Expanding the Use of Ultrasonic Gas Leak Detectors: A Review of Gas Release Characteristics for Adequate Detection

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The physics of ultrasonic gas detection, its efficacy and use as a complement to traditional detection technologies.

Introduction

Since the first gas sensors were invented, researchers have been developing instruments that measure gas concentration. This seems only natural, since concentration is the key determinant of the amount of material that will burn (or explode) if an ignition source is introduced; it also determines the airborne exposure to which nearly all persons can be exposed without adverse effects. Concentration is also the primary means for establishing the identity of a gas: to the extent that a certain amount is present, one may conclude that it can lead to a dangerous situation.

Concentration-based methods can take on many forms as evidenced by open path optical gas detection. With open path detection systems, the relevant measure is concentration times distance. Although concentration itself is unknown, the product concentration-distance can be measured and compared to that of a gas cloud of a certain size and concentration that is generally considered to have the potential to cause consequential damage (e.g. 5 LEL(lower explosive limit) -m or 100% LEL times 5 meters). Such measure makes open path detection a suitable method for fence monitoring, supervising air ducts, and other areas where traditional point gas detection may not be wholly effective.

Nevertheless, there are detection technologies that do not depend on gas concentration, but rely on certain gas properties to identify the onset of a hazard. One that has emerged as a viable means of detecting gas leaks is aptly named ultrasonic gas leak detection (UGLD)[1,2]. Unlike open path detection, UGLD does not use gas concentration as a relevant measure, but rather, employs the ultrasonic noise produced by jetting gas above a predefined threshold to generate an alarm. The fact that UGLD responds to the source of the gas release, not the effect of the release, has significant consequences. First of all, it can respond and alarm quickly, independent of the direction of the gas plume and of ventilation. Since the detectors measure sound over several meters, they tend to cover a wide range, and can be voted (see sidebar) like other area monitors. Finally, the microphones that comprise the sensing element of UGLD are generally robust, do not have consumable parts, and require little maintenance.

> *UGLD responds to the gas source, not the effect of the release,*

Because of these features, UGLD is gaining increasing acceptance in the offshore industry as an additional layer of protection, one that complements fixed point catalytic, electrochemical, infrared or open path gas detection for rapid and efficient assessment of hazardous gas releases[3,4]. Ultrasonic gas leak detection has also found application in oil refineries[5] and carbon capture and storage[6]. In all cases the technology is used in combination, rather than as a replacement for existing detection systems; this scheme proves most effective when UGLD provides early warning of gas leaks and concentration-based methods identify gas accumulations.

Despite UGLD's broader use in recent years, the technology remains poorly understood. For instance, ultrasonic gas leak detectors are thought to respond to audible sound, and as a result, to be prone to false alarms. As with open path detection, the application of another measure of hazard potential raises questions about the suitability of the detectors for critical jobs. "How can we tell the severity of the hazard if we don't know the gas concentration?"

To answer these questions, we will review the acoustics of enclosed spaces and its relationship to jet flow. A study of physical principles will also throw light on the restrictions of the technology as well as its capacity to suit a whole host of industrial processes. Additionally, we will illustrate UGLD's response to various industrial gases and report on recent results on small-orifice leaks and mixed phase leaks.

Physical Principle of Operation

The operating principle of ultrasonic gas leak detectors is that jetting gas from a high pressure vessel or other pressurized system generates ultrasound, which when detected by an acoustic sensor, provides a measure of leak rate. Ultrasound is the term for the range of sound frequencies above those audible to humans. The frequency range of human hearing extends over three orders of magnitude, from about 20 Hz to 20 kHz. A spectrum of sound spanning several frequencies is illustrated in Figure 1. The ultrasonic frequency range of 25 kHz to 70 kHz is typical of most commercial detector models.

The pressure amplitudes of sound waves are commonly measured on a logarithmic scale, called the decibel (dB) scale[7]. Using such scale, one can define sound pressure level (SPL) as

$$SPL = 20\log\left(\frac{p}{p_0}\right) \tag{1}$$

where p_0 is the pressure amplitude of a reference sound, taken to be 20 µPa, considered the threshold of human hearing. Thus, at $p = p_0$, the scale is assigned a sound pressure level of 0 dB.

