Non-intrusive and Highly Sensitive Gas Flow Monitoring based on Distributed Acoustic Sensing

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Abstract: We propose and demonstrate a non-intrusive pipeline flow monitoring system based on the DAS. To the best of our knowledge, this is the first time a DAS system has been used for gas flow monitoring.

1. Introduction

Non-invasive pipeline flow monitoring is a key factor to achieve sustainable development of oil and gas pipelines. Currently, many types of technology have been used for flow measurement, such as Coriolis, ultrasonic, electromagnetic, differential pressure flowmeters, etc [1]. Although there are many high-quality pipeline flow sensors and measurement technologies, such flow sensors can only achieve node-based measurement and reflect the flow rate of only one part for the pipeline. Besides, these sensors also need to invade the pipeline and have electromagnetic interference. In 1977, Dr. Robert Blevins first proposed the flow induced vibration (FIV) [2], which have been introduced for flow monitor. However, most of FIV based flow meters are based on electrical sensors, which is not suit for gas pipeline monitor. Shang *et al.* proposed Michelson fiber flow sensor based on FIV effect [3], but it can only monitor single point flow rate. With the development of oil-gas pipeline network, there is an urgent need for continuous online distributed measurement and practical application of the complex pipe networks in industrial piping systems.

In this work, we proposed a non-intrusive and highly sensitive gas flow monitoring system based on optic fiber distributed acoustic sensing (DAS) system, in which the backscattering enhanced optical fiber (BEOF) is attached outer of the gas pipeline as the sensing medium. The field test results show that the flow error probability can reach 96.88% in the interval of −15% to 15%, demonstrating significant potential in the field of gas flow monitoring.

2. Gas flow measurement principle and scheme

2.1 Gas flow measurement principle

According to the first law of thermodynamics, when the gas molecules impact on the pipe wall, part of kinetic energy of gas molecules is converted into heat energy, but most of kinetic energy will be converted into potential energy in the form of pressure [4]. From Prashun's turbulence theory, the instantaneous fluctuating pressure p is proportional to the flow rate, that is $p \propto \bar{u}\ \bar{v}$ [5].

The gas pipeline can be described by a one-dimensional model of a beam. According to the structural mechanics, the shear stress is the changing rate of the moment along a beam, and dV/dx is the changing rate of shear stress along the length of a beam, which is equal to the pressure fluctuation for per unit length, as shown in Eq. 1.

$$\frac{d^2M}{dx^2} = \frac{dV}{dx} = p^{'}(x) \tag{1}$$

where d^2M/dx^2 represents the rate of the moment along a beam, and dV/dx is the changing rate of shear stress, namely, the pressure fluctuation per unit length of the pipe. Combined with the general formula of engineering mechanics, Eq. 2 can be deduced as:

$$EI\frac{d^2y}{dx^4} = p^{'}(x) \tag{2}$$

To relate the pressure fluctuation to the pipeline acceleration d^2y/dt^2 , consider the differential equation of motion for transverse vibration of a beam in Eq. 3.

$$\frac{\partial^2 y}{\partial t^2} = -\frac{g}{A\gamma}EI\frac{\partial^4 y}{\partial x^4} \tag{3}$$

It can be seen from the above equation that the acceleration of the pipe is proportional to the pressure fluctuation in the fluid. According to the derivation of turbulence intensity [3], we can get:

$$\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}[u_i(t)-\bar{u}]^2} \propto \bar{u} \tag{4}$$

Since flow fluctuations are proportional to pressure fluctuations, and pressure fluctuations are proportional to pipeline vibration, the standard deviation of pipeline vibration is proportional to the average flow rate.

2.2 Gas flow measurement based on DAS

From the above theoretical analysis, it can be seen that flow monitoring can be realized by sensing the gas flow vibration signal generated by fluid molecules hitting the pipe wall. Here, the DAS system based on BEOF is utilized to perform the distributed gas flow monitoring for the first time. The pipe flow vibration signal caused by flow transport at any position can be obtained by demodulating the phase change between two adjacent backscattering enhanced points (BEP) on the BEOF. As illustrated in Fig. 1(a), the heterodyne detection DAS system is used for distributed flow detection, whose detailed working principle is reported in our previous work [6].The BEOF is attached outer of the gas pipeline with spiral layout and the gap is 5cm, as well as the PE winding film is wrapped to increase the coupling between the sensing fiber with the pipe wall. Compared with the single mode fiber, the BEOF could enhance the backscattering signal and eliminate the interference fading [6]. The gas flow test field is shown in Fig. 1(b), each pipeline is equipped with a commercial differential pressure flowmeter for flow calibration, in which the flow information is collected every minute and then uploaded to the SCADA system.

