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Analysis of the Fire Propagation in a Sublevel Coal Mine

Florencio Fernánez-Alaiz [1], Ana Maria Castañón [2], Fernando Gómez-Fernández [2], Antonio Bernardo-Sánchez [2] and Marc Bascompta [3,*]

[1] AITEMINLE SL, Arriba, 31, Villanueva Del Árbol (Villaquilambre), 24197 León, Spain; florencio.fernandez@aiteminle.es
[2] Department of Mining, Topography and Structures, University of León (ESTIM), Campus de Vegazana, s.n, 24071 León, Spain; amcasg@unileon.es (A.M.C.); fgomf@unileon.es (F.G.-F.); antonio.bernardo@unileon.es (A.B.-S.)
[3] Department of Mining, Industrial and ICT Engineering, Polytechnic University of Catalonia (UPC), Manresa, Av. Bases de Manresa, 61-73, 08242 Barcelona, Spain
* Correspondence: marc.bascompta@upc.edu

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Abstract: A fire has been analyzed in a real underground coal mine, using a sublevel method, during an entire year. The study was focused on the collapsed area, reproducing a real mixture formed by coal, waste, and air gap. The analysis was done by means of an experimental analysis, a computational fuid dynamic model (CFD), and simulations using a mine ventilation software. Three scenarios were determined and studied regarding their influence on the evolution of the fire: (a) development of the fire without taking any action, (b) sealing off the affected areas, and (c) sealing and reducing the ventilation in the affected area and surrounding drifts. The study revealed the behavior of the fire in a real mine and the effectiveness of the main fire-fighting measures over time, verifying that none of the measures taken could eliminate the fire-induced in the collapsed area.

Keywords: underground mine; coal mine; gob fire; fire dynamics simulator; FDS; computational fluid dynamic; CFD

1. Introduction

Fires in underground mines, although rare, have a huge potential risk, with large-scale accidents recorded over the years and on a recurring basis [1–3]. This phenomenon is especially dangerous in coal mining due to its intrinsic characteristics [4,5] and the associated risk of explosion [6].

For this reason, it is essential to know the behavior of a fire. The analysis of mine ventilation using specialized software has long been extended, applying it in the study of fires as well [7,8], but it cannot simulate collapsed areas. Computational fluid dynamic (CFD) tools are also used in this field, with an early approach done by Edwards and Hwang [9] to evaluate a fire at the entrance of a coal mine. The analysis of different ventilation features has been increased over time, defining the airflow performance [10] and the evolution of the environmental conditions in a fire [11], obtaining the intensity of the fire generated, its duration, the pollutants generated or the visibility level in the drifts [12]. Their study identified that it is important to understand critical elements of the mine, such as the evacuation route, where to locate the rescue chambers, possible changes in airflow direction or what techniques are useful to extinguish the fire, as well as to determine fundamental elements in underground mine fires like, back-layering [13], smouldering [14] or how to act appropriately when an event of this nature is generated. However, it is necessary to validate the studies in a real mine and see the effectiveness of the measures studied.

There are some interesting studies in small scale tunnels currently. Guo and Zhang [11] have compared experimental data from a fire developed in a very narrow tunnel with CFD analysis, while Sun et al. [15] have studied the effectiveness of a water spray system to extinguish the fire. Full-scale tests have been done over the last decades [16,17], but only a few real-scale fire studies have compared modeled data with actual measurements [18–20], with a lack of studies focused on a long period of time in an ongoing mine. Yuan et al. [18] studied the carbon monoxide spread in a mine fire combining the usage of mine ventilation software and CFD analysis, using an interesting combination of tools. The study of the area is crucial in coal mining, because most of the spontaneous combustion fires are generated within it, but it is very complicated to obtain actual data and access it. Yuan and Smith [21] studied this phenomenon and the airflow influence using CFD, being a good starting point for further research.

The study aimed to carry out a control of an induced fire in an active mine to determine the conditions in which a fire can develop over time and its evolution, predicting the behavior of the fire and its propagation, as well as knowing the influence of the fire on the main ventilation system. The fire is located in a collapsed area of the mine. The specialized code fire dynamics simulator (FDS) (v5.3, National Institute of Standards and Technology, Gaithersburg, MD, US) was used to develop a model, using the parameters validated in a series of fires previously investigated in a full-scale laboratory mine [20]. The mine ventilation software VenPri (v4.2, AITEMIN, Mieres, Spain) was also used in the investigation of multiple scenarios.

Mine Fires in Undergorund Coal Mines

The confined enclosure conditions in a mine or a tunnel creates a feedback heat that varies from open fires, being able to have a heat release rate (HRR) four times higher [22]. Besides, fuel-rich fires can also be found, generating large amounts of toxic products due to incomplete combustion [23]. The characteristics of a mine fire can vary depending on the air conditions; their interaction can lead to changes in the flow direction or hazardous conditions such as the reverse of hot gases and smoke; backlayering. Besides, the directionality of the air creates entrainment of the fire, having a non-axisymmetric plume [24].

The initiation of a fire in an underground space releases large amounts of heat and pollutants that could create a lethal atmosphere and explosive gases during the combustion process [25]. Distance and airflow direction play a key role in the amount of CO and CO_2 and temperature changes [26], while the slope of the drift also has an important influence in the direction of the pollutants generated [23,27]. The heat release can have a large impact in the direction of the fire and the creation of a pressure difference [28].

The fire can be caused by different operations within the mine, related to coal or not, and spontaneous combustion. This last factor is especially relevant in the gob area due to the unavoidable airflow leakages. Coal is able to oxidize, and heat from ambient temperatures [29] is the cause of many fires in underground coal mines and a very complicated issue to analyze [30]. The study of spontaneous combustion, together with the rockmass characteristics, has been investigated as well [31]. The influence of residual coal in the gob and the rockmass characteristics are crucial for potential fires in this area, influencing the mixture of waste with coal and the airflow leakages [32].

