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EARLY FIRE DETECTION IN UNDERGROUND COALMINES

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ABSTRACT: Analysis of mine fire growth and spread is important for improving safe emergency egress for mine workers in fires. In fire engineering, a 'design fire' is the term that describes the characterisation of a fire in relation to its growth and decay. Defining the design fire is the starting point for managing the fire risk of a mine and is the basis for further analysis of emergency response. A current Minerals Industry Safety and Health Centre (MISHC) PhD project is researching methods of improving fire life safety and asset loss control in mining using Video Based Fire Detection (VBFD) in the context of fixed plant fires. Experiments were carried out at Safety in Mines Testing and Research Station (SIMTARS) facilities. This research was part of the MISHC project to better understand the detection capabilities of VBFD in relation to weak plumes from the early combustion of coal associated with fixed plant. This part of the research specifically deals with assessing the physical dimensions and shape of the low energy, non-flaming weak plumes formed from smouldering coal fires. It demonstrates how experimental methods were used to successfully validate the corresponding numerical simulation of the design fire so it can be used for further research.

INTRODUCTION

This paper reports on a part of an ongoing research program that assesses the small smouldering combustion type fires that are the subject of Video Based Fire Detection (VBFD).

The purpose of the primary research is to assess if (VBFD) is an effective means of improving fire life safety and asset loss control in mining.

These fires are likely to occur on fixed plant in such locations where VBFD could be located to detect such early stage smouldering. One of the most commonly reported sources of potential ignition associated with fixed plant in underground coal mines is the frictional overheating of conveyor belt bearings and rollers that are in the process of failure through seizing.

The types of fires prevalent at this early stage of combustion are quite small in terms of the energy released in the coal combustion process and are usually without flames. They typically produce a plume of visible products of pyrolysis termed pyrolates. In the subject research these pyrolates include condensed fragments of volatile hydrocarbons, water vapour and gases such as Carbon Monoxide (CO) resulting from the pyrolysis of coal and grease. Under appropriate conditions there is potential for rapid fire growth and spread, so these small fixed plant fires are considered quite dangerous to mine workers.

This plume analysis and its relationship to the design fire's mass loss rate is the main focus of this paper. Design fires are typically described in a graphical format, which compares Heat Release Rate (HRR) measured in Kilowatts (kW) or products of combustion, such as smoke and pyrolates, against time. Low energy plumes with small or no flames are termed 'weak plumes'. The experimental and numerical assessments of the design fire plume dimensions were compared.

Clearly defining the design fire was a critical step in this VBFD study, as the ongoing accuracy of the research depends on repeatability of the design fire throughout the experiments. The objective of this research therefore was to prove that the numerically estimated plume dimensions could be validated experimentally.

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METHOD

Experimental method

Testing of pyrolates produced from a thin layer of coal and grease on simulated overheated bearings was experimentally carried out at the Safety in Mines Testing and Research Station (SIMTARS) in Queensland, Australia. The experimental purpose was to simulate a frictional heating fire on a typical underground mine conveyor belt bearing or roller, in pre-failure mode.

Study Design. Experimental data relating to the visibility of small sample coal combustion plumes was collected across a range of tests. The sensitivity analysis that was introduced involved varying the levels of ventilation and luminous intensity. Three levels of the two parameters were applied over six repetitions of each experiment. In total, this resulted in 54 individual tests being included in the experimental plan (i.e. 3 air velocity levels x 3 luminosity levels x 6 repetitions). The intention was to alter the shape or visibility, or both, of the plumes to test the capability of VBFD under a range of light conditions and plume shapes. The tests were carried out over several days. The data was analysed to compare the time taken for VBFD to recognise the pyrolate plumes associated with the simulated conveyor belt bearing fires.

Equipment: A circular steel plate of 250 mm diameter was used as the simulated bearing surface with a propane gas burner rig, as shown in Figure 1, used to heat the underside of the steel plate. In an operating underground coalmine the surface of the simulated bearing housing is likely be covered with a thin layer of coal dust. The estimated mass of coal dust was 40 g, having a thickness of 5 mm based on previous mine observations. Due to the likely failure of the bearing's mechanical seal, a small amount of grease was included. The grease quantity was approximately 40 g at a thickness of 3 mm. Figure 2 shows the simulated bearing housing surface with a layer of grease on the left hand side plate and grease covered with a coal dust layer on the right hand side plate.

