DEVELOPMENT AND UTILISATION OF FIBRE OPTIC-BASED MONITORING SYSTEMS FOR UNDERGROUND COAL MINES

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ABSTRACT: The continuous economic growth and depleting shallow reserves have increased the number of deeper mining operations worldwide which has made safety and productivity more challenging due to the higher stresses, heat and increased gas contents. Any major improvements in safety and productivity require a reliable and real-time monitoring system that provides more comprehensive information about various processes. The current monitoring systems suffer from lack of reliability, accuracy and high capital and operating costs. Recent advancements in fibre-optic based sensing technology have introduced unique solutions for various underground coal mine applications such as health and safety, geotechnical, ventilation, borehole, mine environment and condition monitoring. This paper presents recent research, development and utilisation of this technology by a group of researchers at the University of Queensland (UQ) and CRCMining in Australia and Shandong Academy of Science in China.

INTRODUCTION

The capacity of optical fibres to transmit large quantities of information has revolutionised the world of telecommunications. The advancement of research and development of fibre-optic sensing technology has resulted in the production of various fibre-optic sensors such as temperature, strain, displacement, rotation, pressure, gas, liquid level, radiation and vibration sensors. The advantages of these sensors have extended their applications in various engineering and medical fields. Fibre-optic sensors are chemically inert, non-electrical and intrinsically safe. They offer high sensitivity, real-time measurements and immunity to radio frequency and electromagnetic interference. The capacity to transmit light over many kilometres makes fibre-optic sensors a natural candidate for remote sensing in mining applications; however, there has been limited strategic planning for identification and adoption of potential fibre-optic sensing technology in mining applications. The mining industry needs to realise the importance of this technology in improving safety and productivity in various mining operations. The main challenge for the mining industry is to distinguish between the fibre-optic sensing systems that bring immediate value exhibiting a small technology implementation gap and those that need further fundamental research and development.

FUNDAMENTALS

A fibre-optic cable normally consists of a number of optical fibres. An optical fibre mainly consists of three components: the core, the cladding and the coating. The typical structure of an optical fibre is presented in Figure 1. Light propagates mainly along the core of the fibre that is generally made of glass or plastic. The cladding layer is also made of glass or plastic but with a smaller index of refraction compared to that of the core. The role of the cladding is to keep the light within the core and prevent any loss of light from the core into the surrounding. The cladding also increases the strength of the fibre and protects it from the environmental effects. Extra protection of the fibre is provided by the coating that is a layer of plastic on the cladding.

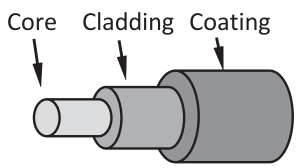

Figure 1 - Main components of an optical fibre

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Fibre-optic sensing

The main parts of a fibre-optic sensing system are an optical fibre cable, an optical source, a transducer, and an optical detector (Figure 2). Depending on the application of the sensing system, the optical source can be lasers, diodes, and/or LEDs. The transducer is either an external sensing head or the optical fibre. In recently developed sensors, new types of optical fibres such as Fibre Bragg Gratings (FBGs) are used as the sensing head (transducer). In a fibre-optic sensor, the variation in the optical signal through the transducer that is caused by the physical perturbation is detected by the optical detector. This variation corresponds to the absorption, transmission, reflection, and/or scattering of the optical light that travels through the core of the fibre. For example; in micro-bending-based sensors, if the fibre is bent due to any physical perturbation, the amount of light that is lost through the cladding due to bending of the fibre is related to the amount of physical perturbation.

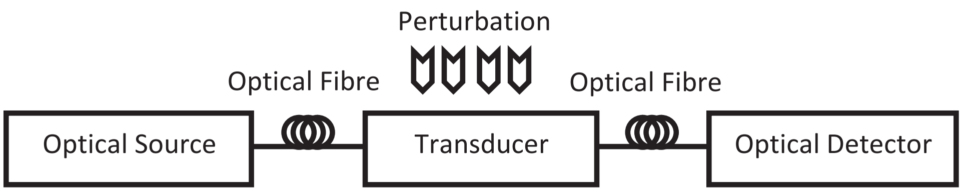

Figure 2 - Main parts of a fibre-optic sensing system

Types of fibre-optic sensors

Fibre-optic sensors are generally divided into two types based on their functionality: intrinsic and extrinsic sensors. Intrinsic fibre-optic sensors utilise an optical fibre as the sensor head as well as the transmitter of the optical light (Figure 3). In these sensors, the light does not leave the fibre until it reaches the end that is connected to the optical detector. Some examples of these sensors that use interferometry configurations are Tapered Fibre, Drilled-hole Hollow-core Fibre, FBG, LPFG and other special fibres such as Doped Fibre.