One important characteristic of sound is that the speed of propagation depends on density and pressure. As a result, the velocity of sound varies with the medium. Such phenomenon has important implications for ultrasound as a means for detecting leaks. As shown in the expression below, the wavelength λ of a wave propagating in an isotropic medium is directly proportional to the velocity of the wave (c) and inversely proportional to its frequency (v)[8].

$$\lambda = \frac{c}{v} \tag{2}$$

Thus, the wavelength of sound decreases as frequency increases into the ultrasound region. For example, assuming a velocity of sound in dry air of 331 m/s, a wavelength in a mid ultrasound, say between 25 kHz and 70 kHz, can range between 5 and 13 mm. Ultrasound generates high energy, short wave signals that are directional and localized. As Figure 2 shows below, a gas leak generates sound through a wide range of the frequency spectrum.

Further, the ultrasonic sound level is proportional to the sound power level of the source[9]:

$$SPL \propto 10\log\left(\frac{W}{10^{-12}}\right) \tag{3}$$

Since the sound power is directly proportional to the power generated by the gas upon expansion, SPL can be expressed as:

$$SPL \propto \log\frac{RT}{M}\dot{m} \tag{4}$$

Here $\dot{m}$ is the mass flow rate of the jetting gas, T is gas temperature at the orifice, M is the molecular weight, and R is the gas constant. It is this relationship between mass flow rate and SPL that airborne ultrasound detectors employ in order to detect leaks. The turbulent flow of the gas in air produces heat and sound energy as the gas molecules collide. And although heat dissipates quickly, the sound energy is transmitted at considerable distances, allowing the detectors to respond to changes in the sound pressure level.

Ultrasonic gas leak detectors measure the airborne ultrasound generated by escaping gas. The amplitude of this sound, expressed in decibels, provides a measure of the leak rate produced by the gas. The relationship between the leak rate, the physical configuration of the leak, and the thermodynamic properties of the gas are well understood [10, 11]. These are derived from assumptions of ideal gas behavior and fixed-geometry choked (sonic) orifice flow. The mass rate that assumes choked flow at the leak source is given by the following isentropic flow relation:

$$\dot{m}_{\max} = pA\sqrt{\left(\frac{\gamma M}{RT}\right)\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{5}$$

where $\dot{m}_{max}$ represents the maximum mass flow rate of gas exiting from the pressurized vessel through the leak orifice, A is the area of the orifice, T and p, represent the stagnation

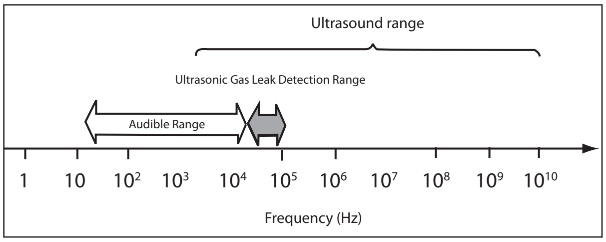

Figure 1. Noise spectrum showing audible and ultrasonic ranges. At a span of 25 to 75 kHz, the ultrasonic gas leak detection range is a small portion of the range of ultrasound.

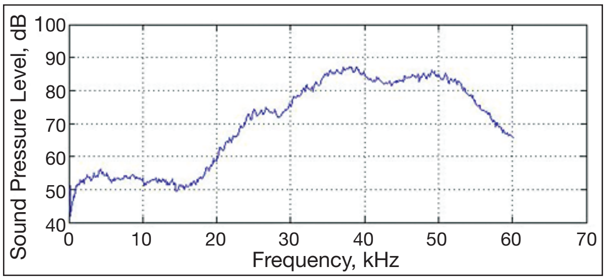

Figure 2. Noise spectrum of nitrogen gas leak in the 20 kHz to 60 kHz frequency band (*d* = *1 mm;* p = *2,758 kPa).*

temperature and pressure within the vessel upstream of the leak orifice, respectively, and $\gamma = c_p / c_v$ is the ratio of specific heats for the gas.

