New Developments in Flaring Liquid Natural Gas Without Vaporization of the Waste Stream

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Abstract

This paper will explore best practices and lessons learned during the development, testing, and implementation of a mechanically atomized multi-jet liquid flare for liquified natural gas (LNG). Liquefaction facilities convert natural gas into LNG by cooling it to a liquid state at -259ºF (-162ºC), which can then be safely and economically transported and exported to help satisfy global energy needs. While preparing equipment for maintenance or during emergency process upsets, the facility must safely dispose of waste fluids such as natural gas feedstock, LNG product, and refrigerants used in the liquefaction process. Typically, these facilities are equipped with flare systems designed to efficiently handle only gaseous waste streams, as liquid waste streams can result in a spray of burning chemicals that could reach the ground level and create a safety hazard. However, a customer of Zeeco requested a flaring solution to safely dispose of cryogenic LNG that would meet noise, flame stability, and radiation requirements, as well as emission regulations. Zeeco designed a pressure atomized multi-jet liquid flare system capable of handling large capacity flows. In the fall of 2019, after engineering, modeling, designing, and constructing a flare system, Zeeco engaged in full-scale testing of the system using cryogenic LNG. This paper will share the requirements, design considerations, system and modeling parameters, testing protocols, and testing results.

Introduction

There exist various elevated flare types for handling natural gas such as utility (pipe) flares, steam-assisted flares, air/gas-assisted flares, and many other variations. For gas flares, API 521 suggests liquid percentages, around 1% by mass, and liquid droplet sizes ranging from 600-1000μm depending on the flare design, that can be handled safely and effectively [2]. This poses a problem when process streams are liquid, such as LNG at a liquefaction or regasification facility. In typical gas flaring systems, liquid process streams would first be vaporized or separated using a knockout drum before sending gaseous streams to the flare. This process can introduce additional complexity and cost to the system.

Flaring presents various other compliance challenges, such as achieving the permitted visible emission requirements and satisfying noise and radiation requirements, and facility challenges, such as allocating adequate plot space for the flare system and its sterile area. A sterile area has restricted access due to excessive flame radiation or noise levels. In some instances, the flare height or sterile radius around the flare is determined by noise limits; therefore, reducing the flare noise level can benefit the health of workers and reduce the costs for facilities. Blowers, compressors, air dryers, heaters, flares, and other sources contribute to the occupational noise levels that must be considered to ensure proper personal protective equipment and signage are used when necessary.

OSHA has reported that, "loud noise can create physical and psychological stress, reduce productivity, interfere with communication and concentration, and contribute to workplace accidents and injuries by making it difficult to hear warning signals" [4]. Reducing noise pollution, especially in densely populated areas, helps maintain positive relationships with neighboring businesses and communities, reflecting well on facilities.

Zeeco developed a pressure atomized flare design proven capable of safely handling waste streams while generating less noise pollution than traditional gaseous flaring, leading to immediate facility noise reduction and potential longer-term community benefits. Full-scale testing was successfully demonstrated using LNG at Zeeco's test facility in Broken Arrow, Oklahoma, United States.

Liquid Flare Design Principles

Proper atomization of the liquid stream is critical to the operation of liquid-injected combustion systems. Atomization breaks the liquid stream into small droplets, increasing the surface area of the liquid and, in turn, the rate of combustion. Three common types of atomization are (1) pressure/hydraulic atomization, which uses the pressure of the fluid, (2) pneumatic/gas atomization, which uses an assist-medium such as compressed air or gas, and (3) mechanical atomization, which uses some external force to induce atomization [6]. Two less common methods are electrostatic and ultrasonic atomization. Pressure atomization is particularly beneficial as it operates without requiring additional utilities or equipment and will be the focus of this paper.

Proper atomization can be evaluated through droplet size distribution and spray pattern shape. This performance is a function of fluid properties (surface tension, viscosity, and density) and mechanical design (orifice diameter, injector pattern, and the relative velocity between the waste stream and ambient conditions).

