High Sensitivity ‘Hot-wire’-based Gas Velocity Sensor for safe monitoring in mining applications

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Abstract: In this paper, building on a design developed from an advanced mathematical model, a practical fiber optic sensor, which is an analog of the familiar ‘hot-wire’ wind velocity monitor, has been developed, as an intrinsically-safe sensor device for use on coal mining monitoring applications. The device response time, the dynamic measurement range, the sensitivity, the sensor probe surface heat transfer coefficient and the effect of the wind (gas) velocity has been investigated in the laboratory and *in situ* and results reported, enabling the mathematical model used in the design process to be validated. The underpinning optical fiber-based principle used is the shift in the center wavelength of a Fiber Bragg Grating which is cooled by the gas flowing over it and the device sensitivity found was determined 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. In the ‘proof of concept’ tests carried out, it was found that the greater the surface dissipation factor of the sensor, the shorter was its response time. Further, the response time was seen to decrease as the wind velocity increased, showing a typical value of 6s, which is suitable for the mining applications envisaged.

Key words: fiber-optic gas velocity sensor; hot-wire technique; probe sensitivity and response time

Introduction

Wind velocity measurement plays an important role in the fields of coal mine gas clearance, roadway ventilation and fire safety warning and is an important measurement parameter both in scientific research and many areas of industrial production. As sensors to measure gas/wind velocity are important for a number of such applications, considerable research has been carried out over the years into optimizing their design and performance, using a range of transduction techniques including fiber optic-based methods[1]. Most devices involve traditional electronic sensor methods, including volumetric measurement, turbines, differential pressure monitoring, ultrasonic measurements or electromagnetic flowmeters[2-6], for example. Intrinsic safety is required for applications such as coal mining and with the electrical methods mentioned amongst the above examples, there is the potential for ‘spark hazards’ which could cause explosions of flammable gases e.g. methane which can build up in mines. Optical fiber sensing technology offers the intrinsic safety required from an ‘all-optical’ measurement approach, at the low optical power levels used in these sensors, with the added benefit of the absence of electromagnetic interference. This allows the development of typically light weight, low power sensors which can readily be placed at considerable distances one from another in a mine (which may be of several kilometers in length) and thus may be sited where flammable gases and explosion hazards can occur[7].

The ‘hot-wire’ anemometer (HWA) is an important type of device that has previously been extensively investigated[8,9] as a familiar electrical device and in its *optical* analog can be used to measure the wind speed on the basis of a similar principle to the electrical ‘hot wire’ anemometer. The underpinning principle is that heat is lost to the air flowing over the heated active sensor element, and this is then related to the flow of gas over the heated element (the ‘hot wire’) and calibrated against the gas velocity. Such a device can be made very sensitive to low wind speeds, such as are experienced in coal mines and thus to be well suited to the application under consideration.

