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DISCUSSION OF ISSUES RELATED TO SURGE IN LNG PIPELINES AT OFFLOADING TERMINALS

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ABSTRACT

Due to requirements of LNG unloading terminals, the pipelines used to transport the liquid operate near the vapor pressure of the LNG. If the operational pressure in the pipeline falls below the vapor pressure, pockets of gas will develop; when these pockets collapse, very high pressure pulses can be transmitted through the pipeline, an event known as surge or waterhammer. This paper discusses transients that occur during normal and upset plant operation and how these transients can induce surge in the pipeline. The paper concludes with an overview of the methods used to evaluate whether surge will occur and the peak pressure associated with surge events, with an overview of cases that are typical candidates for analysis.

INTRODUCTION

A liquid natural gas (LNG) offloading terminal typically consists of a jetty where the ship is unloaded, a piping system to carry the LNG to the storage tanks and a separate piping system to carry the LNG to the vaporizers for distribution. Typically there will be several unloading arms from the ship that are routed to a main manifold for distribution to the storage tanks. Distribution can occur through a single main line or through a series of parallel lines. These lines are then typically routed back into a header for distribution to the tanks.

During operation of the facility, transient events can cause the local system pressure to fall below the vapor pressure of the LNG. When this occurs, a vapor pocket is formed and subsequently collapses, causing a significant pressure pulse to be introduced into the system, a phenomena known as waterhammer or surge. Additionally, the rapid closure of valves, which can cause sudden change in the fluid's momentum, can introduce compression waves on the upstream side of the valve.

Due to the possibility of system transients causing large pressure pulses in the system, prudent design should rely on qualifying the transients that are likely to create these pulses. This analysis should include a review of all of the system's components and how these components will interact with each other during operation.

DESCRIPTION OF WATERHAMMER / SURGE

Waterhammer within piping systems can occur for several reasons. For the LNG pipelines 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[i]. Mathematically, it can be expressed as:

$$\Delta t = 2\frac{L}{a}$$

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 [1].

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.

OVERVIEW OF SYSTEM COMPONENTS

Along the piping system there are a number of different types of valves, including: powered emergency release couplers (PERC), emergency shutdown valves (ESD), venting valves and valves to route the LNG to various areas of the plant.

The PERC valves are located at the interface between the ship and the jetty. Their purpose is to close very quickly if the ship detaches from the jetty due to rogue waves, loss of mooring, etc., so that there is a minimal leakage of LNG, minimizing the safety risk. ESD valves are located along the pipeline and are responsible for isolating areas of the facility during upset conditions. These valves are designed to operate quickly to minimize any damage, but they do not operate as quickly as the PERC valves, as they are not responsible for inhibiting the release of LNG. Venting valves are designed to vent LNG that vaporizes during transport to the tanks. Depending on the operation of the plant, the valves can act quickly and introduce pressure pulses into the system. Routing valves typically are much slower acting than the other valves, but they can be responsible for changing the flow characteristics in the plant's lines significantly when operating on larger terminal lines.

The terminal's pumps are located on the offloading ship. These pumps are typically submerged, impeller-based pumps. The pumps are very specialized and have unique performance characteristics, including a very quick spin-down time after tripping and the ability to operate a very low NPSH. [WHAT'S NPSH?]

The storage tanks are typically top fed and operate near the vapor pressure of the LNG, 3.5 psig. Because of this, some of the system lines also operate near the vapor pressure of the LNG. The tanks are typically fed through a proprietary interface that allows some of the LNG to flash while entering the tank without reflecting pulses to the rest of the system.

CONSIDERATIONS RELATED TO SURGE

Valve actuation is one of the primary causes of surge events. Rapid valve closures can introduce surge into the lines through two methods:

- On the upstream side of the valve a compression wave will be created due to the change in momentum of the fluid. This wave will then travel back to the pumping source.

- On the downstream side of the valve the momentum of the fluid will carry it away from a now fixed wall. This will result in a rapid pressure decrease near the valve that can lead to the formation of a vapor pocket.

Because of their quick acting nature, the effect of PERC valve actuation should always be considered. When the valve actuates, the momentum of the LNG being pumped continues to move it away from the valve, causing a pressure drop and formation of a vapor pocket. Additionally, PERC actuation usually forces actuation of several ESD valves which can lead to vapor pockets being formed in several locations within the facility. Actuation of the main flow control valves can cause distinct pressure changes in lines as the mass flow rate is either increased or decreased significantly. For these reasons, the logic behind valve actuation should be considered and several cases should be developed to determine the maximum line pressures that can occur during valve actuation events.

