FBG-based Sensor Applied to Volumetric Flow Rate Measurements on Flare Systems

Sensor Baseado Em FBG Aplicado A Medições De Vazão Volumétrica Em Sistemas De Queima

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ABSTRACT
The primary purpose of an offshore oil production platform flare is to ensure operational safety at the facility by safely disposing the gas whenever needed. This may involve handling of large amounts of gas over a short period of time. It is essential that any measuring equipment, installed in the burner line, does not obstruct the flow of gas, so as not to cause a significant pressure drop. For these types of measurements many sensor technologies are available, however they are all very expensive, in the order of several thousands of dollars. Therefore, this paper presents an optoelectronic sensor solution

characterized by its small dimensions, electromagnetic free interference and fast response time, besides its non-flammable property.

Keywords: flare, optoelectronic sensor, optical fiber, thermistors, fiber Bragg grating, cross-correlation, flow rate velocity.

RESUMO
O objetivo principal de uma queima de uma plataforma de produção de petróleo offshore é garantir a segurança operacional na instalação, eliminando o gás com segurança sempre que necessário. Isto pode envolver o manuseio de grandes quantidades de gás durante um curto período de tempo. É essencial que qualquer equipamento de medição, instalado na linha do queimador, não obstrua o fluxo de gás, a fim de não causar uma queda de pressão significativa. Para estes tipos de medições estão disponíveis muitas tecnologias de sensores, porém todas são muito caras, na ordem de vários milhares de dólares. Portanto, este artigo apresenta uma solução de sensor optoeletrônico caracterizada por suas pequenas dimensões, interferência livre de eletromagnética e tempo de resposta rápido, além de sua propriedade não-inflamável.

Palavras-chave: flare, sensor optoeletrônico, fibra ótica, termistores, grade de Bragg de fibra, correlação cruzada, velocidade de fluxo.

1 INTRODUCTION

The oil and gas industry are held responsible for the significant share of the greenhouse gas emissions. In the exploration and production of natural gas and oil, the gas which is burned in torches, known as flare or relief system, is a huge source of CO_2 emissions. In addition to contributing to global warming and climate change, the burning of natural gas is considered a waste of valuable, nonrenewable energy resource.

In this context, the need to quantify waste gas volumes correctly is evident. Actions to reduce the burning or ventilation of natural gas and the controls of the greenhouse gas emissions are based on accurate measurements. Due the importance of this fact, constant publications of regulatory directives are developed to the measurements of flare gas flow systems.

For the most part, these regulations establish levels of uncertainty for such measurements. In the United States, Canada and Brazil, operators are required to report ventilated or burnt gases within ±5% uncertainty of measurement. The European Union, on the other hand, applies a different approach when it comes to this subject. For example, in larger installations a larger level of measurement uncertainty is required: ±7.5%, then to ±12.5% for medium-sized installations and ±17.5% for small emitters [1].

Although flare gas measurement is not a novelty, it is still considered challenging and quite different from other flow measurement applications. The unpredictable nature of gas flaring in an often-inappropriate environment, for example, makes the measurement extremely difficult and complex, as well as the economic aspect that prevents very expensive systems from being applied.

The objective of this paper is to present the development of a volumetric flow rate sensor by the application of an optical fiber sensor based on Fiber Bragg Grating (FBG) and a cross-correlation technique.

2 CROSS-CORRELATION TECHNIQUE

Cross-correlation can be useful in many applications in order to calculate velocity. In [2] road traffic velocity was measured by a microphone, whereas in [3], cross-correlation was applied for particle image velocimetry using images of particles sprayed in the air.

By heating the flow and detecting the temperature pulse with high speed temperature sensors the authors in [4] measured fluid flow.

In [5] the respiratory flow was measured by a laser beam and two position sensor detectors (PSD) as sensors.

In [6] the main characteristics and steps for design and simulation of a thermal mass flow micro sensor of calorimetric type were described, aiming to measure flow rate and fluid velocity. The device was designed computationally and its applicability evaluated based on the simulation data.

