterhammer event is determined by the peak pressure and the rate of rise of the waterhammer pressurization, (5) if the system piping includes a swinging check valve, the closure induced by the waterhammer event can cause subsequent forces, in both axial directions (upstream and downstream), that are larger than the waterhammer induced force and (6) the peak forces are a function of both the piping configuration and the initial gas volume."

With the exception of Item 1, We agree with the FAI/08-70 summary. Use of a Froude number of 0.54 may not be sufficient to remove gas from the vicinity of a transition from a horizontal pipe to a vertically downward pipe or in local high points where the full flow does not sweep through the high points.

This report describes waterhammer tests, develops an analytical water hammer model, provides one comparison of test results to the model, and illustrates model application. Coverage includes determination of pressure and axial force due to waterhammer with variation in air volume, high point configuration, pump bypass configuration, and presence of a check valve. Knowledge of pressure is important with respect to potential to violate the system pressure boundary (pipe rupture, relief valve lift). Axial force provides insight into behavior of pipe response when subjected to water hammer loads.

Almost 250 test runs were accomplished. However, no test results are compared to model pressure predictions. When we attempted to compare the model it was unsuccessful in part because Page 28 states the pump shutoff head at the test high point is 27 psig whereas Page 79 states it is 18 psig, and in part because pump shutoff head is not given. One comparison of calculated and measured axial force was provided with scattered results. At smaller initial void fractions the test results were under-predicted by the model by about 20 percent and over-predicted by about 400 percent. The model over-predicted the test data for higher initial void fractions.

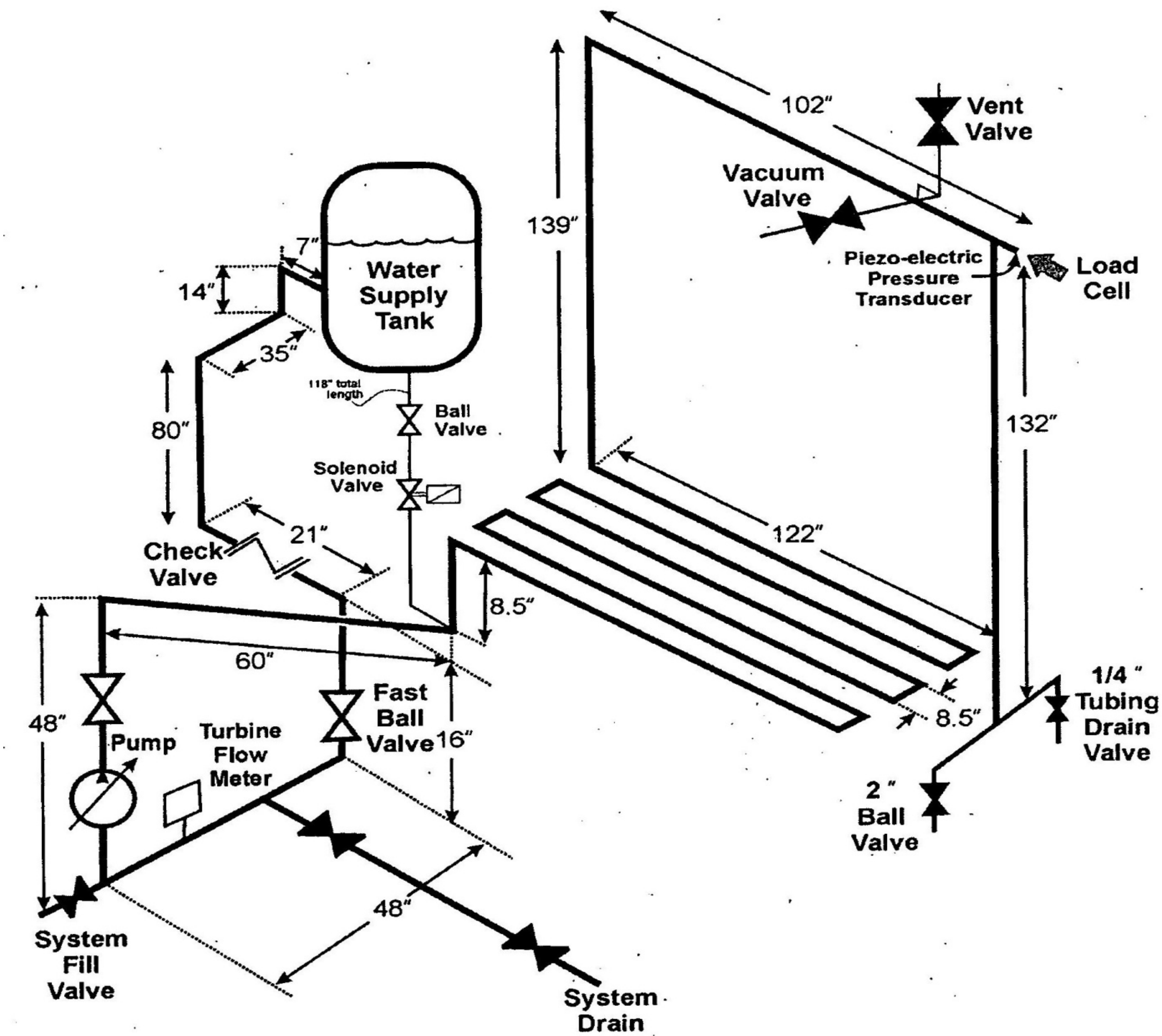
We conclude that FAI/08-70 provides valid test data that provides insights into water hammer behavior and will be useful in assessing water hammer analysis methodologies. The prediction of pressure for different systems with similar configurations is likely to be relatively insensitive to minor perturbations in system design. However, axial force will be strongly affected by the