One important result from the derivation of the equation above is the critical pressure ratio. In order for the mass rate to reach a maximum, the ratio of ambient pressure to the pressure inside the pipe or vessel must be

$$\left(\frac{p_o}{p_i}\right)_{critical} = \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma - 1}} \qquad (6)$$

For methane (γ = 1.32), this critical pressure ratio is 0.54. As a result, for ambient atmospheric pressure, an internal pressure of only 186 kPa (27 psi) is sufficient to produce the characteristic choked flow that generates ultrasound. (In practice, however, larger pressures are required to generate an ultrasonic signal greater than ambient ultrasonic background noise.)

For the case of small size orifices, on the micrometer range, assumptions of ideal gas may not apply, as it is unclear whether flow through the orifices is in the continuous regime. So while isentropic flow is assumed in the derivation of equation 5, a discharge coefficient C_d is required to account for dissipative effects. This coefficient can be defined as

$$\dot{m} = C_d\, pA \sqrt{\left(\frac{\gamma M}{RT}\right)\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma + 1}{\gamma - 1}}} \qquad (7)$$

Discharge coefficients must be determined experimentally and are available in engineering handbooks[12] and journal articles [13,14].

Hydrocarbon Gas Releases

Hydrocarbon gas leaks, principally methane leaks, are the most common type in offshore platforms. If not detected or controlled, such combustible gas releases can ignite, producing jet or spray fires that can lead to structural collapse and more severe consequences.

The Health and Safety Executive (HSE) provides an important classification of hydrocarbon gas leaks based on hazard severity[15]. According to the HSE scheme, hydrocarbon gas releases can be classified as minor, significant, and major depending on release size, release rate, and duration. Minor releases, for example, are those with a mass flow rate of less than 0.1 kg/s and a duration of less than 2 minutes or a total gas quantity released of less than 1 kg. By these criteria, ultrasonic gas leak detection technology should detect a mass flow rate of less than 0.1 kg/s at a minimum.

Ultrasonic gas leak detectors are able to detect minor leaks in a variety of environments, including areas with high ultrasonic noise, like gas turbines or low noise areas (light industrial settings), as long as the ultrasonic signal from the leak is well above the background ultrasonic noise. Figure 3 shows the SPL measured by an ultrasonic gas leak detector for methane and ethylene leaks in a low noise environment (40 dB). As evidenced in the graph, the detector provides coverage of up to 12 meters in radius. Differential pressures for this study ranged from 689 to 5,516 kPa (100 to 800 psi).

> *Gas releases that lie at 45° from the detector produce measurably higher SPLs*

Like methane and ethylene leaks, those produced by propane can also be detected by ultrasonic gas leak detection. Figure 4 shows the curves of SPL versus distance for propane leaks of 0.003 kg/s and 0.012 kg/s. A curve for a nitrogen gas leak with a comparable mass rate is also shown.

Hydrogen Gas Releases

Hydrogen is a major process gas in oil refining, a rocket propellant, and an alternative fuel for vehicles. Due to its low molecular weight, the gas has a high propensity to leak and can cause significant deterioration in the mechanical properties of metals. Hydrogen embrittlement leads to increased surface cracks, loss in ductility, and a decrease in fracture stress. Whether produced by exposure to hydrogen from the environment, absorbed hydrogen in the metal, or reaction with the hydrogen, the gas may cause mechanical failure with little or no warning. Once system rupture occurs, hydrogen escapes into the atmosphere, where it can ignite or detonate.

Ultrasonic gas leak detectors are well suited to monitor hydrogen leaks. As illustrated in Figure 5, a detector can provide coverage to an area of 20 meters in radius as hydrogen is very efficient in generating ultrasound. The resultant sound pressure level in the ultrasonic regime is well above the 50 – 60 dB range of ambient background noise in most industrial plants.

Releases of Incombustible Gases

As with hydrocarbons and hydrogen, ultrasonic gas leak detection can be used to detect leaks of inert gases. These gases are often employed in leak simulations to verify operation of leak detectors and ensure that the measured detection range fulfills the coverage requirements of their installation. Helium and nitrogen are the most common gases used in leak simulation and testing because their molecular weights and thermodynamic properties are comparable to those of hydrogen, in the case of helium, and methane, in the case of nitrogen. The SPL generated by these gases and carbon dioxide are shown in Figure 6.