Cross-correlation is used in signal processing and is defined as the correlation of a series against another series, shifted by a particular number of samples. Suppose two time series (x_k, y_k) having M samples each as in Eq.1 and Eq. 2:

$$[x_k] = [x_0, x_1, x_2, \ldots, x_{M-1}]$$
$$[y_k] = [y_0, y_1, y_2, \ldots, y_{M-1}]$$

Then the cross-correlation function, ϕ_{yx}, is defined as Eq. 3:

$$\phi_{yx}(\tau) = \sum_{t=0}^{M=1} x_t y_{t+\tau} \qquad (3)$$

Where τ is the time delay applied.

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The result of the cross-correlation is a measurement of similarity (in a range from 0 to 1) of the two signals against the displacement of them along the time.

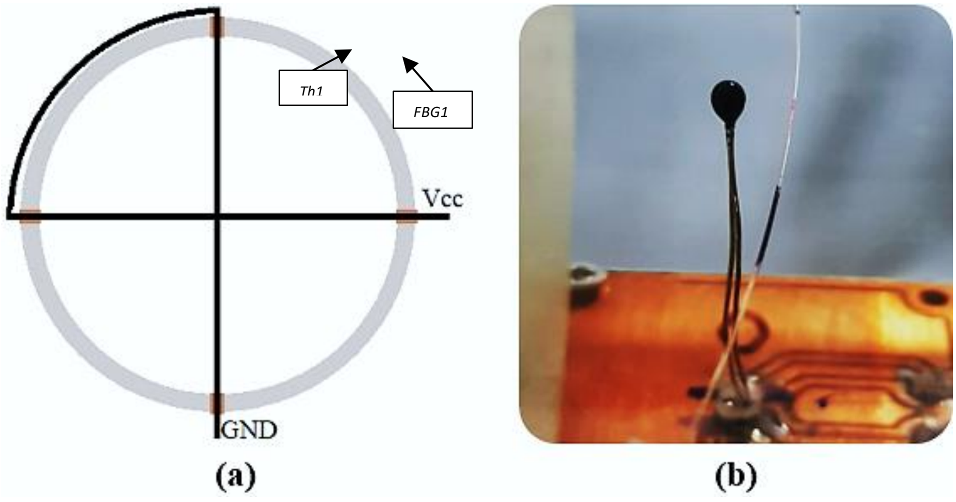
3 MATERIALS AND METHODS

The principle of measurement is based in the transit time of a heat pulse between two temperature sensors separated by a known distance inside the wind tunnel. Then, by applying a random current signal in a resistive heat source, the random signal will be transformed into a random heat signal that will be flowing inside the tunnel with the speed of the gases. As both sensors, the thermistors (*Th1* and *Th2*) and the FBGs (*FBG1* and *FBG2*) receive this heat flow, they will respond accordingly but with a time delay. The cross-correlation, therefore, can detect these few-milliseconds of delay between the signals. Thus, the flow velocity will be calculated by the ratio between the sensors distance and the time delay.

For a proof of concept, it was constructed a small bench-operated wind tunnel prototype. The objective is initially to implement the measurement system using thermistors as transducers and, after the proof of concept evaluation stage, the system was installed in a large-scale wind tunnel with both thermistors and FBGs.