system and its supports. Application of the modeling methodology provided in FAI/08-70 to plant configurations is not acceptably substantiated due to a lack of comparisons to test data.

A-2 Test Facility

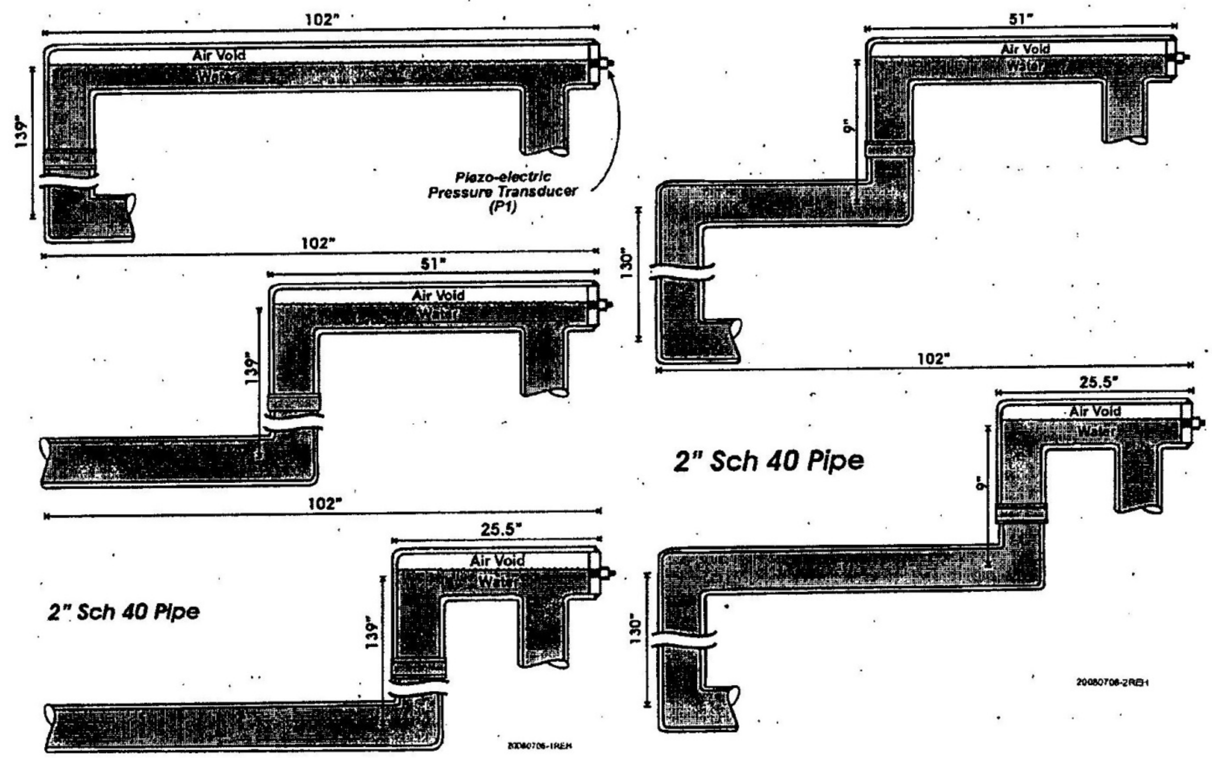
The test facility is illustrated in FAI/08-70's Figure 3-4:

Figure 3-4: Schematic – experimental setup, including mini flow line.



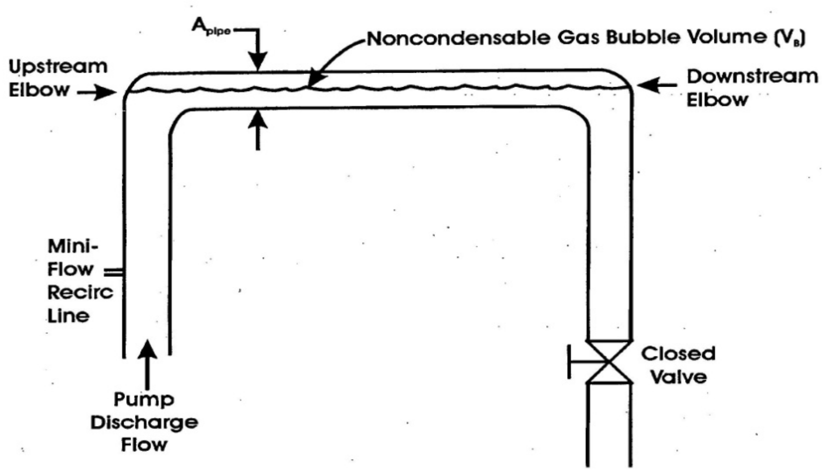
Variations in the 102 inch long upper horizontal pipe configuration are illustrated in the following figure:

Figure 3-2: Schematic of the various highpoint lengths to be studied. Note that the pictures are included for demonstration purposes and actual high point geometry might vary slightly.



and a typical initial gas volume is illustrated in Figure 2-1:

Figure 2-1: Example configuration for a pump start with a noncondensable gas volume in the discharge piping.



Prior to each test, the system was filled from the city water supply until water flowing from the highpoint vent was observed to be free of air. Then the vent was closed and the system allowed to pressurize to the city water pressure of about 50 psig. Remaining air was then addressed as follows: (1) "as-is", which one would expect would leave air bubbles in the piping despite a small pipe slope, with the exception of the high point horizontal pipe, to enhance filling, and (2) following a flow purge at a Froude number of about four followed by pressurization to the shutoff head of the pump. Post filling testing based on the initial pressure followed by draining to atmospheric pressure established that the flow purge was effective at removing the air as determined by measuring the drained water volume and mass. The initial void condition was then established by draining the desired volume with the highpoint vent open, the drain and vent lines were closed, and the desired initial pressure obtained via a vacuum pump connected to the highpoint gas volume. The effect of initial conditions on waterhammer behavior was evaluated by each follow-up transient test.

The pump has a lower shutoff head than typical ECCS pumps. Therefore, the initial test pressure was less than one atmosphere to maintain test pump shutoff head to test initial pressure ratios similar to plant ratios. For perspective in addressing test initial parameters, the volume of the longest horizontal pipe where the initial void is introduced is 6 liters so an initial gas volume of one liter is a 17 percent void.