The atomization process, otherwise described as the condensed-phase process, begins by producing thin liquid sheets that break into ligaments as a result of surface deformations in the liquid. These ligaments then break into smaller droplets. These deformations can be described as waves propagating through the liquid, which continue to grow due to surface tension and aerodynamic forces until the liquid particle severs or a part rips away. Typically, disturbances initiate from jet turbulence, gas bubble formation, orifice imperfections, aerodynamic forces due to relative velocity between the liquid stream and ambient air, and vibrations [1]. Various disturbances act on the liquid surface, each with different growth rates leading to droplet breakup throughout the length of the liquid jet. Figure 1 illustrates how a liquid sheet breaks after the disturbance amplitude is sufficient to sever the liquid jet.

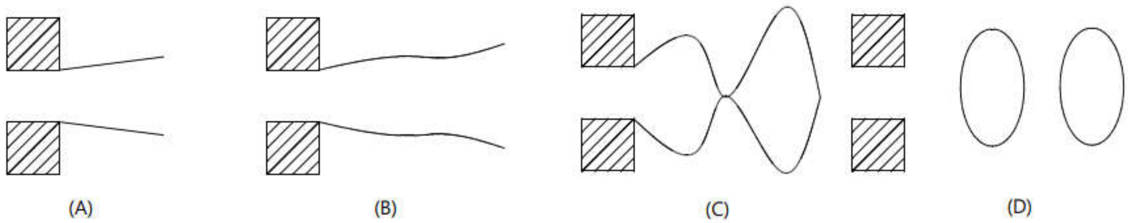

Figure 1: Progression of liquid jet breakup into ligaments/droplets. (A) Liquid jet; (B) disturbances form in liquid jet; (C) disturbances grow; (D) liquid jet severs and smaller droplets form.

Secondary droplet breakup can arise when aerodynamic forces continuing to act on the droplet exceed the restoring surface tension force. Furthermore, it has been proposed that when a surface deformation grows to be greater than the droplet radius, a secondary breakup into an even smaller droplet occurs. Prediction of secondary droplet breakup can be performed by evaluating the Weber number [9] shown below where ρ is the density, ΔV is the velocity difference between the liquid and ambient conditions, d_L is the characteristic length (i.e., droplet diameter), and δ is the surface tension.

$$We = \frac{\rho(\Delta V)^2 d_L}{2\delta}$$

The Weber number is a ratio of the inertial forces and the surface tension force of the liquid [9]. Hinze concluded that secondary droplet breakup occurs when the Weber number exceeds six for low viscosity fluids and ten for high viscosity fluids [1].

Two distinct periods can be defined: (1) the initial time of fluid separation from the jet (i.e., fastest-growing disturbances), (2) time required for the complete jet breakup (i.e., atomization reaches a steady state). At high velocities, separation happens almost immediately whereas the liquid jet continues to break up through the length of the jet as shown below [1] where r_j is the jet radius, ρ_L is the liquid density, ρ is the density of the ambient fluid.

$$t_{seperation} \approx \frac{\delta}{(\Delta V)^3} \sqrt{\frac{\rho_L}{\rho}}$$

$$t_{breakup} \approx \frac{r_j}{\Delta V} \sqrt{\frac{\rho_L}{\rho}}$$

Higher velocity jets tend to have shorter wavelength disturbances leading to faster atomization and reduced droplet size [1]. On the other hand, excessively high waste stream exit velocities can cause flame instability [2]. Flame stability is critical to the safe operation of a flare system and the proper destruction of waste streams. A stable flame means the flare remains ignited throughout the operational and environmental design conditions. Considering the various impacts, droplet size distribution must be achieved while maintaining flame stability. Zeeco accomplishes this by using proprietary mechanisms proven during combustion testing.

After the liquid atomizes, it vaporizes and combusts, otherwise described as the gas-phase processes. This process can be further elaborated upon by examining in more detail the mechanisms surrounding a single droplet. First, a heat-up period during which the droplet surface temperature rises to the wet-bulb temperature with minimal change in droplet diameter. Next, vaporization occurs during which droplet diameter decreases linearly with time, while droplet temperature remains constant. Lastly, a period of increased vaporization rate due to a diffusion flame around the droplet occurs. The heat generated by the local diffusion flame sustains the increased vaporization rate until the droplet is completely consumed [1].