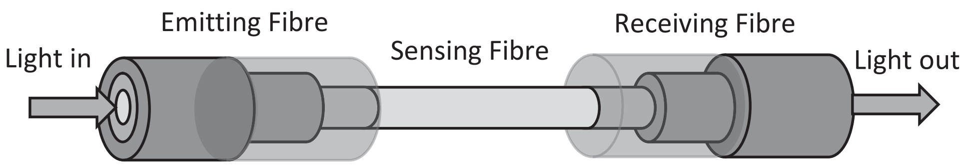

Figure 3 - Schematic diagram of an intrinsic fibre-optic sensor

Extrinsic fibre-optic sensors utilise an optical fibre to guide the light to and from a location at which an external optical sensor head (transducer) is located (Figure 4). The sensor head is basically designed to modulate the properties of light in response to changes in the environment with respect to physical perturbations of interest.

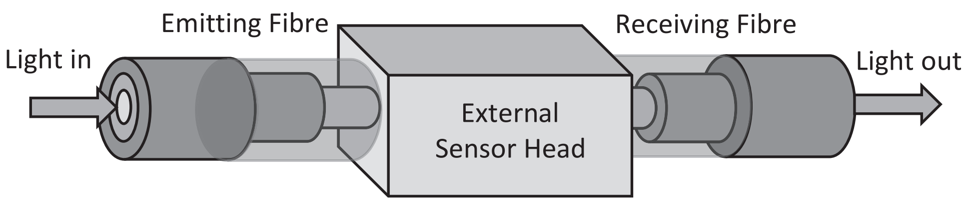

Figure 4 - Schematic diagram of an extrinsic fibre-optic sensor

MINING APPLICATIONS OF FIBRE-OPTIC SENSORS

A number of studies have been reported in the literature that include the research and development of innovative fibre-optic sensors and the application of these sensors in various industries. For example, fibre-optic sensing has been used to measure electrical current (Werthen, *et al.*, 1996), to monitor buildings and structures (Jackson, 1995), to detect the fluid leakage (Vogel, *et al.*, 2001), to perform fluid logging in shallow bore holes (Hurtig, *et al.*, 1994), in different biomedical applications (Passia, *et al.*,

2002) and in buildings and structures (Hurtig and Grobwig, 1998). The optical fibre technology has also been introduced in the mining industry for sensing strain (Naruse, *et al.*, 2007), detecting mine gases such as methane (Li, *et al.*, 2005 *and* 2006) and underground environment monitoring (Sen and Datta, 1991).

The potential applications of fibre-optic sensing technology in mining can be classified into five main categories (Figure 5). Some of these applications have commercially available solutions while other need extensive fundamental research and technology development. It is recommended that a more detailed review in conjunction with technical experts is carried out in order to determine the technology requirements for the development of fibre-optic sensors. The research and development of fibre-optic sensing technology should account for identification of advantages and disadvantages of this technology in various mining applications.