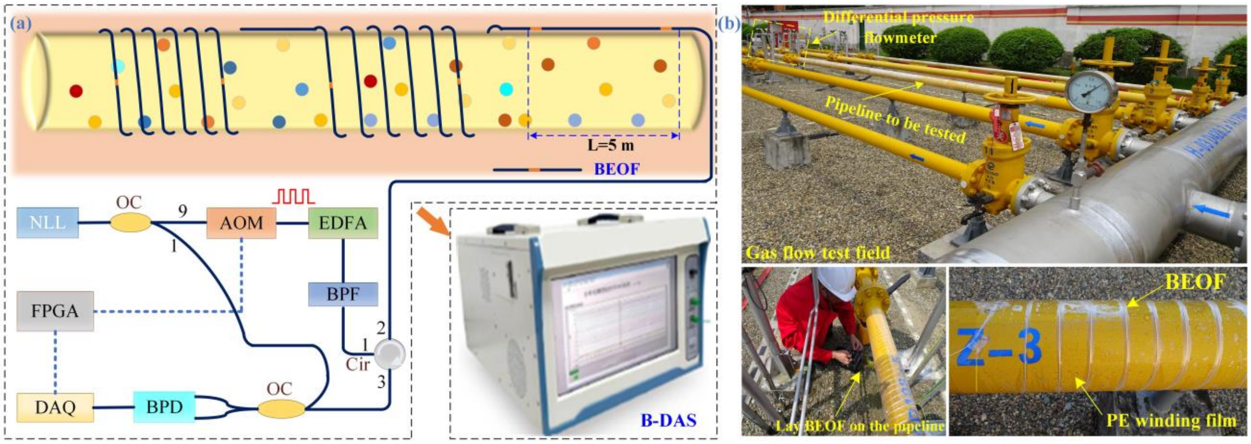

Fig. 1(a) Flow monitoring principle and (b) gas flow test field.

3. Results and discussion

In order to verify the feasibility of gas flow monitoring based on BEOF, several groups of different flows were selected for preliminary tests. As shown in Fig. 2(a), the phase noise floor caused by environment and DAS system itself was around 0.03 rad. With the increase of gas flow, the amplitude of phase also gradually increases, indicating that the proposed scheme has certain feasibility. Owing to the stability of the scattered light signal of BEOF, the phase fluctuation is quite stable in the 2 s acquisition time. Then, 96 sets of flow data for a whole day are collected and analyzed, and the flow vibration signal is processed by the mean of standard deviation. In Fig. 2 (b), with the continuous increase of the flow rate, the standard deviation of the phase has an upward trend, and the relationship between them meets the quadratic fitting with a fitting coefficient up to 0.99, which is completely consistent with the theoretical analysis.

Based on the quadratic fitting function, a flow monitoring model was constructed based on the relationship between the standard deviation of flow vibration signal and gas flow. In another flow test experiment, the flow vibration signal collected by BEOF was sent to the model, and the gas flow data calculated by the model were compared and analyzed with the SCADA. Fig. 3(a) is a comparison between the flow data obtained by the model and the SCADA throughout the day. Due to the concentrated use of gas by residents, the peak flow occurred at 12:00 p.m. and 21:00 p.m., while the flow was fell to zero from 1:00 a.m. to 5:00 a.m., because it was the residents' rest time. The testing results show that the flow fluctuation trend monitored by BEOF is basically completely consistent with the commercial SCADA system, and when the flow is large and small, it can be distinguished significantly and sensitively, demonstrating that this non-invasive flow measurement scheme is feasible. Moreover, to verify the reliability of the proposed scheme, the flow monitoring errors are analyzed. Besides, the probability of flow monitoring error distribution is analyzed. Fig. 3(b)~ (c) is the histogram of the flow measurement error probab-