Harrje concluded that within an inactive environment, the time to reach the wet-bulb temperature is proportional to the diameter of the droplet squared [1]. Therefore, achieving the proper droplet size distribution is critical for the effective combustion of liquid process streams. Then, after the droplet reaches the wet-bulb temperature and nearly all the energy is used for vaporizing the liquid, the droplet surface area decreases linearly with time resulting in a mass rate that decreases linearly with droplet diameter [1].

Lastly, all design parameters must ensure proper fluid flow through the system. Hydraulic flip is a phenomenon during which the fluid flow transitions from attached to detached flow through an orifice and should be prevented. The liquid flow area in the burner tip is designed to reduce cross-velocities, dead spots, and pressure drop [1].

Flare Noise and Stability

Typically, between 10^{-6} and 10^{-5} percent of the thermal input to a flare is radiated as noise. This noise can be broken into two categories: combustion noise and jet noise. Combustion noise is caused by expansions and contractions of the combustion products due to the local variances in the heat release throughout the flame [10]. These expansions and contractions generate pressure waves that are perceived as noise by the human ear. Jet noise (i.e., vent noise) is due to increased fluid velocity through an orifice. Jet noise can be further characterized as turbulent noise, which is pulsations in the flow stream caused by turbulence, and shockwave noise when the exit velocity reaches sonic velocity (i.e., the flow becomes choked) at the flare exit [10].

The noise benefits of liquid flare systems stem from liquids having much higher sonic velocities compared to gases. For example, the speed of sound in methane gas is 925 ft/s (at -259ºF), whereas in liquid methane it is 4,658 ft/s (at -274ºF). Liquids also have greater densities than gases, meaning the exit velocity for liquids is lower at the same mass flow rate. Liquid flare systems generate less, if any, jet noise considering the higher sonic velocity for liquids and the lower exit velocity for a given mass flow rate. This is proven by the flare testing performed by Zeeco, which shows that the pressure atomized liquid flare produced significantly less noise than a gaseous flare at the same mass flow rate. During the bidding process, Zeeco's customer had a major concern that the liquid flow expanding into gas at the flare exit point would produce greater noise than a similar sonic velocity gas flare. Testing proved this not to be a concern.

Noise can be an indicator of flame instability. For example, a low frequency, pounding noise is often associated with a detached, unstable flame caused by the flame-front pulsating [2]. Based on visible and audible observations recorded during the testing, the flare system maintained a stable flame while transitioning from firing natural gas to two-phase natural gas/liquid, and then subcooled LNG.

Modeling and Test Setup

After locating a viable source of cryogenic LNG, the liquid was delivered to the Zeeco Test Facility. Various options were investigated, and Zeeco was able to locate a transport vehicle equipped with a transfer pump which could meet the required transfer rate and transfer pressure specified for testing. The pump onboard the double-wall, vacuum-insulated trailer delivered cryogenic LNG to the stainless-steel test flare header and tip where Zeeco recorded the temperature and pressure of the waste stream to determine the phase (i.e., gas, two-phase, liquid). VMGSim was used to determine the vapor fraction based on waste gas temperature, pressure, and compositional analysis provided by the LNG vendor. Zeeco modeled the process using AioFlow to determine pipe loss and pressure drop at the flare tip exit at the desired flow rate. A cryogenic turbine flow meter measured the liquid flow rate, while multiple Cirrus Sound Level Meter (CR:162C) were used to measure the sound pressure level of the flare throughout the test.

A recirculation line with a cryogenic throttling valve directed flow back to the trailer to avoid over-pressuring the pump. When testing began, and the flare header was at ambient temperature, the waste stream vaporized naturally in the header. As the header cooled and the waste stream transitioned to two-phase, operators slowly opened the recirculation line to direct more flow to the flare tip and allow the fluid to transition to liquid – all while maintaining a stable, smokeless flame throughout the entire range of operation. Figure 2 shows the stable combustion of LNG on Zeeco's pressure atomized flare tip design. During the testing, ice formed on the outside of the inlet piping and the flare tip itself from atmospheric water condensing and freezing.

Figure 2: LNG Firing test performed at Zeeco's Test Facility in Broken Arrow, Oklahoma, United States.