Mixed Phase Releases

The detection of mixed phase (liquid/gas) leaks by ultrasonic gas leak detection is a subject of recent interest. Gases in equilibrium with liquids are common in many process streams. Preliminary work at General Monitors has shown ultrasonic gas leak detectors provide an adequate response to certain water/steam leaks. The SPL generated by these leaks is low, however, restricting the area coverage of the device to a few meters, or areas with low ambient ultrasonic background noise. The results are consistent with those published by the HSE on the response of ultrasonic gas leak detectors to pressurized water leaks[16].

Angular Dependence of Sound Pressure Level

Although ultrasonic gas leak detectors are able to detect gas leaks over a wide range, the response to these leaks varies according to the angle of the detector to the source (Figure 7). Gas releases that lie at 45° from the ultrasonic gas leak detector produce measurably higher sound pres-

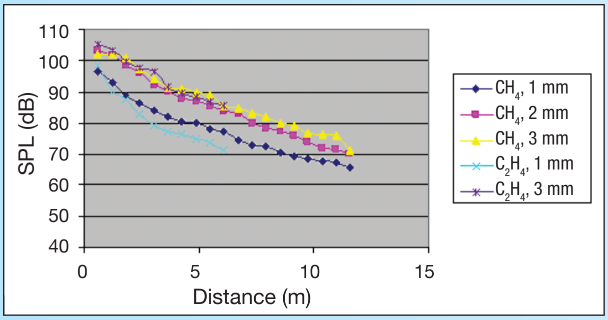

Figure 3. SPL vs. distance for methane and ethylene leaks. (▲) Methane: $\dot{m}$ = 0.008 kg/s, p = 689 kPa (100 psi), d = 3 mm; (■) methane: $\dot{m}$ = 0.007 kg/s, p = 1,379 kPa (200 psi), d = 2 mm; (♦) methane: $\dot{m}$ = 0.007 kg/s, p = 5,516 kPa (800 psi), d = 1 mm; (★) ethylene: $\dot{m}$ = 0.004 kg/s, p = 2,068 kPa (300 psi), d = 3 mm; (x) ethylene: $\dot{m}$ = 0.010 kg/s, p = 5,516 kPa (800 psi), d = 1 mm. Ambient background SPL ≈ 40 dB.

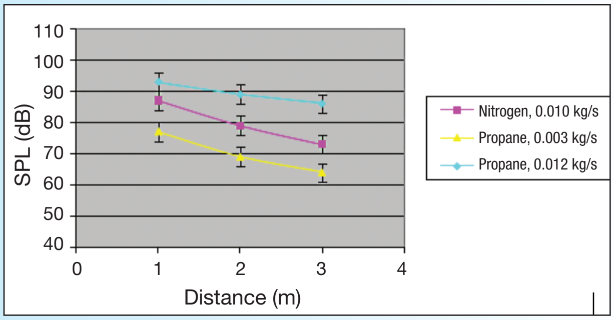

Figure 4. SPL vs. distance for nitrogen and propane leaks. (■) Nitrogen: m& *= 0.010 kg/s, p = 5,516 kPa (800 psi), d = 1 mm; (▲) propane: $\dot{m}$ = 0.003 kg/s, p = 345 kPa (50 psi), d = 2 mm; (♦) propane: $\dot{m}$ = 0.012 kg/s, p = 345 kPa (50 psi), d = 4 mm. Ambient background SPL ≈ 40 dB*

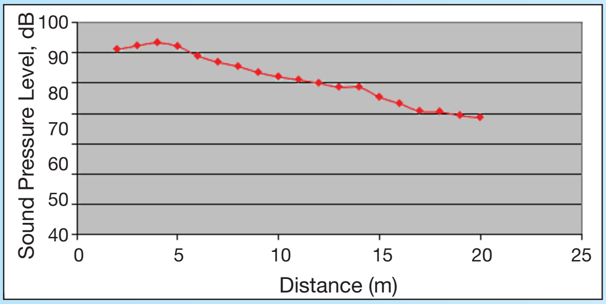

Figure 5. SPL versus distance for hydrogen leaks. $\dot{m}$ = 0.003 kg/s, p = 5,516 kPa (800 psi), d = 1 mm. Ambient background SPL ≈ 40 dB.