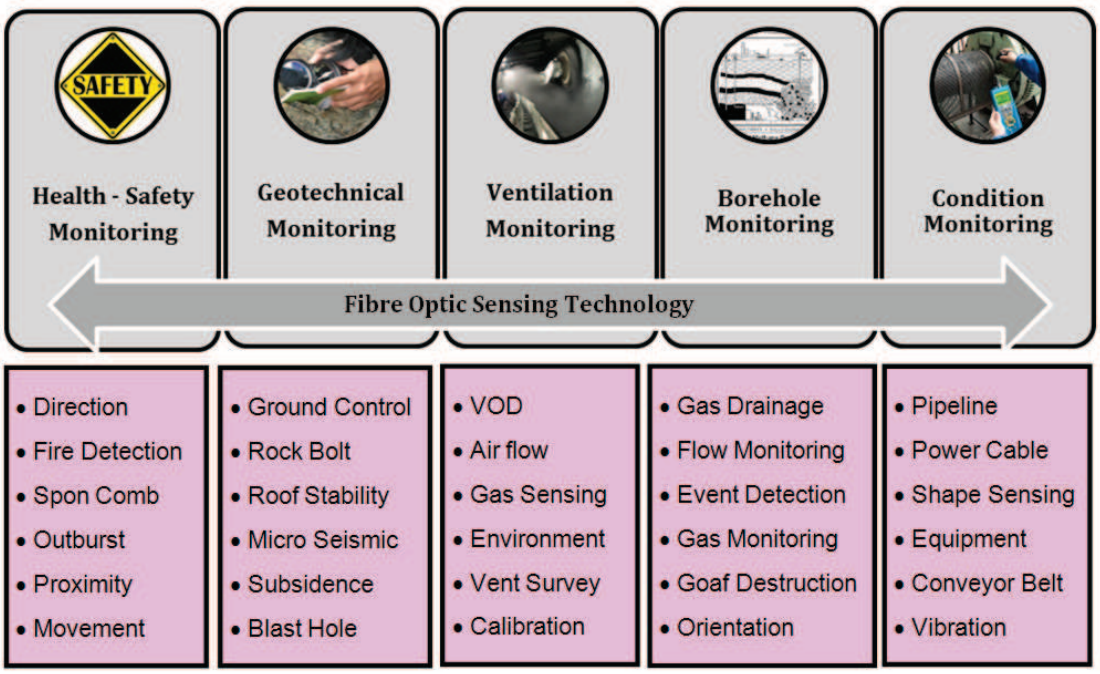

Figure 5 - Main potential applications of fibre-optic sensing technology in mining

FIBRE-OPTIC SENSING RESEARCH AT UQ

Research group formation

A research group in collaborations with the Mining Engineering Division and Quantum Optics Laboratory at The University of Queensland (UQ) and CRCMining was established in 2010 to develop fibre-optic based sensors for mining applications. The research has so far received financial support from UQ, Australian Coal Association Research Program (ACARP) and CRCMining. The scope of research includes the investigation of potential mining applications of existing fibre-optic sensing technology in various mining areas such as ventilation, borehole monitoring, health and safety, geotechnical and condition monitoring. Research has also been conducted on the development of new fibre-optic sensors especially in the area of gas sensing. In the following, a summary of the projects that have been conducted by the research team is presented.

Underground mine environmental monitoring

The research project aimed to experimentally investigate the suitability of a fibre-optic based Distributed Temperature Sensing (DTS) system in monitoring underground mine environments. This study was prompted by earlier studies that examined the application of the DTS system in underground mines for detecting underground fire (Dubaniewicz, *et al.*, 1993; Zhang, *et al.*, 2002), monitoring trailing cables (Dubaniewicz, *et al.*, 1998), and developing automatic underground alarm systems (Zhang, *et al.,* 2000 and 2001).

DTS systems measure temperature by using fibre-optic cables as a continuous linear sensor. The principle of temperature measurement by DTS systems is generally based on the thermal effects inducing lattice oscillations within the core of the optical fibre that is made of silicon dioxide with amorphous solid structure. The light photons interact with the oscillated molecules of optical fibre as it travels through the fibre. As a result of this interaction, the light is scattered (Raman scattering) back which contains Stokes and anti-Stokes line components. The temperature of the optical fibre at any location is determined from the ratio of anti-Stokes and Stokes light intensities. There are basically two basic principles of measurement for distributed temperature sensing, Optical Time Domain Reflectometry (OTDR) and Optical Frequency Domain Reflectometry (OFDR). In OTDR, the location of the temperature event can be determined based on the generation of a narrow laser pulse and the travel time of the backscattered light to return to the detection unit.

DTS systems consist mainly of a mainframe and a fibre-optic cable. The mainframe includes a laser source, a pulse generator, an optical module, a photo detector and a micro-processor unit. The fibre-optic cable may consist of a number of quartz-glass optical fibres that can each be considered a linear temperature sensor. Commercially available DTS systems with normal specifications can measure temperature along more than 30 km of the fibre-optic cable with a spatial resolution of 1 m, accuracy of ±1°C and a resolution of 0.01°C (Figure 6).

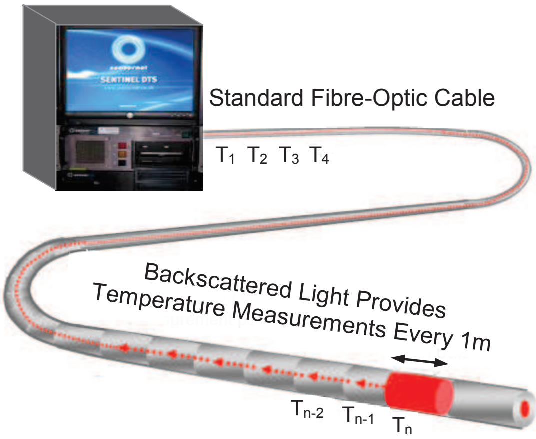

Figure 6 - Schematic diagram of distributed temperature sensing system (after Mendez, 2009)

Approximately, one km of the fibre-optic cable was installed in the University of Queensland Experimental Mine for these experiments (Figure 7). The experimental setup consisted of a *Sensornet* system that included the sentinel DTS unit for control and data acquisition, a display monitor, a multiplexer, a power supply and a fibre-optic cable both as a distributed temperature sensor and a transmission medium. The fibre-optic cable consisted of graded-index multimode optical fibres with a core diameter of 50 μm and a clad diameter of 125 μm sheathed with a low density polyethylene. Sentinel DTS-R system had a temperature sensing range of 10 km with a spatial resolution of 1 m. For a distance of one km, the system had temperature resolutions of 0.01°C and 0.1°C for the measurement times of 60 mins and 10 s, respectively.