Internal and external conditions contribute to spontaneous combustion, the first condition is basically due to the coal properties and geological conditions, whereas the second condition is related to the working face layout and auxiliary and principal ventilation system (which are directly involved with the gob leakages) and mine planning, mainly section and shape of the drifts [33].

The gob usually has a significant amount of coal left, and is exposed to high oxygen levels through leakages that are directly linked to pressure in the drifts. This pressure is influenced by the set of fans. Liang et al. [34] investigated different pressurization systems for the working faces using different types of fans to reduce the differential pressure and, therefore, the leakages. However, a risk assessment must be put in place before the implementation of these type of solutions due to the large and abrupt fluctuations in gas emissions if the ventilation conditions change.

The main concern of a fire study is the identification of the type of fire associated with the potential locations within the mine and the consequences that could cause. Grayson et al. [4] proposed a qualitative and quantitative risk analysis of fires in coal mines to identify the type, root, causes, and extents of the risks in USA mines, stating the six key issues in this type of activities as: (1) the prevention of explosions in sealed areas, (2) preparedness and response in case of emergency, (3) improvement of the escaping routes, (4) better protection of the employees before and after the fire or explosion, (5) improved provision of oxygen, and (6) development of more robust post-incident communication.

On the other hand, the principles of fire management in any underground mine explained by [35] are: prevention of the fire commencement by the usage of appropriate suppression systems, early detection of fire and provision of effective systems to reduce the impact of fire, warning equipment for underground personal, and effective refuge systems.

Many measures have been studied following the statements from the two previous paragraphs. Analyzing the best evacuation routes [36], the usage of airflow reversal [37], applying different techniques to extinguish the fire [15] such as foam [38,39], or recasting the traditional sealing method [23] into a new dynamic seal [40]. Other approaches, like the determination of the limit conditions for firefighters [12] or early detection systems [41] have also been proposed.

Overall, the management of an underground mine fire and the effectiveness of the measures will depend on the ventilation system, the operational conditions, and the geological characteristics in each case study.

2. Materials and Methods

2.1. Case Study

The research was undertaken in an underground coal mine from Langreo, Asturias. The mineral extraction is done using a sublevel method, with drifts and support shafts made in the host rock. The tests have been carried out in the Molino seam from Pozo Candín (HUNOSA).

The control of the fire has been conducted monitoring the temperature in the drifts and sealing points at different levels. The fire has its origin in the coal mass at sublevel 1, between levels 6 and 7, and it extends to the rest of the extraction levels, reaching two lower levels during its development, 7 and 8.

Figure 1 details the mine and the potential area affected by the fire with the distribution of the monitoring sensors (T01–T07), including the ventilation circuit and drifts where the air can flow. The fire induced in the gob has similar combustion conditions to those that could occur in an accidental mine fire. Subsidence is made up of remains of coal, inert rocks, and air gap to allow airflow leakages, facilitating the combustion of the coal.

As already mentioned, the experimental design of the fire monitoring was based on the experience accumulated in other studies previously carried out [20]. The evolution of the fire was monitored during a one-year period, January to December. Before carrying out the sealing of the area, seven control points were defined, to install a thermocouple. Figure 2 shows the detailed locations of the thermocouples in the control areas of the three accessible plants.

- T00–6th level, sealing
- T01–6th level, inner part of the sealing, left side
- T02–6th level, inner part of the sealing, right side
- T03–Molino seam, 1st sublevel, between 6th and 7th levels
- T04–Molino seam, 3rd sublevel, between 6th and 7th levels
- T05–Drift in host rock, 7th level
- T06–Waste Molino, 7th level

- T07–Molino seam, 1st sublevel, between 7th and 8th levels

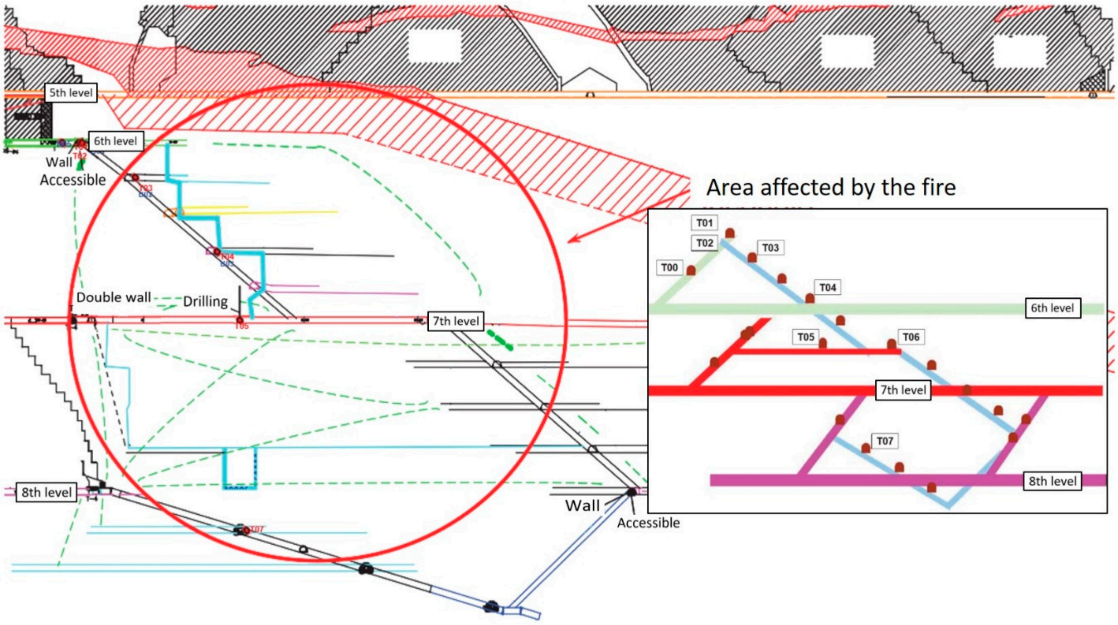

Figure 1. Scheme of the mine, fire zone in detail and distribution of the temperature sensors (Txx).

