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INTERPRETING SURGE ANALYSIS RESULTS

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ABSTRACT

This paper details methods of interpreting maximum surge pressures in LNG pipelines due to valve closures and other transient events. The standard methodology for determining the onset of surge events and the pressure transients involved uses explicit integration; this method of analysis produces inherent "noise" in the solution results due to the integration method. The paper discusses methods of filtering data obtained through explicit integration and demonstrates which filters provide the best results for these analyses. Filtered and unfiltered results are presented for an actual LNG unloading facility subjected to a number of transient events, with discussion provided on determining the maximum peak pressures, their duration and the frequency content of secondary pressure waves.

INTRODUCTION

Transient pressures in system pipelines can be caused for a variety of reasons, including, but not limited to:

- valve closures and openings
- changes in pump operational speeds
- relief valve openings or closures
- changes in tank pressurizations

When these transient events cause the pressure in the system to fall below the vapor pressure of the working fluid vapor pockets can form in the system, a phenomenon known as liquid column seperation. When these pockets collapse, very high pressures can be generated in the piping system. The occurrence of these two events is one source of a transient piping phenomenon known as waterhammer. Predicting whether waterhammer will occur and the peak pressure associated with the event are critical in the design of fluid pipelines. This phenomenon affects the selection of pipe sizes and materials and the design of the pipe support structures.

Typical methods for evaluating the transient pressures in piping systems involve the use of explicit integration techniques coupled with the method of characteristics. While these techniques provide a stable, efficient method for predicting transient behaviors, they also introduce solution "noise" due to the time-stepping process that is used and due to the model used to capture the liquid column separation phenomenon. This noise is evident in the review of the solution variables, through very short duration, high magnitude values of the variables. While the noise does not affect the overall solution for the system, it must be filtered to find the correct solution magnitude for the basis of engineering decisions.

This paper presents an overview of the solution process involved with the prediction of waterhammer events, the types of results that can be expected and methods for filtering these results to determine the maximum peak pressures that can be expected. An example is given involving the analysis of a typical LNG pipeline under several transient conditions

BACKGROUND

Waterhammer within piping systems can occur for several reasons. For the LNG pipeline under consideration the primary mode for initiation of waterhammer events occurs when the operating pressure within the system falls below the vapor pressure of the LNG. It is known that this condition typically occurs when a transient event in the system, such as valve closures, pump trips, etc…, occurs faster than the communication time in the system. The communication time is the time it takes for a transient event to "communicate" its existence to the boundaries of the piping system through pressure waves[1]. Mathematically, it can be expressed as:

$$\Delta t = 2\frac{L}{a} \qquad (1)$$

where L is the length of the piping system under consideration and a is the speed of sound within the pipeline's working fluid.

When an event occurs in less time than the communication time, its effect is said to be instantaneous for the piping system under consideration.

In the LNG pipeline the interruption of flow can cause waterhammer both upstream and downstream of the flow blockage. Upstream of the blockage the fluid's momentum still carries it towards the blockage, resulting in increased pressures. Downstream of the blockage the fluid's momentum still carries it away from the blockage, resulting in decreased pressures. If the pressure downstream of the blockage falls below the vapor pressure of the fluid, liquid column separation occurs, and a vapor pocket is formed; when this pocket collapses the system experiences pressure spikes. This is the primary mode of waterhammer initiation considered in this paper.

Typical LNG unloading facilities consist of a jetty where a barge is connected, a pipeline to the storage tank and the storage tanks. The pipelines between the barge and the storage tanks are typically several kilometers long, which, with a speed of sound of ~1400 m/s in the LNG, leads to a communication time on the order of 4 to 10 seconds. Communication times in long LNG pipelines can be several orders of magnitude longer than this. For this reason, almost all of the transient events described above that occur in the pipelines can cause rates of change in the system pressures which occur faster than the communication time in the system. Therefore, it becomes necessary to mathematically model the transient pressures in these systems to determine if waterhammer will occur.

The typical method for solving for the transient pressures in piping systems is to use the method of characteristics. This method uses conservation of mass and momentum along a characteristic line (between two solution points on the pipe under consideration) to determine the system mass flow rates and pressures. In this method the lowest pressure that may be reached is the fluid vapor pressure. If the fluid vapor pressure is reached, then the solution procedure determines the amount of fluid that becomes vapor to satisfy equilibrium in the system. For the purposes of the analyses presented within this paper the Discrete Vapor Cavity Model (DVCM) was used to model the onset of pocket formation and the volume of the pocket that was formed.