There is an almost certain probability that during the life of the terminal, a pump will trip during the unloading process. Due to the rapid spin down of the pump there will be a rapid pressure loss at the jetty. The pressure at the head of the pump can drop to almost the vapor pressure of the LNG (due to the pumps' low NPSH and their ability to almost completely drain the tank. This will result in the formation and collapse of a vapor pocket.

Elevation changes through the piping run must also be considered as they will cause pressure changes due to the change in fluid head. During transient events the changes in pressure due to varying flow rate as well as differential head can cause the local pressure to fall below the vapor pressure of the fluid leading to the formation of a vapor pocket.

ANALYZING THE SYSTEM

The most accepted method to analyze piping systems for waterhammer events is to use a computer modeling package that is specifically developed to analyze these events. These packages typically involve the use of the method of characteristics and explicit integration to solve for the time-history of the pressure within the pipeline. The packages typically can only model single phase flow, with a mathematical model used to determine the size of the vapor pocket formed when the local pressure reaches the vapor pressure of the fluid [2].

Typically these packages have a variety of element types that can be added to the model including:

- Pipes, with the ability to specify intermediate elevations, friction models and losses due to elbows and tees
- Reservoirs
- Pumps, with several pump models
- Junctions
- Valves, including check valves with specified actuation times, relief valves and vacuum breaker valves
- Gas accumulators

- Surge tanks

For each of the model components listed above, several parameters should be specified with the best information available during the design phase.

For pipes, the length, outer diameter, inner diameter and material must be specified. Additionally, elevation changes should be specified, especially rapid elevation changes. A friction factor should be specified as it will affect the wave's propagation. Steps should be taken to account for minor system losses, either through specifying the factors in the pipe input data or through specifying junctions at elbow and tee locations.

Reservoirs only require the specification of the liquid level at the initiation of the analysis and the reservoir dimensions so that the transient change in head can be calculated during the analysis.

Pumps should be specified with as much information as posible. At the least, a pump curve must be specified. Additional information that can be supplied includes pump inertia and whether backflow can occur through the pump. The figure below shows a typical pump curve for an onboard pump. This data is typically available from the pump manufacturer.

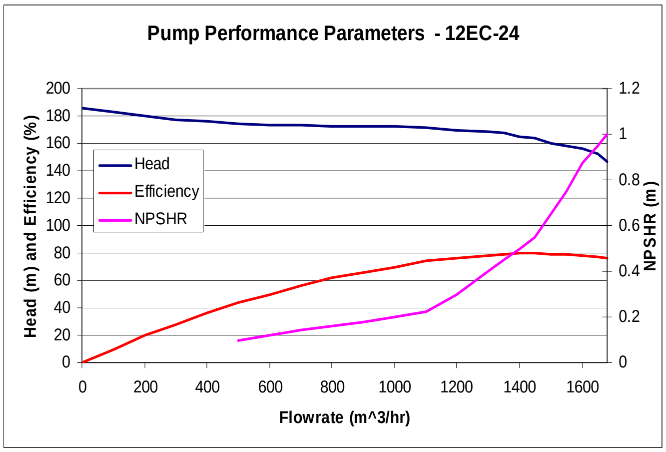

Figure 1 – Typical pump curve for shipboard pump

Determination of the pump inertia characteristics requires detailed information about the inertia of the pump's impeller and motor, and the fluid displacement that is contained within the pump at a given time. There are several inertial models that can be used with standard pump models, including: trip with no backflow, no reverse, trip with backflow, trip with no inertia, and trip with inertia [3].

Valve data that needs to be specified includes the C_v vs. time. It should be noted that this information can usually only be estimated during the design phase, as controls implemented on the system can affect closure times significantly. Therefore it becomes important to conduct sensitivity analyses on the pump closure times to ensure that a slightly different closure time will not significantly affect the results from the surge analysis. The figure below shows typical Cv vs. time plots for valves located in an offloading terminal.

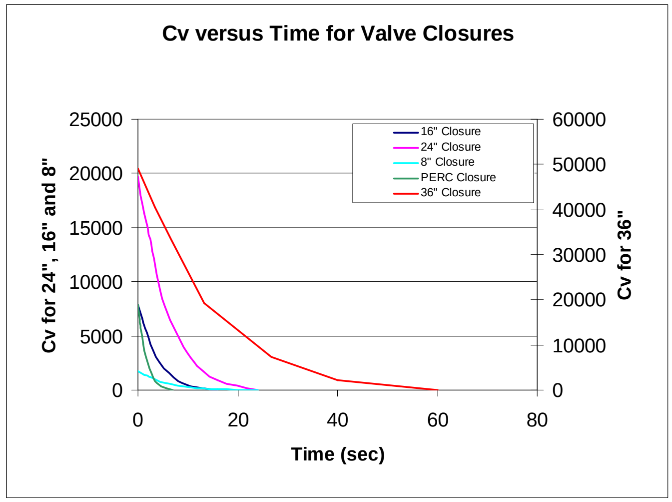

Figure 2 – Typical Cv vs. time curves for valve closures

Using the components outlined above, a model can be developed incorporating the major features of an LNG terminal. It should be noted that with standard surge analysis software the tank filling interface cannot be modeled due to the existence of two phase flow at this location. It is normal practice to terminate the model at this location with a pressure boundary at the tank's operating pressure, typically 3.5 psig.

