POSSIBILITIES FOR SIMULATING THE SMOKE ROLLBACK EFFECT IN UNDERGROUND MINES USING CFD SOFTWARE

MOŽNOSTI SIMULACE ZPĚTNÉHO PROUDĚNÍ KOUŘE V HLUBINNÝCH DOLECH POMOCÍ CFD SOFTWARU

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Abstract

The effect of fire generated smoke rollback in underground mines can be dangerous and a potentially fatal threat to all who are endangered by the fire. Three critical stages in the process of smoke rollback are 3D local phenomena that can be analysed by CFD software simulations. With the help of a 3D-CFD analysis we can observe the critical stages of smoke rollback and their reaction to a ventilation network. The CFD provides the opportunity to expand the range of prediction of smoke spread for a wide spectrum of airflows, fire intensities, mine-section inclinations and layouts. The paper deals with the possibilities for simulating the smoke rollback effect in underground mines using the CFD software. For the purposes of this research paper, the PyroSim software from the company Thunderhead Engineering was used to create three different CFD fire scenarios and then observe the critical stages of smoke rollback effects.

Abstrakt

Zpětné proudění kouře požáru v hlubinných dolech může představovat potencionální hrozbu pro všechny, kteří mohou být jeho dosahem ohroženi. Tři kritické fáze procesu změny proudění kouře jsou 3D místní jevy, které mohou být zkoumány pomocí CFD simulací. Za pomocí 3D-CFD analýzy můžeme sledovat kritické fáze změny proudění kouře a následné ovlivnění větrní sítě dolu. CFD nabízí mnoho příležitostí k rozšíření prognózy proudění kouřů při různých objemových průtocích větrů, intenzitách požárů, v úklonných a horizontálních důlních dílech. Článek se zabývá možnostmi simulace jevu změny proudění kouře v hlubinných dolech za použití CFD softwaru. Pomocí softwaru PyroSim společnosti Thunderhead Engineering byly vytvořeny tři různé CFD scénáře požárů a následně byly pozorovány kritické fáze jevu změny proudění kouře.

Keywords: fighting fires**,** smoke rollback, CFD analysis, modelling, simulation

1 INTRODUCTION

A fire that occurs in an underground mine could have disastrous consequences for employees if the fire is not put under control in its initial stage. Initially, thermal buoyancy forces generated by a fire will produce a growing plume of flame followed by generating fire gases. With enough air velocity (ventilation), the smoke and fire products will be transported in a direction of positive-pressure ventilation. Once the fire develops into its highest intensity, buoyancy forces generated by the fire can overcome the inert forces of the ventilation, and in this stage, the migration of smoke and fire products spreads versus the positive-pressure ventilation located on the roof of the underground mining facility. In case of underground mine fires under low-velocity motion of air, there is often present the effect of smoke rollback. The effects of smoke rollback and fire products can be dangerous and a potentially fatal threat to miners and mine rescue teams, preventing them to approach close enough and be able to effectively extinguish the fire. This fire effect can occur directly over the heads of the firefighters and miners, enveloping them with hot fire gases, and can cause fatal consequences. The local reversing of the ventilation network which will contaminate the clean air flows and make the process of evacuation more difficult is another important scenario among the many harmful scenarios that can cause the smoke rollback effect.

Risks of explosion of fire gases must be taken at a high alert level when there are effects of smoke rollback. Mine explosions can be the result of ignition of an explosive mixture of flammable gases or explosive dust or a combination of the two. Possible explosions also can occur from ignition of fire gases given off by mine fires. In coal and metal/non-metal mines, a flammable gas, usually methane, is ignited by a spark or the flame source which propagates to explosion proportions because of the quantity of gas present or explosive dust picked up by the gas ignition.

The ability to predict the smoke rollback effect in case of fires in underground mines can significantly improve the chances of safely evacuation.

2 SMOKE ROLLBACK EFFECT

A smoke rollback effect usually occurs when the air velocity (ventilation) is too low in dependence of fire intensity, Fig.1.