Solution of the equations involves explicit integration, where the variables involved in the mass and momentum equations are time-integrated based on their previously solved values and their rates of change calculated at the previous time-step[2]. Because this method is based only on the results of the previous time-step and does not involve satisfaction of an equilibrium condition, as an implicit method does, it is possible for solution variables at a given calculation point (node) to reach very high values for a given time-step[3]. While the value of a solution variable at a given node may reach an unreasonable value at a single time-step, the solution variable will tend to reflect the true solution when the integration is performed for the complete event. For this reason, it is necessary to perform filtering on the raw data produced by the explicit integration to determine the true variable maximums for use in the design method.

EXPLICIT METHOD FILTERING METHODS

Explicit methods were first employed for the solution of complex problems in the early 1970's using finite element techniques for military applications. These applications typically involved ballistic impacts, where material and contact nonlinearities made satisfaction of equilibrium conditions, as required by implicit methods, impractical[4]. During the late 1970's, as computing resources became more available, NOAA determined that explicit analysis techniques as applied to climate models provided for a more robust solution methodology[5]. Safety regulations implemented in the 1980's forced auto makers to implement analysis techniques to predict the accelerations and cabin penetrations resulting from vehicle impacts. Due to the extreme nonlinearities involved in this type of analysis, explicit techniques were chosen as the most economical method of performing these analyses. In all of the cases above, it became necessary to develop filtering techniques to determine the actual magnitude of solution variables for the basis of engineering decisions. Therefore, great effort has been expended on determining the best filtering methods for given situations.

Because explicit integration produces a signal at discrete time points, the output from an analysis can be seen as a digital signal. Therefore, filtering the signal requires the use of digital rather than analog filtering techniques. In almost all cases where data from explicit analyses is being filtered, a low-pass filter will be employed. A low-pass filter allows for the lower frequency signal to be passed through the filter, while the higher frequency signals are attenuated. The level of attenuation is dependent on the order of the filter, with the attenuation increasing by 6 dB per decade for each integer increase in the filter's order.

Typical examples of low pass filters include the Butterworth, Chebyshev and Elliptical filters. The Butterworth filter is ideal as it displays no ripples in the passband (the frequencies that are allowed to go through the filter unchanged), but it does roll off slower at the cutoff frequency than other filters. The Chebyshev and Elliptical filters roll off faster at the cutoff frequency, thus reducing the amount of high frequency noise allowed through the filter, but they also display ripples in the passband. These ripples in the passband frequency affect the signal's results in the frequency range of interest. The plots below show the typical characteristics of the digital filters under consideration.

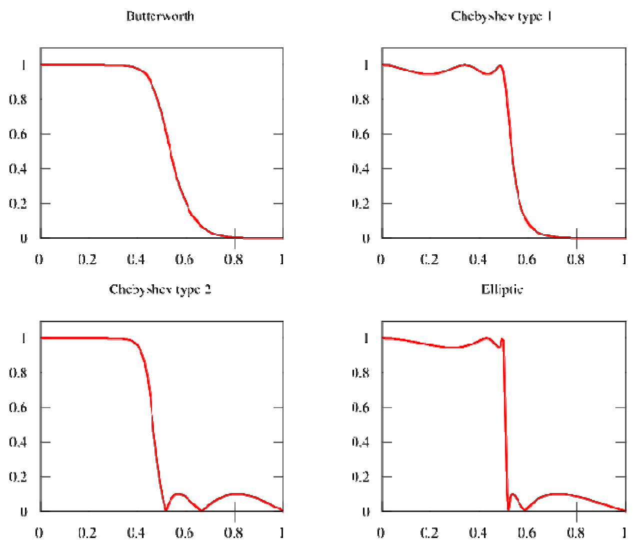

Figure 1 – Sample responses of digital filters[6]

Another method of filtering data to remove high frequency content is the implementation of an averaging filter. This type of filter averages a specified number of points before and after the time point of interest to determine the value at this point. The amount of filtering that this filter provides depends on the number of points selected for the averaging operation. For example, if 1 point is selected, no filtering occurs, if all points are selected the DC signal is returned.