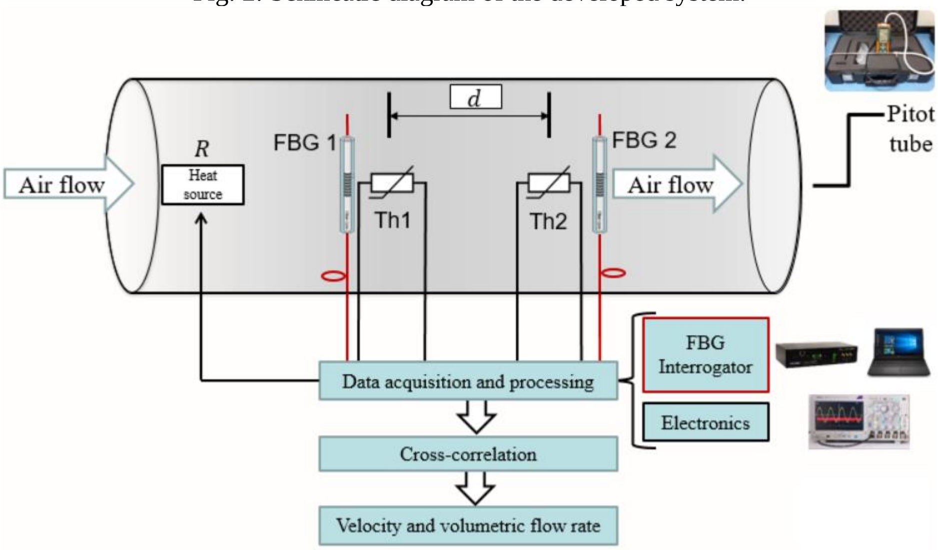
The heat source consists in a 2-Ω resistive wire driven by a current amplifier that receives a random signal from a signal generator. The resistive wire was installed inside the wind tunnel in a cross format, as shown in Fig. 1 (a). Figure 1 (b) shows a picture of the thermistor soldered on a small printed circuit board and the FBG, both inserted inside the tube.

Fig. 1: (a) The heat source is developed through a resisitive conductor (black line) through the cross section of a 2-inch-real-scale wind tunnel (gray line). (b) A picture of the sensors Th1 and FBG1 inserted on the wind tunnel.



The schematic diagram of the developed system is shown in Fig. 2, where *d* is the distance between the two temperature sensors. *Th1* and *FBG1* are the temperature sensors of the proximal location (close to the heat source), while the *Th2* and *FBG2* are the sensors of the distal location. The heat source is represented by *R*.

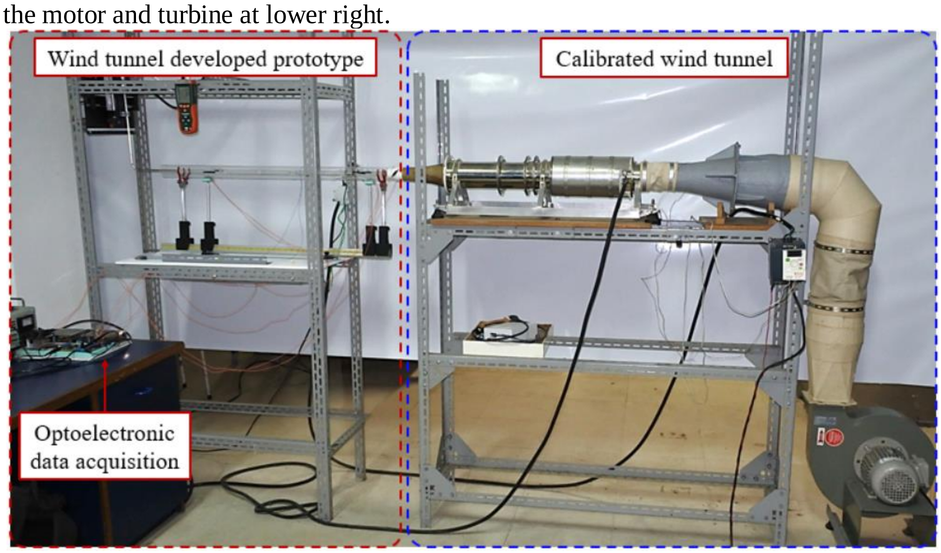
Fig. 2: Schmeatic diagram of the developed system.



The airflow is obtained by a fan, driven by a three-phase induction motor controlled by a frequency inverter. Therefore, the airflow velocity can be controlled by the motor speed and monitored by the Pitot tube used for calibration.