Figure 1 - Heater unit

Figure 2 - Simulated bearing housings with surface coal and grease

Procedure: A thermocouple was placed 5 mm above the surface of the coal layer. The temperature at this point was continuously logged at 10 s intervals throughout each test. The air stream was directed towards the fire and adjusted to achieve three levels of air velocity and subsequent plume shapes.

An initial heating of the simulated bearing housing was carried out to record the surface temperature prior to the introduction of the coal and grease samples. Figure 3 depicts the metal surface being heated and shows the location of the thermocouple. Figure 4 shows an example of a pyrolate plume resulting from heating a coal and grease sample on the simulated bearing housing plate.

In relation to the repeatability of the experiments, six repetitions of each experiment were planned using coal and grease samples of approximately the same amount (40 g each). The samples were applied to the metal plate using the same application tool for each experiment to achieve consistent coal and grease dimensions and quantities.

Figure 3 - Heated simulated bearing housing without fuel

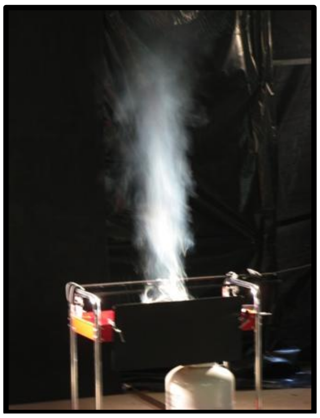


Figure 4 - Typical smoke plume resulting from heating the coal and grease fuel mixture

Data Recorded: For each repetition of each set of experimental conditions involving variations of airflow and light intensity levels, the following parameters were measured and recorded: -

1. Air velocity;
2. Light intensity;
3. Coal surface temperature at commencement of test;
4. CO levels of three CO monitors at commencement of test;
5. VBFD activation time;
6. Coal surface temperature at VBFD activation;
7. CO levels of three CO monitors at VBFD activation.

The height and width of the plumes were estimated from VBFD recordings, video camera recordings and still photographs, for each fire repetition at 'growth', 'fully developed' and 'decay' phases. The visual data was synchronised with recorded time data and readings associated with the coal surface temperature.

The simulated bearing surface was heated to a temperature up to a maximum of 384 ºC using a propane gas burner producing 909 W applied directly to the under surface of the metal plate.

Figure 5 shows the temperature curve of the simulated bearing housing upper surface. This setup was applied to all repetitions of each set of experiments. The metal surface was heated in each experiment until the VBFD detected smoke, or if smoke was not detected by the VBFD, until the plume production was reduced to an insignificant rate due to consumption of the fuel source. The temperature curve associated with the simulated bearing housing surface shown in Figure 5 was also incorporated in the CFD models.

Air velocity was a significant contributing factor to the plume shape and dimensions. Three axial fan settings were used to establish the low, medium and high levels of air velocity used in the testing. The air velocities were recorded using a calibrated hotwire anemometer, as follows:

1. Low air velocity - 0.11 m/s;
2. Medium velocity - 0.5 m/s;
3. High velocity - 1.6 m/s.

For the purpose of brevity in this paper, only the three low air velocities by the six repetitions (that is, eighteen studies in total) are considered in the results presented.

