THE INFLUENCE OF INERT GASES ON THE UNDERGROUND FIRE SOURCE

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ABSTRACT

This paper presents a method of selection of appropriate strategies to be used during fire fighting actions in underground mines.

The selection process is based on a computer simulation of the ventilation process altered and affected by the effect of an underground fire. One of the most effective, rapid and inexpensive inertisation process is based on utilisation of the inert Gas Generator GAG. The turbo jet engine - (the GAG) - was successfully used as a device capable of providing a large volume of inert gasses. Application of this method of fire extinguishing requires a thorough and proper training of the operators and personnel engaged in preparation of an appropriate inertisation or fire fighting strategy.

The computer simulation methodology utilises well proven mathematical modeling to describe unstable flow phenomena which occur during propagation of the fire gases along the ventilation network.

After conducting a series of computer simulations relevant correlation has been established between the parameters characterising the motion of a mixture of the fire gases and an influence of the inert gases (generated by the GAG) on the fire source. The results will be discussed and presented on appropriate graphs.

Such a simulation is possible by using a VENTGRAPH computer software system that is now commonly used by many Polish mines as a matter of everyday mining practice.

The system automatically calculates the flow quantities, static pressures, and current distribution of gases within the ventilation network and presents them in graphical form directly on a ventilation diagram.

It allows ventilation engineers to carry out comprehensive studies of a given ventilation network with emphasis on planning safe escape routes, application of the most effective means of fire control, planning the safest locations of the underground fuel depots, equipment locations, etc.

The entire software architecture allows the users to update it on a regular basis in order to enable them to use it always on the current mine layout.

The paper discusses the simulation of the fire hazards, their influence on the ventilation system and the possible strategy of a fire fighting action based on a layout of an Australian mine.

INTRODUCTION

In spite of long-lasting investigations and experiments, the problem of underground firefighting still inspires both the scientists and mine rescuers.

Recently, application of inert gases in underground firefighting becomes more and more popular. In case of an underground fire a large volume of inert gases is required . Most often nitrogen is used as an inert gas and different types of devices are used to generate it. Application of nitrogen is very expensive and it is difficult to minimise these costs.

The best results gives a device generating large amount of inert gases (ca. 15-20 cub.m/sec) known as the GAG. In this device a turbo jet engine is used, adapted for the operation in an underground mine. The engine is attached to a cooling chamber in which flue gases are cooled down to ca. 80 °C. Till now the GAG was successfully used in Poland, Russia, China and Czech Republic and South African gold mines. The design was systematically improved by the Central Mining Institute (Poland) as well as optimal technique of application was developed by the Central Mines Rescue Station (Poland).

In April 1997 the GAG was extensively tested by SIMTARS at the Collinsville mine in Northern Queensland. The objective of the experiment was to asses the GAG's capabilities of fire extinguishing in the conditions of the Australian mines.

Because of a complicated design of the GAG, further discussion will not include detailed description of the unit. However the GAG should be treated simply as a type of a fan. In this paper the GAG generator is considered as a source of gases with known chemical composition and flow rates [3, 7].

Therefore it appears extremely important to select a proper location of the generator in the mine - in relation to the fire source as well as to the branches along which significant volumes of cooling water and engine fuel would have to be transported.

The influence of the inert gases generated by the GAG on the fire source could be discussed in two aspects: low oxygen content in gases limits the combustion process and : water molecules carried by the flue gases flow reduce the temperature of the fire area.

The efficiency of the GAG operation applied in a complex network of branches depends also on several other actions undertaken as a rule during firefighting process, e.g. making stoppings in branches, creation of a fire field as well as the fan throttling.

The ventilation process which occurs during an underground fire and its suppression is extremely complicated and difficult to predict. There are dynamic phenomena taking place in time and space. The current level of theoretical and practical knowledge related to gas flow along the mine ventilation network combined with contemporary capacity of the science, enabled application of the computer simulation methods in forecasting an optimal version of a firefighting action.

The ventilation process taking place in a network of mine branches is determined by a series of mutually combined physical parameters. A significant feature is also the way of connection of individual branches, i.e. the ventilation network topology. Good understanding of mutual relations of the above mentioned is important and necessary from practical point of view as it is related to safe operation of the ventilation system.

One of the methods of obtaining this information is the creation of a database by direct measurements of the parameters determining the state of the ventilation process. Such an approach reduces the database to the current state only, i.e. to the date of taking measurements.

Another method is a mathematical description which combines all the parameters determining the ventilation process. Application of this method can be facilitated by using the equations which describe the motion of air and flue gases.

