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High Sensitivity Hot-wire based Wind Velocity Sensor using Co-doped Fiber and Fiber Bragg Grating for use in mining applications

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Abstract. In this paper, a mathematical model of the temperature distribution in a fiber-optic version of the familiar 'hot-wire' wind velocity sensor has been established and a practical sensor device realized and investigated for use in coal mining applications. The relationship between the dynamic measurement range, the sensitivity, the sensor probe surface heat transfer coefficient and the wind speed (in the region where the sensor probe is located) has been investigated. The veracity of the predicted performance of the fiber-optic hot-wire mathematical model has then been verified by experiment. The sensitivity of the sensor probe to wind velocity was measured across several wind velocity ranges to be ~1500pm per unit m/s wind velocity (in the range of 0 – 0.5 m/s), ~330pm per unit m/s in the range 0.5 – 2 m/s and ~50pm per unit m/s in the range of 2.0 – 4.5 m/s.

1. Introduction

Sensors to measure wind velocity are important for a number of applications and considerable research has been carried out over the years, using a range of techniques. An important area where such measurements are needed is in coal mine ventilation, and here few sensors can meet the requirements of high accuracy and low wind speed monitoring, coupled to intrinsic safety in the potentially flammable atmosphere of the coal mine. In addition, the problem is exacerbated by the particular characteristics of the underground environment and the nature of the wind field seen in the mine[1]. Currently, various methods for wind velocity measurement have led to the development of a range of different transducers, such as hot-wire sensors, impeller sensors, differential pressure sensors and ultrasonic swirl sensors[2], for example. Looking at their characteristics in some detail, impeller wind velocity sensors are vulnerable to contamination by water vapor and coal dust in particular, resulting in impeller rotation resistance being increased, and thus both greater measurement error and a reduction in the useful working lifetime of the sensor [3]. Ultrasonic vortex wind velocity sensors are currently popular, but due to their complex structure they are difficult to maintain and easily affected by the environment, making them not well suited to mine monitoring systems [4]. Differential pressure wind velocity sensors are commonly used in coal mines, but the nature of the sensor design means that they have limited usefulness, achieving only a narrow wind velocity monitoring range and low accuracy for low wind speed measurements[5]. The major problem with all of these is that traditional wind velocity sensors used in coal mines determine the wind speed measurement directly or indirectly through a correspondence between an electrical signal and the wind speed (which is not intrinsically safe) and thus there is the potential for 'spark hazards' which could cause gas explosions. Optical fiber sensing technology offers intrinsic safety at the low optical power levels used in these sensors and in addition freedom from electromagnetic interference. They can be configured as light weight and low power devices, making them especially suitable for use in mines and in areas where flammable and explosion hazards can occur[6].

In this work, a fiber-optic hot-wire wind velocity sensor is discussed, which measures the wind speed by means of the same principle used in the conventional, electrical 'hot wire' anemometer, where the amount of heat coupled to the air flowing over the heated active sensor element can be directly related to the wind velocity. Such a scheme can be configured to be very sensitive to low wind velocities, such as are experienced in coal mines and where such intrinsic safety is particularly important. The work has directed to optimizing the efficiency of the light applied to the heating of the sensor element, coupled to good thermodynamic model analysis to enhance the sensor probe characteristics [7,8]. In this paper, the fiber-optic hot-wire sensing mechanism is analyzed, through a heat transfer model for a fiber-optic hot-wire sensor, focusing on the factors that affect its dynamic measurement range and sensitivity. A probe device, based on this, has been constructed and its performance assessed in light of operation in the demanding conditions of coal mines.

2. Sensing Principle and Model

The basic sensor principle is based on the heating of an optical fibre by a laser beam, and its cooling by the wind, allowing the wind velocity is to be measured. The principle is of a heated optical fibre, connected to a heat insulating material where the heated fibre is then cooled by the wind blowing over it. The heat is generated by the photothermal conversion effect in the (cobalt-doped) fiber and it's magnitude is given by Q. In the analysis carried out, it is assumed that one part of this, Q_1 is trapped inside the sensor element to increase the internal energy and the other part, Q_2, is used to exchange heat with the outside fluid (the air flow). Therefore

$$Q = Q_1 + Q_2 \tag{1}$$

The heat conduction loss Q_{cond}, the convection loss Q_{conv} and the heat radiation loss Q_{radi} are now considered. The radiation heat transfer Q_{radi} is relatively small compared to the convective heat transfer Q_{conv}, (ignoring the influence of radiative heat transfer), so $Q=Q_1+Q_{conv}$ represents a heat transfer model with an internal heat source, where the derivative differential equation that represents the situation is given by[9]:

$$Q' = \rho c V \frac{\partial t}{\partial \tau} + hA(t - t_0) \tag{2}$$

where Q' is the time derivative of Q； ρ, c, V, h and A indicate the density, specific heat capacity, volume, heat convection heat transfer coefficient and heat dissipation area of the sensing element respectively, t indicates the temperature and t_0 is the initial temperature where τ represents the time.