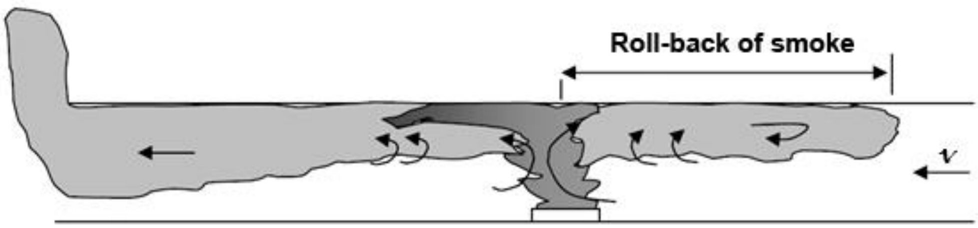


Fig.1 The process of smoke rollback [1]

The critical ventilation air velocity to prevent the effect of smoke rollback is calculated using the following equation [2]**:**

$$v_{crit} = k\left(\frac{g\dot{Q}'}{\rho_0 c_p T}\right)^{\frac{1}{3}} \tag{1}$$

Where:

v_{crit} - Critical ventilation air velocity, [m/s],
g - Acceleration due to gravity, [m/s^2],
k - Constant,
$\dot{Q}'$ - HRR-heat release rate, [kW],
ρ_0 - Ambient air density, [kg/m^3],
c_p - Specific heat capacity of air, [J/kg.K],
T - Smoke temperature, [K].

The development of smoke rollback in an entrance to a mine or a tunnel occurs in three distinct stages [3]:

1. Critical velocity stage, Fig. 2(a),
2. Partial smoke rollback stage, Fig. 2(b),
3. Complete smoke rollback stage, Fig. 2(c).

The critical ventilation velocity (Fig. 2(a)) is the minimum airflow velocity preventing the smoke from rolling back. The critical velocity has become one of the prime criteria used in the design of underground mining ventilation systems. As the fire grows to thermal intensity, the inertial force of the intake airflow is overcome by the fire-generated buoyancy forces, and smoke begins to migrate along the airway roof counter in the positive-pressure ventilation airflow direction. At this time, two directions of flow co-exist in the airway, with the lower layer of fresh air maintaining its forward direction and the upper layer of hot smoke rolling back, as shown in Fig. 2(b). This scenario is defined as a partial smoke rollback stage. If the fire grows to sufficient rapid intensity, it is possible for the airway to completely fill with hot smoke, causing total airflow reversal, as shown in Fig. 2(c).This phenomenon is known as a complete smoke rollback or smoke reversal. The complete smoke reversal rarely happens in road tunnel fires because the pressure differences between the two ends of the tunnel, which are both open to the atmosphere, is insignificant. However, it can and has occurred during underground mine fires because an underground mine fire exists not only in a single airway but also in a ventilation network with many branches, junctions, various controls, and fans.

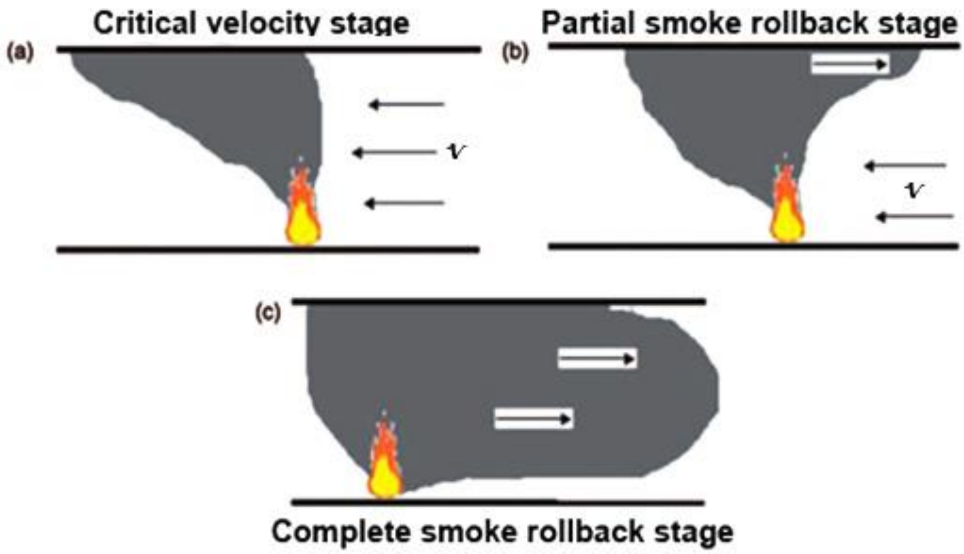


Fig.2 Development phases in the process of smoke rollback or smoke reversal, [3]

