Tunnelling and Underground Space Technology 25 (2010) 220–229

Contents lists available at ScienceDirect

Tunnelling and Underground Space Technology

journal homepage: www.elsevier.com/locate/tust

Distributed temperature measurements using optical fibre technology in an underground mine environment

Saiied M. Aminossadati *, Nayeemuddin M. Mohammed, Javad Shemshad

The University of Queensland, School of Mechanical and Mining Engineering, CRCMining, QLD 4072, Australia

ARTICLE INFO

Article history:
Received 5 January 2009
Received in revised form 21 July 2009
Accepted 17 November 2009
Available online 16 December 2009

Keywords:
Underground mine
Optical fibre
DTS
Temperature
Heat

ABSTRACT

This article experimentally examines the applicability of a temperature measuring and monitoring system using distributed temperature sensing by means of an optical fibre in an underground mine environment. The temperature distribution along an optical fibre can be detected by measuring the Raman backscattering of the stokes and anti-stokes lines. The distributed temperature sensing system provided valuable information for the mine safety control and the mine ventilation system. In addition, it proved to be capable of measuring air temperature in the entire mine with an accuracy of 1 °C and within the distance resolution of 1 m. The heating and cooling processes could be detected and the rate of heat generation at any location of the mine could be accurately determined from the temperature measurements. This technology has the potential to be linked to other measuring devices of an underground mine environment in order to develop a safer ventilation control system.

1. Introduction

Over the past few years, many new measurement devices such as digital, laser and ultrasonic sensors have become available for monitoring underground coal mine ventilation. However, the current monitoring systems suffer from the lack of an active and real-time system. The temperature variation in an underground mine environment is of critical importance to the health and safety of underground miners.

In recent years, most of the fatal accidents that have occurred in underground mines around the world could have been prevented if the mine had been equipped with a dynamic and accurate temperature monitoring system. Most of the major safety issues in underground mines are due to the temperature rise, which is the result of various physical and chemical sources such as blasting, strata, thermal oxidation and human metabolism. It is evident that the lack of reliable and effective monitoring of mine ventilation parameters such as air temperature leads to serious mine disasters. In fact, early detection and localisation of the temperature variation is considered as one of the initial indicators of hazardous situations. A fast and reliable temperature measurement can assist to control escape routes and to minimise the possible damage caused by various hazards such as fire, methane explosion, spontaneous combustion and coal dust explosion. The temperature profile obtained from a real-time and accurate monitoring system helps the mine ventilation operator examine and plan alterations to the mine ventilation conditions and precisely examine the current ventilation conditions.

A Distributed Temperature Sensing (DTS) system using optical fibre technology is an intrinsically safe method which can be applied in an underground mine environment to continuously measure and monitor the temperature variation within the mine. The DTS system is based on Optical Time Domain Reflectometry (OTDR). In this configuration, 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. OTDR offers a number of technical benefits for Distributed Temperature Sensing compared to other systems of Optical Frequency Domain Reflectometry (OFDR). Temperature changes down to 0.01 °C can be detected along sensing cables of distances greater than 30 km and are less affected by potential anomalies within the fibre such as bends and connectors.

The DTS system is a blend of optical, mechanical, electrical and computer integration. The photon flux of anti-stokes Raman backscattering of the optical fibre is modulated by the spatial temperature field. The optical electronic signals carrying the temperature information can be acquired by demodulating the signals. In the DTS system, the optical fibre is used as both a sensing and transmission medium. The main advantages of using the optical fibre as a sensor probe are no need for electricity, explosion-proof, fire-proof, safe in hazardous environments, potentially resistant to ionizing radiation, immune to high voltage and strong electromagnetic fields, immune to Radio Frequency Interference (RFI) and Electro-Magnetic Interference (EMI), solid-state reliability, secure data transmission, self-inspection and self-calibration. The

* Corresponding author. Tel.: +61 7 33653676; fax: +61 7 33653888.
E-mail address: uqsamino@uq.edu.au (S.M. Aminossadati).

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doi:10.1016/j.tust.2009.11.006

OTDR distributed temperature sensing system is safe under all reasonable working conditions and comply with EU regulations EUR16011EN-1994. In fact, conventional fibre is made with silica or plastic and sometimes both. Since these materials are non-conductors, sparking is not a problem. Moreover, the system requires no electrical power within the mine.

A review of the literature indicates that the optical fibre technology has been utilised in measuring the electrical current (Werthen et al., 1996), monitoring buildings and structures (Jackson, 1995), detecting the fluid leakage (Vogel et al., 2001), fluid logging in shallow bore holes (Hurtig et al., 1994), and in different biomedical applications (Passia et al., 2002). Hurtig and Grosswig (1998) introduced the application of optical fibre technology in buildings and other structures. The optical fibre technology has also been used in the mining industry for sensing strain (Naruse et al., 2007) and detecting mine gases such as methane (Li et al., 2005, 2006). Optical fibre has also been used by Sen and Datta (1991) in an underground environmental monitoring system as a medium of transmission of data from underground sensors to the surface stations.