In prior work, Chen et al. (in 2005) have proposed a Fiber Bragg Grating (FBG)-based single-point flow sensor using multi-mode fiber fused to single-mode fiber, so that most of the laser energy is coupled (even with the different mode field diameters seen). A metal coating was placed on the fiber (allowing it to be heated and then cooled in the gas flow), this showing a similar sensitivity to a commercial MEMS-based flow sensor. However the device suffers from a low coupling efficiency, being strongly dependent on the light source used and is thus prone to poor overall performance[10]. In 2006, the same experimenters proposed an ‘X-type cross-section’ distributed multi-point flow sensor which was designed to be used to measure the magnitude and direction of the wind speed. This however used an expensive, high power Ar-ion laser (which required a high current power supply) operating in the green part of the spectrum (514.5 nm) with a view to improving the photothermal conversion efficiency[11]. Also in 2006, Caldas et al. reported a flow sensor that combined a long-period fiber grating (LPG) with a Fiber Bragg Grating (FBG), thus improving the performance of the sensor[12]. In 2011, Zhang Aping et al. proposed a cobalt-doped optical fiber (CDF) containing a FBG, to absorb light from specific pump lasers, to create a sensor designed to achieve good flow rate measurements and incorporating a 'compensation grating' whose purpose was to compensate for the influence of ambient temperature. In this design, a polymer film was coated on the sensor grating to reduce the temperature sensitivity and improve the dynamic measurement range[13]. Further research in 2012 and 2013 by Dong Xin et al. reported an optical Fiber Bragg Grating dot-type active flow sensor design based on dislocation-bonded and non-core optical fiber fusion, using techniques which included dislocation welding, coreless fiber fusion and other methods to avoid the complexity of the doping fiber grating writing. In this approach, through the use of a relevant fusion method to improve the pump light coupling efficiency and to increase the measurement range, higher sensitivity in the high flow rate[14,15] can be achieved. In 2015, Ming Han et al. showed that the sensor, when heated by light from a visible laser and interrogated by broadband infrared (IR) light, has the ability to distinguish signals from wind speed monitoring through better controlling the laser power causing heating and observing the fringe shifts from the cooling effect due to the varying wind speeds[16] across the probe. Jie Wei et al. reported (in 2016) a device based on a combination of two FBGs surrounding a section of cobalt-doped optical fiber (FBG-CDF-FBG). Thus a Fabry Perot (FP) structure was created, with the resonance peak of the FP interferometer being changed as a result of the temperature change of the CDF section. The FBG spectrum was recovered by fitting the FP spectrum to a model used to represent the change of the ambient temperature and thus a self-calibrated sensor can be realized[17]. Wang et al. have also proposed, in 2016, an interesting low-power-consumption fiber-optic anemometer design based on a metal-filled micro-structured optical fiber (MOF) and a FBG. A special six-hole MOF was designed and then fabricated, to allow both FBG inscription and metal infiltration. The metal-filled fiber anemometer designed in this way exhibits a high level of light-heat conversion efficiency, with a significantly low pumping power (of less than 10mW[18]) than was seen in previous designs, in spite of the complexity of the fiber filling process. A compact and low-power consuming fiber-optic anemometer based on a single-walled carbon nanotube- (SWCNT) coated tilted Fiber Bragg Grating (TFBG) has been presented by Yang Zhang et al. in 2017, and which shows high sensitivity at low wind speed. In this device, the output power of the broadband source was increased gradually, from 3.3 to 26.9mW (5.17-14.3dBm) and the wavelength response showed a linear red shift with an efficiency of 0.019 nm/dBm[19].

In summary the above studies, whilst having shown progress over a number of years, have mainly achieved this by including modifications to the fiber geometry, (such as bending, tapering, and creating air holes in the fiber) and having a mismatched fusion coupling of a multimode fiber to a single-mode fiber to form a FP cavity, together with fiber gratings inscribed in a cobalt-doped fiber, as well as using a range of coatings and an unusual fiber metal filling method. However, they still show several problems when applied to the design of a better and more effective fiber optic 'hot wire' sensor for the mining application that is the subject of this work. Firstly, the change in the fiber geometry typically weakens the inherent fiber strength and secondly, the co-doped fiber engraving process to form gratings is complicated and occasionally the gratings formed are inadventently 'chirped', leading to unreliable performance. Thirdly, while the use of metal coatings and metal fillers reduce the overall power consumption of the device, this is achieved at the expense of the simplicity of the sensor, whilst reducing utility and increasing cost and complexity in the fabrication process to reproducibly and consistently fill the microstructured fiber with metal. Furthermore, most of the work reported to date on fiber optic hot wire anemometers has been focused on research into new methods for improving the conversion efficiency of light to heat, as well as employing better temperature compensation methods. A more fundamental approach has significant value – whereby an effective sensor thermodynamic model is created and analyzed to improve the design of the sensor probe for a specific application (such as the mining application which is the focus of this work). Building on that in this paper, a fiber-optic hot-wire sensing mechanism model has been created, analyzed and used with experimental methods then combined, to establish an effective heat transfer model approach to a better fiber-optic 'hot-wire' sensor. To do so allows tackling the factors influencing the dynamic measurement range, sensitivity, and response time of the sensor which are needed, to provide a theoretical reference for the design, packaging, and application-area of the fiber-optic hot-wire sensor design that results. Thus the packaged sensor design created is discussed in detail in the following sections.

1 Sensing Principle and Mathematical Model

The underlying approach to the sensor design is based on the heating of an optical fiber by light from a laser beam, and its cooling by the gas flowing over it (in this application, air) and where the gas/wind velocity is to be measured. The basic measurement principle analyzed is of a heated optical fiber which is connected to a heat-insulating material where the heated fiber is then cooled by the mass of the gas blowing over it, allowing the wind velocity to be measured. The heat in the fiber is generated by using the photothermal conversion effect in the (cobalt-doped) fiber, and this is given by the factor Q in the model. In the analysis carried out, it is assumed that one part of this, given by Q_1, is trapped inside the sensor element to increase the internal energy and the remaining part, Q_2, is used to exchange heat with the outside fluid (through 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 the equation Q = Q_1 + Q_{conv} represents a suitable heat transfer model with an internal heat source, where the derivative differential equation that represents the situation is given by[20]:

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

Here Q' is the time derivative of Q, the factors 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 real-time temperature and t_0 is the initial temperature, where τ represents time in the equation.