When the sensor reaches a steady-state equilibrium, the temperature no longer changes, and the heat generated by the internal heat source is equal to the amount of heat lost, so:

$$Q = hA\Delta t \tag{3}$$

Thus for the Fibre Bragg Grating (FBG) in the fibre which is affected by this, there is a corresponding wavelength change given by:

$$\lambda = \lambda_0 + k\Delta t \tag{4}$$

where λ is the FBG wavelength after the heating/cooling process is applied, λ_o is the original FBG wavelength and k is the fiber grating temperature coefficient. When using this approach in an actual sensor, a simpler heat dissipation formula, King's law, can be used where [9]:

$$N_u = A_c + B_c R_e^{\frac{1}{2}} \tag{5}$$

In this formula, N_u is the Nusselt number, A_c and B_c are constants that depend on the state of the fluid, and R_e is the Reynolds number.

Based on the above formula, the expression for the sensor dynamic range (which corresponds to the change in the wavelength of the FBG used), Δλ, and the response time, τ, is given by:

$$\Delta\lambda = \frac{k v^{\frac{1}{2}} l_2 Q}{k_w \left(A_c v^{\frac{1}{2}} + B_c l_2^{\frac{1}{2}} u^{\frac{1}{2}} \right) A} \tag{6}$$

where v, u and k_w is the kinematic viscosity coefficient, the velocity and the thermal conductivity of the fluid respectively. l_2 is the characteristic length of the sensing element.

It can be seen from the above equations that the wavelength change experienced by the FBG is proportional to the heat capacity of the bushing (used to house the sensor, as seen in Figure 2 below) and also inversely proportional to the speed and heat dissipation area of bushing used.

3. Hot-wire based fiber optic wind velocity sensor design

Based on the above analysis, the fiber-optic hot-wire sensor probe was designed and built, following which its performance was evaluated. The design, shown in Figure 1, consists of a Fiber Bragg Grating (FBG) in one fiber, a further co-doped fiber, a bushing and a thermally insulated base. The fiber grating and the co-doped fiber are inserted, side-by-side, in a packaging outer copper tube with an inner diameter of 0.6 mm and a wall thickness of 0.1 mm. This is filled with silicone oil to allow good thermal conduction and thus to form the complete sensing element of the fiber optic hot wire sensor probe device. One end of the sensing element is brazed to the heat insulating material (to reduce the heat loss caused by the heat conduction of the sensing element) and this design improves the sensitivity of the device. According to the analysis above, the thermal resistance in the sensor element is much smaller than the convection thermal resistance. The mathematical model reported above enables the correspondence between the wind speed and the center wavelength change of the FBG to be estimated. The sensor probe, as shown, is relatively small, has low thermal mass and simple in structure making it relatively inexpensive and convenient to use in different applications.

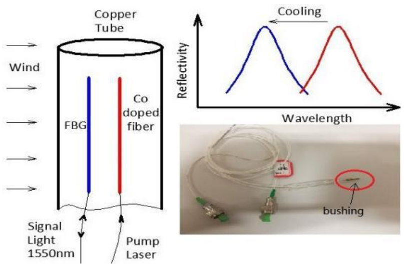

Fig. 1 Schematic of the sensor probe (left), the FBG wavelength change with heating (red) and cooling (blue) (top) and a photograph of the sensor probe showing its small size and compact packaging

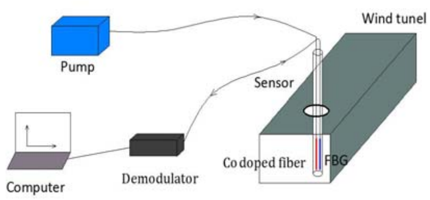

Fig. 2 Schematic of the fiber-optic hot-wire sensing system showing the laser pump, the demodulator/FBG interrogation system, the probe placed in a wind tunnel for testing and evaluation and the computer where the outputs are visualized