There is a large background of research on the application of optical fibre technology in temperature measurements (Boiarski et al., 1995; Ishii et al., 1997; Brehm and Johnson, 2007; Ma et al., 2007). Kluth (2009) deployed optical fibre technology in a DTS system to monitor the flow profiling of a maximum-reservoir-contact (MRC) well. The initial data from the installation proved the required resolution of 0.01 °C despite the length of the optical fibre. It was concluded that the system was able to provide the temperature profile across the length of the well as the high-resolution and real-time flow profiles. Kaura and Sierra (2008) studied the long-term performance of fibres especially at elevated temperatures. They found that the exposure of optical fibres to hydrogen changed the performance of the fibres. They argued that this was because the presence of hydrogen caused a light loss in the fibre. Bernini et al. (2007) predicted the evolution of the hot-spot temperature of dynamically loaded overhead lines using the data acquired through distributed fibre-optic sensor based on stimulated Brillouin scattering. Spontaneous Brillouin scattering-based sensors should be used for longer sensing distances where high peak power levels in the OTDR and high sensitivity detection schemes are required (Cho et al., 2003). Glasbergen et al. (2009) discussed how DTS could be used to quantify the fluid distribution during a matrix treatment. They argued that the DTS system could provide real-time quantification of the flow distribution from the temperature surveys.

The DTS system has also been tested in different underground mine applications. Dubaniewicz et al. (1993) investigated a fibre optic temperature monitoring system for possible application in mine fire detection. The system employed the OTDR techniques based on the Raman effect that allowed the entire length of fibre to function as a distributed temperature sensor. They measured the temperature versus time for a zone of 5 m length of fibre and temperature versus distance for the entire length of 100 m optical fibre. They concluded that the intrinsically safe fibre sensor gave early warning for temperature variation in an underground mine environment and could locate the danger areas continuously over several kilometres. In another study, Dubaniewicz et al. (1998) described a unique approach to measuring temperatures within mine trailing cables under dynamic test conditions. They employed a distributed temperature measuring system based on fibre-optic sensors embedded within the metallic conductors which measured temperatures at 1 m intervals along the entire length of cable. They found the temperature measurements to be accurate to within ± 1 °C. They argued that the OTDR proved to be a valuable quality assurance tool during the test cable manufacturing process. Zhang et al. (2000, 2001), conducted a series of experiments using optical fibre based DTS in an underground coal mine. They successfully utilised an automatic alarm system to forecast any fire or explosion caused by high temperature in the mine. They measured the temperature in a range of 50–100 °C within an uncertainty of ±3 °C. They found the spatial resolution to be less than 5 cm and the measured time to be less than 70 s.

Traditionally, in a routine mine ventilation survey, the data are gathered from point measurements using conventional thermometers. This can limit the speed, accuracy and resolution of temperature monitoring in the mine application. Underground mines need a dynamic measurement system that is capable of providing real-time information on the changes of the mine environmental conditions. In comparison to conventional temperature measuring systems, the advantages of the DTS system are fast, accurate, reliable and continuous response and reduced risks associated with the measurements. Use of this system will provide information that can be used in the safety and environmental improvements of underground mines, by means of reducing hazards associated with overheated areas.

In underground mine applications, where the time history of the temperature profile is required, the DTS system offers a more efficient way to take real-time readings of temperature along the fibre. This system is very useful particularly for measuring temperature in hazardous zones of the mine where people access is not recommended or practical. The DTS system uses low power and is not capable of causing ignition. Therefore, it is perfect for gaseous environments where only safe instrumentation devices are allowed. The system is also capable of measuring ranges of up to 60 km in distance which makes it very functional in mining applications.

There are previous studies reported in the literature which have examined the application of optical fibre technology in the measurement and monitoring of air temperature in underground mine environments. To the best knowledge of the authors, none of these studies has quantitatively assessed the performance of a DTS system under various ventilation conditions. As such, the contribution of this study is to examine the performance of a DTS system under various ventilation conditions in a controlled underground environment. This will be carried out by investigating the results of DTS measurements against the readings of conventional instrumentation and the theoretical modelling.

2. Principles of operation

In the OTDR technology, a pulsed laser is coupled to the optical fibre which is the sensing element. The light is backscattered as the pulse propagates through the fibre owing to the changes in density and composition as well as due to molecular and bulk vibrations. The distance along a fibre optic cable is determined by the time-of-flight of the returning backscattered light because the velocity of light propagation in the optical fibre is known. The backscattered light consists of different spectral components due to different interaction mechanisms between the propagating light pulse and the optical fibre. A portion of the backscattered light is guided back to the source and is split off by the directional coupler to the receiver. The backscattered light consists of Rayleigh, Brillouin and Raman backscattering light.

- The Rayleigh backscattering component is the strongest due to density and composition fluctuations and has the same wavelength as the primary laser pulse. The Rayleigh component controls the main slope of the intensity decay curve and may be used to identify the breaks and heterogeneities along the fibre. However, the Rayleigh component is less sensitive to temperature variations.