Jun 17th, 12:00 AM - Jun 20th, 12:00 AM

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ABSTRACT: Tube-rupture events in shell and tube heat exchangers can result in significantly high surge pressures. Steady state and dynamic methods can be used to assess the impacts of these events on heat exchanger system piping networks. This paper presents the findings of a set of dynamic surge simulations on the impacts of tube-rupture events in a Propane-Feed Gas Heat Exchanger System. Once adjacent piping design is considered, the Joukowsky formulation-based method is not always appropriate to estimate tube-rupture surge impacts. Dynamic simulations need to be conducted to assess the tube-rupture impact on piping systems due to the surge wave amplification as it is transmitted and reflected in the complex pipe network. For blocked-in (no-flow) or isolated systems, properly designed relief mechanisms are required to alleviate the tube-rupture resultant pressure build-up.

Keywords: hydraulic transient, surge, tube-rupture, heat exchanger.

INTRODUCTION

It is not uncommon for the design of shell-tube type heat exchangers to involve high-pressure differentials between the shell and tube sides. Driven by sufficiently high-pressure differences, a tube-rupture event would generate fluid flow from the high-pressure side to the low-pressure side, significantly increasing the pressure sometimes beyond its design pressure. The pressure pulse generated by the tube-rupture will then propagate to the system at wave speeds close to sonic speed. Depending on the system configuration, transmitted and reflected surge pressures could be considerably higher than the initial rupture pressure pulse.

Design considerations vary with the location and proximity of the pressure relieving system. If the relief device is located on the heat-exchanger shell, assuming an instantaneous response, the pressure pulse is not likely to propagate to adjacent piping. If the relieving system is located some distance away from the heat exchanger shell, the pressure pulse travels into the piping network and exposes different equipment and piping to high surge pressures.

A common method used to estimate surge pressures due to a tube-rupture event is based on the Joukowsky equation [Eq. (1)] (WYLIE & STREETER 1993)

$$\Delta H = \frac{a}{g}\Delta V \tag{1}$$

where ΔH is the change in head in [m], a is the pressure wave speed in [m/s], ΔV is the change in velocity in the low pressure fluid due to the high-pressure fluid discharge in [m/s], and g is the gravitational acceleration in [m/s^2]. The initial pressure pulse of the tube-rupture is determined by solving the Joukowsky equation and determining the mass flow rate of the incoming high-pressure fluid taking into account the changes in its properties due to interaction with low-pressure fluid.

Eq. (1), also known as the basic water hammer equation, holds in the absence of pressure wave reflections. This key concept makes the use of this equation alone inappropriate for the design of heat exchanger piping systems where surge waves can magnify as they propagate. This is particularly applicable for piping networks involving piping dead ends, reducers, enlargers, and throttled valves. WYLIE & STREETER (1993) note that pressure waves double at piping dead ends due to reflections (WYLIE & STREETER 1993). PARMAKIAN (1963) provides a simplistic approach for estimating reflection and transmission coefficients at junctions in piping systems indicating that the pressure wave can be magnified as it propagates due to pipe cross-sectional flow area changes (PARMAKIAN 1963). The coefficients of transmission and reflection of a surge wave are a function of the ratios of pipe cross-sectional areas to wave speeds at the junction. A reducer would amplify the surge wave upstream, while an enlarger would dampen it. While this approach gives some guidance on the magnitude of pressure waves in the system, it would not address the complexity of the hydraulic response of the system in the event of a tube-rupture.

Recent changes in codes and standards provide limited guidance on how to address pipe network designs for tube-rupture events. The American Petroleum Institute (API) Standard 521 (2007) recommends that dynamic simulations be performed to analyze tube-rupture events when the pressure differential in the heat exchanger is in excess of 70 barg (API 2007).

A one-dimensional liquid-phase model was established to conduct a hydraulic transient analysis to assess the hydraulic response of a piping network to a tube-rupture event in its shell-tube type Propane-Feed Gas heat exchanger where the pressure differential exceeded 70 barg.

Simulation results were used to evaluate the need for surge mitigation. The findings of the analysis were used to provide guidance for designers on tube-rupture mitigation measures.