Close to 250 tests were conducted with variations in highpoint lengths and configurations; with and without a check valve; with and without a pump bypass line; with and without an initial flow purge; at initial pressures of -24, -20, -15, -10, and -5 inches of mercury; with initial gas volumes of 0.5, 1, 1.5, 2, 2.5, 3, 4, and 5 liters for several single high point lengths, and for several initial volumes in configurations with two highpoint elevations. Good agreement was obtained when comparing test results with test parameters and with respect to developed understanding of transient behavior such as the reasons for multiple pressure spikes following the initial pressure spike and the influence of check valve slam.

Each test consisted of simultaneously starting the pump and opening the pneumatic ball valve which compressed the gas volume and initiated the waterhammer. Pump run-up time was several hundred milliseconds and valve opening time was about 100 milliseconds.

A-3 Waterhammer Pressure Modeling

The modeling approach considers the early fluid acceleration phase of the hydrodynamic transient, the deceleration waterhammer phase, and the propagation and reflection of the sonic wave.

Several assumptions are made:

"a) pump run-up (increase in the volumetric flow rate) varies linearly with time until the pump operating point is reached,

b) initially the bubble resides at the top of the designated high point with its length equal to that of the high point ...,

c) The noncondensable gas can be represented as an ideal gas and in the early acceleration phase follows a polytropic path, i.e. pV^n = constant, where n is a semi-empirical coefficient based on experimental data, n = 1 for an isothermal (constant temperature) process and = $\gamma = C_p / C_v$ for an adiabatic (perfectly insulated) process where C_p = heat capacity at constant pressure and C_v = heat capacity at constant volume. For air, $\gamma = C_p / C_v = 0.24 / 0.17 = 1.4$.

d) maximum bubble pressure at the end of the acceleration phase is equal to a pressure that is larger than the pump shut-off pressure and less than the waterhammer pressure,

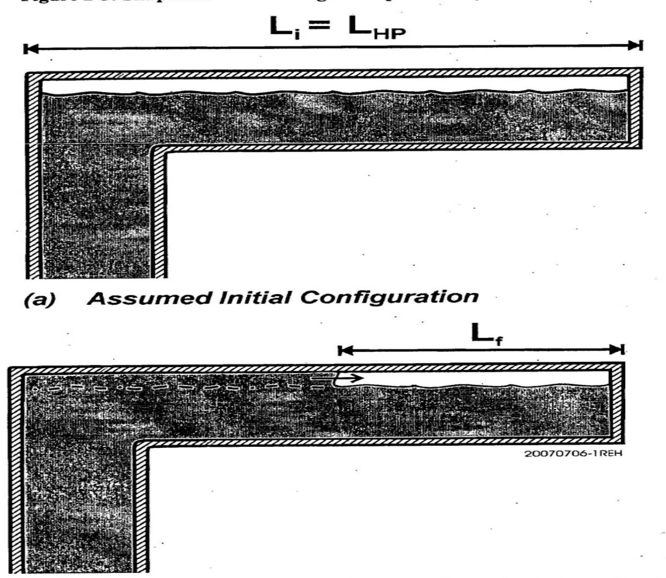
e) maximum water flow rate is equal to the pump discharge flow rate, and

f) water sonic velocity is constant throughout the piping configuration being analyzed."

Data provided in the report and in other references substantiate Assumption a. The high point associated with Assumption b is one or two horizontal 2 inch diameter Schedule 40 pipe sections with air above water in the pipe. (Some experiments were run with transparent pipe and substantiated that air compression involved a hydraulic jump with a water-solid condition upstream of the jump.) The horizontal pipe(s) were connected at each end to downward-oriented vertical pipes that were essentially water-solid. In some cases, the water-solid condition was achieved by flushing at a high Froude number to sweep air out of the system. In others, sweeping was not performed, residual air remained at locations other than the high point, and tests were conducted to quantify the residual air volume and to assess the effect of residual air on the waterhammer results.