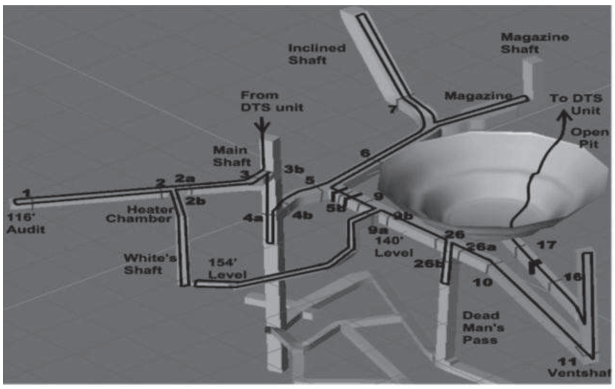

Figure 7 - Fibre optic cable installation in UQEM (Aminossadati, *et al.,* 2010)

The fibre-optic cable was installed in the mine covering all the accessible roadways. The experimental conditions were varied by opening and closing the ventilation doors located on level 140 at station 9a. Various experiments were conducted to measure the air temperature throughout the mine and during the heating and cooling processes at different air flow and heat generation rates. With a distance resolution of within 1 m and temperature accuracy within 1°C, the DTS system could scan the entire underground mine and locate any high temperature spots. An example of the results is presented in Figure 8. The DTS system proved to be a reasonably accurate temperature measuring device as an underground mine environment monitoring system. The DTS system deploys a standard telecommunication fibre and does not need any special sensor to take the temperature measurements. Thus, this system is a very cost effective solution when a large number of measurement points are required. This system provides many of the features and benefits required by underground mine ventilation designers and operators.

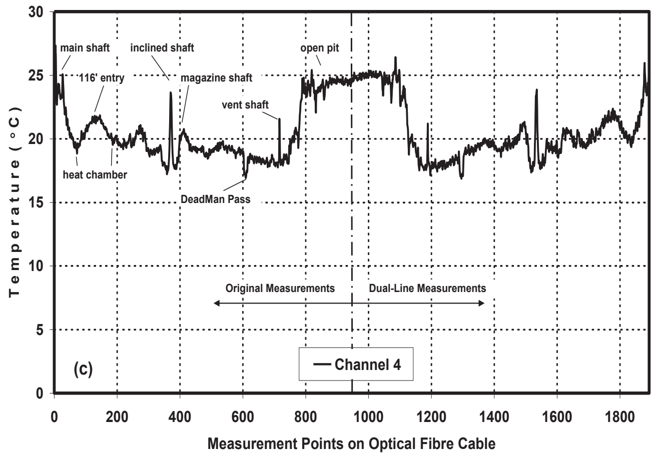

Figure 8 - UQ experimental mine temperature profile obtained by DTS (Aminossadati, *et al.,* 2010)

Multipoint fibre-optic based methane gas sensing

Many research studies have attempted to develop and test fibre-optic based methane gas sensing systems in underground coal mines using single open-path gas cell sensor heads (Zhang and Zhang, 1992; Ni, *et al.,* 2008; Tong, *et al.,* 2010; Shemshad, *et al.,* 2012a and 2012b). The aim of this project was to experimentally investigate the performance of a sequential multipoint fibre-optic sensing system using open-path gas cells for the measurements of methane gas concentration. The potential advantages of utilising a multipoint fibre-optic sensing system is that measurements can be taken from different locations using a single laser and a single fibre-optic line. The system has potential applications in underground mines. For instance; a network of open-path gas cells could be installed around a mine exhaust shaft to accurately measure the average concentration of methane entering the atmosphere. In this research project, open-path gas cells containing certified concentrations of methane were purchased from Wavelength References Inc. and used in the experiments. These gas cells consisted of sealed chambers containing a known methane concentration (0.1% – 10%) in nitrogen. The gas cells had a fibre-optic input and output so that light could be passed through the gas in the cell and then focused back into a fibre and detected at a photo detector. Thus, each individual cell simulated a situation where methane diffused from the environment into the cell for detection. However, for these initial tests the cell remained sealed (Figure 9).