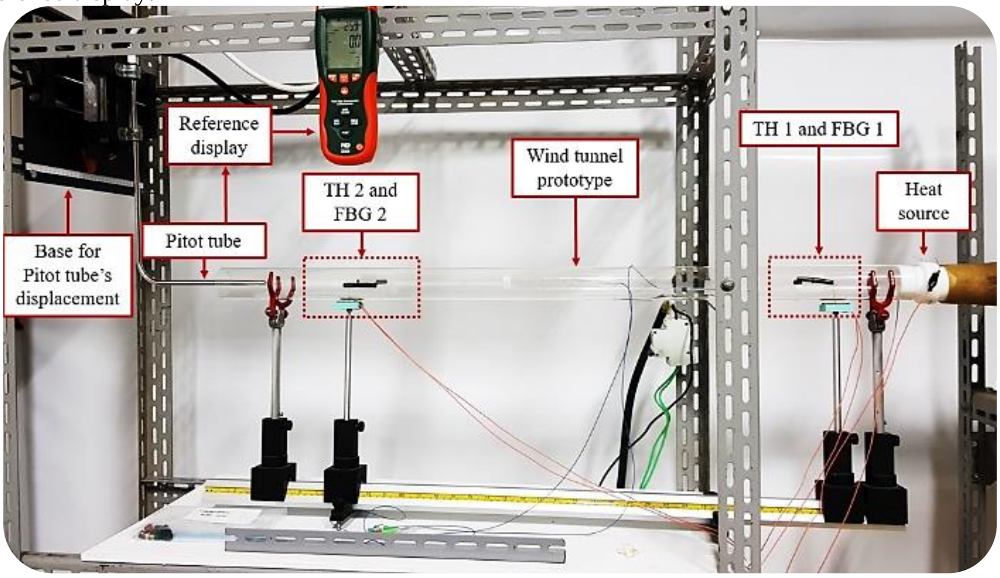
Figure 3 shows a picture of the full system with the wind tunnel developed prototype and the calibrated wind tunnel. Additionally, Fig. 4 shows a detail of the developed wind tunnel indicating the location of the sensors.

Fig. 3: A picture of the full system with the calibrated wind tunnel and the wind tunnel developed prototype showing the motor and turbine at lower right.



The left dotted box of Fig. 3 is shown in details in Fig. 4.

Fig. 4: A detail of the wind tunnel developed prototype showing the sensors location and the Pitot tube with its reference display.



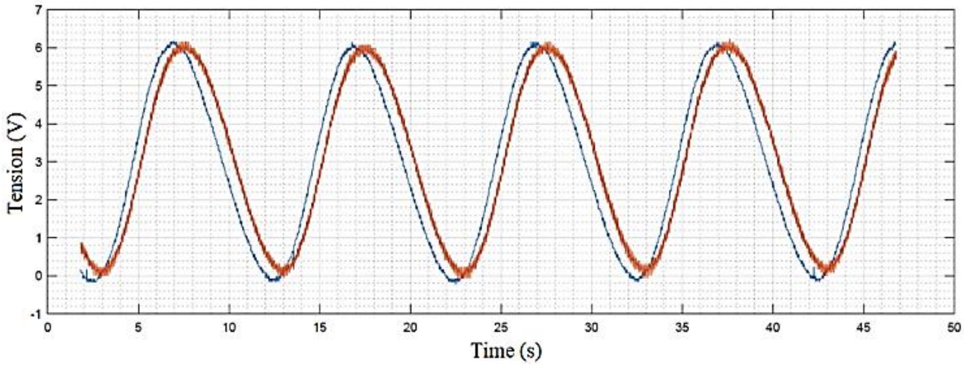
4 RESULTS AND DISCUSSION

4.1 TESTS WITH THERMISTORS AS TEMPERATURE SENSORS

By applying a sinusoidal current waveform on the heat source, a sinusoidal temperature variation is created inside the flow. When this temperature profile reaches the thermistors, they will respond accordingly, both producing an approximately sinusoidal output. There are though, two main differences between these two signals. The first one is that, due to the fact that the heat produced will be vanishing along the tube, the proximal thermistor will experience a higher temperature variation than the distal thermistor. The other difference is that both signal will be delayed in phase due to the time that the flow takes to reach the distal thermistor after reaching the proximal one. The distance between the two thermistors divided by the time delay will give the desired the flow velocity. However, as the two signals are not perfectly sinusoidal waveshapes, the time delay estimation is not straightforward; it can only be calculated by applying the cross-correlation between these signals.