LNG PIPELINE EVALUATION

This paper's analysis example is an LNG offloading facility, which includes the barge storage tanks, the pumps, the jetty lines, all of the valves in the pipeline, the pipeline to the tank and the tank. The pipeline under consideration consisted primarily of 6", 8", 16" and 36" lines. The model terminated at the top of two LNG tanks. There is a filling nozzle at this location that allows for 2-phase flow to occur while the LNG enters the storage tank. The gas bleed off from the main stream prevents cavitation. Two-phase flow can be expected at this location because the fluid stream pressure entering the tank is very near to the vaporization pressure of the LNG and the tanks are filled from the top. Therefore, the pressure at the elbow above the tank will be below the vapor pressure of the fluid. The filling nozzle is able to bleed off the flashing LNG and allow the main stream to enter the tank without entraining a large vapor volume. As the nozzle technology was proprietary, and it was known to function acceptably in other installations without introducing pressure pulses into the upstream system, it was not included in the model. Additionally, due to the limitations of the theory applied with the DVCM vapor model, 2-phase flow cannot be considered – the flow either exists as a fluid or as a vapor, as previously described. Therefore, including the nozzle dynamics in the simulation would have required a much more complicated model.

To analyze the offloading facility, a model was constructed using Applied Flow Technologies' (AFT) Impulse 3.0. This model is shown in Figure 2, below.

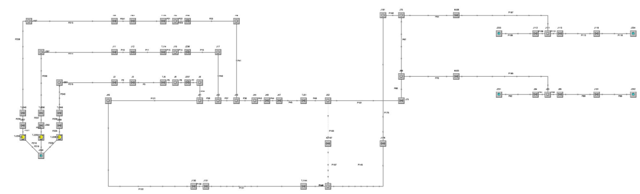

Figure 2 – LNG pipeline layout used for analyses

The pipeline lengths and intermediate elevations were defined based on P&ID drawings of the facility, with valves and pumps located at their correct locations. The input to the model was a tank containing LNG at the barge location, the fluid level in the tank was defined to provide the minimum NPSH required for pump operation without cavitation. This boundary was reasonable, as the barge has sensors to shut down the primary pumps and change to secondary drainage pumps before cavitation occurs. The system outlet was defined as a tank at 0.1 psia above the vapor pressure of the fluid (normal tank operation). The choice of these minimums ensured that the system was as close to a waterhammer event as possible before initiating any of the pipeline transients that were considered.

Four cases were considered for the analyses, two involving pump trips with several Emergency Shut Down (ESD) valves closing and two involving closing the primary filling valve to the tank, so that only one tank was filling instead of two.

The pumps were modeled using a Four Quadrant Trip with Inertia as derived by Wiley, et. al[7]. The inertial value of the pump was selected through an iterative procedure so that the pump reached zero speed within three seconds after tripping, a typical value for pumps in this application. The pump curve was created using information supplied by the pump manufacturer and can be seen in Figure 3, below.

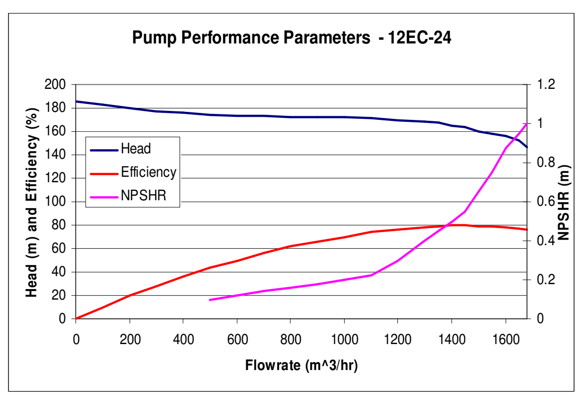

Figure 3 – Pump curve used for analyses

Using the pump curve information and the system layout specified in the P&IDs, the nominal steady-state system flow rate in the mathematical model was determined to be 12,300 m^3/hr, which agreed well with the nominal system design flow rate of 12,000 m^3/hr.

The valve C_v values were estimated based on percent closure and the closure times specified for the valve[8]. Figure 4 shows the valve C_v values versus time for the valves used in the analyses.