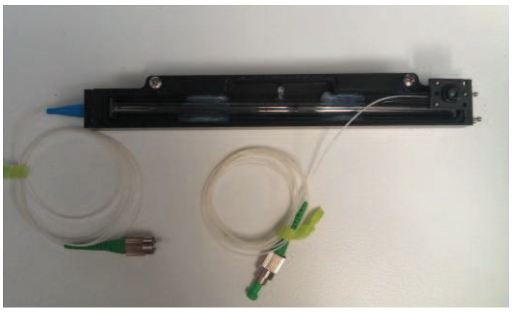

Figure 9- A pre-filled methane gas cell from Wavelength References Inc. (Shemshad, 2012)

The experimental set-up is shown in Figure 10. Light from a Distributed Feedback (DFB) laser was split so that 90% passed through the open path gas cell and then reached a photo detector. The other 10% went straight to a detector so that the absorption intensity could be normalized to variations in the laser output intensity. Both direct absorption and wavelength modulation spectroscopy were used. For the direct absorption spectroscopy, absorption at a particular wavelength was determined by subtracting the intensity of light transmitted through the gas cell from the intensity in the absence of methane. The open path gas cells could be switched so that the methane concentration could be varied. When wavelength modulation spectroscopy was employed, the experimental set-up remained the same, except the wavelength was modulated using a function generator and the output was monitored with a lock-in amplifier.

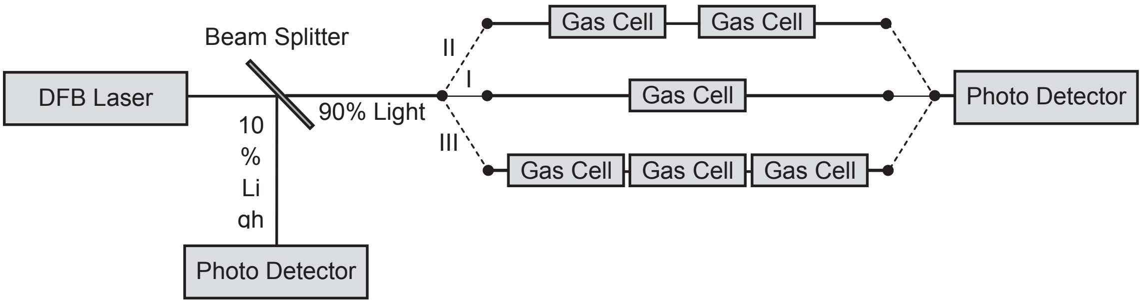

Figure 10 - Schematic diagram of experimental set-up for methane sensing in open-path gas cells

Having experimentally determined the appropriate conditions for sensing methane in a single open-path gas cell (I), the method was adapted to perform sensing of multiple open-path gas cells (II: two gas cells - III: three gas cells) connected to a single laser and fibre optic line. Light from the DFB laser is passed through multiple gas cells containing varying methane concentrations, and the second harmonic response signal is linear with respect to the average methane concentration of the cells (Shemshad, 2012). So, for instance, Figure 11a shows that the response increases as the average methane concentration of two cells, connected in series, increases, and Figure 11b shows that the same trend occurs when three cells are used instead of two. The important point is that the response is proportional to the average methane concentration in all of the cells. The results also showed that the response was independent of the order in which the gas cells are connected. This was the first time that an experimental study was conducted to investigate the feasibility of second harmonic measurements using multiplexed open-path gas cells.

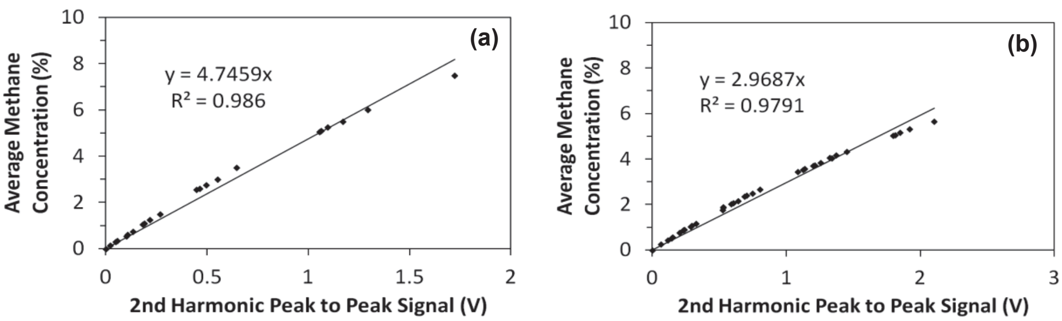

Figure 11 - Calibration curve for second harmonic peak to peak signal from light passed through (a) two, and (b) three open path gas cells to determine the average methane concentration in those cells. Methane peak was at 1,665.9 nm at different concentrations. Wavelength modulation depth was 0.10cm^{-1}.
T = 296 K, P = 101.325 kPa, l = 16.5 cm. (Shemshad, 2012)

Development of all-fibre methane gas sensor

The aim of this research project was to develop three all-fibre methane gas sensor heads (1- Tapered fibre, 2- Drilled single mode fibre and 3- Drilled hollow core fibre) and experimentally evaluate their methane gas detection capabilities for underground coal mines (Figure 12). Details of development of the sensor heads can be found in the research paper published by Sheridan *et al.* (2012). All-fibre methane gas sensor heads are expected to have several advantages over conventional open-path gas cell sensor heads. These advantages include relatively faster response, easier and cheaper installation, more flexibility and manageable size and minimal temperature effects on the physical characteristics of the sensing head.