The fiber optic hot wire sensor system is shown schematically in Figure 2. The pump light source used operates at a wavelength of 1480 nm, with the laser power being controllable over the range 0-500mW, with a 1kHz commercial fast fiber grating interrogator used to determine $\Delta\lambda$. The pump light source is connected to the co-doped fiber and the interrogator to the fiber with the FBG, both in the sensor probe. In operation, the co-doped fiber converts the input light energy into heat energy from the laser pump source, as a result of which the temperature around the FBG rises, and its central wavelength shifts (towards the red, this depending on the power applied). Convection-based heat transfer occurs when the fluid flows through the bushing surface, heat is dissipated, the temperature around the FBG decreases, and its central wavelength shifts in the opposite direction (towards the blue) as the probe cools.

4. Experimental Evaluation of the System

Three different versions of the fiber-optical hot-wire sensor probe, shown in Figure 1, were manufactured and evaluated. These are designated Probes 1, 2 and 3. Probes 1 and 3 were copper sleeved, with lengths of 13mm and 18mm respectively and Probe 2 was in Teflon tube, with length of 13mm. In still air (and thus under the condition of no wind blowing) the power of the pump light source was adjusted so that the co-doped fiber absorbs the pump laser to allow photothermal conversion to occur. As a result of the thermal transmission, the FBG in the other fiber experiences a wavelength shift due to the heating effect. A series of experiments was carried out to determine the level of wavelength shift with applied optical power to the co-doped fibre, for the three probes discussed. The experimental results are shown in Figure 3.

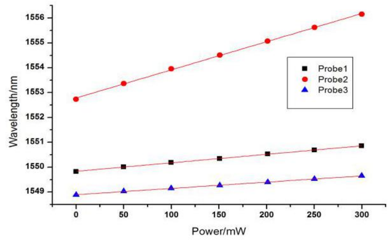

Fig. 3 Wavelength variation of the FBG in the parallel fiber with laser power applied to the co-doped fiber, for three different probe designs

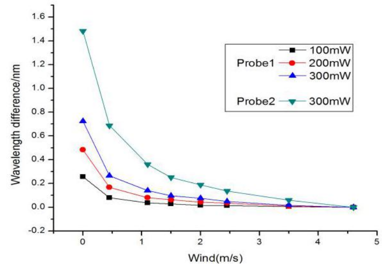

Fig. 4 FBG wavelength in Probes 1 and 2, with change of wind speed, under the laser power levels in the co-doped fiber shown

Figure 3 shows that the FBG wavelength changes linearly with the power of the pump light source in the co-doped fiber. The sensitivity of the copper sleeved sensor probes, Probes 1 and 3, was found to be 3.4pm/mW and 2.5pm/mW respectively, while the sensitivity of the Probe 2 (with a low heat transfer coefficient material packaging) was 11.3pm/mW. This also shows the predicted linear relationship between the power applied to the co-doped fibre (and transferred to the fibre with the FBG). Further, comparing Probes 1 and 3, the shorter probe has a higher sensitivity (of these two) while Probe 3 with the low heat transfer packaging material shows the highest sensitivity of any of the three. The probes were now subjected to flowing air in the test wind tunnel. Given its higher sensitivity (over Probe 3), Probe 1 was selected and its performance compared with that of Probe 2.

From the results obtained, it can be seen that with the increase of wind speed, the FBG wavelength change observed is non-linear, with a higher sensitivity of each probe to wind velocity in the low velocity (0 – 1 m/s) range. This occurs irrespective of the laser power applied to the co-doped fiber. The probe sensitivity was determined to be ~1500pm/(m/s) when the wind speed is in the range of 0 – 0.5m/s, ~330pm/(m/s) in the range of 0.5 – 2m/s, and ~50pm/(m/s) in the range of 2 – 4.5m/s.

5. Discussion

Using the principle of the hot-wire sensor, combined with the optical fiber sensing characteristics, this paper has reported on both a theoretical analysis and the results of experiments carried out with different probe designs for wind velocity measurement. Theoretical analysis shows that the dynamic range and sensitivity of the probe designs are related to the power of the light source used, the wind velocity and the heat transfer coefficient of the hot-wire sensor package. The results show that the fiber-optic hot-wire wind velocity sensor is particularly sensitive at low speeds and has excellent performance. Work is on-going to improve the device and the next step will be to study how to increase its upper limit of measurement.

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