In this time, many software packages are available such as [4]: MFIRE, Ventgraph, MineFIRE Pro+, VentFIRE™ and many others that can predict the complete smoke rollback stage. However, the partial smoke rollback stage, Fig. 2(b), is a three-dimensional phenomenon which represents a critical point in dealing with this fire effect and is beyond the scope of the above mentioned software packages. The best method for analysing the stage of a partial smoke rollback effect, which represents a key point for dealing with this fire effect, is the method of a CFD (computational fluid dynamics) analysis. It should be noted that the CFD analysis can represent only a small portion of the ventilation network because of the large number of calculations performed by the analysis, it means that we are limited by computer performance so this computing method can be used only for local effects and can't completely replace the above mentioned software packages.

3 POSSIBILITIES FOR SIMULATING THE SMOKE ROLLBACK EFFECT IN UNDERGROUND MINES USING A CFD SOFTWARE

For the purposes of this research paper, the PyroSim software from the company Thunderhead Engineering is used [5]. The PyroSim software is a graphical user interface for the Fire Dynamics Simulator (FDS) which was originally developed by the National Institute of Standards and Technology (NIST) USA. The Fire Dynamics Simulator (FDS) [6] is a computational fluid dynamics (CFD) model of fire-driven fluid flow. The software solves numerically a large eddy simulation form of the Navier-Stokes equations [7] appropriate for low-speed, thermally-driven flow, with an emphasis on smoke and heat transport from fires. This approach is very flexible and can predict and simulate different fire scenarios, including the ventilation in the same process. The FDS and Smokeview are two free computer codes that can simulate the process of fire and smoke development, which was originally developed by the NIST (USA), and are combined to one software interface by the PyroSim software from Thunderhead Engineering.

For the purposes of this research paper, a 3D computer horizontal mining drift with the following dimensions is generated: a width of 4m, a height of 3m and a length of 50 m, Fig. 3.

