Empirical analysis of fire-induced pressures for mine-wide emergency response planning

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ABSTRACT

Emergency response planning is an integral part of any modern mine's engineering workload. Potential underground fires and personnel evacuation as well as rescue teams' response algorithms must be considered. The Ventsim®, version 6.0 (by Howden, A Chart Industries Company) offers powerful tools for detailed fire modelling, however when the risk of fire exists everywhere inside the mine, such as in coalmines, planning emergency response for an extensive network could be time-consuming and thus posing a risk of neglecting a potential high-risk issue like a fire-induced recirculation. It is often necessary to assess this recirculation potential since the rescue team must approach the fire source from the fresh air side. In this paper, this issue is illustrated by a model example, where a fire in an incline causes air reversal in the parallel entry, cycling large quantities of toxic gases and decreasing visibility in the loop to nearly zero, making it impossible to approach the source.

To find a solution for quickly highlighting potential recirculation loops caused by fires, a methodology for an underground coalmine fire empirical approximation is proposed. This method uses the airway's area, length, gradient, and initial airflow passing through it to calculate the pressure change caused by the fire at a given moment in time. These values are then applied as fixed pressures, approximating the fires, to an existing mine's model and the results are compared to the VentFire script applications.

INTRODUCTION

Coal remains to this day one of the major sources of electricity generation in the world (IEA report, 2021). Therefore, increasing the safety of the coalminers is still a goal that ventilation engineers should strive to achieve. Routinely designing potential fire scenarios is one of the ways mining operators have been using to approach that task. That involves identifying potential high-risk places inside of a mine where a fire could take place, assessing fuel load, numerically modelling the fire output parameters such as the heat release rate, and drafting adequate response measures.

Extensive work regarding full-scale mine fire experiments has been published (Hansen, 2018, 2019, 2022). However, the author concentrated heavily on metal mine fires, citing the Australian statistics that indicated that fires happened in them more frequently than in coalmines. This, however, might not apply to mines in other parts of the world. Various models and tools for calculating mine fire parameters had been developed as early as the 1980s (Chang and Greuer, 1987). With the onset of mine ventilation networks' modelling and the inclusion of various processes taking place inside the mines, an emphasis was placed on using the ventilation software to predict the hazardous impact of fires on underground mines in terms of transient heat and contaminant distribution (Brake, 2013). The VentFire modelling is also being used to optimise potential escape routes (Sarvestani, 2023).

An underground fire spreading through an entry greatly increases the temperature and volume of the air moving downstream from it, decreasing its density. In a situation when the pressure gradient caused by the fire reaches its critical value and outnumbers the circuit's gauge pressure drop provided by the main fans, the potential for recirculation within that circuit exists. Figure 1 illustrates an example circuit with three inclines, each with a gradient of 15°. The air moves downwards through the rightmost incline, and the ventilation in the other two inclines is upcasting. With the fire source placed in the middle incline, at a certain point during its progression, the fire causes increased pressure, and the air in the leftmost entry starts moving downwards, forming a recirculation loop.

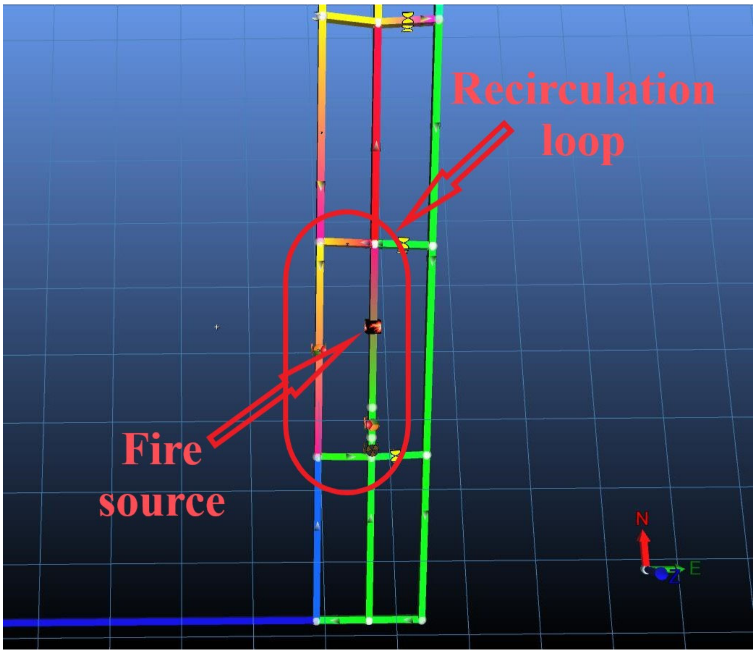

FIG 1 – Recirculation circuits caused by underground fires.