PROPANE-FEED GAS SYSTEM AND MODEL DESCRIPTIONS

System Description

The heat exchanger in which the tube-rupture was postulated to occur is one of two identical heat exchangers located downstream of a propane source vessel (Figure 1). Liquid flowing out of these heat exchangers is routed to downstream kettle-type heat exchangers and other equipment. Propane discharges into these components via letdown valves. Pipe branches with closed valves create dead ends to the system. Fast closure valves located on both sides of the heat exchangers create isolation points. Two small pressure relief valves are located near the outlets of the heat exchangers for fire protection purposes.

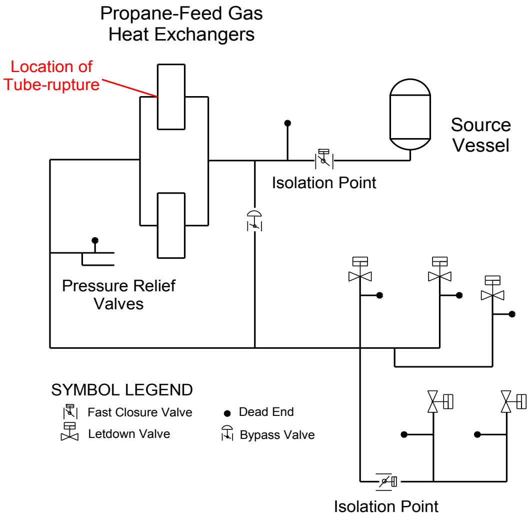

Figure 1 – System Schematic Drawing

Tube-side feed gas is heated by shell-side propane as it goes through the heat exchanger under consideration. The tube-side maximum operating pressure is approximately seven times that of the shell-side. Calculated liquid propane wave speeds for this system vary between 590 m/s and 630 m/s with pipe size and liquid temperature changes.

Methodology and Model Description

An in-house hydraulic transient simulator was used to conduct the analysis. Like many other software of its kind, this simulator is based on the method of characteristics that is used to solve hydraulic surge propagation in piping networks. The model extent was determined based on known boundary conditions. Two operational configurations were considered for the purposes of the analysis: (1) normal operating conditions at design volumetric flow rate and normal system operating pressure, and (2) isolated system conditions with no flow in the lines and where the pair of heat exchangers is completely isolated. Under normal operating conditions, the liquid level in the upstream vessel is maintained at normal level. Propane flow into the downstream kettle-type heat exchangers flashes through the letdown valves. This creates a pressure break in the continuity of the liquid flow stream. The downstream boundaries of the transient model were therefore established at these valves as discharging flows at the elevation of the flashed liquid vapor pressure. Under isolated system conditions, letdown valves and fast closure valves downstream and upstream of the Propane-Feed Gas heat exchangers are closed.

The heat exchanger was modeled using an equivalent pipe diameter preserving the hydraulic properties through the heat exchanger such as pressure drop and the representative design flow velocity. The length of the equivalent pipe corresponds to the total baffled flow path length in the heat exchanger. Pressure relief valves were modeled allowing free discharge. Their operation was considered to follow a pressure-liquid flow relationship derived from the valve characteristics and flow capacities using the orifice discharge relation.

Tube-rupture Description and Modeling

In shell-tube heat exchangers, bundled tubes are welded to the backside of the tube sheet. The rupture is described in API Standard 521 (2007) as a sharp break in one tube at the tube sheet. As the tube breaks, the low pressure side is exposed to high pressures from the tube stub remaining in the tube-sheet and the longer end of the broken tube. Sonic flow conditions develop as the high-pressure fluid flows from both ends of the broken tube into the low-pressure side. The development of the initial pressure pulse is best described by solving Joukowsky's equation (1) and determining the mass flow rate of the high-pressure fluid.

Reported tube-rupture time frames in the literature are in the order of milliseconds. SIMPSON (1971) notes that a theoretical tube-rupture time of 0.6 milliseconds provides an excellent fit to his mathematical model results on rupturing mechanisms. Developments of peak pressures within milliseconds are reported in Institute of Petroleum Guidelines (IP 2000).