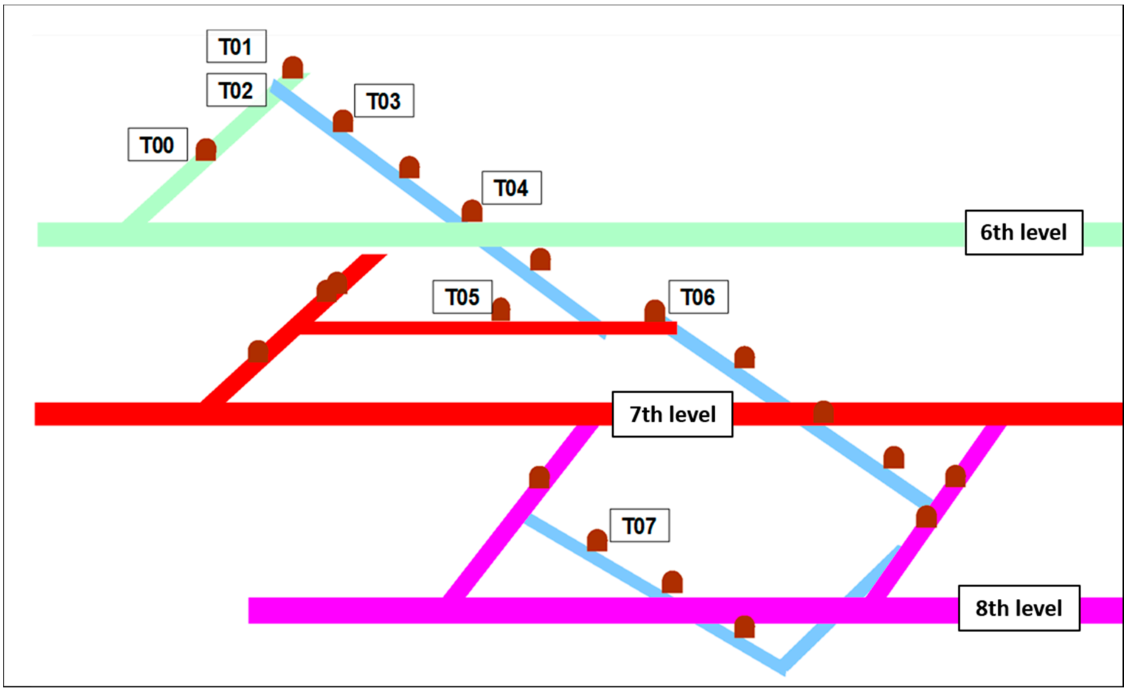

Figure 2. Detail and distribution of the temperature sensors (Txx).

The ventilation system consists of a main exhaust fan located in a shaft 1500 meters away from the fire, generating a practically constant under-pressure condition over the fire area. The intake airflow to the area is about 30 m^3/s, distributed over the different levels by doors. The air flowing through the shafts between the levels is around 15 m^3/s, regulated depending on the needs in the operating sublevels. Due to the heat load that can be generated by the fire, the leakage conditions in the sublevels are measured at the entrance, levels 8 and 7, and exit, level 6. During the fire control period, three milestones were set to modify the local conditions in the area and, thus, applying the desired conditions to study in the development of the fire:

1. Scenario 1: behavior of the fire without the implementation of any countermeasure. January.
2. Scenario 2: sealing the access to the fire zone on the 5th level, which is above the affected area, the 6th level, and the 8th level. Applied in February.
3. Scenario 3: Reduction of the airflow on the 7th level. Applied in June. The fire monitoring, applying both countermeasures, was done from June to December.

2.2. CFD Characteristics

The evolution of a fire generated in the collapsed extraction area, a mixture of coal and waste rock, has been carried out using the fire dynamics simulator (FDS) v5.3 software, defining the mesh, boundary conditions and solving the equations, while the smoke view (SMV) (v5.3, National Institute of Standards and Technology, Gaithersburg, MD, US) was used to visualize the results. The version of the software was chosen to be consistent with the previous analysis used in this research.

The model displayed in Figure 3 represents a working section between levels 6th, 7th, and 8th, with a distance of 90 meters between levels. The thickness of the coal seam is assumed to be 2 meters, and the collapse affects a total distance of 10 meters; a mixture of coal and waste rock. The horizontal extension of the area analyzed for the case study was 180 m.