Figure 5 shows the signals collected from each Wheatstone bridge, where the thermistors are inserted, for a flow rate of 5 m/s. The blue line represents the output from the proximal thermistor while the red line represents the output from the distal thermistor, 70 cm away.

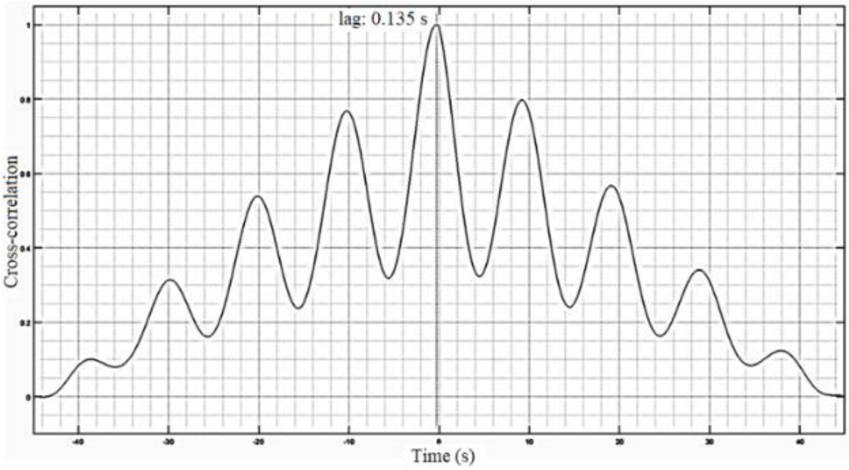
Fig. 5. The signals produced by the thermistors at a flow rate of 5 m/s. It is possible to notice the phase delay between them.



In order to see clearly the time delay between these signals we amplified the signal from the distal thermistor to become superimposed over the proximal thermistor. Notice the distinguishable delay between them.

Figure 6 shows the result after application of the cross-correlation algorithm (run in Matlab ®) on the signals shown in Fig. 5. The maximum probability occurred in 0.135 s.

Fig. 6: The cross-correlation results. Y-axis plots the probability of similarity whereas X-axis plots the time delay.



With the calculated delay with maximum probability of 135 ms, corresponding to the lag time that the heat pulse takes to travel 70 cm from the upstream sensor to the downstream sensor, it is possible to calculate an airflow velocity at 5.19 m/s.

There were tested four different velocities producing a linear regression with $R^2 = 0.9842$. The turbine was adjusted in order to measure velocities of 1 m/s, 2 m/s, 3 m/s and 4 m/s (measured with the Pitot tube). The proposed system measured, respectively, 0.75 m/s, 1.50 m/s, 3.25 m/s and 3.97 m/s.