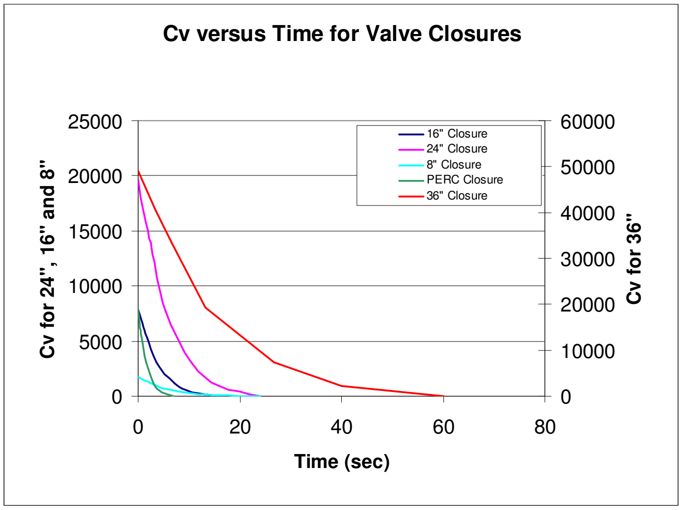

Figure 4 – Valve Cv values used for analyes

The working fluid was LNG, with the following material properties used for the analyses:

Material Property	Value	Units
ρ	425.53	kg/m^3
ν	0.00011	Pa-sec
B	0.816	GN/m^2
E	195100	MPa

Table 1 – LNG fluid properties used for analysis

The analyses were conducted as transient analyses for a period of 70 seconds (10 seconds after the last valve closure occurred in any case). The time-history pressure from the analysis was saved at several locations (nodes) along each pipe.

RESULTS

Results are presented for a pump trip case where the pump trips, initiating the closing of the ESD valves on the ship and four other ESD valves located on the 36" and 24" lines in the pipeline. For the purposes of these analyses, the pipes of interest were the 36", 24" and 8" pipes, as these comprised the majority of the pipeline.

The unfiltered, maximum pressure results in each of these lines are presented below.

