Contents lists available at ScienceDirect

Process Safety and Environmental Protection

journal homepage: www.elsevier.com/locate/psep

Experimental study on acoustic propagation-characteristics-based leak location method for natural gas pipelines

Liu Cui-wei[a,c,d], *Li Yu-xing*[a,c,d,*], *Fu Jun-tao*[b], *Liu Guang-xiao*[a]

[a] *College of Pipeline and Civil Engineering in China University of Petroleum (East China), Qingdao 266580, China*
[b] *Sinopec Qingdao LNG Co., Ltd, Qingdao, 266400, China*
[c] *Key laboratory of Qingdao oil and gas storage and transportation technologies, China*
[d] *Key laboratory of CNPC heavy gas transportation and LNG technologies, China*

ARTICLE INFO

Article history:
Received 22 November 2014
Received in revised form 22 March 2015
Accepted 13 April 2015
Available online 20 April 2015

Keywords:
Gas pipelines
Leakage acoustic wave
Propagation characteristics
Attenuation model
Experimental study
Leak location

ABSTRACT

In order to study the fundamentals of leak detection and location for natural gas pipelines based on acoustic method, the propagation model of leakage acoustic waves is established and modified. First, the wave equations of leakage acoustic waves are researched in theory and the propagation law in actual pipelines is analyzed to obtain the damping impact factors which cause the attenuation. Then, the fundamental characteristics of leakage acoustic waves are obtained through experiments by time-domain, frequency-domain and joint time–frequency-domain analyses. Third, the actual propagation model is established which can be used to calculate the installation distance of the acoustic sensors. Finally, a new leak detection and location method is proposed based on the propagation law which is validated by the field experiments and the fundamental, the steps and the merits of the method are concluded. The results indicate: the propagation model can be established and modified by the experimental method combined with theoretical method, which can direct the acoustic sensors to be installed into the pipelines; the propagation-characteristics-based leak location method is effective. Conclusions can be drawn that the modified propagation model can make acoustic leak detection method used in natural gas pipelines better.

1. Introduction

At present, many leak detection methods (Murvay and Silea, 2012; Lay-Ekuakille et al., 2009; Kajiro et al., 1986) have been developed for gas pipeline leakages, such as methods based on mass/volume balance, negative pressure wave, transient model, distributed optical fiber and acoustic waves, etc. Among them the traditional negative pressure wave method detects leakages based on the change of the absolute pressure in pipeline monitored by the pressure transmitter, while the acoustic method is based on the dynamic pressure monitored by the acoustic sensors. Therefore, acoustic method can perform full-scale display of pressure fluctuations caused by the leakages. This method is superior to traditional ones with its advantages: higher sensitivity, higher location accuracy, lower false alarm rate, shorter testing time and greater adaptability.

The fundamental of the acoustic leak detection and location method is: when leakage occurs, the coupling interaction between flowing gas and tube wall generates acoustic waves which propagate to upstream and downstream in the form of elastic wave and are captured by the acoustic sensors. Then the leakage signals are processed in computer to detect and locate the leakages.

Though acoustic method has many advantages, the quite high installation cost of acoustic sensors restricts its popularization and application. Also, the propagation distance of acoustic waves directly determines the installation cost. Therefore, a group of scholars conducted researches on the

* Corresponding author. Tel.: +86053286981818.
E-mail addresses: chuyun_lcw@163.com, liyx@upc.edu.cn (L. Yu-xing).
http://dx.doi.org/10.1016/j.psep.2015.04.005
0957-5820/

propagation characteristics of acoustic waves. Hunaidi and Chu (1999) collected leakage acoustic signals propagating in the medium inside plastic water pipes and propagating through the pipe wall using microphones and accelerometers, respectively. Experimental results show that the amplitude of signals attenuates with the propagation distance at the speed of 0.25 dB/m, and the propagation velocity of signals whose frequency is lower than 50 Hz is independent of frequency, and acoustic signals propagate faster by 7% in winter than in summer. Muggleton et al. (2002) analyzed the mechanism of propagation behavior of sound and vibration waves caused by leakage of fluid-filled round pipeline and established the propagation model of signals and also analyzed the attenuation characteristics of the acoustic signals. Liu et al. (2003) studied the attenuation characteristics of the wave of fluid-filled pipeline and the results show that longitudinal wave attenuates slower in pipeline. They also compared the propagation characteristics of waves in different pipe wall materials and came to a conclusion that waves in steel tube attenuate slower than in PVC pipe. Sun et al. (2008) analyzed the characteristics of acoustic emission waves in pipelines with the liquid. Meanwhile they measured the propagation and attenuation characteristics of acoustic emission waves of different modes in steel liquid pipelines.