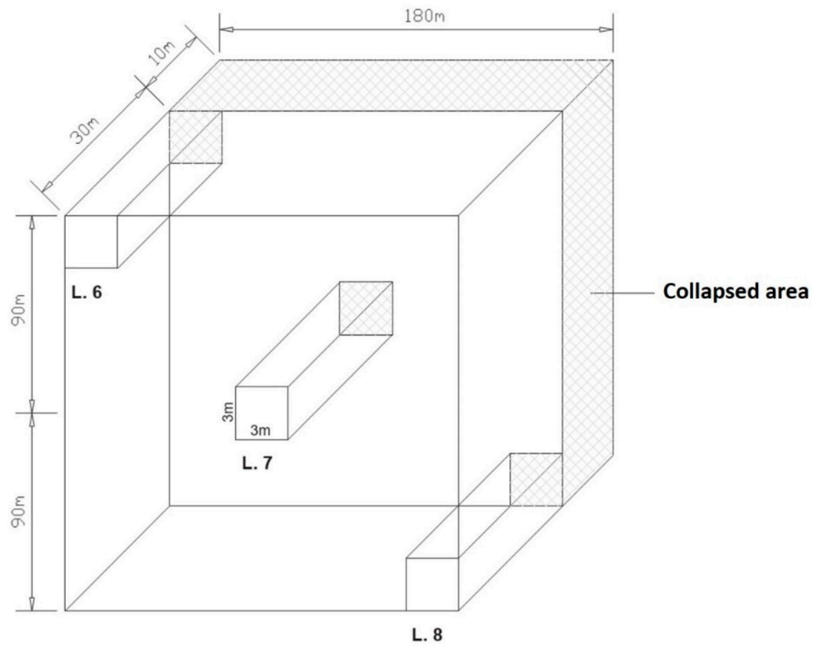

Figure 3. Model of the working section designed.

The cell size used in this case is 0.6 × 0.6 × 0.6 meters. The mesh was previously validated, following the same conditions specified in [20]. An intake airflow of 2.0 m^3/s was imposed through the 8th level and return airflow of 0.5 m^3/s through 6th and 7th levels, taking into account scenario 3. A set of holes were left to allow the contact between coal and air on the sides and at the top of the collapsed area to boost the connection with other close working sections. The start of the fire was located in the sinking material, 8th level, next to the entry drift.

Figure 4 shows the simulated working section, including the mesh, collapsed area, starting point of the fire, and different levels (6th, 7th, and 8th). Blocks of coal and inert waste material were represented in the collapsed area, mixed in an approximate proportion of two parts of coal for every three parts of inert and one part of holes, which is a similar proportion to a real situation in this type of mining. Table 1 shows the coal characteristics in the simulations, extracted from several samples. In addition, three samples from the gob have been analyzed, obtaining the mean values necessary for this type of model [42]: total moisture = 1.86%, volatiles = 28.42%, ashes = 29.55%, carbon = 55.95%, Hydrogen = 2.92%, Nitrogen = 1.47%, and Sulphur = 0.54%. The lower and higher calorific values are 5933 and 6183 kcal/kg, respectively.

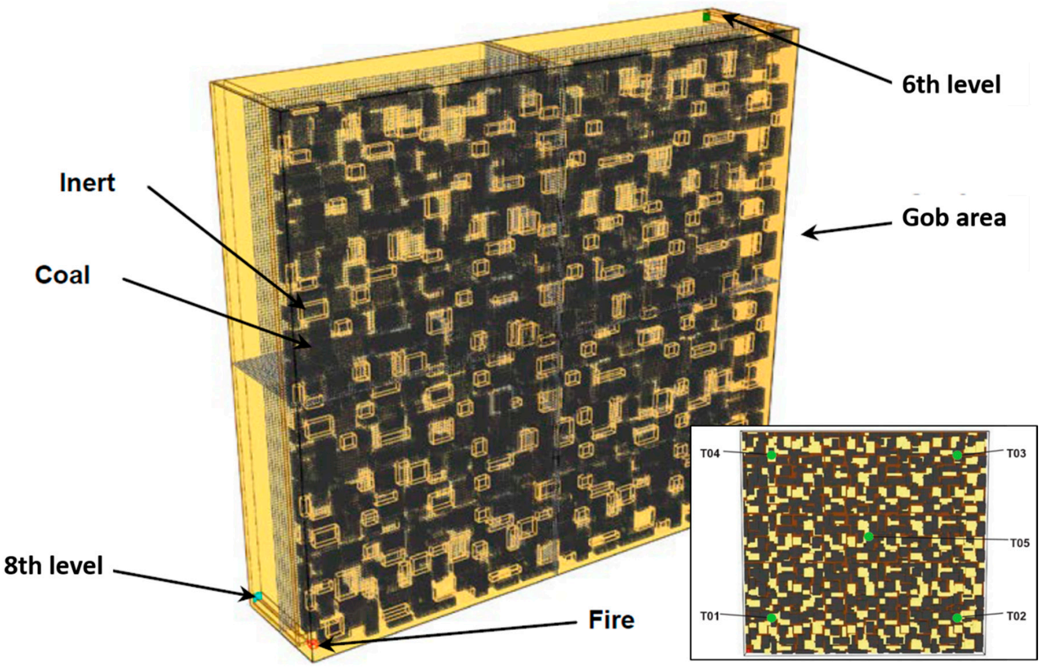

Figure 4. Model to calculate the working section.

Table 1. Characteristics of the coal used in the simulations.

Coal Properties	Value	Units
Coal particle density	1200	kg/m^3
Coal bulk density	870	kg/m^3
Coal specific heat	1.0	kJ/(kg·K)
Conductivity	0.2	W/(m·K)
Heat of reaction	209	kJ/kg
Heat of combustion	$2.8402 \cdot 10^4$	$kJ/mol \cdot O_2$
Activation energy	$6.65 \cdot 10^4$	kJ/kmol
Pre-exponential factor	$1.9 \cdot 10^6$	K/s
Initial coal temperature	20	°C

A large eddy simulation (LES) model was used, that is widely applied in combustion problems and fire modeling [18,20,43], considering the fluid as incompressible. It is a technique that allows the resolution of turbulent models in a computational calculation time shorter than other options by filtering the Navier–Stokes equations.

The five thermocouples in the model from Figure 4 are placed within the collapsed area. T01 and T02 are placed at the height of the first sublevel between 7th and 8th levels, on each side of the gob. T05 is located at the middle of the gob modeled. T04 and T03 are placed on each side of the gob at the height of the 6th level.