By using the equations of motion, continuity, energy and state, appropriate mathematical models can be created which are combined with the physical parameters. Because of a very complicated character of ventilation process, especially in the case of various disturbances, e.g. fire, squealer, gas explosion, crump, etc. and the influence of these irregular phenomena on ventilation process, the mathematical models are very complex. Furthermore, the level of complexity of these models depends on the character of analysed phenomena as well as on the methods of reaching the solutions.

The main purpose presented in this paper is to select an optimal strategy of firefighting action in which the GAG generator is used. The problem was solved by a computer-aided simulation of the ventilation of the network of the Collinsville mine , destabilised by an underground fire and operation of the GAG.

Methodology of forecasting of the ventilation network operation, mathematical model

The capabilities of a computer-aided simulation of a ventilation process by using the VENTGRAPH software system allows to obtain the required results quite quickly. The VENTGRAPH software system is being continuously developed by the Mine Ventilation Laboratory of the Strata Mechanics Research Institute of the Polish Academy of Sciences, Cracow, in cooperation with the users of this software in Polish mines. Significant contribution of the Central Mining Rescue Station, Bytom (Poland), resulted the program being supplemented with an optional simulation of the effect of operation of the GAG generator on the gas flow along the mine branches. More than 30 of these programs have been already utilised by the Polish mines, the Central Mines Rescue Station and Universities for analyses, teaching and training purposes.

The VENTGRAPH software system consists of computer programs for database generation and a program named POZAR (FIRE) for simulation of the unstable motion of air and fire gases. The exemplary calculations presented in this paper have used both these programs for preparing the computerised databases. Apart from the database, application of the numerical simulation requires a computer program which uses an appropriate mathematical model of the analysed phenomena.

The mathematical model used in the program named POZAR.EXE takes into consideration the following phenomena that are of particular interest to the ventilation engineers :

- changes of parameters describing air flow along each branch, i.e. flow rate, temperature distribution, concentration of oxygen and combustion products;
- mixing processes which take place in the network junctions and crossings;
- influence of flow describing parameters on an unstable propagation of air through the ventilation network, in particular the effect of the air flow reverse;

- description of the process of coal combustion in the fire source (oxygen consumption);
- unstable heat exchange in the fire source ;
- simulation of firefighting actions: stoppings, application of inert gases and their influence on the simulated processes;
- transportation of hot fire gases along the mine branches, exchange of heat with rock mass;
- generation of inert gases.

In case of a complex network of headings, the mathematical model consists of a large number of nonlinear differential equations combined into a network structure by means of two Kirchhoff's laws. A detailed information concerning the mathematical model has been presented in papers [4], [5], [6]. The computer simulation of a mine ventilation process destabilised by the fire needs a specific method of solution of the set of equations in order to obtain parameters as functions of time and space. Furthermore, initial and boundary conditions have to be determined, which must comply with the conditions prevailing in the mine ventilation network just before the start of fire.

Computer simulation of an underground fire

The computer program which manages the discussed simulation is based on the approximating method of solution of the assumed set of equations. Finite differential equations corresponding with the differential equations in the mathematical model and the iterative method have been used in order to obtain solutions with an arbitrary predetermined accuracy. This allowed to design a computer program which is able to calculate the sequences of values of the parameters describing the ventilation process concerned, with the assumed initial and boundary conditions. The subprograms have also been developed in order to visualise the results of simulation (i.e. calculation) in the form of a sequence of screen images representing the state of the process on the mine's ventilation network diagram. The values of certain individual parameters are presented in this animation by numerical values in attached boxes (flow rate, pressure, etc.) while the other ones are visualised using various colours to represent smoke, gas concentration, temperature, etc...

The developed simulation method enables interaction with the program allowing for dynamic changes of conditions or various parameters and introduction of the new elements into the network at any time during the simulation (e.g. setting up stoppings and/or opening/closing doors).

A network which comprises 1000 branches, 450 junctions, 10 fans, 400 stopping stoppings/doors, 10 sources of gas, 30 monitoring stations can be simulated by the VENTGRAPH software, which has been developed by the Mine Ventilation Laboratory of the Strata Mechanics Research Institute of the Polish Academy of Sciences, Cracow, in cooperation with the users from the Polish Coal Industry.

An exemplary application of the computer-aided simulation of the investigated phenomena caused by an underground fire as well as an influence of inert gases generated by the GAG on the firefighting process is presented below.