When the sensor reaches a steady state equilibrium under a particular power level applied from the optical source, the temperature rises (and is assumed to be t_w), so the following formula for Q' can be obtained and is given by:

$$Q' = -hA(t_w - t_0) \tag{3}$$

When the sensor is placed in the air flow whose velocity is to be measured, the temperature gradually decreases as the wind speed increases and this situation is given by:

$$\frac{\theta}{\theta_0} = \frac{t_w - t}{t_w - t_0} = e^{-\frac{hA}{\rho c V}\tau} \tag{4}$$

where $\theta = t_w - t$ represents the difference between the sensor temperature in real time and the steady-state temperature ultimately achieved, $\theta_0 = t_w - t_0$ indicates the maximum temperature difference achieved when the sensor is in use.

When the sensor is placed in the flow field and the air velocity gradually decreases, the temperature gradually rises, as is given by Equation (5).

$$\frac{\theta}{\theta_0} = \frac{t - t_0}{t_w - t_0} = 1 - e^{-\frac{hA}{\rho c V}\tau} \tag{5}$$

In the above equation, t_0 indicates the initial temperature, the quantity $\frac{\rho c V}{hA}$ is the time constant, which is denoted by τ_c[20]. From the above analysis, it can be seen that the relationship between the temperature and the time during which the heated element is heated or cooled is shown in Figure 1.

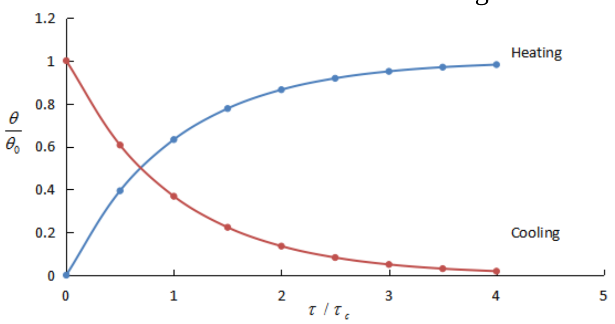


Fig. 1 The relationship between temperature and the normalized heating (blue) and the cooling (red) times

From the above figure, it can be seen that as the wind velocity increases and then decreases (that is when θ/θ_0 is equal to 63.2% and 36.8% respectively), the time τ associated with that is defined as the response time constant and expressed as τ_c. (When the wind speed decreases, due to the heating effect the maximum temperature rise is θ^0, but when the time is given by $\tau = \frac{\rho c V}{hA}$, the temperature increases by θ, where the value of θ has then reached 63.2% θ^0. In the heat transfer process, the specified time $\tau = \frac{\rho c V}{hA}$ is termed the *time constant*).

A fast response time for the sensor is desirable and θ can be used to replace θ^0 in the sensor system algorithm. The results for θ/θ^0=63.2% can be deduced from Equations 2, 3 and 4 and also for the cooling process θ/θ^0=36.8% can be deduced from Equations 2, 3 and 5. 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, and hence:

$$Q = hA\Delta t \tag{6}$$

Thus for the Fiber Bragg Grating (FBG) in the optical fiber which is affected by this thermal effect, there is a corresponding wavelength change given by:

$$\lambda = \lambda_0 + k\Delta t \tag{7}$$

where λ is the FBG wavelength after the heating/cooling process is applied, λ_o is the original FBG wavelength (under ambient conditions) and k is the Fiber Bragg Grating temperature coefficient. When using this approach in an actual sensor, a simpler heat dissipation formula, King's law, can be used where:

$$N_u = A_c + B_c R_e^{\frac{1}{2}} \tag{8}$$

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[20] of the fluid.