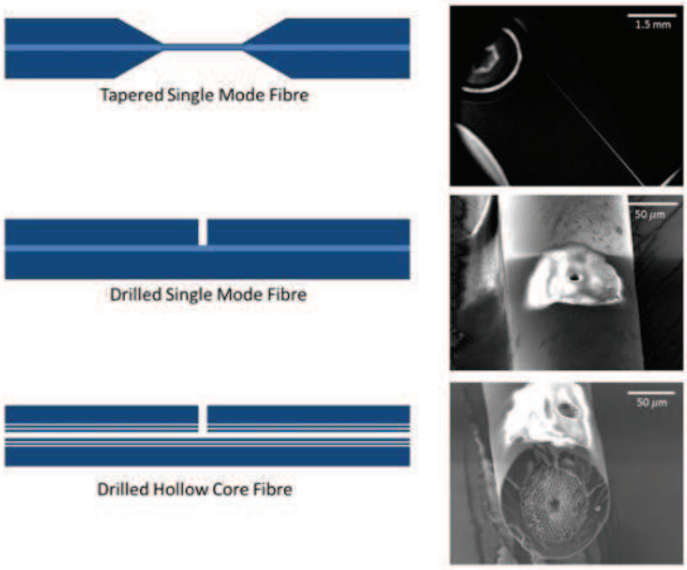

Figure 12 - Fibre optic sensor heads (Aminossadati, *et al.*, 2013)

An experimental setup was developed to accommodate and test the three all-fibre sensor heads at various known methane concentrations. The details of experimental setup can be found in the research paper published by Amanzadeh *et al.* (2012). The methane concentration setup consisted of a chamber, two gas cylinders and two flow meters (Figure 13). All the parts are connected through stainless steel pipes and flexible hoses. Flexible hoses are used to connect an IR detector to monitor methane concentration inside the chamber.

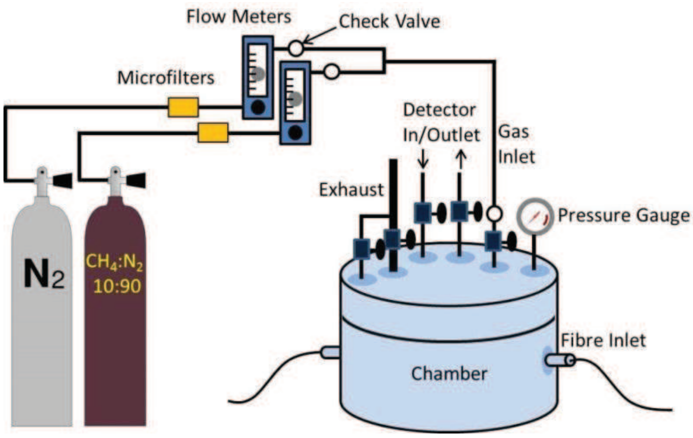

Figure 13 - Schematic diagram of all-fibre methane sensing setup (Amanzadeh, 2014)

Tapered fibre sensor heads had a relatively simpler configuration than open path gas cells (no lenses/alignment), but at the cost of a much smaller interaction volume compared to an open path gas cell and this resulted in these sensor heads being unable to detect methane. Drilled single mode fibres were simpler than open path gas cells and more robust than tapered fibres, but the light interaction volume was even smaller meaning methane could not be detected with these sensor heads. Drilled hollow core fibres offered the simplicity of an all-fibre set-up and the advantage of a large light interaction volume, but are more expensive than single mode fibre. Drilled hollow core fibres had good sensitivity but unacceptable accuracy when direct absorption was used. When wavelength modulation spectroscopy was used, the accuracy levels improved significantly. The response time for drilled hollow core fibres was slower than open path gas cells due to the time required for methane to diffuse into the hollow core fibre. This response time was a function of the fibre sensor length, and an inverse function of the number of holes in the fibre (Aminossadati, *et al.,* 2012). The advantage of drilled hollow core fibres are their compactness, flexibility, high light interaction volume, low gas sample volume requirement and theprospective development of a distributed gas sensing system.