Simulation of the application of the GAG in a firefighting action

A simulation of the influence of inert gases generated by the GAG has been carried out on the basis of the room and pillar Collinsville Mine No.2 ventilation network. An exemplary network of branches is shown in Fig. 1. The mine's network has three fresh air intakes and the return flow forced by means of one fan. The system of slightly sloped branches consists of parallel galleries crossed by perpendicular cross-headings. These cross cuts are appropriately closed with particularly tight concrete stoppings or less tight brattices.

For this simulated ventilation network the mine's plan was used to read out the length of branches and leveling spot heights; furthermore the cross-sectional areas and resistance coefficients have been estimated. Based upon these data the aerodynamic resistance of individual branches has been calculated and consequently - using the known characteristic curve of the fan - air propagation through the network has been determined as presented graphically on Figs 1 & 2.

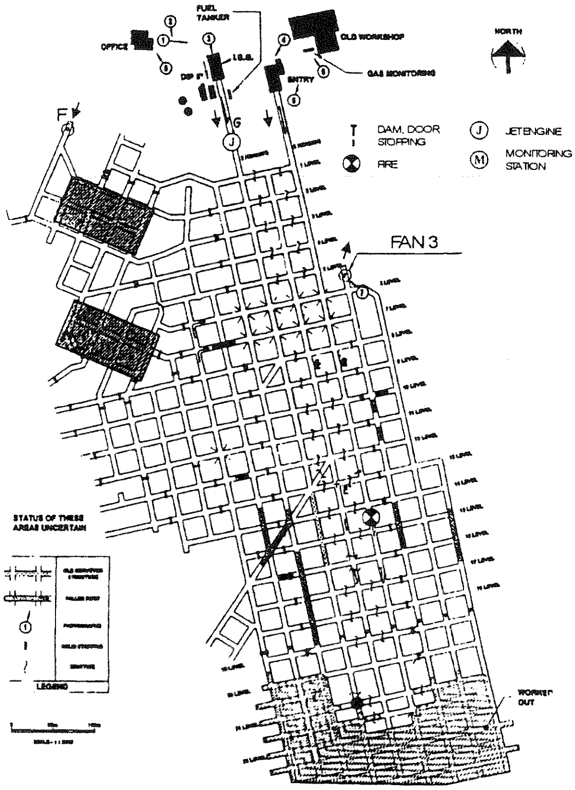

Fig.1. Mine map of the ventilation network products

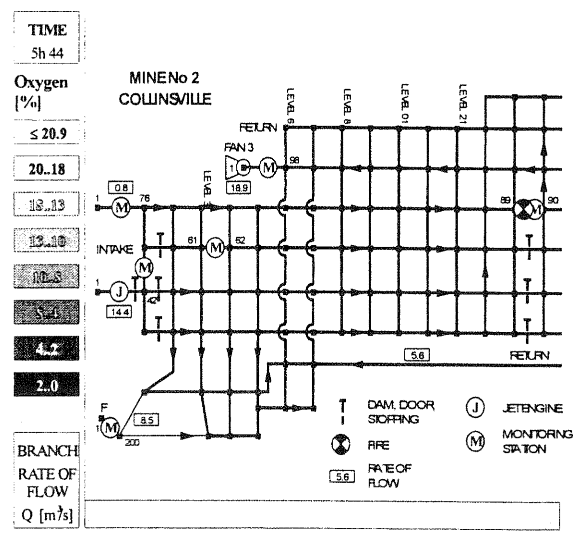

Fig. 2. State of flow and circulation of combustion time: 5 h 44 min - computer simulation.

A series of fire simulations were carried out for the presented network of branches, combined with the effects of various actions influencing the ventilation process and namely:

- erection of necessary stoppings in order to reduce fresh air inflow towards the fire source;
- erection of stoppings in order to direct the flow of inert gases to the fire source;
- activating the GAG generator after a predefined period of simulation;
- adjustment of the fan operation in order to reduce the total amount of returned air. (throttle effect).

The results obtained from these simulation runs are presented in the Fig. 2 copied from the monitor screen which illustrates the distribution of oxygen concentration contained in the fire gases.

Another method of presentation of the simulation results is by recording the values indicated by chosen sensors of the monitoring system in the analysed network of branches. For this presentation the following parameters have been selected : air flow rate, air temperature, oxygen concentration in fire gases, heat flux generated in the fire source.