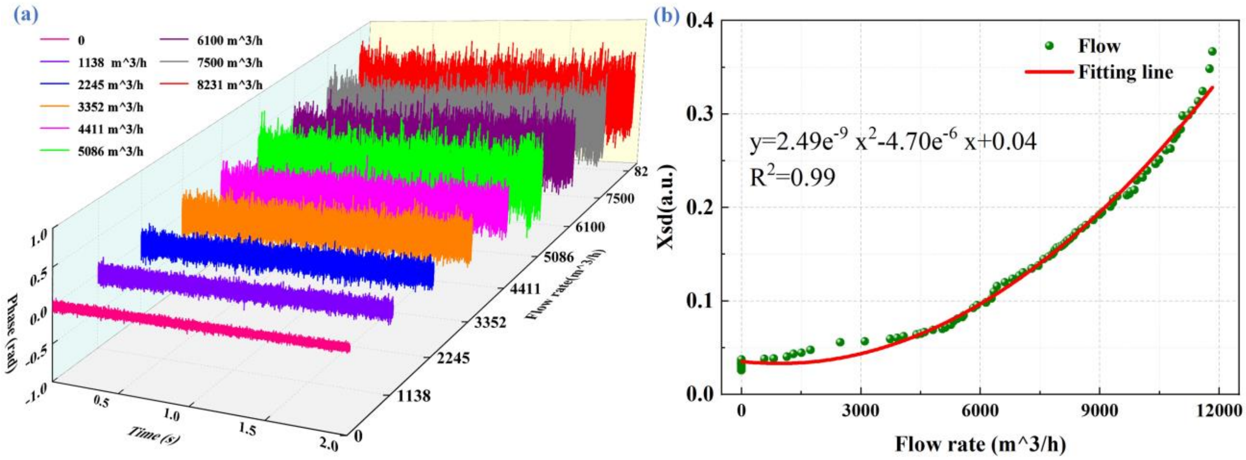

Fig. 2. (a) Flow vibration signal amplitude under different flow rates and (b)The relationship between the standard deviation of flow vibration signal and gas flow.

-ility, from Fig. 3 (c), we can derive that the flow error probability in the interval (−10%, 10%) reaches 89.59%, and it reaches 96.88 in the interval of −15% to 15%, and some other discrete error points may be caused by factors such as environmental noise.

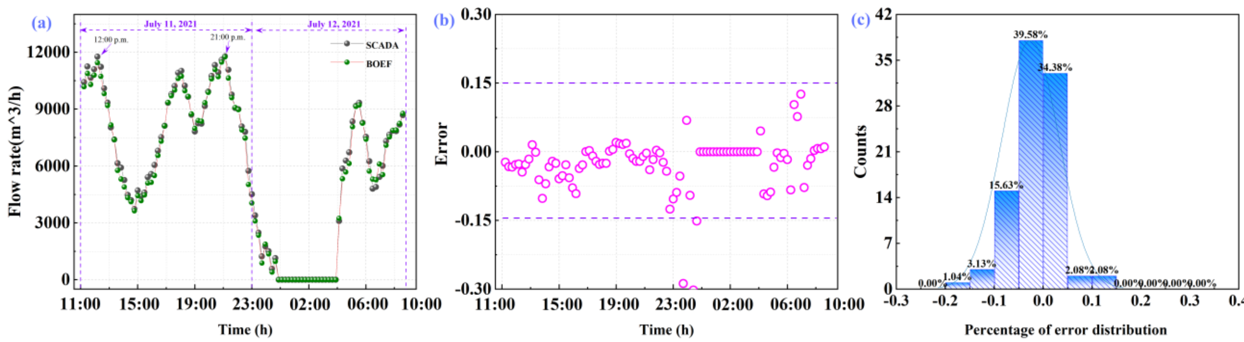

Fig. 3. (a). Comparison of flow fluctuation trends throughout the day monitored by BEOF and commercial SCADA, (b) The error probability in the interval -15% to 15%, (c) The percentage of error distribution.

4. Conclusion

We propose a non-intrusive, low-cost, real-time online gas flow monitoring scheme based on BEOF sensor DAS system. The field test results show the flow error probability can reach 96.88% in the interval −15% to 15%. To the best of our knowledge, this is the first time a DAS system has been used for online monitoring of gas flow. In the future, the system is expected to realize the integrity monitoring of gas pipeline network.

5. Acknowledgement

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6. References

[1] R. P. Evans, *et al.* "Flow Rate Measurements Using Flow-Induced Pipe Vibration," Journal of Fluids Engineering, **126**, 280-285(2004).
[2] R. D. Blevins, "Flow-induced vibration,", Van Nostrand Reinhold Co, New York, 1977, pp.377.
[3] Y. Shang, "Study of Non-intrusion Optical Fiber Fluid Flow Monitoring System Using Flow-induced Pipe Vibration," International Conference on Industrial Control and Electronics Engineering, IEEE, 1284-1286 (2012).
[4] M. T. Pittard, *et al.* ''Numerical Modeling of LES Based Turbulent-Flow Induced Vibration,'' ASME International Mechanical Engineering Congress & Exposition, Washington, D.C.
[5] A. L. Prashun, Fundamentals of Fluid Mechanics, Prentice Hall, Engle- wood Cliffs, NJ, 1980, pp. 202–222, Chap. 7.
[6] F. Ai, *et al.* "Wideband Fully-Distributed Vibration Sensing by Using UWFBG Based Coherent OTDR," Optical Fiber Communications Conference & Exhibition. IEEE, W2A.19.(2017).