Fibre optic sensors for mine hazard detection

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ABSTRACT
We report the development of a comprehensive safety monitoring solution for coal mines. A number of fibre optic sensors have been developed and deployed for safety monitoring of mine roof integrity and hazardous gases. The FOS-based mine hazard detection system offers unique advantages of intrinsic safety, multi-location and multi-parameter monitoring. They can be potentially used to build expert systems for mine hazard early detection and prevention.

1. INTRODUCTION
Coal as a primary energy source in China currently provides over 70% of the total energy. Annual coal production in 2008 reached 3 billion tons. The fact that over 55% of Chinese coal mines are gassy and coal production sites by average get 10 m deeper every year, with the deepest mine reaching 1400 m below the ground level, this makes mine safety situation ever so severe. Major mine disasters have occurred frequently in recent years and caused thousands of casualties every year. Coal mine hazards include the following major types: (i) methane gas outburst and explosion; (ii) roof fall and coal and rock outburst; (iii) coal in goaf spontaneous combustion; (iv) water flooding and (v) hazards caused by electrical machinery failures. Fibre optic methane sensor system developed for landfill site monitoring by Culshaw et al [1] has created lots of interest for coal mine applications. Field trials of DFB laser diode based fibre optic sensors were reported [2]. Conventional coal mine roof condition monitoring is carried out using strain gauge array surface mounted on a steel bar, which tends to drift and typically on manual survey to take the data reading. Fibre optic strain sensor array mounted on steel bars were developed for continuous coal mine roof strata condition monitoring [3]. Fibre optic accelerometer-based seismic sensors were developed for roof monitoring in coal mine and mineral mine [4]. Coal in goaf when exposed in air can cause spontaneous
combustion. Early detection of spontaneous combustion can be made via monitoring the concentration of index gases such as CO, C₂H₄ and C₂H₂ [5]. The CO level is closely related to the oxidization state of the coal. Conventional technique is to pump ambient gas sample from the goaf underground via a tube system and test it using an IR analyzer and a gas chromatograph, which is very troublesome and time consuming. Fibre optic CO gas sensor based on 1567nm DFB diode laser absorption provides a promising means for on-line monitoring [6]. Water flooding is another major hazard which can be monitored via detection of water level of the reservoir in coal mines or pH and other water parameters in the reservoir [7]. Most fire incidents in the mines ignited by external fire source, which quite often due to electrical machinery failure, such as electrical spike or conveyer belt fracture and split. Fibre optic Bragg grating temperature and distributed temperature sensors have been developed for monitoring conveyor belt fire [8] and electrical power switchgears.

Studies on mine hazards have shown that micro-seismic events, methane output rate, roof loading are all linked to methane outburst, which has been the single biggest hazard of heavy casualties [9]. Conventional methane monitoring system only monitor methane concentration, as a consequence the system is not capable of hazards pre-warning. In this paper, we report a comprehensive mine condition system which integrates fibre optic temperature, seismic, methane, roof displacement, and water pressure to provide a comprehensive on line remote monitoring information in the mine, and offering the potential as an intelligent hazard detection and prevention system [10].

2. FIBRE OPTIC SENSOR BASED MINE HAZARD DETECTION SYSTEM
The fiber optic coal mine hazard detection system is designed to acquire all the critical mine condition information in real time. The system consists of the following functionalities:

1. CH₄ gas monitoring;
2. roof condition monitoring including displacement and strain monitoring;
3. micro-seismic events detection based on fibre optic accelerometers;
4. coal in goaf spontaneous combustion detection using fibre optic CO, C₂H₄, and C₂H₂ multi-gas sensors;
5. water pressure monitoring, temperature monitoring for ambient temperature, switchgears, electrical cables and conveyer belts;

The operation principle of the above fibre optic sensors are well described in the literature, here are briefly described with emphasis on the specific requirement for the coal mine application environment.

2.1. Fibre Optic CH₄ Gas Monitor
The principle of the methane sensor was described in detail by Ni et al [2]. The sensor heads consists of a pair collimating lens separated at distance 5 cm and 20 cm respectively for 0-100% and 0-1% range respectively. A 1650 nm DFB laser diode is used as light source. The laser diode is temperature controlled such that its operational wavelength is around the methane absorption line at 1650 nm. A saw-tooth driving signal is used to sweep the driving current, as a consequence, its wavelength is swept across the methane absorption line. The absorption signal can be normalized by a baseline signal, hence the fluctuation due to light source power, fibre link and gas cell loss are all self-compensated.
Fig. 1. (a) Fibre optic methane detection unit; (b) fibre probe for methane extraction pipeline monitoring.

Calibration data

![Calibration Data Graph]

\[ y = 1.0034x - 0.2836 \]
\[ R^2 = 0.9999 \]

Fig. 2. Fibre optic methane sensor calibration data.

Photographs of a fibre optic methane detection unit which simultaneously supports three fibre methane sensors is shown in Fig. 1a. The methane sensor probe for methane pipeline monitoring is shown in Fig 1.b. The calibration data is shown in Fig. 2.