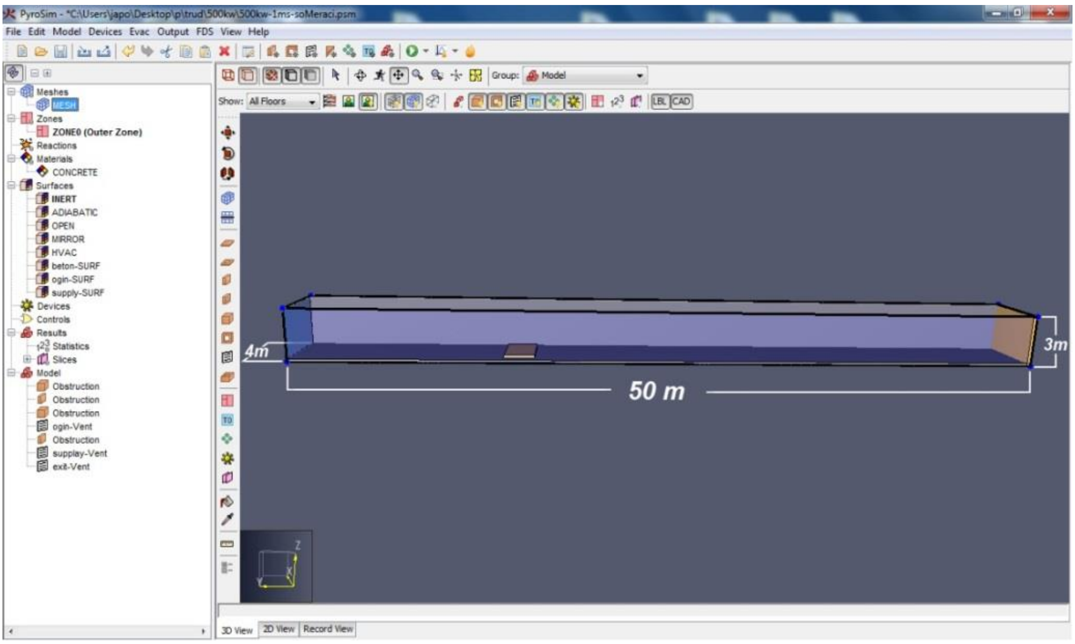


Fig. 3 Process of 3D modelling a horizontal mining drift

The location of the fire is 35 m from the beginning of the 3D horizontal mining drift, and the fire covers an area of 6 m^2 (2 m length, 3m width). To measure the properties of the fire and smoke effects in this simulation, we placed devices and sensors exactly six meters from the fire (we assumed that an optimal place for firefighters) Fig. 4, Tab. 1.

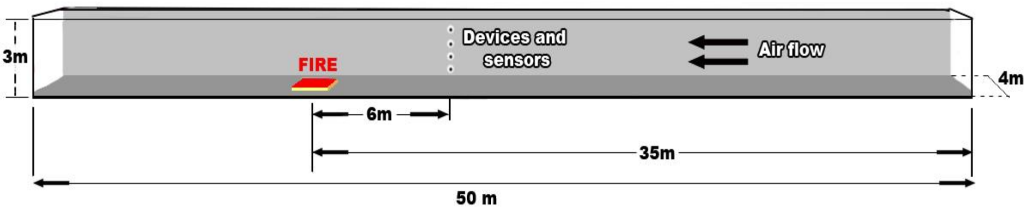


Fig.4 Scheme of horizontal mining drift

In this large eddy simulation (LES), the grid size is an important factor to be considered. A smaller gird size gives more detailed information of the turbulent flow but needs more computation resource and longer computing time. However, the basic methodology of LES is that the accuracy increases as the numerical mesh is refined. The cell size (dx) for the given simulation can be related to the characteristic fire diameter (D*), i.e.; the smaller the characteristic fire diameter, the smaller the cell size should be in order to adequately resolve the fluid flow and fire dynamics. The characteristic fire diameter (D*) is given by the following relationship [8]:

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{\frac{2}{5}} \quad (2)$$

Where:

$\dot{Q}$ - Expected heat release rate, [kW],

ρ_∞ - Density, [kg/m^3],

c_p - Specific heat, [J/kg.K],

T_∞ - Ambient temperature, [293K],

g - Acceleration due to gravity, [m/s^2].

For this simulation, we take into account a moderate cell size (dx) of 14.88 cm, Fig 5. The mesh line for FDS is as follows:

- actual (dx) size is 0.148(x), 0.139(y) 0.15(z), [m],
- distances are 4(x), 50(y), 3(z), [m],
- total number of cells is 194,400.

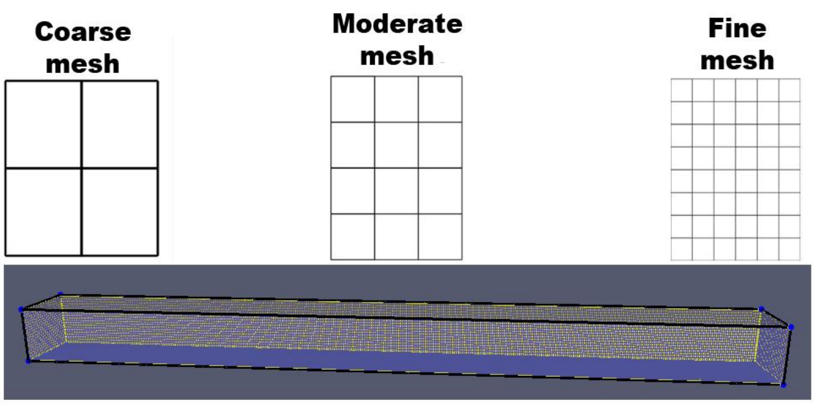
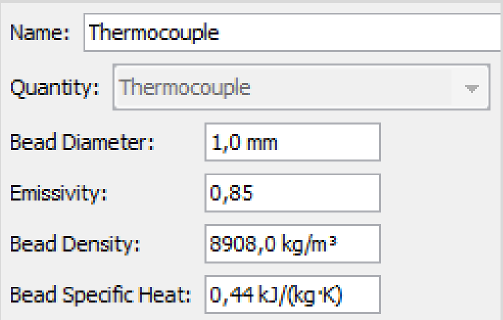
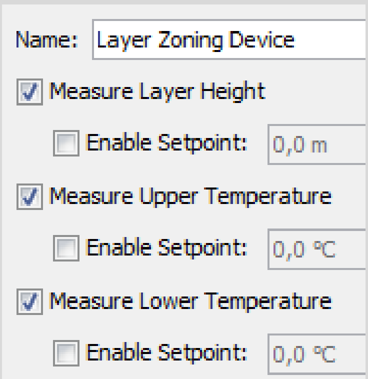
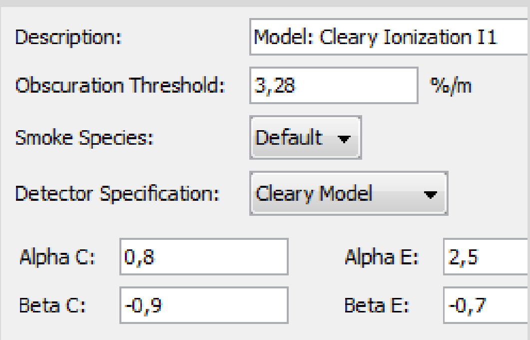