3. Results and Discussion

3.1. Experimental Results

The actual data has enabled the analysis and validation of the ventilation system, and the model created, taking into account the characteristic areas of the fire. Figures 5–7 show the data collected by the thermocouples from the three levels affected by the fire. The intermediate location of the thermocouples between levels was chosen to study the experimental data (T03, T05, and T07). The moment when the measures were applied, sealing in February and airflow reduction in June, can also be seen in the three Figures.

The behavior of the three thermocouples showed a similar trend. Temperatures fluctuated within a particular range for T03, T05, and T07, having the same cycle in all cases. However, the range of variation was wider in T07 and, particularly in T03. This fact is caused by the vertical pull of the fire and the presence of the collapsed area, extended vertically, while the affection is smaller in the horizontal drifts, T05. These conditions are in accordance with the main literature [23,24]. After monitoring the temperature evolution during several months, it is confirmed that the implementation of the measures, either individually or in conjunction, temperatures stabilize, but the fire is not completely extinguished.

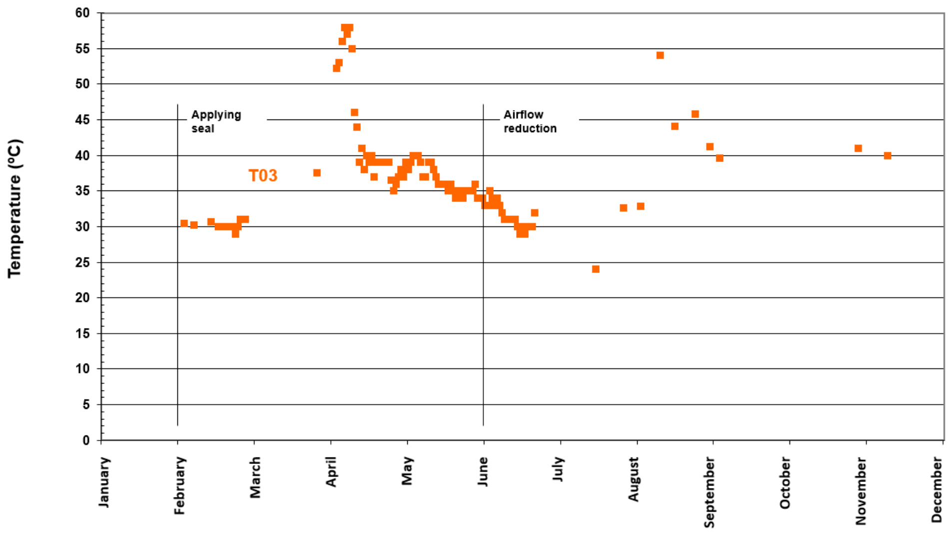

Figure 5. Evolution of temperature in thermocouple T03 during the entire test.

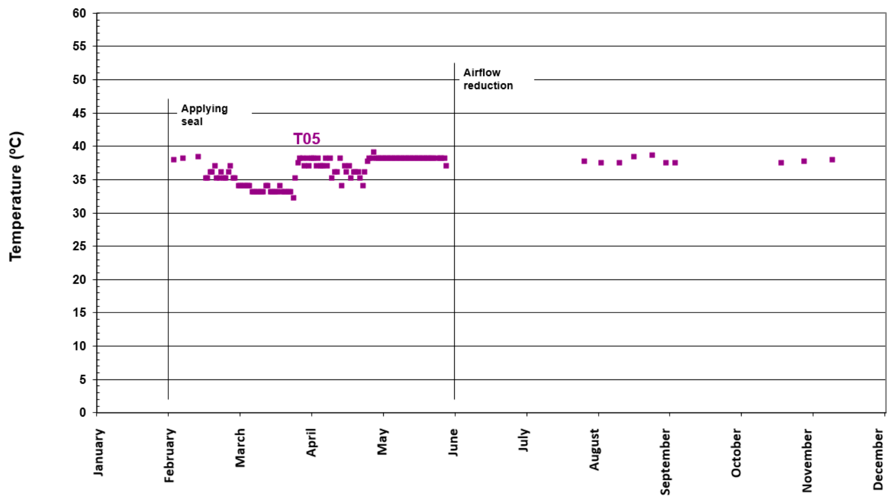

Figure 6. Evolution of temperature in thermocouple T05 during the entire test.

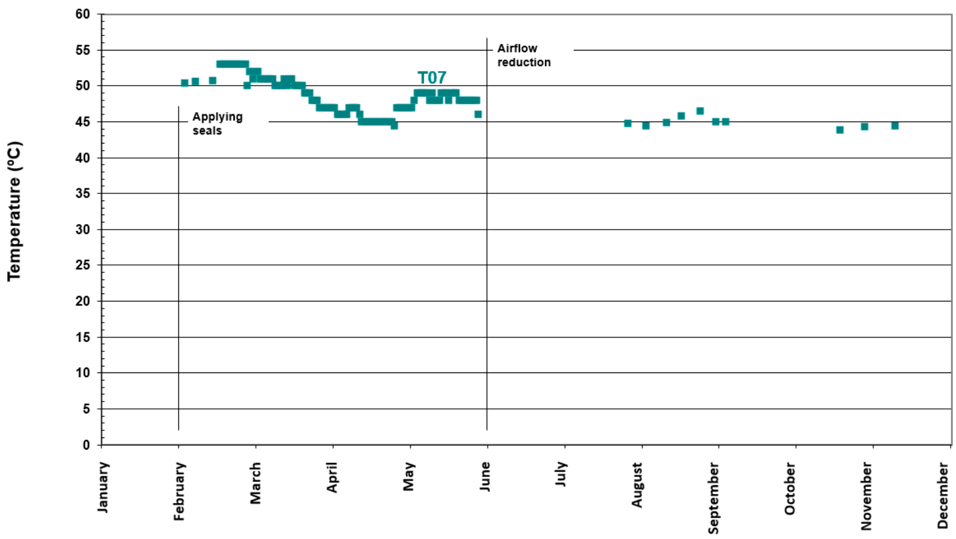

Figure 7. Evolution of temperature in thermocouple T07 during the entire test.