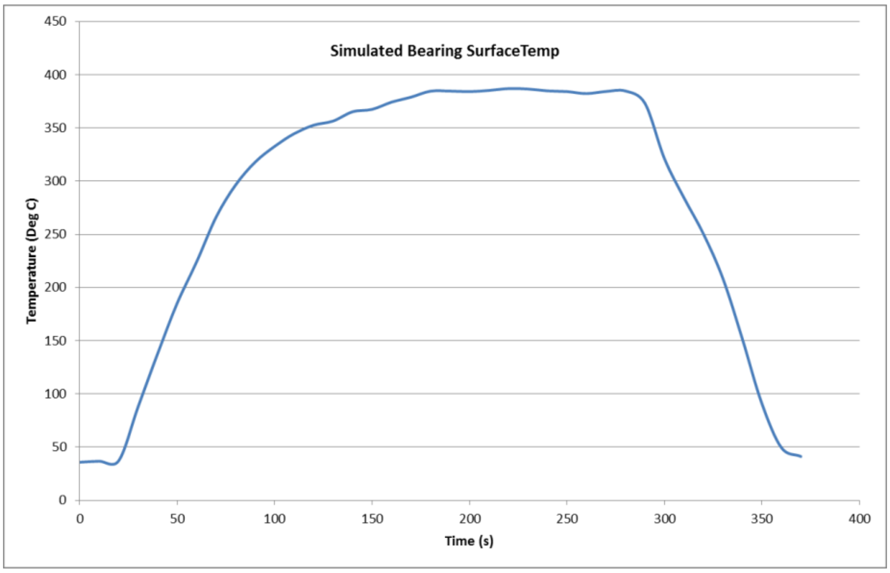


Figure 5 - Surface temperature of simulated bearing housing

Numerical assessment method

Several Computational Fluid Dynamics (CFD) models were developed after the SIMTARS VBFD experiments in order to make use of the actual physical setup parameters and the experimental space dimensions. This was done in preference to using estimated parameters before the experiments so as to reduce uncertainty in the CFD models.

The purpose of the CFD models was firstly to compare the numerical results with the experimental results in terms of similarity of plume dimensions and related characteristics.

Secondly, if the numerical CFD simulations were validated by the experimental results, CFD would be considered a useful tool for simulating the design fire in a range of computer generated mine environments for further analysis. These potential environments would vary in air velocity, ambient temperature, spacial dimensions, obscuration and light intensity levels.

The CFD program utilised for the modelling was Fire Dynamics Simulator (FDS) Version 5 (McGrattan, *et al*., 2007). This software is widely used in the field of fire engineering for estimating fire conditions within built structures and transport tunnels to assist in the development of safe design. The CFD modelsoftware solves numerically a large eddy simulation form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires. Further investigation into the use of an alternative CFD model that models chemical combustion was not concluded at the time of writing this paper

The CFD models were useful in estimating the pyrolate plume dimensions and temperature in the model space by resolving mass continuity and energy conservation equations for the smouldering combustion of the coal samples. It was assumed for the simulated conveyor belt bearing housing that the coal layer itself would offer negligible resistance to the release and subsequent flow of pyrolates from the porous dust samples. It was further assumed, and subsequently shown experimentally, that the resistance by the coal layer to the released pyrolates from the grease layer located below the coal sample was also negligible.

The Cox and Kumar explanation provided in the SFPE Handbook 3rd Edition (Cox and Kumar, 2002) discusses how the behaviour of solid combustibles during pyrolysis can be described using the mass and energy conservation principles in the following terms: -

> "This application of the conservation of mass and energy is subject to the boundary conditions set by the gas phase. Because of this low resistance to the release of pyrolates, the CFD engine can incorporate the mass continuity and energy conservation equations.

The mass continuity equation is: -

$$\frac{\partial \rho_s}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j) = 0$$

with ρ_s being the instantaneous local density of the solid.

The energy conservation equation is: -

$$\frac{\partial}{\partial t}(\rho_s c_s T_s) + \frac{\partial}{\partial x_j}(\rho u_j c_p T_s) = \frac{\partial}{\partial x_j}\left(k_s \frac{\partial T_s}{\partial x_j} - \dot{q}_R\right) - H_p \frac{\partial \rho_s}{\partial t}$$

with Hp being the heat of pyrolysis.

The terms on the left side represent the unsteady accumulation of energy in the solid together with the energy carried by the gas pyrolysates through the elementary control volume.

The right side comprises terms describing thermal conduction, the influence of in-depth absorption of thermal radiation, and the energy lost in the phase change.

An Arrhenius pyrolysis rate equation closes the system of equations:

$$\frac{\partial \rho_s}{\partial t} = -B\rho_s \exp\left(-\frac{E_s}{RT_s}\right)$$

These equations are solved by the CFD model subject to the boundary conditions at the solid surface that:

$$\dot{q}''_{\text{net}} = -k_s \frac{\partial T}{\partial x_j}$$

where ***q*·"** net represents the net heat transfer to the solid. "(Cox and Kumar, 2002)

RESULTS

The shape and dimensions of the pyrolate plumes from small smouldering coal fires plumes is the subject of this paper. A close correlation was found to exist between the shape and dimensions of the CFD simulated pyrolate plumes and the experimental plumes that were observed and measured. These plumes were used as the target source of 'smoke' for the VBFD assessment carried out at SIMTARS. Being able to validate a numerical model of the design fire is very important, as CFD models may now be used as a means of incorporating the virtual design fire in any CFD modelled mine environment for ongoing VBFD or other research.