Fig.5 Process of modelling a moderate mesh

Tab. 1 Properties for devices and sensors in horizontal mining drift 6m placed upstream the fire

Thermocouple 	The temperature of the thermocouple itself, which is usually close to the gas temperature, but not always, since radiation is included in the calculation of the thermocouple temperature, is the output of the thermocouple.
Layer Zoning Device 	There is often the need to estimate the location of the interface between the hot, smoke-laden upper layer and the cooler lower layer in a burning compartment. The FDS uses an algorithm based on integration along a line to estimate the layer height and the average upper and lower layers temperatures.
Smoke Detector 	A smoke detector measures obscuration at a point with two characteristic fill-in or "lag" times. The percent obscuration per meter is the output.

On the same 3D horizontal mining drift, we will perform a total of three simulations in the following order, Tab 2.

Tab. 2 Properties for performing simulations

	Location of fire (m)	Area of fire (m^2)	Heat release rate HRR (kW/m^2)	Ventilation air velocity (m/s)
1.	35 m	6 m^2	500 kW/m^2	1 m/s
2.	35 m	6 m^2	500 kW/m^2	1,5 m/s
3.	35 m	6 m^2	500 kW/m^2	2 m/s

All three simulations will be analysed from the same time at the 200-th second from the development of the fire. The development of peak intensity of the fire is from 0 to 60 seconds.