Due to the nature of coal extraction operations, their environment usually has a continuous fuel load, which excludes the option of just letting the fire burn out by itself. Rescue teams' safety and efficiency heavily depend on their ability to approach the fire source from a fresh air entry, provided that the decision to extinguish the fire is made, otherwise they risk being exposed to the temperatures that exceed the upper threshold values of their protection equipment as well as operating in near zero visibility. It is therefore important to be reasonably sure that the approach route the rescue team is going to take does not go through potential recirculation zones caused by the fire.

The dynamic monitors, recording trends of airflow, gas and visibility during the fire simulation, were placed in the airway parallel to the one that caught fire in the example. Figures 2 to 4 illustrate those trends.

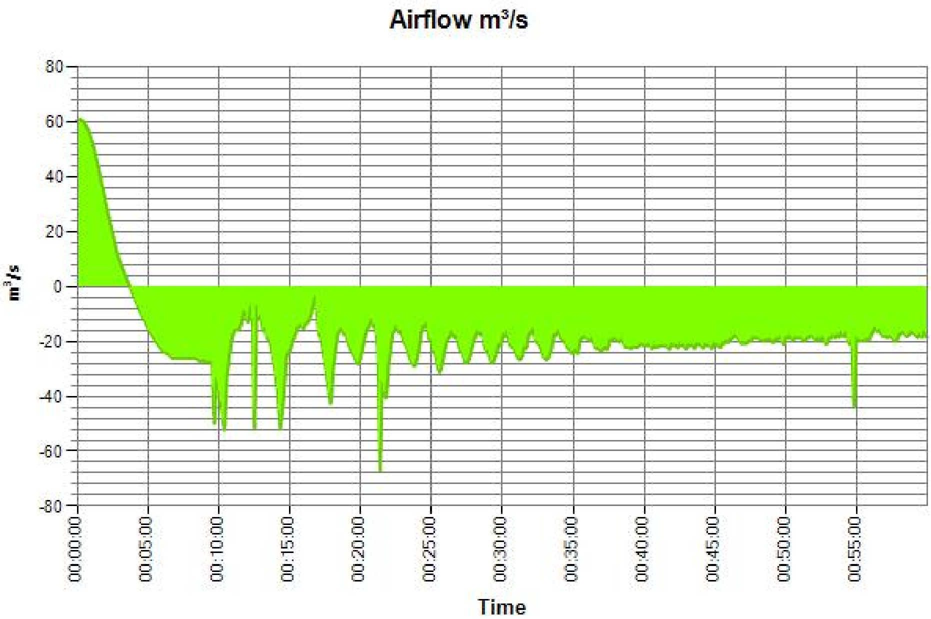

FIG 2 – Airflow in the parallel entry.

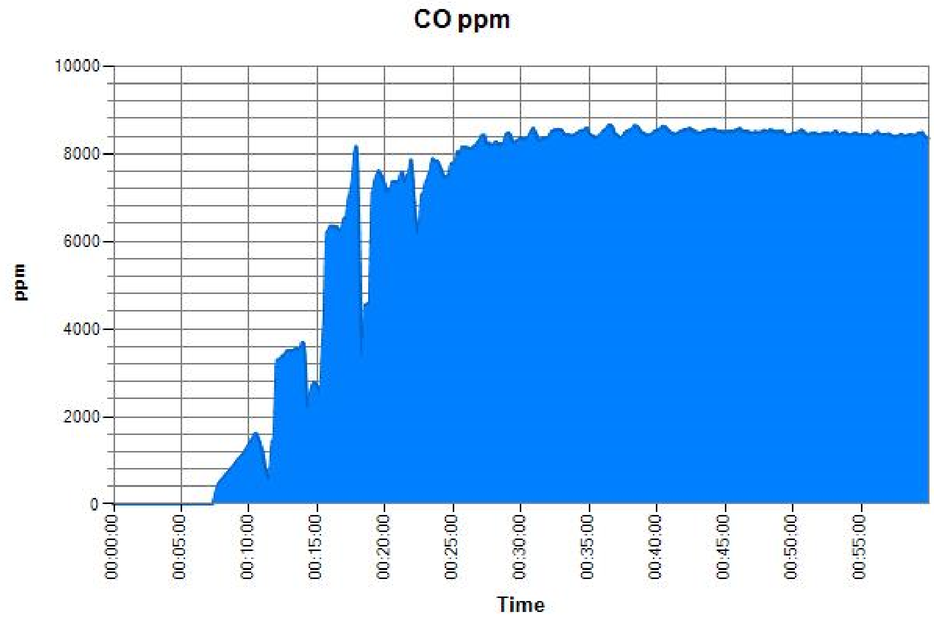

FIG 3 – Carbon monoxide concentration in the parallel entry.