In relation to the plume formation, the time synchronised simulated bearing housing surface temperature that heated the coal and the relationship to the coal surface temperature are graphically shown in Figure 6.

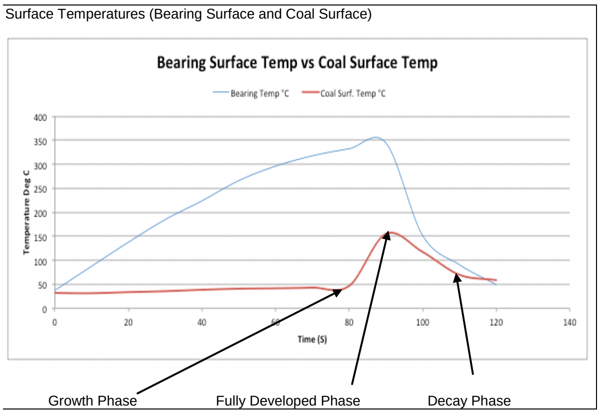
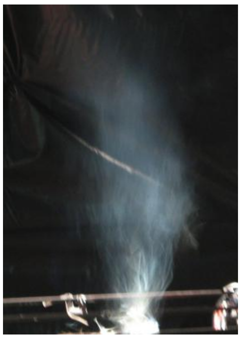


Figure 6 - Assessment of numerical, experimental and analytical plume dimensions

In Table 1, images from the CFD model and photographs of the experiment are compared at the three fire development stages, growth, fully developed and decay stage.

Table 1 - Comparison of pyrolate plumes

Growth Phase	Fully Developed Phase	Decay Phase
CFD Simulation Result		
		
Experimental Result		
		

Observations

Growth Phase:

The CFD simulation indicates that the pyrolate plume width is approximately 200 mm and extends to the ceiling 3.65 m above the fire surface. This is validated by the experiment, as shown in the Table 1 growth phase image.

Fully Developed Phase:

The plume appears considerably denser in the fully developed phase CFD simulation and in the experiment photograph at the same stage of growth. In both the simulation and the experiment, the width of the plume is the same diameter as the heated metal surface, which is 250 mm. Stratification of the pyrolate plume is occurring at approximately 3 m above the fire surface in both the simulated and experimental images.

Decay Phase:

In the decay phase, the plume is at its weakest and most turbulent. Stratification remains below the ceiling even though the plume is diminishing in width to 200 mm in both the CFD simulation and in the image of the experiment.

Furthermore, it was observed that the rate of accumulation of smoke or pyrolate particulates in the plume in the subject experiments was not as a result of flaming combustion, but of radiant heat transfer through the heated metal surface of the simulated bearing housing. Also it was noted that when the coal was heated, a pyrolate plume formed. The entrainment of nearby air diluted and cooled the pyrolate plume as it rose above the hot surface.

DISCUSSIONS / CONCLUSIONS

The experimentation carried out at SIMTARS as part of the VBFD early fire detection in coalmines project has been successful in validating the numerically modelled CFD simulation of the subject design fire.

Importantly, further CFD models of specific mine layouts incorporating their environmental conditions may be developed in the future to include this validated design fire. This provides the ability to safely estimate the movement of early developing fires in underground mines and also assists in the ongoing development of VBFD.

The research has produced some very positive findings to support the further development of CFD simulated design fires and VBFD for mine site use. A number of correlations between the results of the weak plume analysis of the subject design fires used for this VBFD research and the methods developed by Drysdale (Drysdale, 1998) for much stronger plumes have been demonstrated. This is particularly evident in the dimensions of the plume size at the various stages of design fire development.

From a practical viewpoint, in relation to non-flaming weak pyrolate plumes, when the plume entrains air, a possible flammable pyrolates mixture with air above the Lower Explosive Limit (LEL) can form. Delayed flaming can occur within the pyrolate plume or beyond, if a pilot ignition source exhibiting an adequately strong energy level above Minimum Ignition Energy (MIE) level is introduced.

Where adequately strong ignition sources, such as a frictional sparks or a hot metal shard from a failing bearing housing may become present in conjunction with a space that has accumulated a significant volume of volatile hydrocarbons from a pyrolate plume, the potential for an explosion exists.

It is clear that weak low energy non-flaming plumes in underground coalmines are a complex topic with many variables that might affect the outcome. Little previous research has been carried out in this area; as such, the studies reported in this paper could not build on an established body of knowledge here, however this fact underpins the importance of the research itself.

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