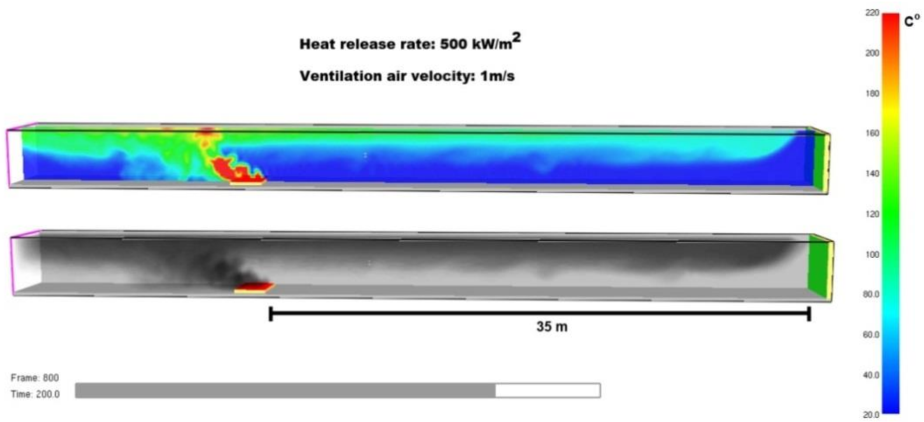


Fig. 6 Simulation 1

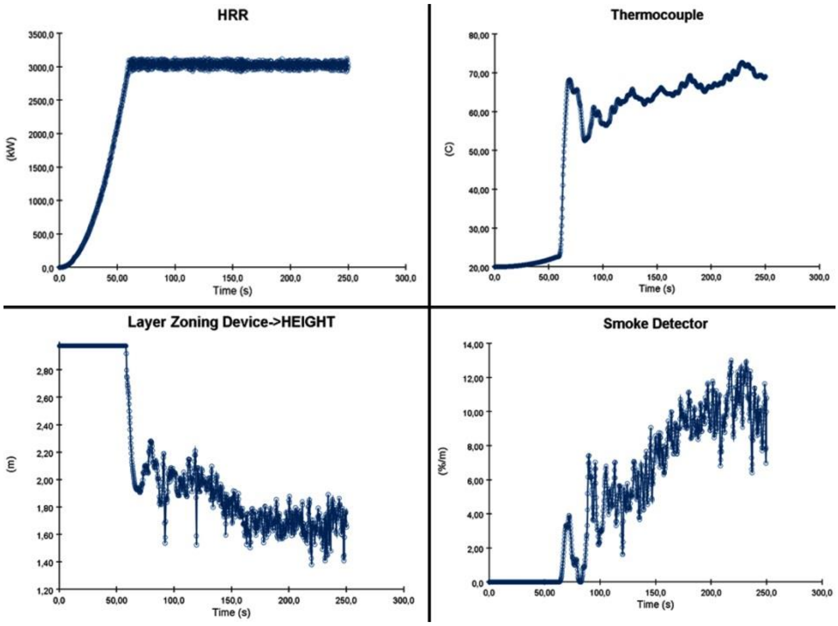


Fig.7 Results of devices and sensors for simulation 1

Based on Simulation 1 (Fig. 6), we can conclude that the fire with a heat release rate of 500 kW/m^2 and a ventilation air velocity of 1m/s can cause a complete smoke rollback stage with a mean temperature in the first 35m of smoke rollback layer of 70 °C versus the positive-pressure ventilation. With the help of devices and sensors placed 6 m in the upstream position of the fire, different parameters of smoke and fire products can be observed depending on time (Fig. 7). This critical stage of complete smoke rollback can cause difficulties in dealing with the fire because of the inability of firefighters to approach close enough to the fire. The risk of possible explosions that can occur as a result of the ignition of accumulated fire gases given off by the mine fire is another possible critical factor. This complete smoke rollback stage also have detrimental effects of contaminating and putting to risk other underground mining areas with a flow of fresh air.