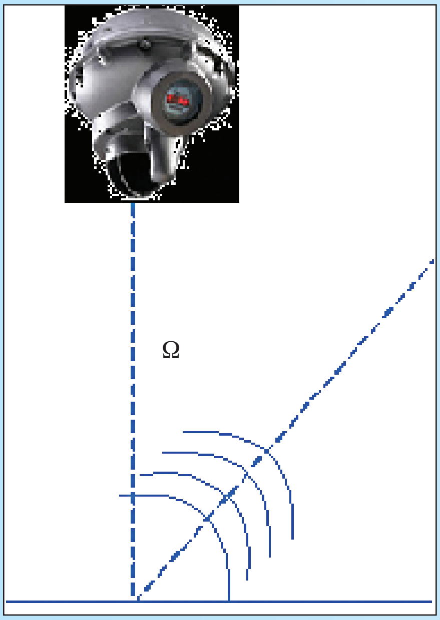

Figure 7. Diagram showing orientation of leak source to an ultrasonic gas leak detector.

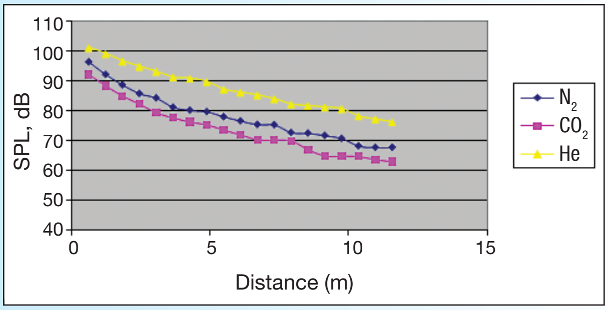

Figure 6. SPL versus distance for carbon dioxide, helium, and nitrogen leaks. (■) Carbon dioxide: $\dot{m}$ = 0.011 kg/s, p = 4,826 kPa (700 psi), d = 1 mm; (▲) helium, $\dot{m}$ = 0.004 kg/s, p = 5,516 kPa (800 psi), d = 1 mm; (♦) nitrogen, $\dot{m}$ = 0.010 kg/s, p = 5,516 kPa (800 psi), d = 1 mm. Ambient background SPL ≈ 40 dB.

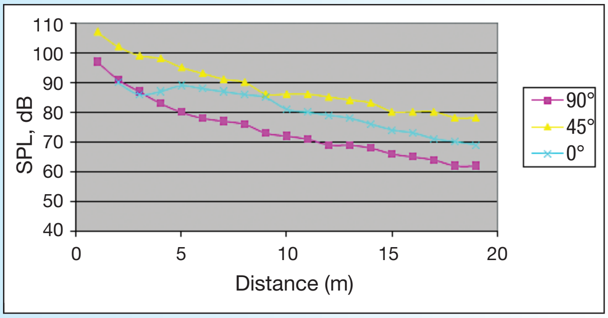

Figure 8. SPL versus distance for methane gas releases according to angle of leak source to detector. $\dot{m}$ = 0.007 kg/s, p = 5,516 kPa (800 psi), d = 1 mm, SPL error = ± 3 dB.

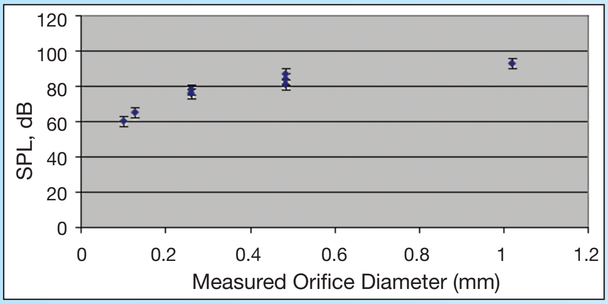

Figure 9. SPL at 1 meter versus orifice diameter for nitrogen leaks. Pressure range = 5,516 – 8,067 kPa (800 – 1,170 psi). SPL error = ± 3 dB. Ambient background SPL ≈ 40 dB..

