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Computational fluid dynamic simulation of pressure perturbations generation for gas pipelines leakage

Cuiwei Liu [a,b,c], Yuxing Li [a,b,c,*], Lingya Meng [d], Wuchang Wang [a], Fangsheng Zhao [e], Juntao Fu [f]

[a] College of Pipeline and Civil Engineering in China University of Petroleum (East China), Qingdao 266580, China
[b] Key Laboratory of Qingdao Oil and Gas Storage and Transportation Technologies, China University of Petroleum (East China), Qingdao 266580, China
[c] Key Laboratory of CNPC Heavy Gas Transportation and LNG Technologies, China University of Petroleum (East China), Qingdao 266580, China
[d] College of Information and Control Engineering in China University of Petroleum (East China), Qingdao 266580, China
[e] Offshore Oil Engineering CO., Ltd., Tianjin 300451, China
[f] Sinopec Qingdao LNG Co., Ltd., Qingdao 266400, China

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ABSTRACT

A computational fluid dynamic (CFD) simulation research on the pressure perturbations generation is accomplished and verified by experiments to study the fundamental of acoustic leak detection and location method for natural gas pipelines. When leakage occurs, gas flows out of the pipeline, and the flow field, the sound field are obtained by the established CFD simulation model. And the simulation analyses of pressure perturbations are verified by the experiments. Then, the simulation method is compared with the experimental one under variable conditions to find out the laws of pressure perturbations. Finally, the experimental demonstration of the leak location based on the pressure perturbations and the pressure perturbations attenuation are given. The results indicate that the main reason of pressure perturbations generation for natural gas pipelines is the sonic source fluctuations which are induced by turbulent fluctuations. Conclusions can be drawn that CFD simulation on the acoustic leak detection and location method for natural gas pipelines is an efficient way to carry out research and provide theoretical basis for its application.

1. Introduction

Leak detection is an important way [1] to protect natural gas pipelines from failure and to decrease the risks. In order to reduce the economic losses, casualties and environmental damages caused by leakages, many technologies and systems for gas pipelines leak detection have been developed and studied, such as [2–4], methods based on mass/volume balance, static decision, negative pressure, transient model, distributed optical fiber and acoustics. Among them, the acoustic method can full-scale acquire and display the pressure perturbations caused by leakages, which can contribute to a more sensitive leak detection. As the pressure perturbations acquired by dynamic pressure sensors propagate to both ends of the pipeline at the speed of sound, the pressure perturbations are termed as acoustic wave and the method is termed as acoustic method. Compared with other methods [2–4] acoustic method [5,6] has many advantages over them, such as higher sensitivity, more accurate leak location, longer detection distance, lower false alarm rate, quicker leak detection and higher adaptability capacity.

Great efforts have been made on acoustic method and continued [7–10]. An equation of ax symmetric wave motion for a fluid-filled pipe was developed [11], which can be applied for two different wave types (a fluid dominated wave and an axial shell wave). The expressions of a complicated wave number for each wave were also given. Afterwards experiments [12] were conducted to validate those models. During the experiments, the wave number including both wave speed and wave attenuation were made on a water-filled pipe in vacuo and on a buried water-filled pipe. Liu et al. [13] derived the dispersion equation of structure acoustic coupling system for fluid pipe from shell dynamic equation. The fluid pipe was surrounded by elastic media under ax symmetric motion. The attenuation characteristics of wave propagation in fluid-filled metal and PVC plastic pipes were studied. Acoustic System INC (ASI) developed the leak detection system for pipelines based on acoustic method. Due to great efforts, a lot of achievements have been obtained. But currently, most of the researches are focused on the liquid transportation pipelines while the problems of natural gas pipelines are still unsolved, such as

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* Corresponding author at. College of Pipeline and Civil Engineering in China University of Petroleum (East China), Qingdao 266580, China. Tel.: +86053286981818; fax: +86 053286981822.

E-mail address: chuyunlcw@163.com (Y. Li).