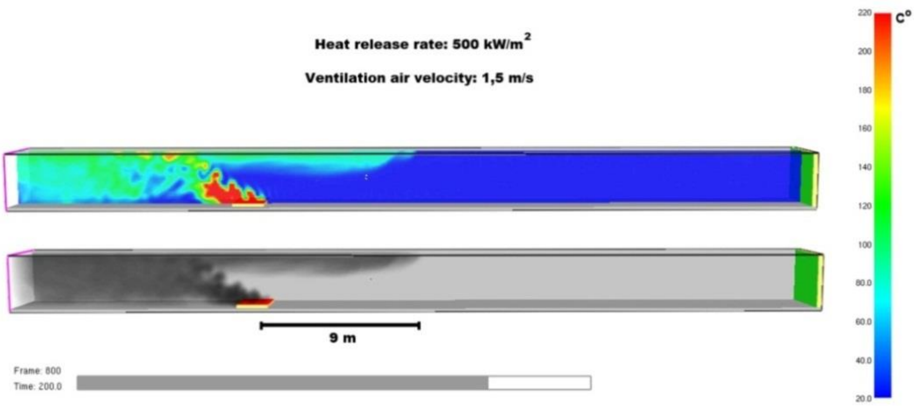


Fig. 8 Simulation 2

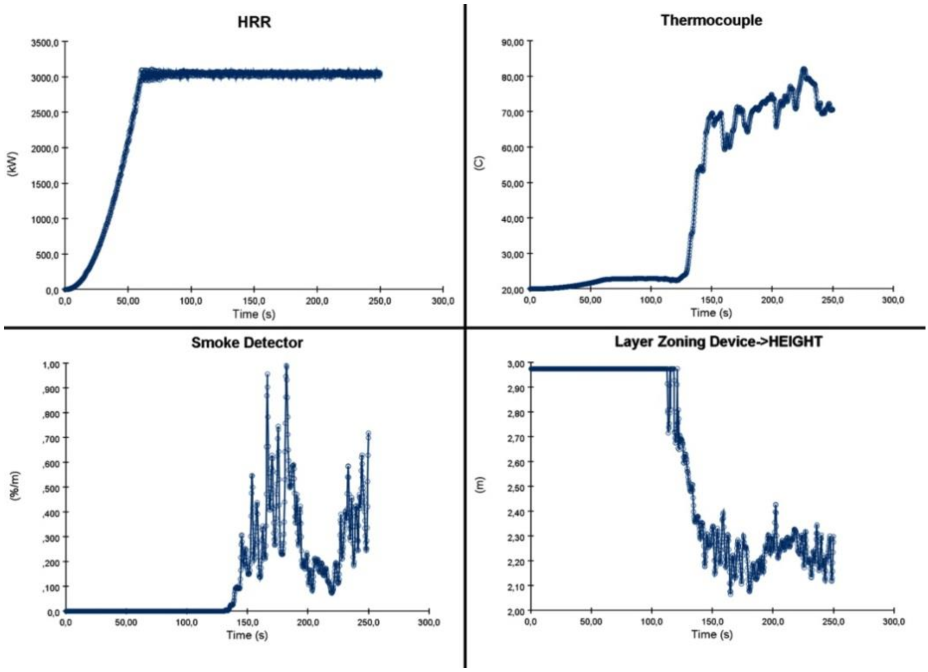


Fig.9 Results of devices and sensors for simulation 2

Based on Simulation 2 (Fig. 8), we can conclude that the fire with a heat release rate of 500 kW/m^2 and a ventilation air velocity of 1.5 m/s can cause a partial smoke rollback stage versus the positive-pressure ventilation with a length of rollback (reversal) smoke layer of about 9 m and a mean temperature of the same smoke layer of about 75 °C. The information about the length of the rollback (reversal) smoke layer and its properties that can be observed from the placed devices and sensors (Fig. 9) is crucial information for possible methods that can be implemented to handle and control a fire.