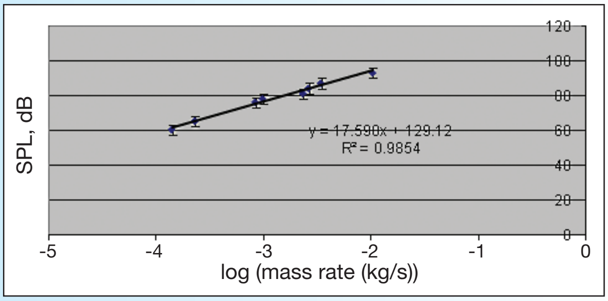

Figure 10. Relationship between SPL measured at 1 meter from leak source and mass flow rate. SPL error = ± 3 dB.

sure levels than equivalent releases with the source directly on axis with the detector (0°) or perpendicular to it (90°). Figure 8 shows SPL-distance curves for methane gas discharged at 0.004 kg/s at three incident angles to the sensor axis.

Gas Leaks from Small Orifices

The HSE has identified the lack of information on the effectiveness of gas detectors to detect low rate gas releases as an "area of uncertainty" within its fire and gas detection framework[4]. These releases, defined as those with mass rates of less than 1 kg/s, do not have the destructive potential of larger escapes, but may evolve into large releases over time. SPL measurements show that detectors can sense leaks with mass rates of a few tenths of a milligram per second and of less than 1 mm in diameter, suggesting the technique can be used to identify incipient leaks. Figure 9 presents SPL as a function of orifice diameter for nitrogen leaks. All sound pressure level measurements were taken with the leak source at 1 meter from the sensor.

The same data set, displayed as SPL versus the logarithm of mass flow rate, shows the relationship to be linear ($R^2 \approx 0.99$), as predicted by equation 4 above.

Detection of leaks from small orifices has practical implications for fire and explosion protection. Aside from the fact that leaks can become progressively larger as mechanical components wear, small leaks themselves can support fires. Recent experiments by Butler et al. suggest a pinhole leak as small as 0.4µm can sustain a hydrogen flame[17]. The minimum flaming flow rates are about 0.3 mg/s for methane and propane and 0.03 mg/s for hydrogen, consistent with those rates that are detectable by ultrasonic gas leak devices.

Conclusion

The challenges to produce and deliver oil and natural gas remain daunting and their contribution to energy supply is vital to world economies. Interruption of supply through the escape of process gases, through detonations, together with the potential for severe injury can have devastating economic and social consequences. In this context, ultrasonic gas leak detection stands as a complementary technology that helps secure the safe production, storage, transport, and processing of many of the gases on which society depends. UGLD has wide application to hydrocarbons, hydrogen, as well as to inert gases. Indeed, the detection technology appears to be restricted only by the requirement that the released material be a gas, and that said gas be sequestered at sufficiently high pressure to produce ultrasound upon discharge. In addition, UGLD has proven capable of detecting leaks from sub-millimeter sized orifices, albeit at very high pressures and within a small range. Research on small leaks confirms SPL is directly proportional to the logarithm of mass flow rate (eq. 4), and hence, it provides a measure of hazard potential.

With the limitations described herein, the technology has shown a promising start, and if widespread use in the offshore industry is an indication, the next ten years are bound to see improvements in design that rival or exceed those of the previous ten.

The technology complements traditional means of detecting gas leaks and should be regarded as an addition, rather than a replacement, of existing systems. According to the HSE's Offshore Safety Division (OSD) strategy, it is combinations of sensing techniques that stand the best chance to provide early warning of hazardous situations[4]. As complementary systems, ultrasonic gas leak detectors are a first line of defense for detecting leaks; other systems like infrared point and catalytic sensors identify the gas cloud accumulation, allowing personnel to respond more effectively to an alarm. G&I

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Voting in Safety Instrumented Systems

"Voting" is a term used in safety instrumented systems to describe a structured approach for issuing a system response based on the number of detectors that detect the hazard. On a so called 1oo2 (one out of two) configuration, for example, if one sensor detects a hazard, the configuration produces an alarm; on a 2oo2 configuration, the response from two sensors is required in order to produce an alarm, and so on. In consequence, voting reduces the incidence of false alarms at the expense of speed of response. (It also implies unreliability of individual sensors to respond to all gas release or flame scenarios.) In the case of ultrasonic gas leak detectors, it is not uncommon for two detectors to be considered at a single location to provide for voting, particularly if the cost of a false alarm is high (e.g. plant shutdown).