Behavior is separated into an early fluid acceleration phase and a waterhammer deceleration phase. The modeling is illustrated in the report's Figure 2-3:

Figure 2-3: Simplified view of the gas compression by a water column.



(a) Assumed Initial Configuration

(b) Assumed Configuration During the Transient

Pump start compresses the bubble toward the downstream elbow to a maximum pressure that is greater than the pump shut-off pressure. Bubble lengths follow from the polytropic assumption[1]:

$$L_f = L_i \, (P_i / P_f)^{1/n} = L_{HP} \, (P_i / P_f)^{1/n} \qquad \text{(A-1)}$$

[1] The report contains inconsistent nomenclature and Equation 2-5 contains a typo. This unnecessarily complicates understanding of the modeling.

where: P = pressure,
subscript f indicates the end of the acceleration phase, and
the other terms are defined in Figure 2-3.

For time $t \leq$ the pump run-up time, $t_{run\text{-}up}$, the pump flow rate is given by:

$$Q_{pump}(t) = Q\ t / t_{run\text{-}up} \tag{A-2}$$

where: Q = pump flow rate at the fully run-up condition.

The volume discharged during the run-up time becomes:

$$V_{run\text{-}up} = Q\ t^2_{run\text{-}up} / 2 \tag{A-3}$$

on the basis of the assumed linear pump flow rate behavior following pump start.

The report authors next assume time at the end of the acceleration phase, t_f, can be approximated by the time the pump discharge volume is equal to the initial bubble volume, V_i. This leads to:

$$t_f = t_{run\text{-}up} \left(V_i / V_{run\text{-}up} \right)^{1/2} \tag{A-4}$$

where: $V_i = \alpha_i L_{HP} A$, α_i is the initial void fraction and
A is the pipe flow area.
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Since the maximum pump discharge flow rate occurs at the end of the acceleration phase, it is given by:

$$Q_{max} = Q \left(V_i / V_{run\text{-}up} \right)^{1/2}. \tag{A-5}$$

We note that Q, the pump flow rate at the fully run-up condition, is not given in the report and inconsistent values are given for pump shutoff head. Consequently, it is not possible to straightforwardly compare test data to model predictions. We did not attempt to calculate model predictions in order to obtain comparisons.

Finally, the water-hammer velocity that would result if a moving column of water was instantaneously stopped follows from the 1898 Joukowsky-Frizell equation for waterhammer pressure due to steam-water interaction (Reference A-1):

$$\Delta P = \rho\ C_w\ U \tag{A-6}$$

where:
ΔP = pressure difference due to waterhammer,
ρ = density of water,
C_w = speed of sound in water, and
U = water velocity immediately prior to the waterhammer.

A-4 Comparison of Model Pressure Predictions to Experimental Data

The discharge pressure due to the gas-water waterhammer should now be able to be calculated by the following:

(1) Use the Eq. A-1 relationship to calculate the compressed gas volume when the gas is compressed to the pump shutoff pressure. We note that pump shutoff pressure is given on FAI/08-70 Page 28 as 27 psig and on Page 79 as 18 psig. Immediately, there is the question of which value should be used.

(2) The volume of water added during the pressure increase immediately would follow by subtracting the compressed gas volume from the initial gas volume.

(3) Next, one would calculate the time required for the pump to run up to the shutoff condition using Eq. A-3. Note this requires Q, the pump flow rate at the fully run-up condition that is not provided for the pump used in the experiments.

(4) Then one would calculate the volumetric flow rate at the Item 3 time via Eq. A-2.

(5) Superficial velocity could then be calculated by dividing the Item 4 flow rate by the cross-sectional area of the pipe. With respect to superficial velocity, this assumes the water upstream of the hydraulic jump is moving as a piston that fills the entire pipe diameter while the bubble is being compressed. The possible condition of the water contributing to the compression being the flow at the top of the pipe with water at the bottom of the pipe not moving, or some combination, is not addressed.

(6) The Item 5 velocity could then used in Eq. A-6 to calculate the waterhammer pressure if the moving water column is instantaneously stopped. Note this is conservative because the final gas volume is not zero and the moving water column will not be instantaneously stopped.