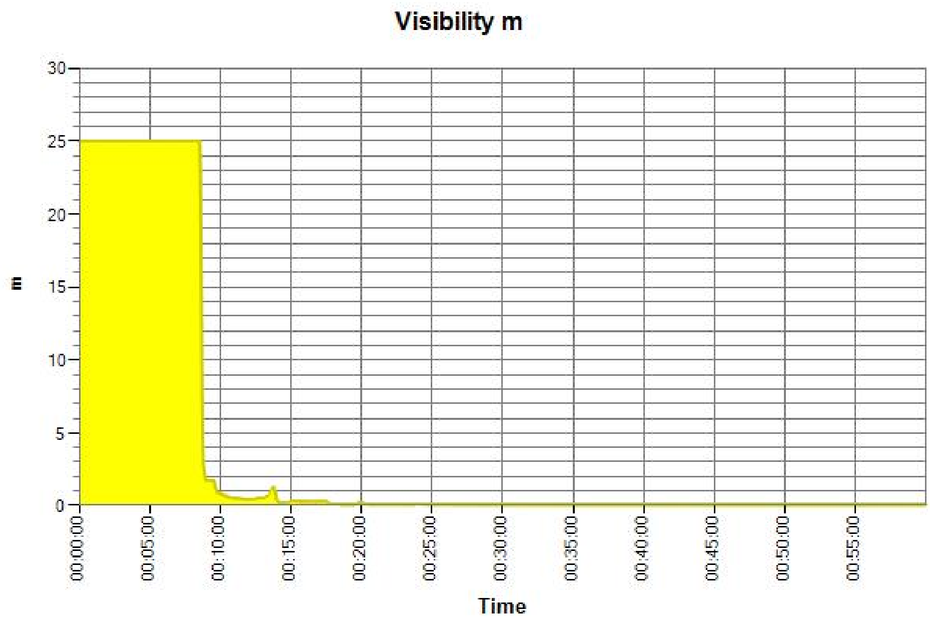

FIG 4 – Visibility in the parallel entry.

It is evident that after 5 mins from the start of the fire, the airflow is reversed, and after 10 mins high concentrations of CO are recirculating through the circuit, and visibility is near zero. Visibility readings from the dynamic monitor placed below the fire, the direction from which the rescue teams are supposed to approach and extinguish it, are shown in Figure 5.

It is evident from the graphs that after 10 mins have passed, and the airflow has reversed, reaching its peak values, it is impossible for the rescue team to safely approach the fire source and extinguish it. In coalmines the recirculation causes the possibility of methane build-up within the circuit, posing an explosion threat.

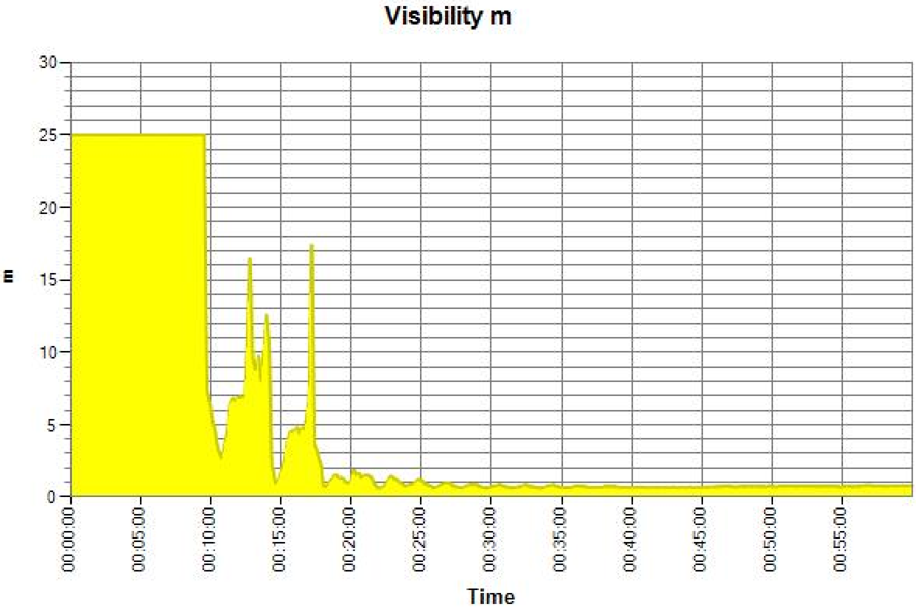

FIG 5 – Visibility below the fire.