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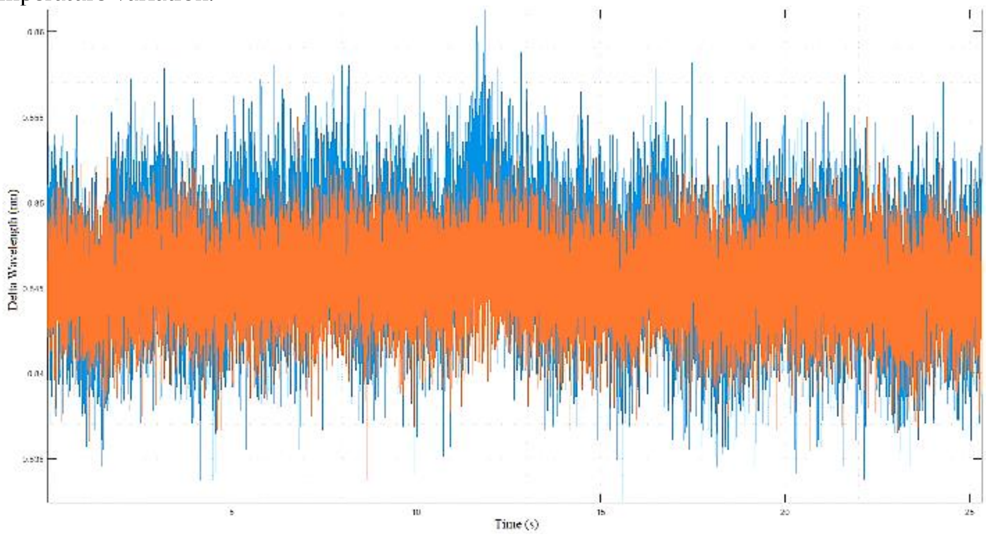
4.2 TESTS WITH FBGS AS TEMPERATURE SENSORS

After the proof of concept tested with thermistors, we inserted one FBG close to each thermistor and used a commercial FBG interrogator the read the wavelength variations of the FBGs. The interrogator (Micron Optics si155) reads the center wavelengths of each FBG correlating these values with the temperature. As the response time of the interrogator is about 1 ms for each reading and the wavelength resolution is about 2 pm. Although the primary results with FBGs, we did not get results as good as with the thermistors. Figure 7 shows the response of the two FBGs for an arbitrary waveshape.

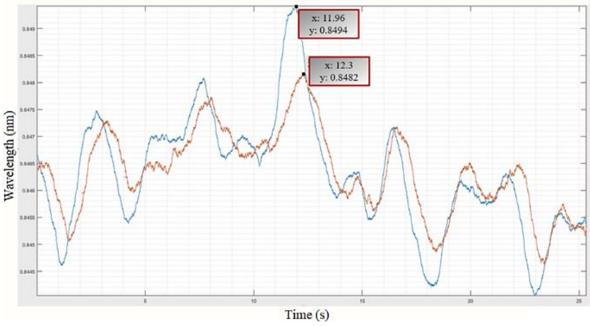
Fig. 7: Signals produced by the FBGs at a flow rate of 5 m/s. The signal-to-noise ratio is too large to notice any temperature variation.



Notice that the signal-to-noise ratio is inverted, that is, the noise is larger than the signal and, as expected, no response was possible with the cross-correlation technique. On the other hand, by applying a moving average on the signals presented in Fig. 7, we end up with the signals shown in Fig. 8. It is possible to notice that the temperature pulse measured by the downstream FBG is only about 0.3ºC, which is obviously much below the interrogator sensitivity.

Now, by applying the cross-correlation algorithm to these signals, no response is obtained as the downstream pulses are much different from the upstream pulses and the cross-correlation technique detects just the similarities between two signals.

Fig. 8: Results for a 2.2 m/s airflow detected by the FBGs.



However, it is possible to observe a time delay of about 340 ms between the signals. Once the distance between the FBGs was 70 centimeters, the estimated velocity was approximately 2.1 meters per second which is close to the value from the reference sensor.

5 CONCLUSIONS

A new methodology to measure volumetric flow rate inside flare ducts based in FBG and through cross-correlation technique was presented for possible applications over oil platforms and refineries.

The thermistors presented a linear behavior up to a velocity of 5 m/s as this was the limitations of the oscilloscope data logger. The FBGs response did not correlate due to limitations of the commercial interrogator.

The preliminary results with the thermistors proved the proof of concept of the proposed technique.

The twin-FBG technique will be applied to interrogate the FBGs in order to improve resolution and allow the use of the cross-correlation algorithm to measure the time delay.

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