(7) The final waterhammer discharge pipe pressure would be obtained by adding the Item 6 pressure to the pump shutoff head pressure.

Compression waves from the waterhammer would propagate upstream through the pump and pressurize the suction side. The pressurization to stagnate this velocity would be calculated from Eq. A-6 using the velocity corresponding to the typically larger diameter suction pipe and would be added to the suction side pressure to obtain the peak waterhammer pressure.

As seen in the above list, We have not been able to compare the model to experimental data. Therefore, the model has not been shown to be acceptable.

A-5 Waterhammer Force Modeling

FAI/08-70 introduces this modeling by stating that the deceleration results from rapid compression of the gas combined with the impact of the water on the end of the pipe, and the pressurization is caused by bringing the water to rest by a single wave compression that has the magnitude of:

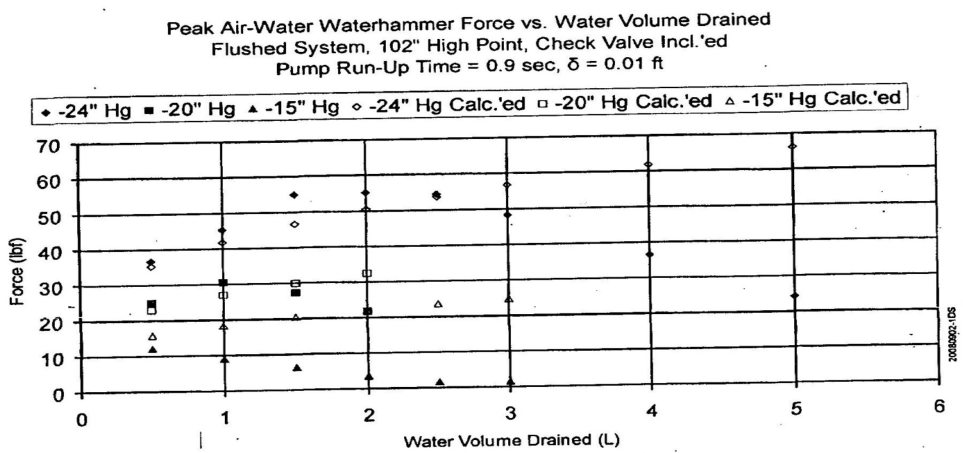
$$\Delta P = \rho\ C_w\ \underline{U}\ \alpha_i / 2 \qquad \text{(A-7)}$$

where: $\underline{U}$ = velocity of the water front at the top of the voided section that is taken as the average water transport velocity during the rise interval,

and the void fraction is included since the waterhammer pressure is calculated based on an average flow velocity that assumes the liquid and gas are moving at the same rate. The 1/2 is included because the deceleration is assumed to be caused by collision with the stagnant water column in the downcomer from the high point and this is stated to be typical of a water-water impact. This differs from the Eq. A-6 assumption that the moving water column is instantaneously stopped by collision with the end of the horizontal pipe.

The derivation, which is not discussed further here, continues with introduction of parameters that are determined from experimental data. The model is compared to the experimental data in the following figure:

Figure B-1: Peak Air-Water Waterhammer Force versus Water Volume Drained: Data and Calculations with Analytical Model.