The tube-rupture was postulated to occur at the heat exchanger outlet for modeling purposes since it is very close to the tube sheet in the internal arrangement of the heat exchanger under consideration. The rupture was modeled by linearly increasing the pressure outside of an orifice type air inlet valve, used as an internal boundary condition, with a fixed coefficient of discharge of 0.7 over 1 millisecond. The cross-sectional area of the air inlet valve was considered twice the broken tube area to account for discharge from both ends. The coefficient of discharge of 0.7 was used with the assumption that both halves of the break behave as square edged orifices. A linear variation of the coefficient of discharge over the rupture time frame is a better representation of the physical phenomena itself. Upon careful consideration, test results for both approaches were insignificantly different.

SIMULATION RESULTS

System Response during Normal Operation

A pressure time-history at the location of the tube-rupture is shown in Figure. 2 for a tube-rupture event at the Feed Gas design pressure. Due to the proprietary nature of some of the information, all reported design pressures and resultant surge pressures are relative to the liquid-side system operating pressure at the source vessel. For a tube-rupture at 0.002 seconds, the initial pressure pulse simulated was found to equal 3.4 barg as shown in Figure 2 at 0.003 seconds. This value is close to the estimate from the Joukowsky based approach. The variation of the pressure surge between 0.003 seconds and 0.06 seconds is due to reflected waves from adjacent piping as they come back to the heat exchanger. The unobstructed ends of the system under normal operating conditions provide sufficient relief to alleviate the tube-rupture pressure build-up as shown in Figure 2 with the decreasing pressures after 0.2 seconds.

The overall system response to the tube-rupture event under normal operating conditions indicated that the initial pressure pulse significantly amplified as it was reflected and transmitted in the pipe network (Figure 3). Maximum pressure envelopes are plotted versus cumulative pipe length starting from the source vessel.

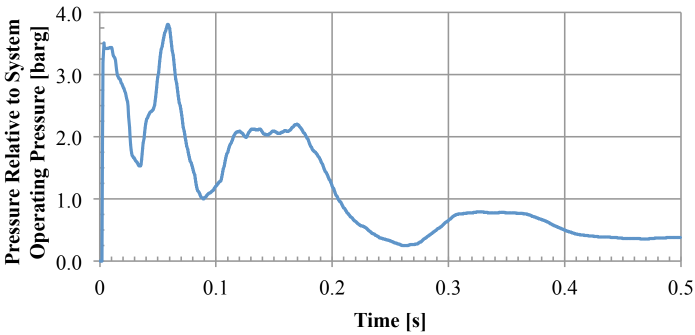

Figure 2 – Tube-rupture Pressure Time-history

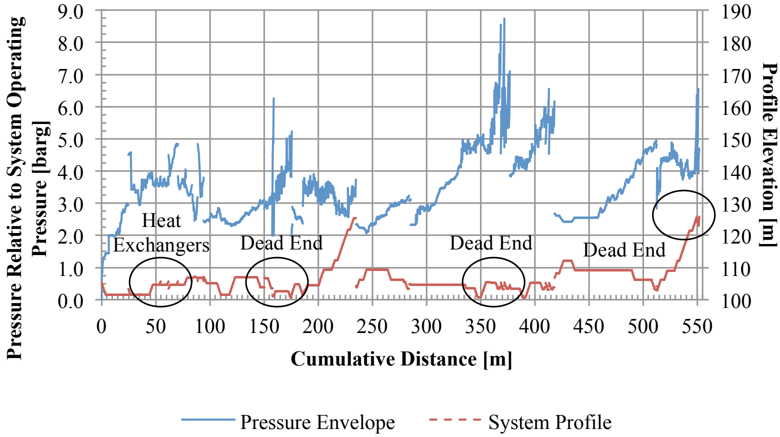

Figure 3 – Normal Operating Conditions Maximum Pressure-Envelope

Simulated pressures were significantly higher than the initial pressure pulse of 3.4 barg. As the surge wave travelled away from the heat exchanger, it was transmitted through several junctions, where it was dampened, and reflected at several dead ends, where it doubled. The maximum surge pressures imposed on the system exceeded by more than two and a half times the initial Joukowsky estimate (Figure 2). The above results highlight the transformation and amplification of the initial tube-rupture pressure pulse as it propagates in the piping network as a result of the superimposition of reflected and transmitted waves.