Identifying all the potential recirculation caused by underground fires using Ventsim involves implementing the VentFire feature to various circuits where the user suspects it might occur. The length of this identification process is heavily dependent on the user's experience, their familiarity with the mine and the ventilation circuit's complexity. VentFire itself is a complex modelling tool that simultaneously runs dynamic simulations of heat, airflow as well as gas and smoke spread (Brake, 2013). Properly modelling fires in multiple entries could be time-consuming, especially if complex geometry requires smoke rollback pathways to be constructed before simulation (Stewart, Aminossadati and Kizil, 2015).

It is reasonable to assume that when working in conditions of a limited time frame and an extensive ventilation network, a user might neglect their modelling of a potential fire recirculation loop. What can be useful in that case is a method that would apply fixed pressures, approximating peak fire pressure gradient, to quickly test for the potential of recirculation. In the case of the example mine reviewed previously, a fixed pressure of 150 Pa applied to the airway instead of the fire causes the same effect of creating a recirculation loop as demonstrated in Figure 6, but without the time and complexity required to perform a full fire simulation.

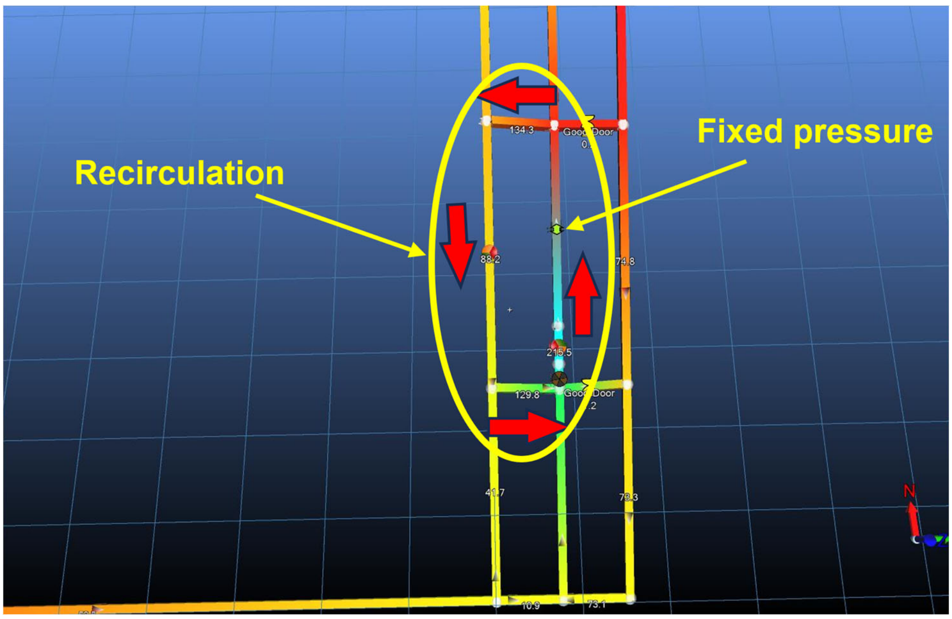

FIG 6 – Substitution of a VentFire preset with a fixed pressure causing recirculation.

The goal of this study then, is to propose a function that could approximate the pressure differentials caused by underground fires, compare it to the VentFire module output with varying initial conditions, and estimate whether its application can be practical to facilitate mines' networks analysis during emergency response planning.

METHODOLOGY

To arrive at a function successfully approximating a worst-case scenario of a fire in an underground coalmine, existing approaches to calculating a fire pressure gradient have been compared to peak pressures modelled in Ventsim with varying 'high Q' coal fuel load. The amount of coal that is going to burn in the actual fire event is assumed to be unknown, and values ranging from 1000 kg to 55 000 kg are estimated.

The continuity of the fire is modelled in the VentFire preset as an event that has growth and sustain periods, but no decay.

For each simulation time step, fire-induced overpressure is calculated as the difference between the pressure loss in the airway at that specific time step and the initial pressure loss:

$$h_{vs} = P_{ti} - P_{init} \text{, Pa} \quad (1)$$

Those resulting values were compared to the ones calculated using an empirical methodology (Bolbat, Levedev and Trofimov, 1992):

Fire zone length:

$$l_f = t\left(0.28 + 0.07\frac{Q}{S}\right) \text{, m} \quad (2)$$

Where

Q	airflow, m^3/s
t	time passed from the beginning of the fire, min

Empirical parameter *a*:

$$a = \frac{\sqrt{S}}{l_f} \quad (3)$$

Relative distance:

$$\bar{x} = \frac{l}{l_f} \quad (4)$$

Fire zone's vertical projection:

$$z = l_f \sin\beta \text{, m} \quad (5)$$

Where β is the airway incline angle, in degrees.