Test Results

This section describes the test results and provides pertinent data gathered during the testing. Figure 3 illustrates the process stream temperature and pressure at the burner tip.

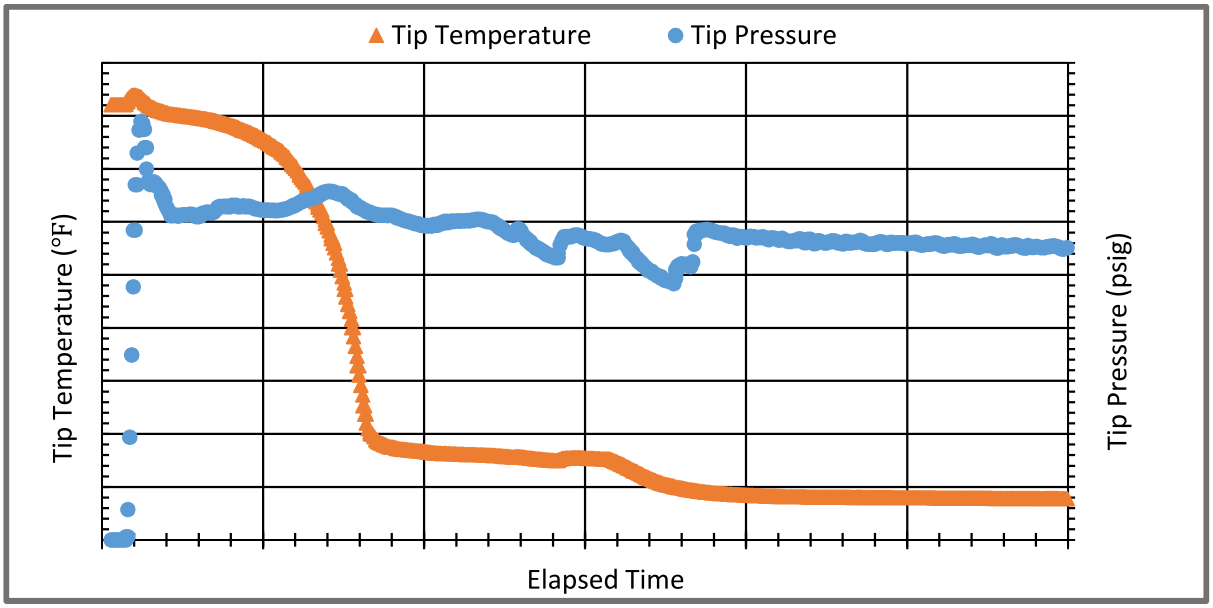

Figure 3: Process stream temperature and pressure vs time during the full-scale testing.

Zeeco calculated the predicted noise from a gas flare at the same mass flow rate and compared it with the pressure-atomized liquid testing results. The physical arrangement of the gas flare was modeled to match the as-tested liquid flare, and the noise was evaluated at the same horizontal distance from the flare stack. Figure 4 shows the gas flare noise prediction to be 85 dB(A).