Isolated System Response

Under isolated system conditions, the absence of a relief point in the isolated portion of the system results in a continuous pressure build-up that equilibrates once the system-wide pressure reaches that of the high-pressure fluid (Figure 4).

In order to mitigate the effects of the tube rupture under isolated conditions, pressure relief is needed to halt the pressure build-up. The response of the analyzed system indicates that the system of small pressure relief valves located near the outlets of the heat exchangers—originally sized for fire protection purposes—does not provide the necessary relief for tube-ruptures. The relief requirements for fire protection are significantly lower than those of tube-rupture.

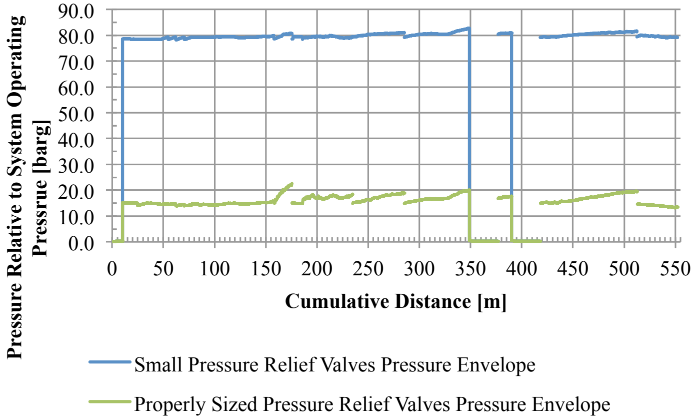

Figure 4 – Isolated Conditions Maximum Pressure-Envelope

Conventional pressure relief valves are spring-loaded devices designed to open at a predetermined pressure and protect a system from excess pressures by relieving liquid, gas, or liquid-gas mixture. When the valve is closed during normal operation, the system pressure acting against its disc is resisted by its spring force. The valve opens as soon as it senses a pressure equal to its set pressure, and it gradually starts relieving pressurized fluid. The opening behavior of the valve depends on its service (liquid vs. gas) and is mainly driven by pressures.

The pressure relief valves were resized to provide the required relief capacity to alleviate the pressure accumulation. The set pressure of the valves was determined to avoid nuisance bursts during normal operation. The relief capacity of the valves was determined from the dynamic simulations for a set pressure 8 barg above the normal system operating pressure. Valves were assumed to be fully open at 110% of their set pressure per API Standard 520 Part I (API 2008). Simulation results indicate that a peak liquid discharge of 1,910 m^3/hr is required to stop the pressure build-up at acceptable levels. Once the total volume of liquid contained between the heat exchanger and the pressure relief valves is exhausted, gas starts flowing out of the relieving devices. The sizing of the pressure relief valves considered both liquid service and gas service peak discharges. For the system analyzed, the sizing was governed by liquid discharge requirements. This finding is in alignment with API Standard 520 Part I, whereby spring-loaded pressure relief valves designed for liquid relief are recommended for two-phase applications where the fluid being relieved may be liquid, gas, or multi-phase mixture.

CONCLUSIONS

The study described in this paper provides guidance on the design of heat exchanger piping systems for tube rupture events. The method based on the Joukowsky formulation provides a good estimate of tube-rupture resultant surge pressures for the design of heat exchanger shells in unobstructed systems, with a fast responding relieving device located on the shell. If the relieving device is located away from the shell, the transmitted surge wave needs to be evaluated for reflections. However, the Joukowsky based pressure estimate does not account for wave reflections and superimposition in the piping network. Hydraulic transient analyses are therefore required to properly design the piping systems for tube-rupture events.

In isolated systems, properly designed and sized, relief mechanisms are required to alleviate the tube-rupture resultant pressure build-up. The sizing and selection of the devices should consider both liquid service and gas service discharge. Relief devices sized for liquid service are recommended for multi-phase application.

ACKNOWLEDGMENTS

The study described in this paper was completed with the much appreciated contributions and guidance of Principal Engineer John O'Sullivan who had an instrumental role in devising the tube-rupture modeling approach.

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