3.2. Ventilation Circuit

A detailed analysis of the ventilation conditions has been carried out using the VenPri v4.2 ventilation software in the area near the fire. Starting from the initial ventilation conditions and analyzing the three cases described in Section 2.

As the gob area expands vertically, there are different extraction levels, and the flow of the air has an upward tendency when the ambient temperature increases because of the fire. Figures 8–10 display the leakage direction in the collapsed area. The blue arrows represent an air supply to the gob, activating the fire, while the red arrows represent the addition of smoke, pollutants, and heat from the fire to the drifts.

- Scenario 1. Development of the fire without countermeasures:

The fire acts as a source of overpressures, generating an upward push with an overpressure in the upper levels and under-pressure conditions in the lower levels. The air supply to the fire comes from levels 7 and 8, whereas level 6 receives all the pollutants and heat. Although the conditions of this overpressure was not easy to estimate, it could be quantified by measuring the leakages in the seals. Figure 8 shows the ventilation model competed and the nature of these leakages.

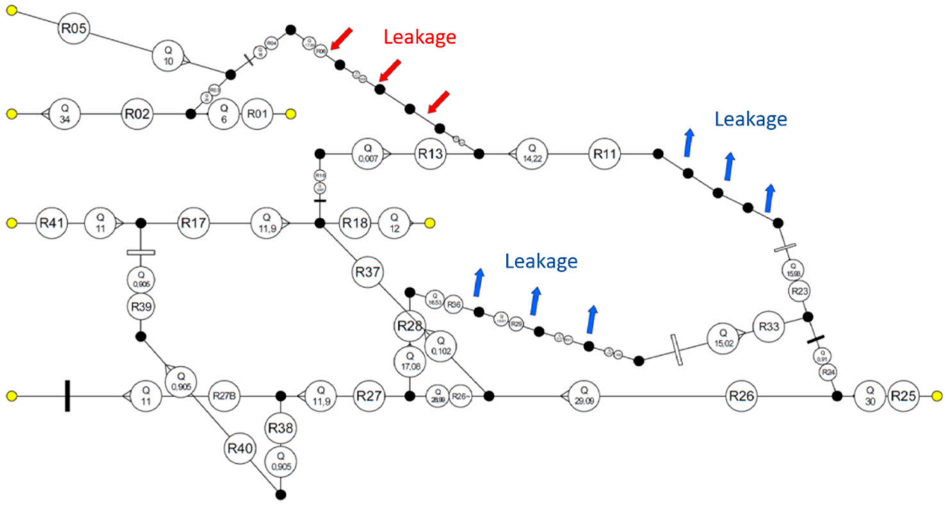

Figure 8. Scenario 1, ventilation behavior, levels 6th to 8th.

- Scenario 2. Fire developed and sealing of the levels

Sealing the levels in the fire area is one of the immediate measures usually carried out in the event of a fire, extinguishing it due to a huge airflow reduction [23]. However, results after applying this measure did not end the fire in the case study, with leakages to the gob concentrated in the lower part of the working section and drifts from the 6th and 7th levels contaminated by the fire. Two seals were applied in the 6th and 8th levels based on examination of the mine ventilation circuit, Figure 9.

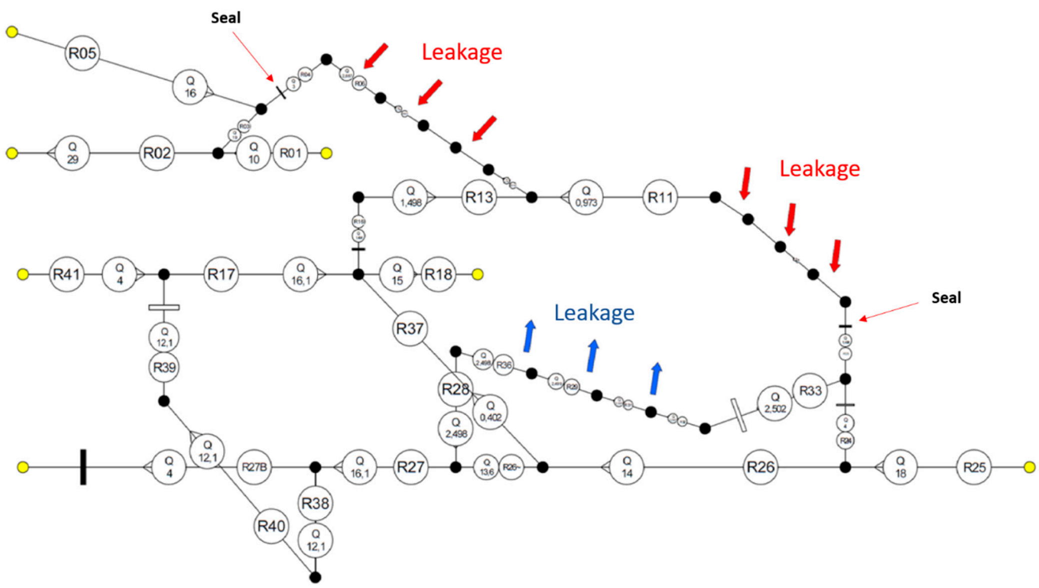

Figure 9. Scenario 2, ventilation behavior, levels 6 to 8.

