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Analysis of methodologies for calculating the heat release rates of mining vehicle fires in underground mines

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ABSTRACT

Four different methodologies for calculating the ignition of different components on a mining vehicle in a mine drift were analysed. The results were compared with two full-scale fire experiments on mining vehicles. The four different methods are based on physical relations for fire spread between combustible components of the mining vehicles. The first two methods use a critical heat flux as ignition criterion while the other two methods use an ignition temperature. A sensitivity analysis was performed and the most influencing parameter of the methods was further analyzed. The calculated results were compared with the measured results from the experiments. The two methodologies applying an ignition temperature criterion were ruled out at as the surface temperatures of all fuel components never achieved the corresponding ignition temperatures. For the two methods applying a critical heat flux criterion it was found that the expression not including a flame radiation term was not suitable as it was found that the flame radiation played an important part with respect to spread mechanisms. The expression containing a flame radiation term was found to come very close to the observed ignition times, except in the case of the left, rear tyre of the drilling rig where it predicted a much higher ignition time than the one observed. The difference is unclear and would have to be investigated further. It was also found that the surface heat losses had none effect on the output results and could therefore be neglected in the calculations. In the case of the wheel loader the calculated heat release rate curves did not match the measured curve as well as in the case of the drilling rig. The difficulty in this case consists of accurately predicting the mechanical failure of a component – in this case a suction hose – that would initiate the very significant hydraulic oil pool fire.

1. Introduction

Mining vehicles are generally involved in most of the stages of mining: exploration, drilling, blasting, loading and excavation, haulage, service and maintenance. Needless to say, the vehicles in an underground mine play an extremely important role being the main component in the primary mine operation – loading/excavation. Mining vehicles can be found in practically all parts of a mine.

Generally the environment of an underground mine will pose great demands on the mining vehicles as the wear and tear on for example the tyres is great due to tough and harsh environment, some types of vehicles such as loaders are designed to withstand falling rocks in the operator section. Thus the design of mining vehicles is often distinguished by a compact design and rugged construction.

The major combustible parts of mining vehicles will vary from type to type of vehicle, where for example the tyres will generally dominate on loaders and hydraulic hoses and hydraulic oil will generally dominate on drilling rigs. The most common fire cause is flammable liquid on a hot surface, very often hydraulic oil sprayed onto equipment hot surfaces [1,2].

In order to reduce the fire risk, some vehicles are equipped with an automatic extinguishing system installed in the engine compartment. Another approach is to use materials that are fire resistant or non-combustible and thus reduce the fire load and the risk of fire spread, one example is the use of fire resistant hydraulic fluid.

In order to quantify the heat and smoke spread the heat release rate of the fire must be determined. A methodology for calculating the overall heat release rate of various types of mining vehicles in an underground mine would thus be of great use as an engineering tool when designing the fire safety of a mine. The output of a methodology would provide us with data regarding for example the maximum heat release rate, the time to maximum heat release rate as well as the duration of the fire. The maximum heat

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Nomenclature

A	cross-sectional area of the tunnel or mine drift (m^2)
$c_{p,air}$	specific heat of air (kJ/kg K)
$c_{p,fuel}$	specific heat of solid fuel (kJ/kg K)
D	diameter of the fire (m)
E_{tot}	total calorific value (MJ)
F	view factor
h	lumped heat loss coefficient (kW/m^2 K)
h_c	convective heat loss coefficient (kW/m^2 K)
h_f	mean flame height (m)
h_r	radiative heat loss coefficient (kW/m^2 K)
H	tunnel or mine drift height (m)
H_f	vertical distance between the fire source centre and the tunnel/mine drift ceiling (m)
H_t	height of mine drift or tunnel (m)
k	thermal conductivity (W/m K)
k_s	time width coefficient
L_f	flame length (m)
L_f^*	dimensionless flame length
$\dot{m}_a$	mass flow (kg/s)
n_s	retard index
P	perimeter of tunnel or mine drift (m)
$\dot{q}''_{cr}$	critical heat flux (kW/m^2)
$\dot{q}_{flux}$	incident heat flux (kW/m^2)
$\dot{q}''_{net}$	net heat flux (kW/m^2)
$\dot{Q}$	heat release rate (HRR) (kW)
$\dot{Q}_{max}$	maximum HRR (kW)
$\dot{Q}_f^*$	dimensionless heat release rate
r_s	amplitude coefficient
s	pile number in a sequence of piles
t	time (s)
$t_{ignition}$	time of ignition of fuel component (s)
$t_{max,s}$	time to attain maximum HRR (s)
T_a	ambient temperature (K)
T_{avg}	average gas temperature (K)
T_f	average temperature at the fire (K)
T_{flame}	flame temperature (K)
$T_{flame\ tip}$	flame tip temperature (K)
T_g	gas temperature (K)
T_s	surface temperature (K)
ΔT_{avg}	average excess gas temperature (K)
ΔT_f	average excess temperature at the fire location (K)
u	longitudinal velocity (m/s)
x	location of interest (m)
ε	emissivity factor
ρ	density (kg/m^3)
ρ_a	density of the ambient air (kg/m^3)
σ	Stefan–Boltzmann constant, 5.67×10^{-11} kW/m^2 K^4