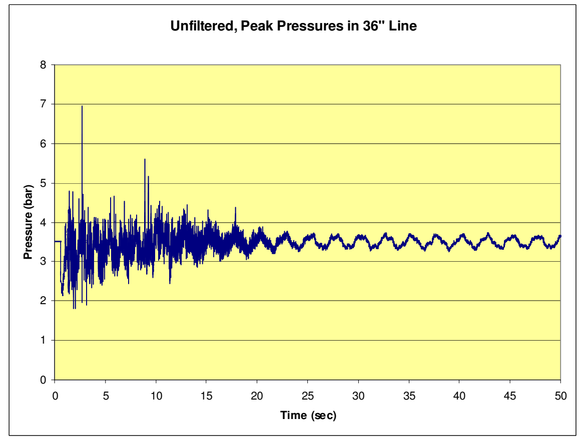

Figure 5 – Unfiltered, peak pressure results in 36" line

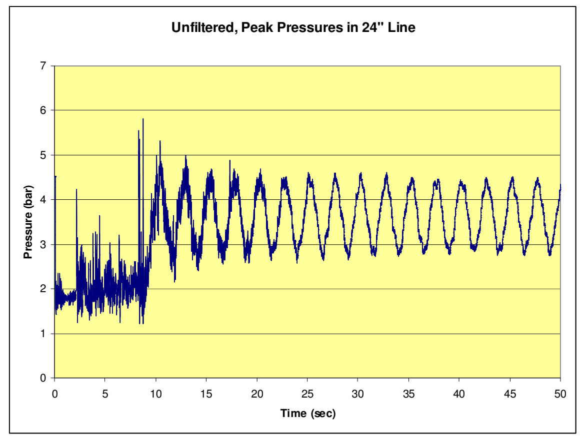

Figure 6 – Unfiltered, peak pressure results in 24" line

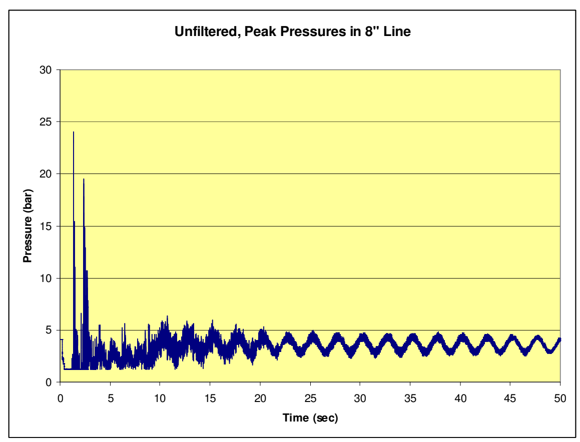

Figure 7 – Unfiltered, peak pressures in 8" line

It can be seen from the pressure traces presented above that the maximum system pressures all occur before any of the valves become fully closed. For this reason it can be stated that the initiator for the waterhammer event was the pump trip and 3-second spin-down rather than the valve closures associated with the event. The results also demonstrate that there are very high frequency spikes in the solution data associated with the waterhammer event. Also apparent is noise in the transient pressures that occurs due to the explicit integration that was employed during the analysis. Proper consideration of the significant pressure magnitudes in the pipeline requires filtering of this data to remove the transients caused by the solution methodology, while still maintaining the peak pressure values that the pipeline can realistically be expected to experience. The pipes' most significant response will occur when pressure pulses occur at or near the fundamental frequency of the pipes or of the pipeline, while the pipes' response to very high frequency pulses will be negligible. Therefore, to determine the pulses of interest for the stress design of the piping system it was necessary to remove the high frequency pulses from the solution data.

Several filters were developed by the authors within MATLAB and Microsoft Excel and then applied to the data produced by the Method of Characteristics analysis to determine the best filtering technique for removing the unwanted noise and maintaining the fidelity of the low pass signal. The filters included the Butterworth, with and without additional averaging the Chebyshev and the time averaging filters. To determine the cutoff frequency for the filters, it was necessary to know the frequencies of interest in the piping system.

To determine the frequencies of interest, finite element models were constructed of representative pipe sections for all three sizes of pipe under consideration. The models were constructed using shell elements with the thickness defined based on the pipes specified for the pipeline. These models were then analyzed using a free-body modal analysis within Algor to determine the first "breathing" mode of the pipes. This frequency will be the most significant frequency in the stress design of the pipeline, as the first bending frequency of the pipeline should be much lower. The image below shows a representative displaced shape for the first breathing mode in the pipe for the 24" pipe model; Table 2 shows the frequencies calculated for each pipe size.

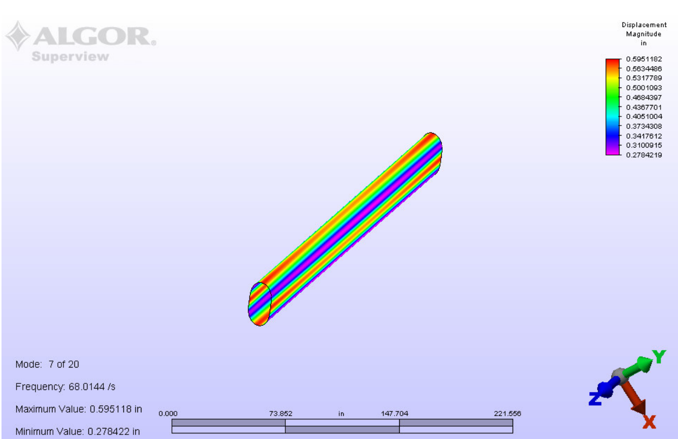

Figure 8 – Displaced shape for first breathing mode, 24" pipe

Pipe Size (in)	***First Natural Frequency (Hz)***
8	261.288
24	68.0144
36	29.5807

Table 2 – Fundamental breating modes for pipe sizes under consideration

The fundamental frequencies shown in Table 2 were used to determine the cutoff frequencies when the filters were applied to the data. Because the digital filters display 3 dB of attenuation at the cutoff frequency, the cutoff frequency for the filters was increased from the pipe fundamental frequency so that there was zero attenuation at the fundamental frequency. The following figure shows the pressure results in the 24" pipe when a first-order Butterworth filter, with a cutoff frequency of 85 Hz (zero attenuation at 68 Hz) is applied.