Empirical parameter *A*:

$$A = \frac{100a}{1.21 + 1.51\frac{S}{Q}} \quad (6)$$

Maximal temperature downstream from the fire:

$$T_M = 1273 - 975e^{-\frac{S}{A}} \text{, K} \quad (7)$$

Temperature at the end of the entry downstream from the fire:

$$T_K = 298 + (T_M - 298)e^{-\frac{\bar{x}-1}{A}}, \text{ K} \quad (8)$$

Finally, the heat pressure differential is:

$$h_t = 12z\left(0.766 + \ln\left(\frac{T_M}{T_K}\right)\right), \text{ Pa} \quad (9)$$

To estimate the linear relationship between the overpressure change over time modelled in Ventsim and heat pressure differential over the same period, calculated from Equation 9, the sample Pearson correlation coefficient was calculated for each fuel load mass value:

$$r = \frac{\sum_i h_{VSi} h_{ti} - n\overline{h_{VS} h_t}}{\sqrt{\sum_i h_{VSi}^2 - n\overline{h_{VS}^2}} \cdot \sqrt{\sum_i h_{ti}^2 - n\overline{h_t^2}}} \quad (10)$$

Where:

n sample size

h_{vsi}, h_{ti} individual sample points

$\overline{h_{VS}} = \frac{1}{n}\sum_{i=1}^{n} h_{VSi}$ the sample mean

The resulting pressure differentials were applied as fixed pressures to the airways where VentFire scripts had been implemented previously, and occurrences of recirculation loops due to VentFire and approximating empirical function were compared.

RESULTS AND DISCUSSION

The methodology was tested on two examples with different ventilation parameters shown in Figures 7 and 8. The first example represents a real coalmine model, while the second one is an abstract network with considerable differences between surface connections' heights. The purpose of the second example is to investigate the effects of increased natural ventilation pressures on fire stability and its correlation with the proposed approximating function.

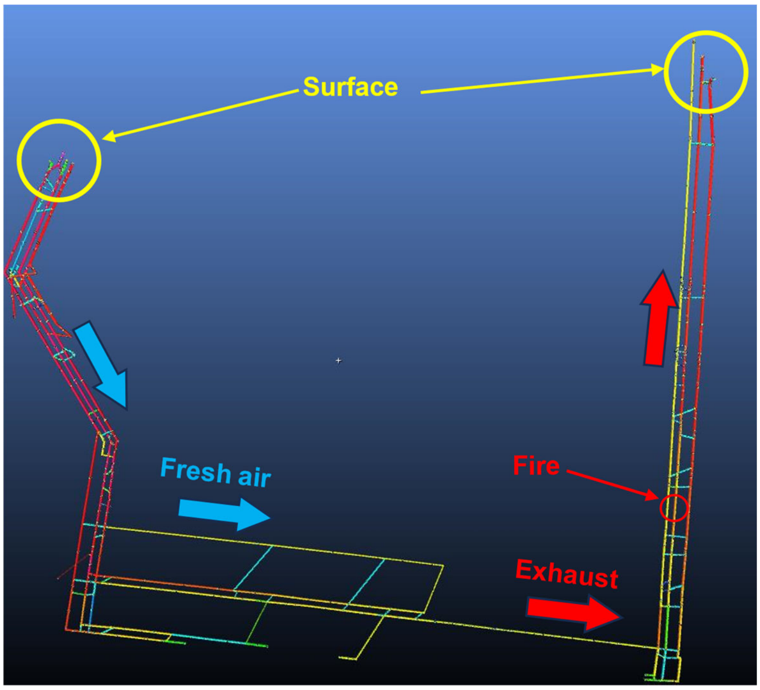

FIG 7 – Mine network example 1.

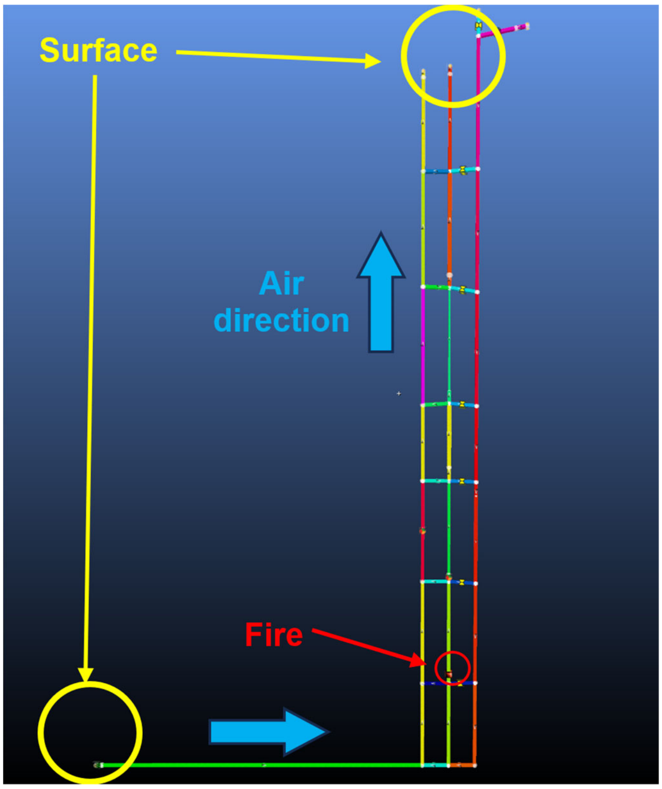

FIG 8 – Mine network example 2.