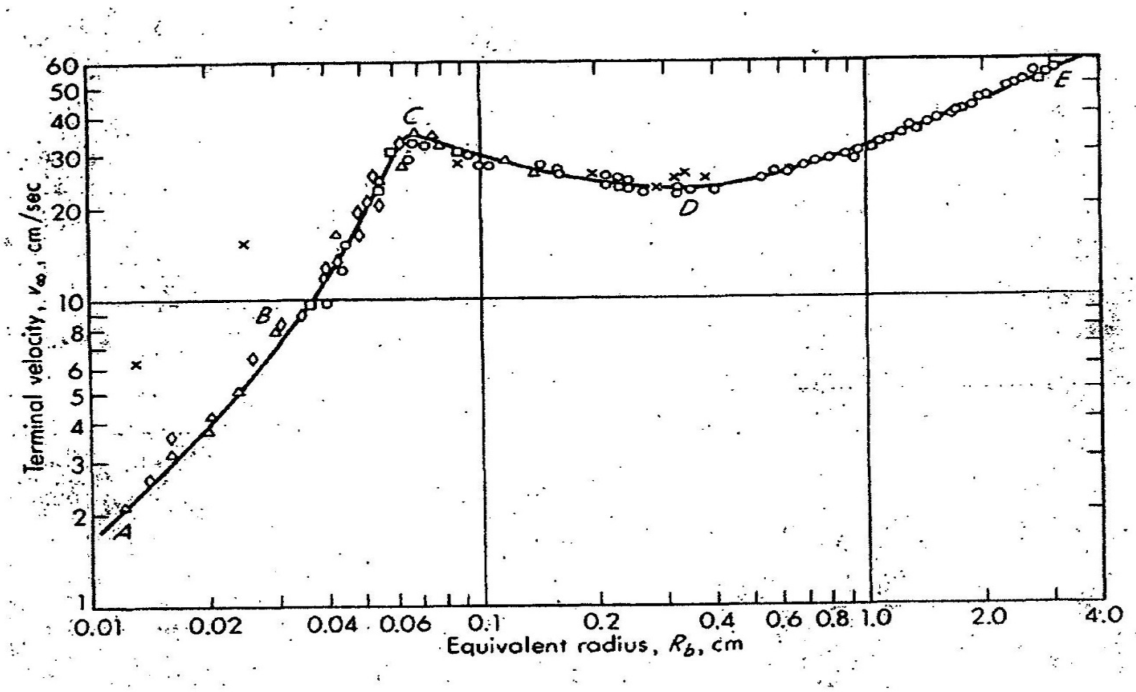


At smaller initial void fractions the test results are under-predicted by the model by about 20 percent and over-predicted by about a factor of three. The model over-predicts the test data for higher initial void fractions. We note that the results are hardware-specific and different configurations will result in different forces. This aspect of the modeling is not quantitatively addressed nor supported with other experimental data.

A-6 Dynamic Flow Behavior and Froude Number Testing

Most tests were conducted with steel pipe. However, additional tests were conducted with a transparent PVC highpoint pipe. FAI/08-70 stated that "these tests were performed by first forming a stratified gas volume in the piping highpoint under stagnant conditions and then sequentially increasing the water velocity through the test section and observing when the gas volume was swept out." The tests confirmed that the hydraulic jump behavior was approximated by the Figure 2-3(b) behavior and provided a picture of flow behavior as a function of flow rate and Froude number ranging from 0.18 to 0.55. At a Froude number of 0.45, the gas was pushed toward the downstream end of the horizontal pipe and some gas was pulled downward when the water velocity was greater than the bubble rise velocity. To illustrate data applicable to this behavior, FAI/08-70 provided the following data taken from Reference A-2:

Figure 5-5: Terminal velocity of air bubbles in filtered or distilled water as function of bubble size (taken from Wallis, 1969).



FAI/08-70 noted that the applicable bubble rise velocity is about 1 ft/sec and a Froude number of 0.54 exceeds 1 ft/sec for all pipes with an inner diameter greater than about 1 1/4 inches and therefore applies to all pipes of interest here. FAI/08-70 then stated that "from these data we conclude that the criterion developed by Wallis et al is directly applicable to the piping highpoint configuration. This can be used to determine if the recent hydraulic history shows that gas would have been removed due to the imposed water flow rate and it can also be used to evaluate whether an accumulated gas volume could be removed by the developed water volumetric flow rate as a plant strategy for controlling the extent of gas accumulations." It also states "this is important since this provides the user with a technical basis to determine whether a specific highpoint configuration has experienced system operational conditions sufficient to either prevent gas accumulation or purge existing accumulations, as well as to potentially provide a means to remove a gas volume that might accumulate." "While not applicable to every system, there are systems where such considerations can be utilized such as those that have a "piggy-back" operational mode during a accident. For many of these systems, or parts of systems they have already been exposed to a sufficient water flow rate to satisfy the Froude number criterion before the 'piggy-back' operating mode begins. When this is the case, the 'piggy-back' mode does not have to be evaluated."