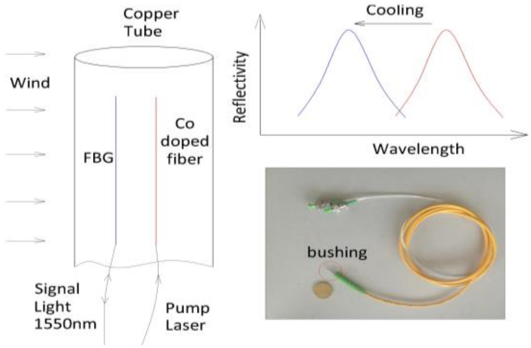
Based on the above formula, the expression for the sensor dynamic range (which corresponds to the change in the wavelength of the FBG used), Δλ, and the time, τ, is given by:

$$\begin{cases} \Delta\lambda = \dfrac{k v^{\frac{1}{2}} l_2 Q}{k_w\left(A_c v^{\frac{1}{2}} + B_c l_2^{\frac{1}{2}} u^{\frac{1}{2}}\right)A} \\ \tau = \dfrac{\rho c V v^{\frac{1}{2}} l_2}{\left(A_c v^{\frac{1}{2}} + B_c l_2^{\frac{1}{2}} u^{\frac{1}{2}}\right)A} \end{cases} \tag{9}$$

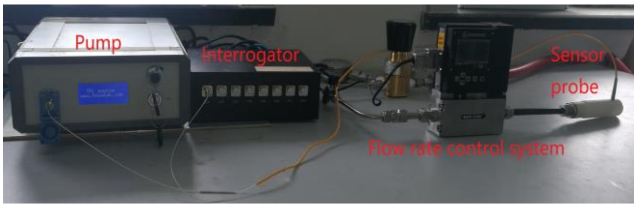
It can be seen from the above equations that the wavelength change experienced by the FBG and the response time of sensor are both proportional to the heat capacity of the copper tube (used in practice to house the sensor, as shown in Figure 2 below) and also inversely proportional to the speed and heat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

2 'Hot-wire' based fiber optic wind velocity sensor design

Based on the above analysis, a practical fiber-optic 'hot-wire' sensor probe was designed and built, following which its performance was evaluated. The design, shown in Figure 2, uses the principles established in the analysis and consists of a Fiber Bragg Grating (FBG) in one fiber, a further co-doped fiber, a bushing and a thermally insulated base. The FBG and the co-doped fiber are inserted, side-by-side, into a 'packaging' designed for the purpose and consisting of an 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. One end of this is then 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 device sensitivity. The modelling carried out and reported above shows that the thermal resistance in the sensor element is much smaller than the convection thermal resistance and enables the correspondence between the wind speed and the center wavelength change of the FBG to be estimated. The sensor probe has the advantage of being relatively small, of low thermal mass and simple in structure, making it relatively inexpensive and convenient to use in different applications.



(a)



(b)

Fig. 2 Experimental set up: 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. (a) Schematic of the system and (b) Photograph of the actual device

Following on from the set up shown both schematically and as a photograph in Figure 2, the system used for the actual calibration of the fiber optic 'hot wire' sensor system used is shown schematically in Figure 3. Here wind speeds up to 8 m/s per possible. The pump light source shown operates at wavelengths of either 1480 or 1550 nm, with the laser power being available over a wide range, up to 500mW. A commercial fast fiber grating interrogator of accuracy ±2pm, and repeatability of 2pm, operating at a frequency of 1kHz is used to determine the wavelength shift in the grating, Δλ. The pump light source is connected to the co-doped fiber and the interrogator to the fiber with the FBG, both in the 'packaged' sensor probe. In operation, the co-doped fiber converts the input light energy into heat energy from the laser pump source, allowing the temperature around the FBG to rise and its central wavelength shifts towards the red, (the magnitude of the shift depending on the power applied). Then 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.

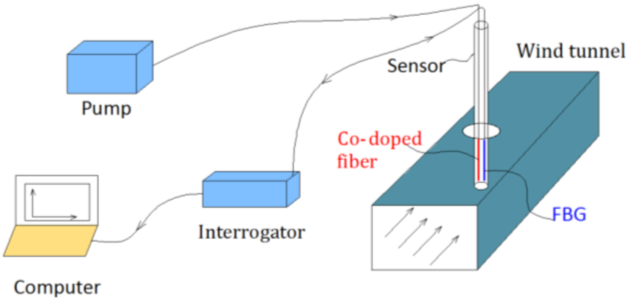


Fig. 3 Schematic of the fiber-optic 'hot-wire' sensing system showing the laser pump, the demodulator/FBG interrogation system, the probe placed in a wind tunnel for testing and evaluation and the computer where the outputs are visualized

3 Experimental Evaluation of the System

3.1 Sensitivity

Three different versions of the fiber-optical hot-wire sensor probe, based on the schematic design shown in Figure 2, were manufactured and evaluated, and designated Probes 1, 2 and 3. Probes 1 and 3 were copper sleeved, with lengths of 13mm and 18mm respectively and Probe 2 was used with a Teflon sleeving. The probes were tested in the wind tunnel which was home built and capable of generating wind velocities in the range of 0.2 – 8m/s (which could be measured with a conventional device for cross-calibration to an accuracy ≤0.1m/s). With no wind blowing (<0.2 m/s i.e. still air), 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 and set the 'baseline' conditions. As a result of heat then being transmitted, the FBG in the other fiber experiences a wavelength shift (due to this heating effect). With the system set up in this way, a series of experiments was carried out to determine the magnitude of the wavelength shift as a function of the applied optical power to the co-doped fiber, this being done for the three probe designs discussed, and results obtained are shown in Figure 4.