release rate and the time to maximum heat release rate will be essential when designing the smoke ventilation system at the part of the mine where the specific type of vehicle can be found as well as overseeing the ventilation system of the entire mine. An increase in the maximum heat release rate may alter the flow situation in the mine and will also increase the demands and the capacity of the ventilation system. Data regarding the fire duration will be crucial when designing the egress safety of the miners at the specific location, as refuge chambers with a limited supply of air are commonly used in underground mines as an egress solution.

Earlier papers [3,4] presented methodologies to calculate the overall heat release rate of multiple objects located in a tunnel or an underground structure. The output of the methodologies was compared to model scale tunnel fire experiments with varying number of wood cribs and pallets placed at equal distances as well as varying distances from the ignited wood crib and the pile of wooden pallets. The two different methods are based on physical relations for the time of ignition of the different fuel components: the first method uses a critical heat flux as ignition criterion while the second method instead uses an ignition temperature. It was concluded that the method using the critical heat flux as ignition criterion matched very well with the corresponding experimental results; and that the method using the ignition temperature as ignition criterion did not agree well with the corresponding experimental results. But the accuracy of the ignition temperature criterion improved considerably as the distance between the fuel components was increased. As the method shows potential for cases of long distances between fuel components, the ignition temperature criterion was included in the analysis of this paper.

The work presented here continues with analyzing potential methodologies where the results from two full-scale fire experiments were used for validation. The purpose of this paper is to investigate the validity of the methodologies with respect to the conducted full-scale fire experiments on mining vehicles in an underground mine. Until now, no methodology for calculating the overall heat release rate of mining vehicles has been validated against full-scale fire experiments on mining vehicles.

The experimental data used during the validation of the methodologies was obtained from two separate full-scale experiments [5]. The objects used during the fire experiments were vehicles typically found in mining operations: a wheel loader and a drilling rig. The aim of the full-scale fire experiments was to determine the heat release rate for vehicles common in the mining industry.

In the following, earlier conducted full-scale experiments [5] are described briefly together with the potential methodologies for calculating the total heat release rates. The findings of earlier papers [3,4] are outlined and a sensitivity analysis of the methodologies is performed. This includes the most influencing input parameter of the methodologies. The calculated heat release rates are compared to earlier results and put into the context with the calculated values from the full scale experiments. Additional sensitivity analysis on selected parameters were performed and discussed.

2. Performed full-scale fire experiments

An earlier paper [5] presented two full-scale mine fire tests, carried out in an active underground Dolomite mine in mid-Sweden. The heat release rate in the fire experiments was calculated with aid of the oxygen calorimetry [6]. The parameters measured during the tests were: the temperature at various positions, the incident heat flux at each tyre, the ventilation velocity at various positions at the end of the mine drift and the level of oxygen, carbon monoxide and carbon dioxide at a measuring station at the end of the mine drift. The vehicles used in the full-scale fire tests were a wheel loader and a drilling rig respectively. The initial fire in both cases was a diesel pool fire positioned just beside the rear, right tyre. In Fig. 1a sketch of the experimental set-up is presented.

The width and height of a mine drift may vary from mine to mine and also within a mine. When designing a mine drift the