Development of conveyor monitoring system

This research project aimed to develop a real-time fibre-optic based temperature monitoring system that predicts the costly failure of conveyor idlers. The project involved a DTS system and fibre-optic cables as temperature sensors. Various fibre-optic installation strategies were investigated to identify the most effective technique. The laboratory tests on conduction and convection proved that the conduction-based system was only able to detect the temperature rise due the heat emitted from the hot source. This means that the fibre-optic cable should be installed on the frame and as close as possible to the rollers to detect the temperature rise as a result of heat build-up in the faulty idler (Aminossadati and Yang, 2013). A number of laboratory and site tests were conducted using different installation configurations of the fibre-optic cable at UQ Fibre-optic Sensing Laboratory and Queensland Bulk Handling (QBH) site (Figure 14).

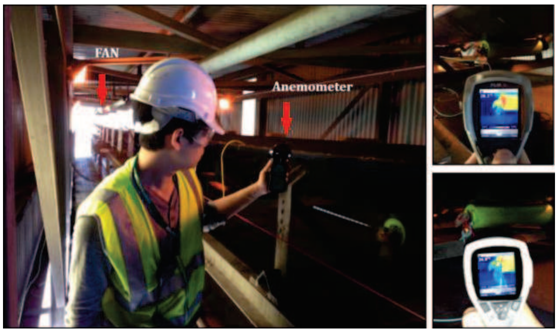

Figure 14- Fibre-optic based conveyor belt monitoring tests at Queensland bulk handling site

The results of this study suggested that four fibre-optic cables must be installed along the frame of the conveyor belt at each end of the rollers. A schematic diagram of the proposed system is presented in Figure 15. The fibre-optic cables accurately measure the temperatures of the frames in the vicinity of the end of the rollers. This temperature was indicative of the intensity of heat generation by the roller. If this temperature was greater than the ambient temperature, this could indicate that the roller starts to get hot.

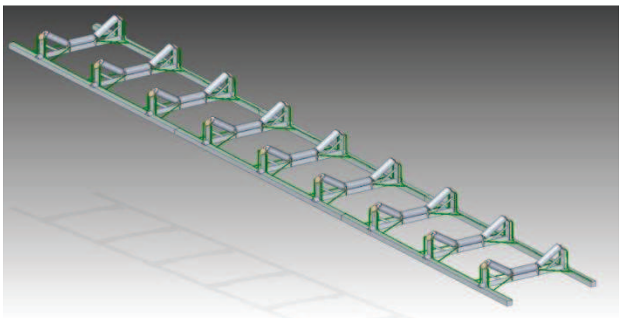

Figure 15 - Schematic diagram of fibre-optic based conveyor belt monitoring system

FIBRE-OPTIC SENSING RESEARCH AT SHANDONG ACADEMY OF SCIENCE

Research team scope

Shandong key laboratory of fibre-optic sensors at Shandong Academy of Science is located in high-tech development zone of Jinan City of Shandong Province in China. The scope of activities in this laboratory is research, development and production of various novel types of industrial fibre-optic sensors, intelligent instruments and integrated monitoring systems. In the field of coal mining, the projects include fibre-optic based sensors for methane detection, goaf spontaneous combustion alarm system, seismic monitoring, rock stress and roof pressure monitoring and electric equipment safety. Field test data of these new sensors demonstrated that the fibre-optic sensors offer a number of advantages compared to conventional electrical sensors on sensitivity, accuracy and reliability. As a result, there is a great potential for coal mine safety monitoring and hazard detection. A summary of the two recent projects developed by the research team follows

Mining machinery fault diagnosis system

The mining machinery fault diagnosis system includes fibre-optic vibration acceleration sensors, fibre-optic temperature sensors, fibre ring, light source, optical demodulator, data analyser and computer display. The fibre-optic vibration and temperature sensors are fixed on the shell surface of the machinery. Through the transmission cable, the sensor connects the first output terminal of the fibre ring. The fibre ring is connected to the output of the broadband light source and the second output terminal of the fibre ring is connected to the optical demodulator. The optical demodulator transforms optical signals into electrical signals and converted electrical signals are transmitted to the data analyser by the TCP/IP protocol. The temperature and vibration signals are finally processed and displayed by the data analyser (Figure 16).

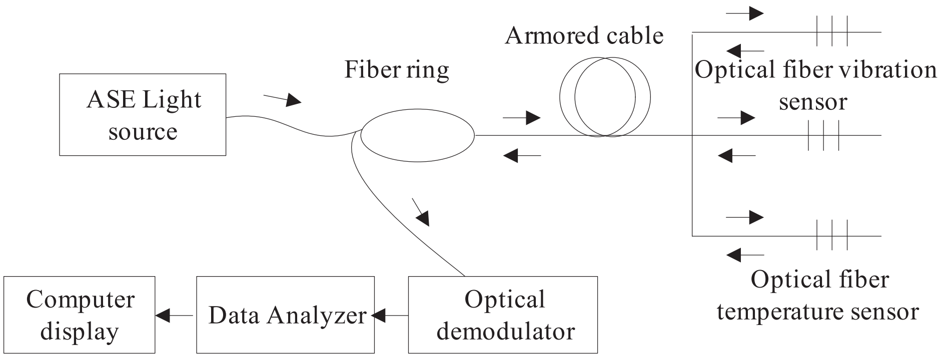

Figure 16 - Schematic diagram of the fibre-optic machinery fault diagnosis system

This system has been tested in Xinglong Zhuang coal mine of Yanzhou Mining Group in China. In this system, the vibration acceleration sensor was installed at different locations on a motor as shown in Figure 17.