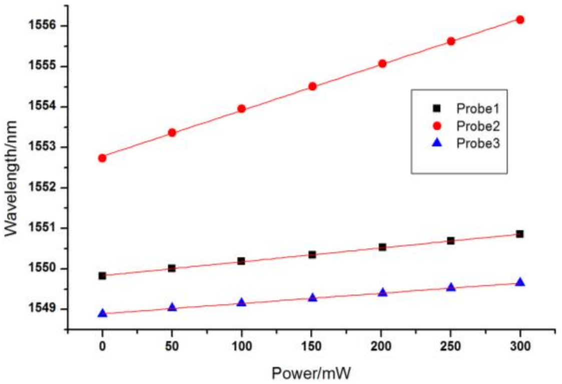


Fig. 4 Wavelength variation of the FBG in the parallel fiber with laser power applied to the co-doped fiber, for three different probe designs (Probes 1, 2 and 3)

Figure 4 shows that the FBG wavelength changes linearly with the increase of the power of the pump light source in the co-doped fiber. The slope in Figure 4 indicates the relationship between the wavelength of the sensor probe and the power of the pump laser, this being done for different materials and under different packaging modes. A larger slope indicates the greater is the change in wavelength of the same power. 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 measured as 11.3pm/mW. Comparing the performance of Probes 1 and 3, the results show that 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 designs reported.

The study undertaken and the results obtained provide a basis for the best design and packaging of the sensor, and paves the way for the sensor sensitivity experiment carried out. The sensitivity of the sensor is described through the results seen in Figure 5 which shows that all the sensor designs have the same nonlinear response to the change in the wind speed, as would be expected from Equation (9). The sensitivity is greater, as can be seen, at lower wind speeds for Probes 1 and 2, as indicated. This design of sensor probe, compared to others previously discussed and reported in the literature, relies on optimizing the packaging of the sensor and the optimum choice of materials to achieve the highest sensitivity and thus avoids the complexity involved with special fiber coatings and filling metals into microstructured fibers, all of which can be difficult to reproduce from one probe sample to another.

To evaluate their performance, the probes were subjected to air flows at different (and known) velocities in the test wind tunnel. Probes 1 and 2 were used in these tests, and their performance compared.

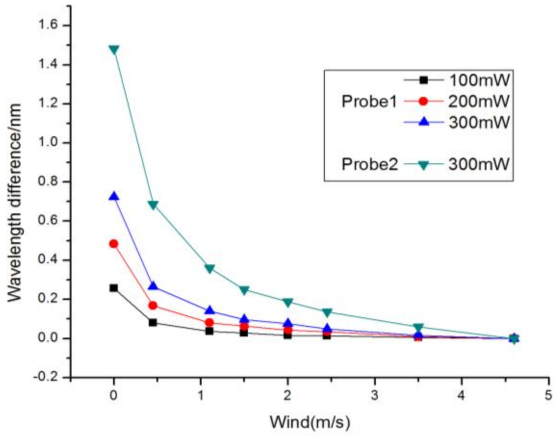
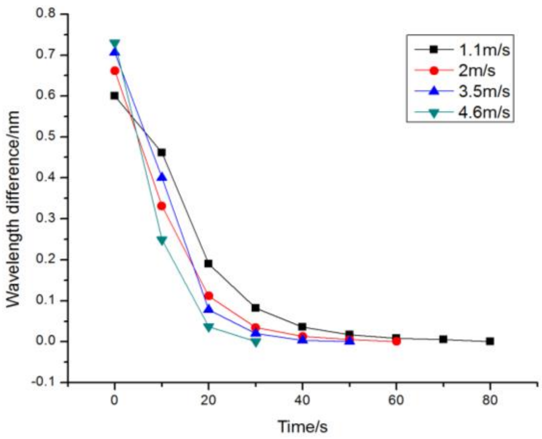