The discussion of "wash-out" of gas as a function of Froude number is oversimplified and could be mis-applied when considering in-plant behavior because the FAI/08-70 "wash-out" tests apply only to horizontal pipes that do not have local high points where gas can accumulate. This is in part illustrated by the Reference A-2 information where FAI/08-70 states that "Wallis et al (1977) (Reference A-2) performed tests on the liquid velocity that is sufficient to "washout" a gas bubble at the discharge of the pipe into a large reservoir. This resulted in a criterion of a Froude number equal to 0.54 as being sufficient to "washout" the gas volume....” A summary of Reference A-2 stated that “The data for horizontal tubes were successfully correlated with some simple limiting theories and dimensionless representations. The vertical tube results were influenced by stability phenomena and nonsymmetrical flow patterns; as a result only a partial understanding was obtained.” Further, the Wallis conclusion is consistent with Purdue test results during downward flow in a vertical pipe that then connected to a horizontal pipe. Gas was observed to accumulate in the lower part of the vertical pipe and the connected lower horizontal pipe and then moved up the vertical pipe despite downward flow at Froude numbers greater than 0.54.

The above information justifies assuming that flow in a horizontal pipe that has no local high points will move any gas toward the downstream end of the pipe when the Froude number is greater than 0.54. The 0.54 criterion cannot be applied to the downstream end of a horizontal pipe unless gas can flow freely from the end of the pipe.

A-7 Conclusions

The following conclusions may be drawn with respect to the range of test parameters:

(1) Peak waterhammer pressure is a function of such items as total gas volume, initial gas pressure, and the flow run-up transient. System structural properties affect waterhammer force calculations and require structural evaluation.

(2) Presence of the swing check valve or the miniflow line does not influence the peak waterhammer pressure. However, subsequent rapid check valve closure introduces a second waterhammer transient that has a faster rate of rise. This can increase the magnitude of the force imbalances. Presence of the miniflow line reduces the peak force imbalances.

(3) Peak pressure for equal initial gas volumes is not significantly influenced by the length of the high point.

(4) For equal initial gas volumes, peak pressure increased as initial pressure decreased.

(5) For equal initial gas volumes, peak pressure appeared to be highest when all of the gas was located at the high point and lower if some of the volume was elsewhere in the test system.[2] This is not the case for waterhammer forces where the force can be significantly greater if gas exists in more than one location. This is apparently due to out-of-phase oscillations of the gas volumes. In one test, the difference was a factor of seven.

(6) Within the range of initial pressures from -20 to -5 inches Hg, the data exhibited an increase in waterhammer pressure followed by a decrease as initial gas volume was increased.

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[2] This was claimed by the report and our verification was limited to comparison of two tests. Most comparisons could not be accomplished because the available reports are in black and white and the figures often define symbol nomenclature with respect to color, not the black and white symbols that were provided.

FAI/08-70 concluded that the test data indicate that relief valves can be lifted due to waterhammer pressures if there is gas in plant systems depending upon the initial conditions. We agree and note that this has occurred.

Finally, the developed model for pressure behavior is not compared to the experimental data and only one plot of waterhammer force is provided that compares the waterhammer force model to data. In addition, waterhammer force is a strong function of the equipment layout. Therefore, we do not find the modeling to be acceptably verified.

A-8 References

A-1 Joukowsky, N., "Uber den hydraulischen Stoss in Wasserleitungsrohen," Memoires de l'Academie Imperiale des Sciences de St.-Petersbourg (1900), Series 8, 9(5), 1-71, 1898.

A-2 Wallis, G.B., 1977, "Conditions for a Pipe to Run Full When Discharging Liquid Into a Space Filled With Gas," Journal of Fluids Engineering, June, pp 405 - 413.