Figure 17 - Installation of machinery fault diagnosis system

A sample of the results (Figure 18) shows the temperature and vibration velocity profiles for one of the motors. The results showed that the motor power instantaneous shock and vibration was relatively large when the motor was started. The temperature gradually rose and the vibration fluctuation range became relatively stable within a certain range.

Micro-seismic monitoring

Fibre-optic based micro-seismic monitoring sensing system consists of fibre micro-seismic sensors (Figure 19a) demodulator and data processor (Figure 19b) and fibre transmission cable. It is an intrinsically safe sensing system that requires no additional power supply and can achieve long distance transmission. The system is also an all-fibre design that is able to work in a strong magnetic field and high-risk environments. The measurement accuracy is independent of ambient temperature, light fluctuations and optical fibre bending loss. The system includes the demodulating unit that is placed in a ground dispatch room with high-speed synchronous data acquisition that detects the abnormal activities in the surrounding rock area.

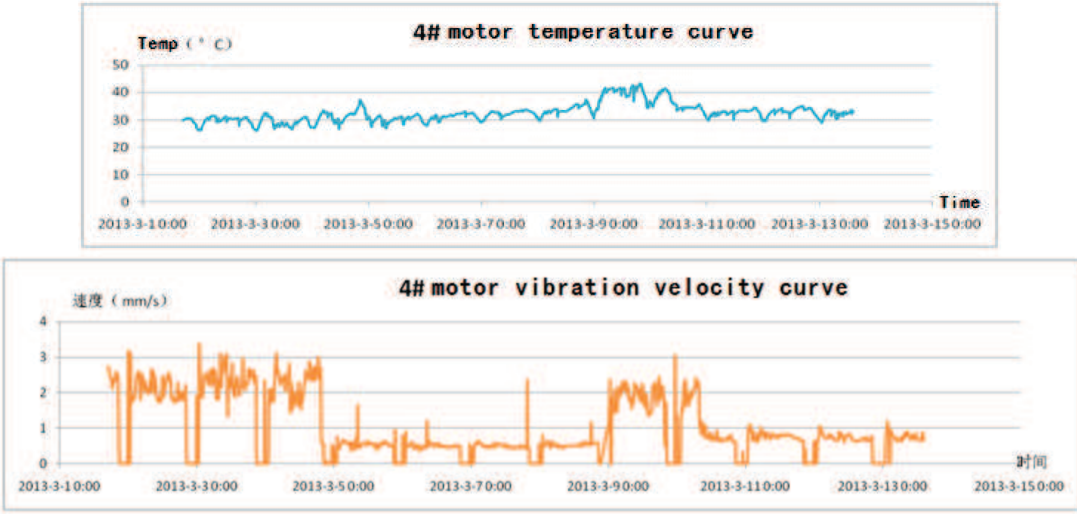

Figure 18 - The temperature and vibration history curve

Figure 19 - (a) Micro-seismic acceleration sensor (b) Micro-seism*ic* demodulator and data processor

CONCLUSIONS

Fibre-optic sensing technology has the potential to revolutionise the way mines are monitored, planned and controlled. The remote and real-time sensing capabilities of passive fibre-optic sensors indicate that fibre-optic sensing has obvious application in the mining industry where hazardous area compliance limitstechnology uptake. Recent research, development and production of fibre-optic sensors as well as the field trails of these sensors by the fibre-optic sensing research teams at the University of Queensland and Shandong Academy of Science demonstrate that fibre-optic sensors offer a number of advantages compared to conventional electrical sensors on sensitivity, accuracy and reliability. Future collaboration between the teams from Australia and China will enhance the research capabilities in the area of fibre-optic sensing technology for mining applications. This can be achieved by extending the understanding of the present states of monitoring systems used in the mining industry in Australia and China and actual conditions of quality assurance. The focus of future work should be towards accumulating and organising knowledge about potential and innovative monitoring systems that would contribute to the improvement of mining safety and economics. The research teams need to identify and implement plans for potential areas of research, development and utilisation of fibre-optic sensors in the mining industry and develop international exchange programs.

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