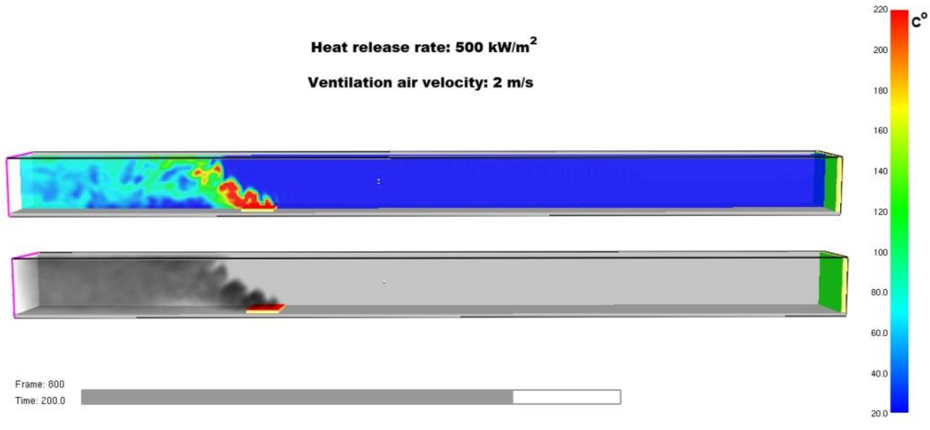


Fig. 10 Simulation 3

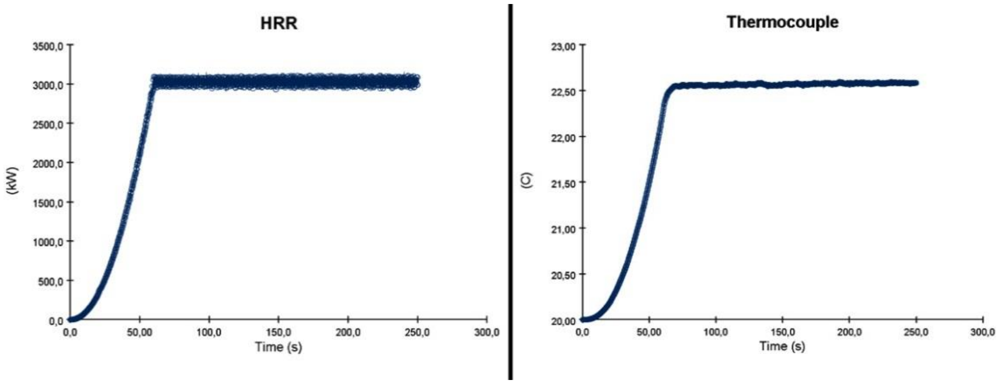


Fig.11 Results of devices and sensors for simulation 3

Based on Simulation 3 (Fig.10), we can conclude that the fire, with a heat release rate of 500 kW/m^2 and a ventilation air velocity of 2 m/s for this scenario and, under these circumstances, completely direct (blows) smoke and fumes in a direction of positive-pressure ventilation and space in front (upstream) of the fire, is free of smoke and fire gases, which is a favourable and conducive environment for firefighters to be able to come close and successfully extinguish the fire.

From these three simulations we have performed we can conclude that the process of smoke rollback mostly depends on the critical ventilation air velocity which is closely related to the power of fire (HRR-heat release rate) which can be calculated from Equation 1. The above three performed simulations give crucial information for possible and safe ways of extinguishing and controlling the fire.

4 CONCLUSIONS

Fires that occur in underground mines pose one of the most serious hazards. At a low air velocity in case of fire in underground mines, the effect of smoke rollback is often present. The process of smoke rollback can be dangerous and a potentially fatal threat to miners and mine rescue teams. In case of underground mining fire, evacuation of people can be extremely difficult. Opportunities for safe evacuation out of the affected area are strongly associated with the development and spread of smoke and fire products through a mining ventilation network. The ability to predict the dangerous smoke rollback effect in case of fire in underground mines can help to a successful response of mine rescue teams. The partial smoke rollback stage represents a critical moment for getting the fire under control. This critical stage can be observed and analysed using CFD methods, by which we are able to analyse the time of its development and the possibilities to prevent this effect from transforming itself in a complete smoke rollback stage that can bring catastrophic consequences. The above three performed CFD simulations give crucial information for possible and safe ways of extinguishing and controlling the fire. This CFD computing method for predicting the stages of smoke rollback during an underground mining fire can be applied to different fire scenarios and can help us gather crucial information. The CFD modelling is a viable method for analysing potential hazards associated with smoke from an underground mining fire.

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RESUMÉ

Důlní požáry představují jedno z nejzávažnějších rizik hlubinného hornictví. Nízké objemové průtoky větrů v důsledku důlních požárů mají často za následek způsobení jevu změny proudění kouře. Proces změny proudění kouře představuje závažnou hrozbu nejen pro pracovníky ale především pro báňské záchranáře. Důlní požár může také značně zkomplikovat evakuaci pracovníků. Evakuace v případě důlního požárů je značně ovlivněna vývinem a prouděním kouřů a produktů hoření obsažených ve větrném proudu. Možnost předpovědi vzniku změny proudění kouře může pomoci báňským záchranářům k úspěšnému zásahu. Částečná změna proudění kouře představuje kritickou fázi bezpečného zásahu při potlačení důlního požáru. Tato fáze může být zkoumána a analyzována pomocí CFD metod, pomocí kterých můžeme analyzovat čas vývoje a možnosti prevence tohoto jevu s cílem dosáhnout změny stavu zpětného postupu kouřů, který by mohl způsobit katastrofální následky. Simulace pomocí CFD poskytuje související informace k možnosti účinného hašení a kontroly při potlačení požárů. Výše uvedená CFD metoda predikce vzniku jevu změny proudění kouře může rovněž poskytnout rozhodující informace také pro odlišné důlní požáry. CFD modelování je jednou z možných použitelných metod analýzy rizik spojených s vývinem kouřů v průběhu důlních požárů.