2.2. Fibre Optic Mine Roof Condition Monitoring

During the coal production, the underground mine roof is subject to dynamic loading conditions. Real-time monitoring of the roof load is important for the safe production and detection of a potential roof fall. Fibre Bragg grating arrays were surface-mounted on steel bars as strain gauges and long gauge length displacement sensors were developed to monitor the rock displacement. The range of the fibre optic displacement sensor is 0- 200 mm, accuracy of 0.1% were achieved.

2.3. Fibre Optic Micro-Seismic Detection

A fiber optic accelerometer was developed for the detection of micro-seismic events in the mine, which can be not only used to monitor the roof condition, but also used as an indicator for early warning of methane outburst. The schematic of the accelerometer is shown in Fig. 3. The FBG element will subject to strain variation in response to vertical acceleration due to the movement of the cantilever below. The selection of the mass at the end of the cantilever, the geometry and material property of the cantilever determines the resonant frequency and the sensitivity. The dynamic strain of the FBG is detected by actively locking the wavelength of a DFB laser diode to the 3 dB point of the FBG reflection spectrum. Details
of the work will be reported in future paper. The frequency response of the accelerometer is shown in Fig. 4. The useful bandwidth exceeds 10-400 Hz range, which is adequate for mine applications. The minimum detectable acceleration is better than 0.1 mg, and its dynamic range exceeds 100 dB.

Fig. 4. Frequency response of the accelerometer. Fig. 5. Block diagram of C_2H_2 gas detection system.

2.4. Fibre optic CO, C_2H_4, and C_2H_2 multi gas sensors for coal in goaf spontaneous combustion detection

CO has been a major indicator for determining the onset of coal in goaf spontaneous combustion. Recent study shows that combination of CO, C_2H_4 and C_2H_2 can determine the status of the coal in the goaf. The required accuracies are +/-1 ppm for CO detection and +/-0.5 ppm for both C_2H_4 and C_2H_2. The measurement ranges are 0-1000 ppm for CO and 0-100 ppm for the later 2 gases.

Fibre optic multi-gas detection is also based on NIR absorption. CO, C_2H_4 and C_2H_2 gases have absorption bands at around 1650 nm, 1630 nm and 1530 nm, respectively. In order to achieve sub-ppm sensitivity, multiple reflection long path length gas cell is required. A laser diode array emitting at the above wavelengths are connected to the same gas cell sensor via an optical switch. Hence one gas cell is used to detect multi-gases. The gas detection system is illustrated in Fig. 5. A DFB laser diode with its operation wavelength corresponding to the gas absorption wavelength is modulated using both saw-tooth and sinusoidal wavelength. As the laser sweeps pass a gas absorption band, a second harmonic signal will be generated, which is proportional to the gas concentration. By normalizing signals between the second harmonic and fundamental modulation frequencies, the gas concentration can be determined. Phase-locked-in signal processing is used to enhance the detection sensitivity [1]. Test results of C_2H_2 measurement using a gas cell with a 9m optical path length is shown in Fig. 6. Sensitivity of 1 ppm was obtained with this device. Further work is undergoing to manufacture 50 m path length gas cell, with which the sensitivity will be improved to better than 0.5 ppm.
2.5. Pressure And Temperature Monitoring

Fibre Bragg grating (FBG) based pressure and temperature sensors have been well developed. We have developed a series of water pressure sensors to monitor water pressure in the mine reservoir [7]. FBG sensors also developed for monitoring hot spots in switchgears and cable joints. Fibre optic Raman scatter based distributed temperature sensor [8] was incorporated in the coal mine hazard detection system for power cable and conveyor belt monitoring.

3. FIELD TRIAL AND SUMMARY

An all FOS-based comprehensive mine hazard detection system was developed which consists all the above sub-systems described in section 2 [10]. The system consists of methane sensors, strain monitoring in the rock roof, micro-seismic sensors, water pressure sensors and ambient temperature sensor arrays all installed in underground coal mine. The sensor distances from the monitor centre were between 5 to 6 km. The data were remotely interrogated and stored in a database and can be accessed via internet. An integrated data fusion system, providing sensor condition self-diagnosis and statistical analysis, visual, audio and mobile text message warning capability was also developed. The system exhibit tremendous advantage over conventional mine condition monitoring system. In particular, fibre optic methane sensors do not need routine calibration as required by conventional electro-chemical methane sensors. Field trial of the fibre optic micro-seismic sensor was proved to be very useful, typical data recorded from a rock roof is shown in Fig. 7. Further work is under the way to develop seismic analysis routine which can be used to locate the seismic energy source.

In summary, we have developed a number of fibre optic physical and chemical sensors for mine hazard detection, including methane gas, roof condition, seismic events, as well as onset of spontaneous combustion. The FOS hazard detection system offer advantage of intrinsic safety, comprehensive information, which can be used as the basis for intelligent mine hazard prediction and control system. We are currently undergoing a series of field trial in typical seismic, and combustible mines. The results will be reported in due course.
4. REFERENCE

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