Figures 9 and 10 illustrate the comparison between fire-induced overpressures modelled in Ventsim and those calculated based on the proposed empirical function for examples 1 and 2 accordingly. In the first example, where the initial natural ventilation pressure effect was less pronounced than in the second one, correlation coefficients for various fuel mass values do not drop below 0.7 which signifies that a considerable linear relationship between the values exists. However, when the network is not stable over time and overpressures tend to fluctuate, as can be seen in Figure 10 for the second example, the correlation coefficient drops below 0.5 with increased fuel load, which means that linear modification of the proposed methodology cannot be applied to better approximate the results obtained by Ventsim modelling.

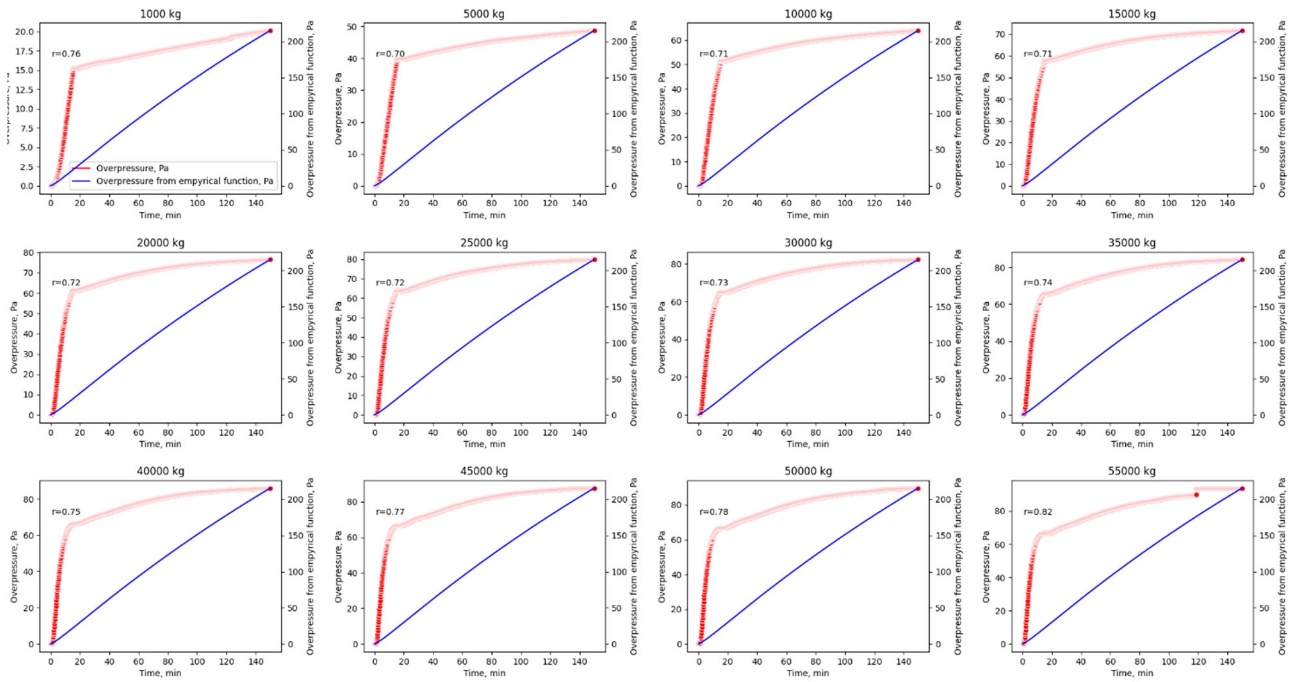

FIG 9 – Pressure change correlation, example 1.