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Nomenclature

a_0	velocity of sound outside the flow (m/s)
a_1	propagation velocity of acoustic pressure perturbation in the section of pipeline ($0 \rightarrow x$) (m/s)
a_2	propagation velocity of acoustic pressure perturbation in the section of pipeline ($x \rightarrow L$) (m/s)
c_1	the average velocity of the fluid in the section of pipeline ($0 \rightarrow x$) (m/s)
c_2	the average velocity of the fluid in the section of pipeline ($x \rightarrow L$) (m/s)
f	generalized function
L	the distance between upstream and downstream sensors (m)
p'	acoustic pressure (Pa)
p_0	the undisturbed pressure of flow field or the average pressure of flow field (Pa)
p_{ij}	the stress tensor (Pa)
t	flow time (s)
t_1	the time of the arrival of the acoustic pressure perturbation at upstream (s)
t_2	the time of the arrival of the acoustic pressure perturbation at downstream (s)
Δt	the time interval between upstream and downstream sensors received (s)
T_{ij}	the Lighthill stress tensor (Pa)
$\vec{u}$	velocity vector of natural gas (m/s)
$\vec{u}_i$	velocity vector of x (m/s)
$\vec{u}_j$	velocity vector of y (m/s)
$\vec{w}$	vorticity vector
x	the distance between the leak point and the upstream acoustic sensor (m)
x_i	value of i-axis in Cartesian Coordinates
x_j	value of j-axis in Cartesian Coordinates
∇	Hamilton operator
Greek letters	
δ_{ij}	unit tensor
$\delta(f)$	Dirac δ function
ρ	the density of natural gas (kg/m^3)
ρ_0	the undisturbed density of gas or the average density of gas (kg/m^3)
ρ'	the fluctuations of gas density (kg/m^3)
τ_{ij}	viscous stress tensor (Pa)

what kind of acoustic wave is generated, how the acoustic wave is generated, which restrict the application of acoustic leak detection method for natural gas pipelines.

In this work, the acoustic leak detection is studied by the combination of simulation [14–16] and experimental methods. The simulation and experimental models are proposed and designed. The acoustic pressure perturbations are the research object for acoustic leak detection method instead of the acoustic pressure itself. This view is firstly put forward. So the leakage acoustics generation mechanism is definite and the leakage signal is clear to be processed according to the fact. The basic laws of pressure perturbations which are obtained by simulation and experiments under variable operating conditions are concluded. All of these provide theoretical and experimental bases for the application of acoustic leak detection.

2. Theoretical analysis

Gas jets out of the leakage orifice when leakage occurs. Severe eddies generate due to the differential pressure of inside and outside the pipe and the gas-pipe interaction which lead to the quadrupole sonic sources and the dipole sonic sources. Quadrupoles and dipoles are superimposed which presents an acoustic pressure perturbation which transmits through gas to both ends of the pipeline. It means the quadrupoles and dipoles are interacting on each other and a pressure perturbation is the result of the interaction. And it is measured by the dynamic pressure sensors installed to the pipeline, which will be signal-processed by computer to determine whether leakage occurs or not.

The acoustic pressure perturbation generation mechanism for natural gas pipelines is based on the aero-acoustics theory [17,18]. So the sonic sources distributed in the fluid field can be derived from Lighthill equation [19] and Ffowcs Williams and Hawkings equation called FW–H equation [20,21].

Lighthill equation is suitable for sound induced by fluid flow with its fluctuating stresses acting on an acoustic medium and propagated in an acoustic medium at rest, which is derived from the Navier–Stokes equation:

$$\frac{\partial^2(\rho-\rho_0)}{\partial t^2} - a_0^2\nabla^2(\rho-\rho_0) = \frac{\partial^2}{\partial x_i x_j}T_{ij} \tag{1}$$

$$T_{ij} = \rho u_i u_j + p_{ij} - a_0^2(\rho-\rho_0)\delta_{ij} \tag{2}$$

$$p_{ij} = p'\delta_{ij} - \tau_{ij}, \begin{cases} \delta_{ij} = 1, \text{ if } (i = j) \\ \delta_{ij} = 0, \text{ if } (i \neq j) \end{cases} \tag{3}$$

Ffowcs Williams and Hawkings used generalized function method to solve the acoustic problem induced by moving object in fluid and obtained Ffowcs Williams and Hawkings equation called FW–H equation.

$$\frac{\partial^2\rho'}{\partial t^2} - a_0^2\nabla^2\rho' = \frac{\partial}{\partial t}\left[\rho_0 u_i \frac{\partial f}{\partial x_i}\delta(f)\right] - \frac{\partial}{\partial x_i}\left[(p'\delta_{ij})\frac{\partial f}{\partial x_i}\delta(f)\right] + \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \tag{4}$$

In the right hand side of the equation, the first part is the monopole sonic source resulted from surface acceleration or displacement distribution; the second one is the dipole caused by surface pressure fluctuations and the third one is the quadrupole caused by fluid turbulence.

When leakage occurs, an acoustic pressure perturbation is generated which propagates to upstream and downstream in the gas. The high-frequency component of acoustic pressure perturbation attenuates quickly, while the low-frequency component can propagate for a long distance. Acoustic sensors installed at both ends of the pipeline receive the acoustic pressure perturbation which will be signal-processed by computer to determine whether leakage occurs or not. Meanwhile, leak detection system can calculate and verify the leak location based on the acoustic propagation velocity and the arrival time of acoustic pressure perturbation at two adjacent acoustic sensors. When the pipeline is under normal conditions, acoustics received by the acoustic sensors are treated as background noises. Once leakage occurs, both the acoustic pressure perturbation and the background noises are received by the acoustic sensors. At the same time the system will send out leak alarms and the leak location will be determined. The fundamental