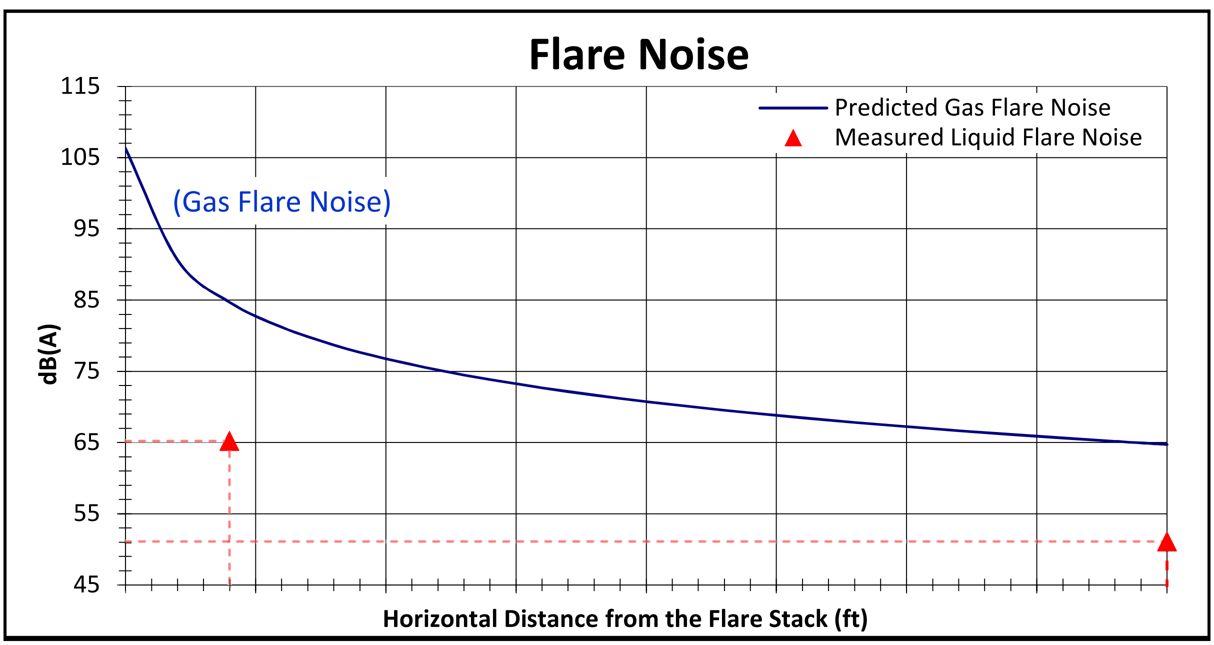

Figure 4: Predicted gas flare and measured liquid flare sound pressure level vs horizontal distance from the flare stack.

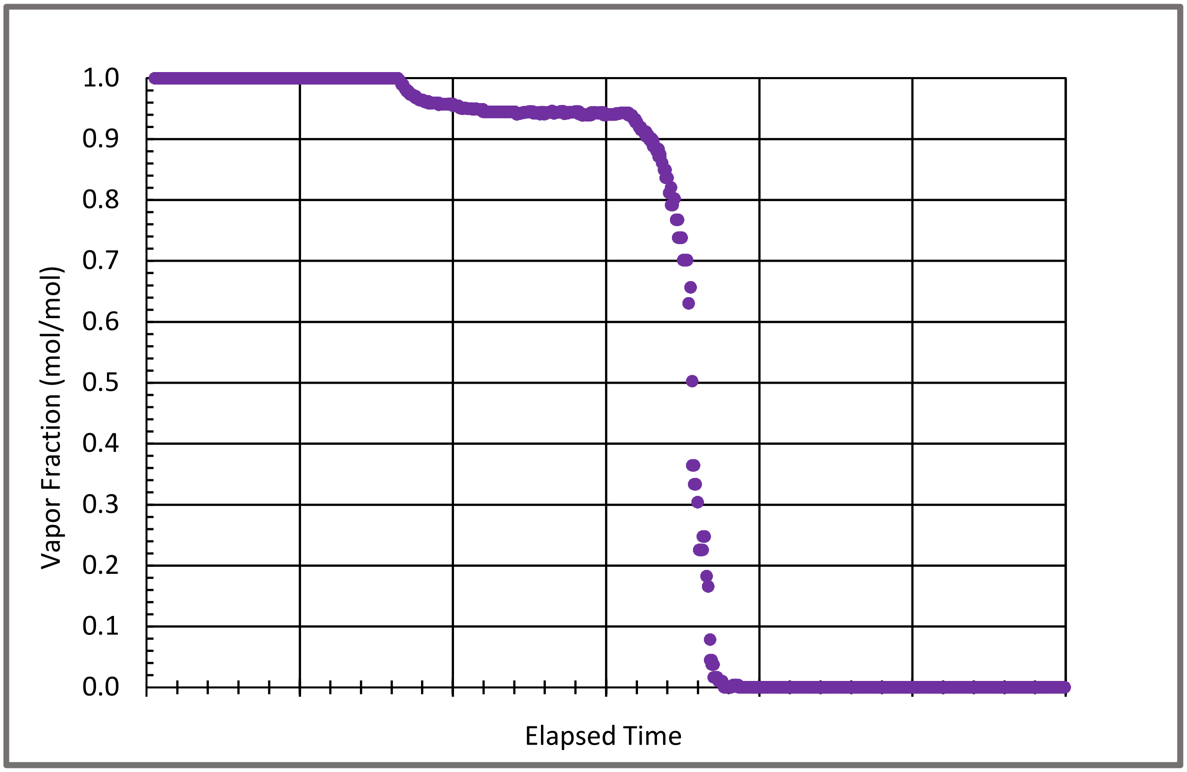

Figure 5: Vapor fraction vs time illustrates the transition from gas to two-phase to liquid.