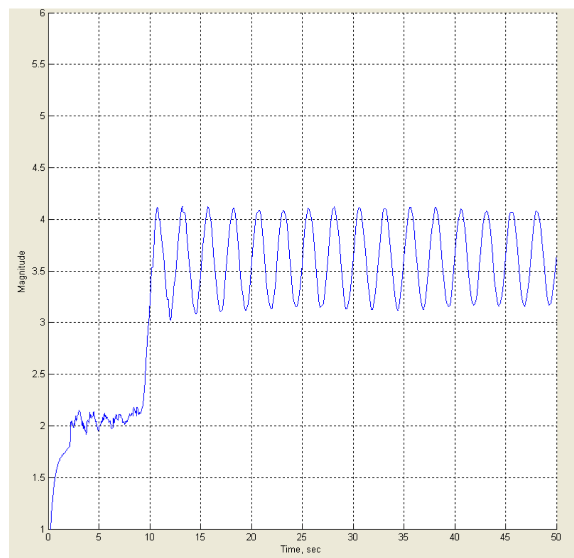

Figure 9 – Peak pressures in 24" pipe when filtered with Butterworth filter

As can be seen from the image above, the application of the filter has removed the high frequency noise from the solution. It can also be seen from the figure that the peaks that occurred prior to 10 seconds have been completely removed from the data, possibly resulting in a non-conservative peak pressure value. For this reason, additional filters were explored to ensure that the true peak pressure value was captured from the analysis.

The next filter that was explored was the time averaging filter. To implement this filter, the breathing mode was used to determine a time frame for averaging the data. This time was then divided by the time-step from the analysis, 0.00221 seconds, to determine the number of time-steps that were averaged to produce a data point. The figure below shows the averaged data from the 24" pipe.

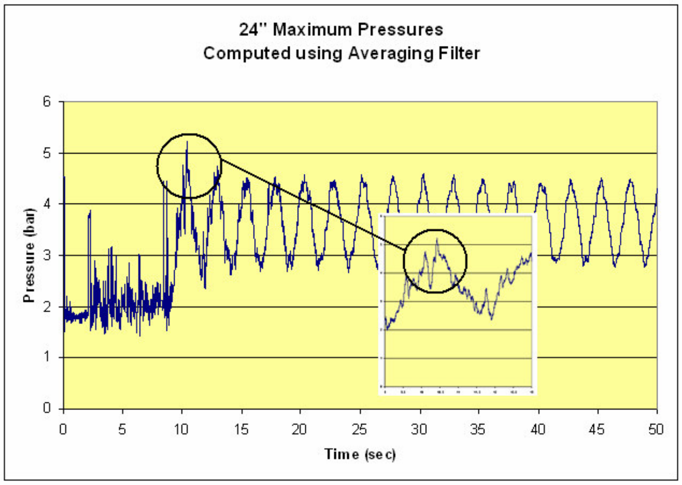

Figure 10 – Peak pressures in 24" pipe using time-averaging filter

As can be seen from the figure above, the use of a time averaging filter maintains the peaks in the first 10 seconds of data, but significantly reduces their magnitudes. The transient pressure reflections in the piping system are not smoothed as much with the application of this filter as they were when the Butterworth filter was applied. This is because the time averaging filter does not remove data based solely on its frequency content. As can be seen in the close-up in the preceding figure, the use of a time averaging filter allows some of the high frequency solution noise through. The results circled in the figure show an area where the noise was allowed through the filter, resulting in an over prediction of the peak pressure result.

CONCLUSIONS

Transient analyses were performed on an LNG offloading pipeline to determine the peak pressures expected in the pipeline due to waterhammer events. Due to the nature of the explicit integration methods required for solution, the values tracked for the pipeline contained high frequency noise. To determine the actual values of the variables that were tracked, it was necessary to filter the data.

Several digital signal filters were tested on the data to determine their performance. In all cases, the first breathing mode of the pipes was used to determine the cutoff frequency of the filters. A time averaging filter technique was also applied to the data. The filtered results showed a significant difference in the peak pressure results obtained through the use of the different filters. In all cases the pressures at the frequencies of interest were significantly reduced from the peak pressure results obtained during the analysis. This demonstrates that when specific filter types are not specified for the application, that multiple filters should be evaluated for their suitability in the application.

As previously mentioned, the results presented in this paper are for a cavitation event that can be modeled using the DVCM. Because LNG system operating pressures can be very close to the vapor pressure of the fluid it is possible for persistent cavitation, instead of temporary cavitation, to occur within the system. This would preclude the use of the DVCM. A review of the unfiltered, system-wide operating pressures during the entire transient solution should be conducted to ensure that pressures below the vapor pressure do not exist. If pressures below the vapor pressure of the system do exist the DVCM model is not appropriate, and a more rigorous 2-phase flow analysis is required.

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