- Scenario 3. Fire developed, sealing and reduction of the airflow supply

The airflow is reduced to a minimum input value, from 30 to 6 m^3/s. A further airflow reduction was not operationally viable in the case study. Part of this flow was diverted to the fire area due to leakages from the seals in level 8th, having the same number of drifts affected than in Scenario 2, but with a smaller contamination. Besides, it was observed that the area could not be totally sealed because of the geomechanical conditions, being unable to guarantee the extinction of the fire, keeping it latent with the small airflow leakages, Figure 10.

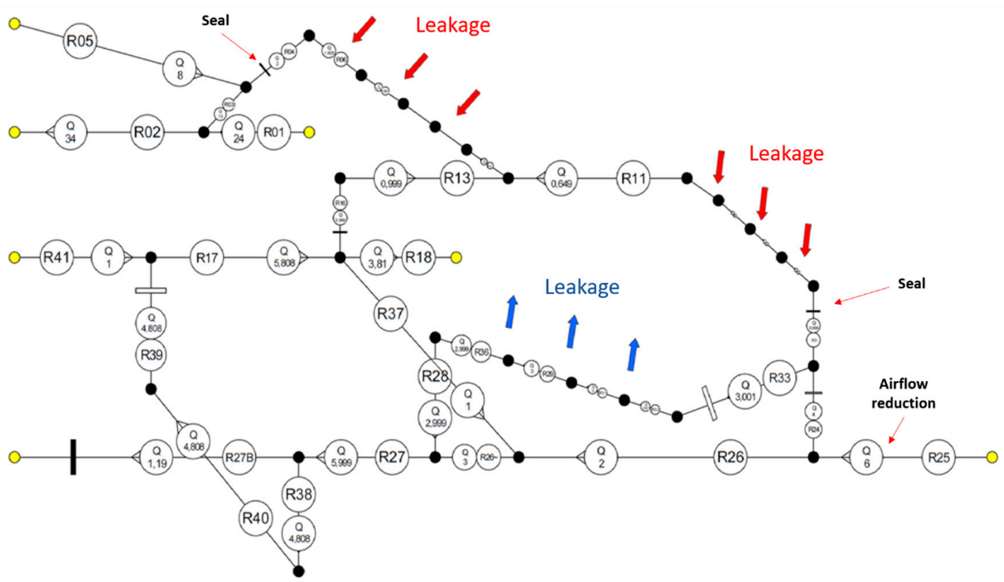

Figure 10. Scenario 3, ventilation behavior, levels 6th to 8th.

The ventilation conditions in the working sections were crucial for the appearance of fires, since, both, the supply of oxygen required for the oxidation of coal, and the dissipation of the heat generated in it, depend on the flow and velocity of the air. It has been observed that further measures to fully extinguish the fire are necessary in a sublevel coal mine.

3.3. CFD Results

The evolution of the fire over time by means of the FDS software is shown in Figure 11. The black area is coal available, while brown means that the coal has been consumed. On the other hand, temperatures are represented by a color range from red, high temperature, to blue, low temperature. The temperature range is from 0 to 1500 °C, with steps of 150 °C.

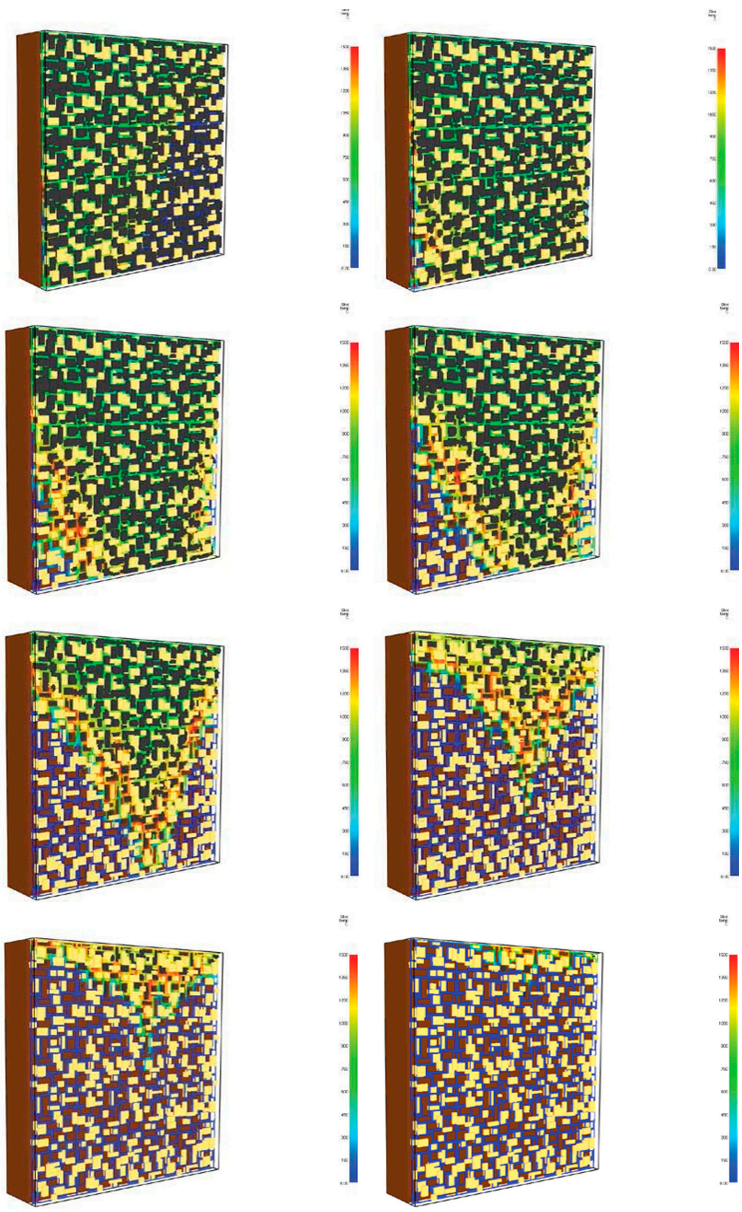

Figure 11. Temperature evolution over time during the combustion process.