Domestic and international scholars have carried out researches on the propagation characteristics of acoustic waves for leak detection and location. However, they focused attention on the liquid pipelines. For gas pipelines, Kim and Lee (2009) proposed a detection method based on the time–frequency analysis of leak acoustic signal for buried gas pipe. The results show that the time–frequency method is a useful tool for analysis of acoustic wave propagation and identifying cut-off frequencies for acoustic modes in a circular duct. Meng et al. (2012) established a formula for gas pipelines leak location. As a result, the positioning accuracy can be significantly improved with relative error between 0.01% and 1.37%. Jin et al. (2014) proposed an integrated leakage detection and localization model for gas pipelines. The paper proposed a modified acoustic velocity and location formula, given that the spread velocity of acoustic waves in pipelines is related to the properties of the medium, such as pressure, density, specific heat, and so on. From the researches on the acoustic leak detection method for gas pipelines, it can be concluded that firstly the propagation model of the acoustic waves in the gas pipeline is not established. And then most of the location methods nowadays depend on the velocity and the time difference of the two measured signals which are calculated by GPS or cross-correlation method (Liu et al., 2014). The accuracy of the velocity and the time difference restricts the application of the acoustic leak detection and location method. Then the location method is proposed which is based on the propagation model and takes no account of the velocity and the time difference. Therefore, propagation characteristics of leakage acoustic waves in gas pipelines are necessary to study, which can provide foundation for the new leak detection and location technology for gas pipelines.

2. Preparation for the experiments

2.1. *Basic wave equations*

First, the basic equations of acoustic waves can be established based on some assumptions. Then they can be modified according to the actual working conditions. Assumptions are described as follows (He et al., 2006):

(1) The media is ideal fluid. Therefore the effect of heat conduction and the viscosity on the propagation of acoustic waves can be ignored. (2) During the propagation process, acoustic waves can lead to condensation and expansion of the media, which is considered to be an adiabatic process and the heat exchange between neighboring sections can also be ignored. (3) Acoustic waves propagate through the media with small amplitude and all acoustic quantities are the first-order traces.

Based on the assumptions above, the equation of one-dimensional acoustic wave is derived from kinetic equation, equation of continuity and equation of state (He et al., 2006):

$$\frac{\partial^2 p}{\partial x^2} = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} \tag{1}$$

The equation of three-dimensional acoustic wave is illustrated as follows:

$$\nabla^2 p = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} \tag{2}$$

where ∇^2 is the Laplacian and it is illustrated as follows in Cartesian coordinates:

$$\nabla^2 = \mathrm{div}(\mathrm{grad}p) = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2} \tag{3}$$

2.2. *Basic characteristics of acoustic waves*

According to the difference of wave front, acoustic waves can be divided into three categories: the spherical wave, the cylindrical wave and the plane wave. Wave fronts of the spherical wave are a series of concentric spheres. Wave fronts of the cylindrical wave are coaxial cylinders. Wave fronts of the plane wave are planes.

Acoustic waves produced by spherical sound sources are spherical waves whose sound pressure can be expressed as follows:

$$p = \frac{jk\rho_0 c_0 q_0}{4\pi r} e^{j(\omega t - kr)} \tag{4}$$

where $k = \omega/c_0$ is the wave number of acoustics, q_0 is the power of sound sources which is determined by the radius of the spherical sound source and the vibration amplitude of sphere surface, dB.

Plane wave refers to the acoustic wave propagating only in one direction and in other directions all particles have the same amplitude and phase. The equation of the plane wave is one-dimensional. The sound pressure is illustrated as follows:

$$p(x) = p_a e^{j(\omega t - kx)} \tag{5}$$

where p_a is the amplitude of the sound pressure.

In general, the sound source radiates spherical waves in unbounded space. However, when the radiation is constrained within the pipeline, acoustic waves will be affected by the shape, size and materials of tube. The cylindrical pipe is concerned here, so formula (2) can be expressed under cylindrical coordinates as follows:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial p}{\partial r}\right) + \frac{1}{r^2}\frac{\partial^2 p}{\partial \theta^2} + \frac{\partial^2 p}{\partial z^2} = \frac{1}{c_0^2}\frac{\partial^2 p}{\partial t^2} \tag{6}$$