Once the model has been developed, it must be sectioned for solution. The process of sectioning the model involves dividing the pipe lines into discrete points where each characteristic line can be determined and used to advance the solution. The process of sectioning the model requires some level of forethought. When more sections are used, the results achieved during the analysis will be more accurate but at the added expense of greater computational time and resources. The greater resources are required for two reasons; first there are model nodes within the model that increases the computational cost linearly. The second reason is that the maximum stable time step for an explicit solver is based on the time for the wave under consideration to travel through the smallest section of the model,-. If the model is sectioned finer this time decreases, resulting in the need for a greater number of time steps. For these two reasons the relationship between the computational resources required is approximately inversely proportional to how fine the model is sectioned.

Once the mathematical model of the system has been developed the analyst should determine which cases should be considered. As previously mentioned, the actuation of the PERC valves as well as pump trips during normal operation should be considered, as these are events that can quickly cause large changes in the system's pressures and flow rates. Also, additional trips that could occur within the terminal (including the actuation of the ESD valves) should be considered, as these are another source of rapid flow variance within the system. It is also good practice to study the effects of the closure of large valves within the system, as these will cause large changes in the flow rates through various areas of the terminal. It is typical for 4-8 cases to be analyzed to capture the relevant effects of component's operation within the terminal.

While the PERC valve actuation and pump trips are the most likely candidates for causing high pressure surge events within the system, it is best practice to begin modeling with slow acting events to allow for debugging of any model components that are not functioning correctly. Typically, debugging tools are also provided within the software to allow validation of the model inputs such as pump spin-downs and valve actuations. A review of the pressure results from a steady-state analysis performed on the system will provide verification that the intermediate elevations are defined correctly along the pipes.

MODEL OUTPUT

The use of explicit integration to solve the time-dependent equations can result in solution noise. This is due to the fact that explicit integration only relies on the solution at the node at the previous time-step. This results in no need to meet an equilibrium condition as would be required with implicit integration methods. Therefore, if the rate of change at a node point is very great at one period of time the solution will spike for one time-step [4].

Due to this ability to have very large solution values occurring at high frequency, it becomes necessary to filter the solution data to obtain the results of significance. The use of filtering techniques is well accepted for results produced by explicit integration. The techniques were first developed in the early 1970s by the military for studying the results of ballistic impacts. Later in the 1970s NOAA discovered that filtered results from explicit analyses provided the best correlation between their weather models and the actual weather [5]. Today many industries use explicit integration to solve problems of interest. This has resulted in a great deal of research being published on the operation of specific filters.

For LNG terminals, the filtering is commonly performed using standard low pass filtering techniques to filter out the high frequency content data. This is due to the fact that the pressure waves that are of interest in a piping system are typically the pipe breathing modes. These are typically at frequencies that are several orders of magnitude less than the frequency at which the explicit analysis is performed, 50,000 – 100,000 Hz. 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 image below shows the performance characteristics of common filters.

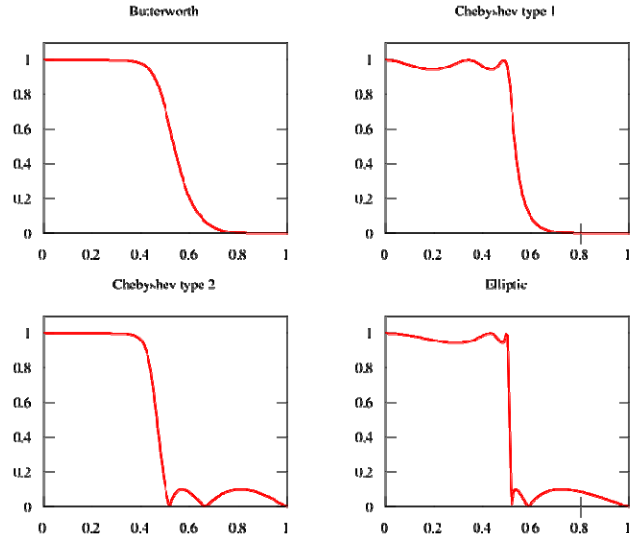

Figure 3 – Typical examples of filter performance for common filters [6]

Below are examples of raw data from a surge analysis, and the data that was filtered to find the information in the frequency range of interest, the fundamental breathing mode of the pipe. This filtering was performed using a Butterworth filter which was developed in Matlab. The cut-off frequency was defined so that the roll off at the frequency of interest was zero.