Fig. 5 FBG wavelength difference (from ambient) in Probes 1 and 2, with change of wind speed, under the laser power levels in the co-doped fiber shown

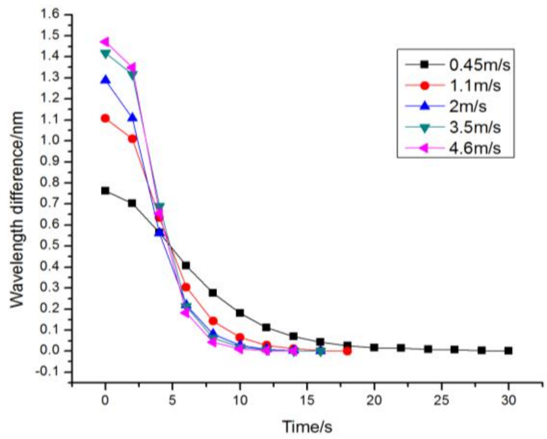
From the results obtained, it can be seen that with the increase of wind speed, the FBG wavelength change observed is non-linear, with a higher sensitivity of each probe to wind velocity in the lower velocity (0 – 1 m/s) range. This effect is seen irrespective of the laser power applied to the co-doped fiber. If a commercially available wavelength interrogation device with a 1 pm precision is used to extract the measurement data, the resolution of the sensing system is given from the figure as ~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) beyond that (up to the maximum measured 4.5 m/s in this work). The sensitivity of the device in the important 2 – 4.5 m/s range is 50pm/(m/s) thus the device is well suited to the wind tunnel facilities in which it was tested and to practical measurements in the mining applications considered. Thus the sensing system discussed offers a satisfactory sensitivity (from the wavelength change response that can be measured), with performance comparable with the most recently reported low-power-consumption fiber anemometer designs, while at the same time offering a significant advantage with a low cost and simple sensor design, which makes reproducible manufacturing of the sensor straightforward, which then makes it competitive for the type of coal mine applications considered.

3.2 Response time

With a pump light power of 300mW used, experiments were carried out to evaluate response time of the sensor probes, Probe 1 and Probe 2. These were tested under different wind speeds and at the same ambient temperature (to allow a close comparison), as shown in Figure 6 (a) (for Probe 1) and 6 (b) (for Probe 2) where the wavelength shift caused by the different wind velocities used is monitored with time, until a steady state change is reached.



(a)



(b)

Fig.6 Measurement of the response time of the probes tested, monitoring the change in the FBG wavelength with time, each for a series of different wind velocities (as shown in the inset). (a) Probe 1 and (b) Probe 2

As can be seen from Figure 6, as expected the response times of the two sensor probes decrease with increasing wind velocity and the wavelength dynamic range increases. The effect on the FBG wavelength change (for each wind velocity shown) is nonlinear with time. In summary, For Probe 1, the FBG wavelength shift reaches 60% - 70% of the maximum wavelength change seen within 20 seconds, and for Probe 2 it reaches that same 60% - 70% of the maximum FBG wavelength change within a shorter period of 6 seconds. From the above results, it can be seen that the response of both the fiber-optic hot-wire sensor probes evaluated show similar characteristics, which match those predicted by the theory discussed above. Here it can be seen that the probe design with the lower heat transfer material, Probe 2, has a higher sensitivity under constant power applied to the co-doped fiber. Further in comparison, the FBG wavelength change is greater for the lower wind velocities used and the sensitivity to this parameter decreases with increasing wind velocity. Probe 2 shows not only a higher sensitivity but also a faster response time, making it the preferred design for future work.

4 Discussion

Using the principle of the 'hot-wire' anemometer, combined with optical fiber sensing phenomena, this paper has reported on both a theoretical analysis and the subsequent results of experiments carried out with several different probe designs for wind velocity measurement. Theoretical analysis shows that the dynamic range and sensitivity of the 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 response time of the probe is shown to be related to the heat capacity of the packaging material, the wind speed, and the heat dissipation area. The results show that the fiber-optic 'hot-wire' wind velocity sensor is particularly sensitive at low speeds and has excellent performance. In the experiments carried out, Probe 2 encapsulated in Teflon was seen to show better sensitivity and faster response time, which conforms to the principles of the theoretical model reported. As a result, the simple and low-cost sensing system suggested not only provides a promising platform for coal mine applications but is solidly based on the results of a theoretical analysis which can then be used for further optimization of the sensor design, for specific applications. Work is on-going to improve the device, where the next step will be to study how to shorten its response time and increase its upper limit of measurement.

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