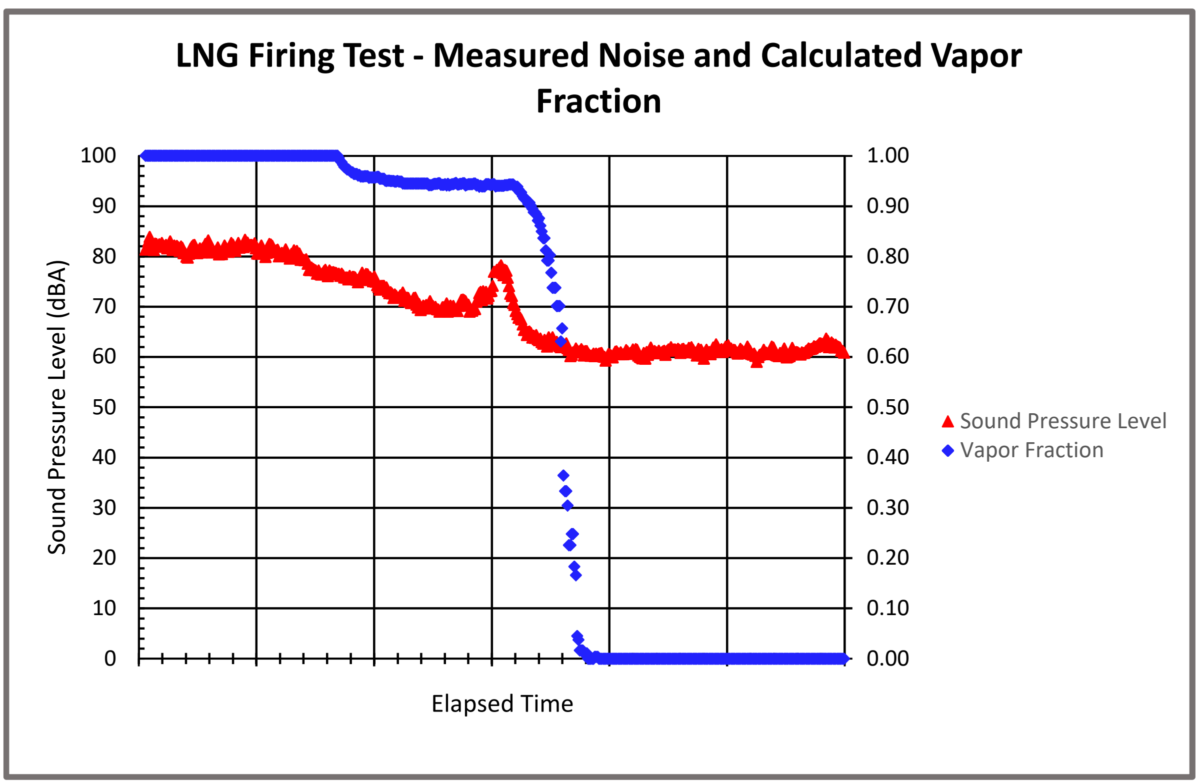

Figure 6: Measured flare sound pressure level and calculated vapor fraction of the natural gas vs time.

Conclusion

Liquid atomization and droplet behavior are complex, transient processes; however, understanding these principles offers new and innovative solutions within the combustion equipment industry. Pressure atomization is beneficial as it relies on the energy within the liquid and does not require additional assist-media. Liquid flaring reduces noise levels, which benefits the facility personnel, environment, and neighboring communities.

Existing gas flare technology has major limitations when faced with process streams containing significant amounts of liquids. Zeeco has designed and tested a pressure atomized liquid flare system for LNG, capable of handling subcooled natural gas and operating reliably within severe, cryogenic operating conditions.

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