The observation of the fire development presents a progression from the source towards the entire extension of the simulation contour. At the beginning of the combustion, high temperatures, above 1000 °C, are progressively observed in the model, decreasing again once the coal locally available is consumed. Combustion progresses by contact and/or diffusion of fumes to adjacent areas.

A significant vertical component of the temperature gradient is observed, which corresponds to the upward pull of the fire development. This circumstance causes the fire to progress faster to higher levels as long as coal is available, introducing fresh air, below 300 °C, from the lower part of the gob, increasing the airflow leakages, and fueling the fire. This behavior remains until the fire consumes the coal at the top of the gob.

As can be seen in the temperature values from the model detailed in Figure 12, there is a sudden increase in all thermocouples, corresponding to the start of combustion, until the airflow leakages are stabilized. The initial temperature is around 20 °C, reaching a maximum between 1200 and 1400 °C depending on the thermocouple modeled.

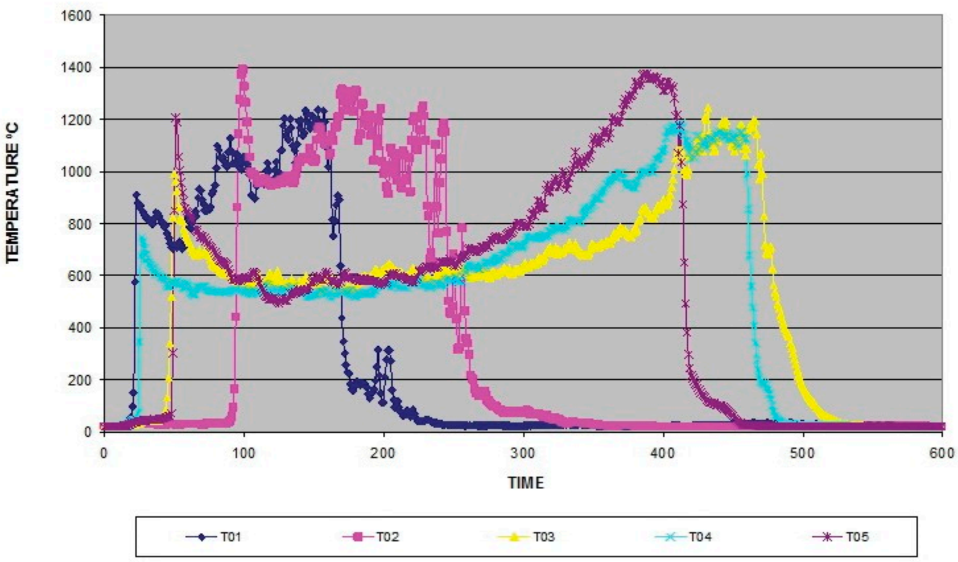

Figure 12. Temperature evolution, in days, of the thermocouples modeled.

In the first phase, it can be assumed that oxygen present in the collapsed area is consumed due to the coal oxidation. Later on, the fire would progress based on the mixture conditions and airflow contribution. Once the ventilation circuit is stabilized, temperatures vary depending on the progress of the fire in the sinking area.

Combustion proceeds, in the first place, through the lower part where the airflow supply is greater, with an initial temperature increase observed in thermocouples T01 and T02. The next increase in temperature is observed in T05, located in the center. Finally, the temperature rise occurs in thermocouples T03 and T04, at the moment when combustion reaches the upper part of the collapsed zone. The temperature in the control thermocouples decreases as the coal burns. The drop in temperatures occurs in the same order, as the available coal is consumed.

It is necessary to deepen the adjustment in future research, taking into account the firepower and the conditions of current leaks due to possible subsidence. Besides, there are certain limitations in the generation of models, regarding its geometry and the inclusion of other factors that have a certain influence on heat generation, such as the oxidation of pyrites, bacterial action, compression of coal due to ground movements or absorption of water vapor [44,45].

The variation of the airflow obtained from VenPri and CFD is between 10 and 20% in all the scenarios. This fluctuation can be considered as acceptable for the conditions of the study [20].

4. Conclusions

Monitoring a real mine fire over a year has provided insight into the processes and disturbances that occur in the ventilation circuits. It has been possible to verify the behavior of the working areas attached to the fire, detect zones with under-pressure or overpressure, and to evaluate the effect of airflow reduction to the fire.

It has been proven that the control of the fire in an underground coal mine using a sublevel method is extremely complex through common actions like sealing or isolating the fire area, especially in the case of a fire in the gob. Further actions are necessary to fully extinguish the fire. Besides, the application of the countermeasures to reduce the fire, either individually or combined, increase the number of drifts affected by heat and pollutes than not applying any action. This fact is very important for the strategic planning of the mine in case of a real fire.

The main factors influencing the combustion initiation, and the subsequent propagation of the fire, are the ventilation conditions and the collapse characteristics in terms of combustible material available. It has not been possible to fully prevent airflow leakages in the whole study. However, the distribution of the leakages that kept the fire latent was determined.

On the other hand, a model able to define the behavior of a fire located in the collapsed area of a descending sublevel coal mine has been obtained, analyzing potential measures to be taken into account to eliminate, or mitigate, the consequences of a fire in an inaccessible area of the mine. A temperature range between 20 and 1400 °C has been observed during the evolution of the fire. The increase of fresh air, below 300 °C, introduced to the gob has also been verified, feeding the fire. The combination of CFD tools and mine ventilation software allows the possibility to examine different fire scenarios and the effectiveness of the measures applied in a short computation time, obtaining sufficient results.

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