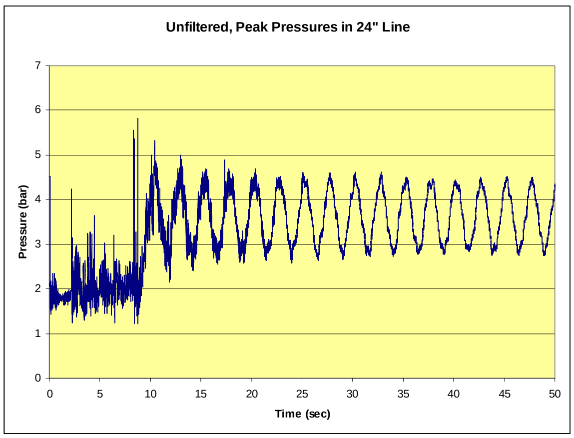

Figure 4 – Unfiltered pressure results from surge analysis

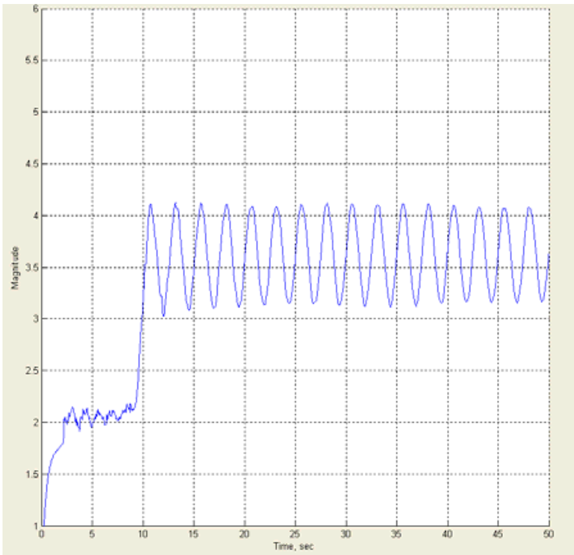

Figure 5 – Filtered pressure results from surge analysis, butterworth filter

As can be seen from the figures above, the filtered results significantly reduce the amount of noise in the solution data, resulting in smooth waveforms being evidenced in the pipe. It should be noted that several of the available filters should be applied to the data to ensure that no pressure spikes or frequencies of interest have been suppressed by the initial filtering technique applied to the results.

This data can then be used to compare to the maximum line pressure for which the piping system was designed. The system pressures can also be assumed to be completely reversing, allowing for the forces at elbows to be calculated and used in support design.

CONCLUSION

It has been shown that a mathematical model can be developed of an LNG offloading terminal to study the effects of waterhammer/surge events occurring in the terminal's pipes. This analysis is typically performed using a commercial software package that uses the method of characteristics combined with explicit integration to predict the transient behavior of the system.

To perform these analyses a model is developed that includes the major system components at the terminal. These components include, but are not limited to, the offloading pumps, the PERC valves, the ESD valves, major system valves, the piping network and the offloading tanks. Additionally, as much information about the intermediate elevations along the piping network should be included so that variations in head along the pipeline can be properly accounted for.

It is critical that as much information as available be input into the model. This includes the pump characteristics such as pump curve, spin down time and pump inertia. The valves should also be specified as well as possible. Due to the ability of the valve's actuation characteristics to be modified through control systems, sensitivity studies should be performed to ensure that slight changes in the valve's closing performance will not significantly affect the pressure results predicted from the analysis.

The model will then be sectioned prior to the analysis. Sectioning involves dividing the model into individual nodal points where the characteristic equations can be solved. Sectioning the model is an involved process, as more sections provide for a higher quality solution at added computational expense. Once the model has been sectioned it should be run as a steady-state model to ensure that the intermediate elevations defined on the pumping runs were defined correctly. Also tools provided within the software should be used to verify the operation of the transient phenomena defined in the model.

The analyst must choose cases that will be considered. Typically a PERC trip as well as a pump trip should always be considered as these events are the most likely to introduce large surge pressures into the system. The interaction of other systems components needs to be considered and several more cases should be developed to ensure that there are no spurious interactions within the system.

Once the analysis has been performed, the output data will have a degree of noise associated with it. The analyst will need to determine the frequency range of interest for the system, typically the first breathing mode of the pipe, and apply a low-pass filter at that frequency. There are several filter types available and several of the filters should be applied to the output data to ensure that the pulses of interest have been sufficiently captured. Once the data has been extracted to produce data that is useful in an engineering environment, it can be used to compare to the peak system design pressure and to determine the maximum forces that are expected for the system supports.

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