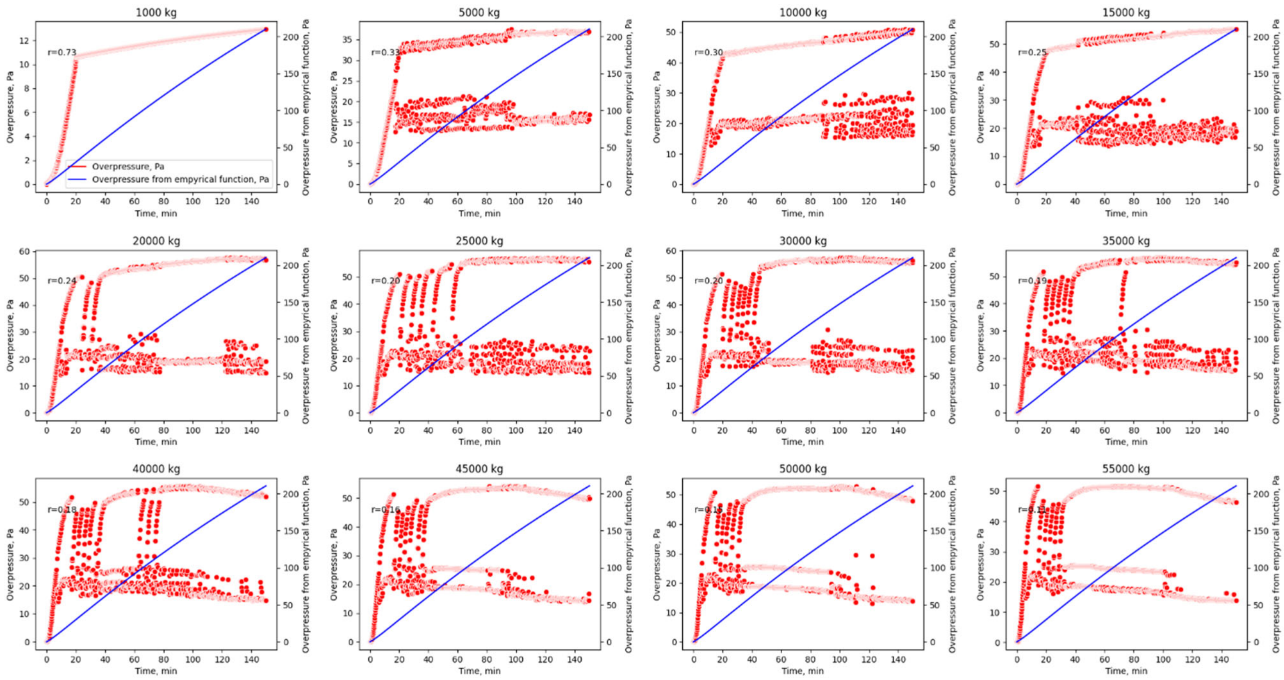

FIG 10 – Pressure change correlation, example 2.

For several incline airways in example 2, the modelling results ($H_{t\ model}$) were compared to the heat pressure differentials $H_{t\ calc}$ calculated from Equations 2–9. After the calculation was complete, pressure differentials from Equation 9 were applied as fixed pressures to the corresponding airways, and the occurrences of the recirculation loops ($R_{l\ calc}$) were compared to the results from VentFire script applications ($R_{l\ model}$). Table 1 contains the comparison between the results of the VentFire modelling and empirical calculations.

TABLE 1

Fire pressure differentials and recirculation comparisons.

Q, m^3/s	S, m^2	β, deg	l, m	Ht model	Ht calc	D Ht,%	Rl model	Rl calc
43.9	22	9.6	271.8	220.3	59.8	73	N	N
96.0	21	8.9	84.2	49.9	56.3	13	N	N
105.6	20	9.0	55.1	31.9	57.9	81	N	N
29.6	21	11.5	162.9	175.7	58.3	67	Y	Y
28.3	18	12.6	46.0	47.2	50.6	7	Y	Y
36.4	20	12.2	298.9	278.7	77.7	72	Y	Y
75.1	18	9.2	81.5	38.8	56.4	45	N	N
86.1	22	10.8	207.2	172.5	77.1	55	N	N

The average deviation of the modelled results compared to the empirical fire pressure differentials was 52 per cent, effectively rendering the calculated values unsuitable for any further value-based determinations. However, recirculation loops were found for every case they occurred during the VentFire script applications.

Considerable value deviations can be explained by the fact that natural ventilation pressures during a fire event modelled in Ventsim represent values resulting from calculations applied to every airway in the network as opposed to just the one in which the fire is placed. In the future, the proposed method can potentially be improved by conducting an extensive statistical analysis and obtaining correction factors for the proposed empirical function that would improve the approximation of the values produced by the VentFire script implementations. The function calculating overpressures induced by the fires can be applied to every airway of interest using a script that takes as input a spreadsheet output from Ventsim, containing initial ventilation conditions as well as airways' dimensions, and produces a heatmap-type graph, highlighting the airways with the highest ratio between overpressures produced by the fire and the initial pressure drops in the loops, and thus the highest recirculation risk.

Figure 11 is an example of such a script's output. It might be possible to use the method to quickly highlight potential recirculation loops caused by fires for the user to inspect and apply detailed VentFire modelling to those circuits. It cannot by any means replace the detailed network analysis but could potentially help users during emergency planning find high-risk areas within their mines they possibly have missed.

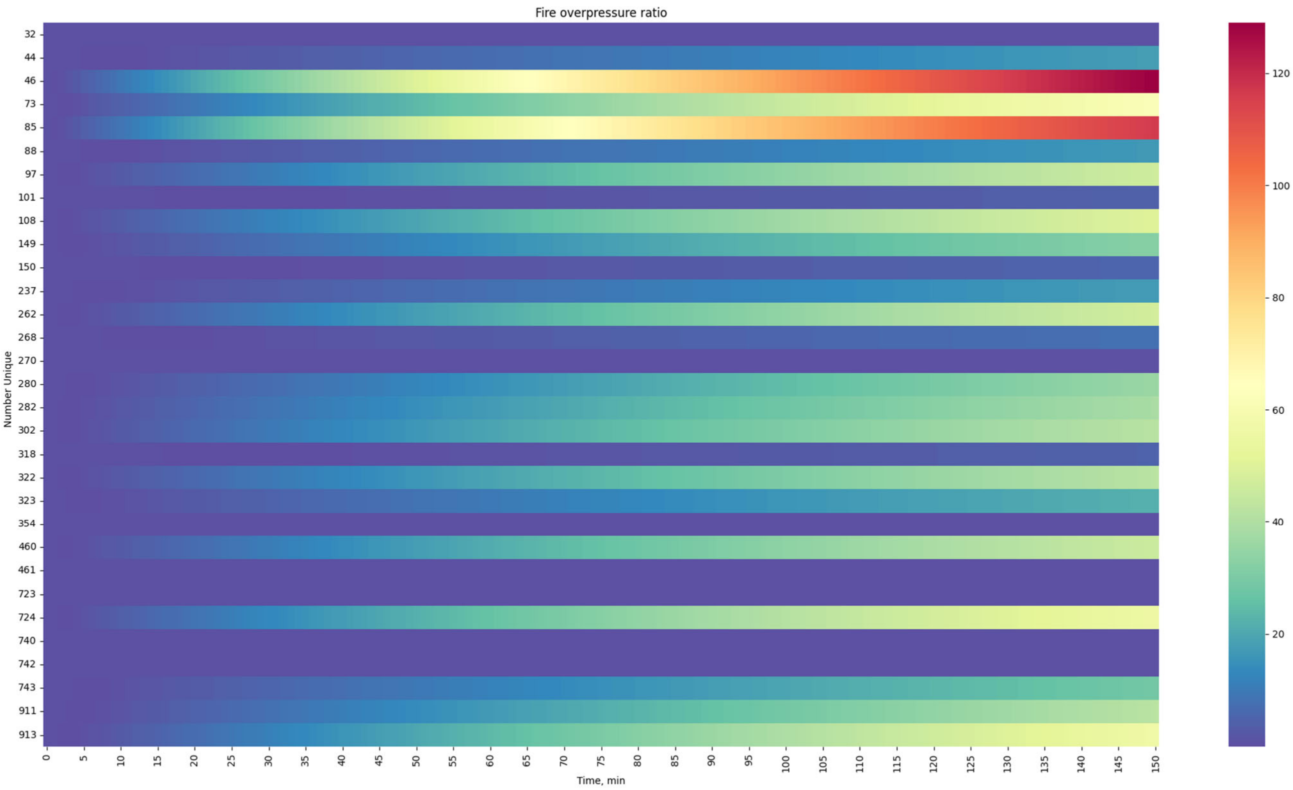

FIG 11 – Fire pressure ratio over time.

CONCLUSION

Approximating fires with fixed pressure differentials can potentially predict recirculation pathways due to fire. The iterative application of the process may guide ventilation professionals into performing more detailed analysis in areas that show a high likelihood of recirculation. To eventually develop such a feature, a function, approximating fire-induced pressures was proposed. Correlation coefficients between the overpressure values produced by the VentFire script application and the proposed empirical function were calculated for various fuel load mass values.

In some cases, the linear relationship between the two data sets existed, in others, when instability caused by the significant impact of the initial natural ventilation pressure values produced overpressure fluctuations, VentFire application results could not be approximated with the proposed empirical function. Overpressure values obtained from the empirical function were compared with the overpressures modelled in Ventsim, the average deviation was 52 per cent, while all resulting recirculation loops matched.

A way to reduce the deviations between the approximating function and VentFire script output by introducing linear coefficients based on further statistical analysis was proposed. A script, iterating overall selected airways and highlighting all branches with high overpressure ratios was created.

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