The figures and graphs illustrate the following phases of simulation:

- development of the fire and propagation of fire gases;
- influence of the operation of the inert gas generator (GAG) and other undertaken actions on the network

The practicability of the method of computer-aided simulation of these phenomena aimed at the selection of the best strategy of application of fire extinguisher has been illustrated on an example. The simulation has been carried out for the following input :

- the fire source was located in the branch between the junctions 89 and 90;
- the GAG was located at mine entry in branch 1-42 , No. 3 Heading ,
- fire source was characterised by the following parameters:
  - › type of fuel burnt - coal (4000 kcal);
  - › maximum length of the fire zone - 120 m;
  - › intensity of combustion process - 2 (psi = 0.03 kg/m2/s);

- time constant of fire development - t = 300 s.

- the GAG :
  - engine speed: 8,000rpm;
  - oxygen content in return air 1.6%;
  - output 14.6 cub.m/s;
  - assumed mass of water reaching the fire source: 2 % of device output. together with inert gas flux

The simulation began with data input for the POZAR program of the VENTGRAPH software system and with entering the fire source location - in the discussed network the fire source was always located in the 89-90 branch. Once all the fire source parameters had been entered, location of the GAG had to be selected. In this example the GAG was situated in 1-42 branch, i.e. at mine inlet. All these operations were facilitated by using appropriate options and procedures of the computer program. As the analysed phenomena were changing in time, the simulation scenario has been presented as a sequence of actions dependent on the course of the investigated phenomena:

1. The period of fire development and observation of fire gas propagation in the network: 2 hours. After this period of time the fire source reached the maximum assumed size, fire temperature reached 1400 °C and oxygen concentration behind the fire amounted 19.6 % (oxygen loss: 1.4 %)

2. After 2 h 30 min. the actions preceding activation of the GAG unit have been commenced :
   At first, using the command "Door" the stopping's resistance related to the GAG was set at the value of : R = 50 kg/m7. The stopping was located behind the generator's outlet, in front of the junction 42. Erection of this stopping was aimed at reducing fresh air inflow, which would have diluted (and contaminated by oxygen) the inert gas. The outlet of the GAG was situated behind this stopping. Then the GAG was turned on with the minimum engine speed, i.e. 8,000 rpm. The rotational speed of the GAG determined the concentration of the components of the exhaust gases as well as their total output.

   After 3 h 30 min. the flow at the second intake of the mine was restricted with a stopping situated in 1-76 branch with the flow resistance set to R = 10 kg/m^7. This action changed favourably the pressure distribution in the network as well as the direction of the flow of air and inert gases.

3. The ventilation actions undertaken up to this point have not sufficiently reduced the inflow of the fresh air into the ventilation network. In this exemplary simulation the fan was throttled by increasing the resistance of the fan stopping in three consecutive stages:

   R_1 = 5 kg/m^7 t = 4 h 00 min.;
   R2 = 10 kg/m7 t = 4 h 30 min.;
   R3 = 18 kg/m7 t = 5 h 30 min.

The situation after these actions is shown on Fig. 2. The heavy lines illustrate the paths of inert gas movement towards the fire source (intake) and the paths of the fire gases behind the source and towards the return.

There were two purposes of this reduction of the air intake to the network:

a) reduction of the fresh air inflow to the fire source (meeting the rules formulated by W. Budryk - main stopping);

b) intensification of the influence of the generated inert gases on the fire source.

During implementation of these actions aimed at the reduction of the fresh air intake to the mine with the GAG running, one should avoid the reversion of ventilation and inflow of gases to the place where the GAG is situated.

Such a case may occur if both intake and return of the mine were throttled too intensively.

4. Continuing the observation of the fire development and the influence of the inert gases on the fire source, certain ventilation actions, i.e. adjustment of the network were implemented in order to improve the efficiency of the fire extinguishing process.

The pressure distribution in the network of branches depends on the operation of the main fan, operation of the GAG (inert gas output source) and on distribution of air density and transport gases along the sloped branches. Such a situation results in refreshment of the inert gases in the junction 76 from the intake of the 5 Heading .

After 6 hours of simulation run, stoppings were placed in the branches 2-3, 42-43 and 59-60 (resistance R = 2 kg/m^7).This operation increased the influx of the inert gases towards the fire source and resulted in efficient extinguishing of the fire . Such an action can be successfully simulated using the „*Door*" option. Obviously, in the case of a real ventilation network such a potential action should be prepared in advance, before activating the GAG.

The graphs in Fig. 3 present the changes of the parameters, which characterise the discussed case. The course of changes of fire source temperature - Fig. 3d - shows that under the circumstances of the simulated situation, the fire source was successfully extinguished after 13 hours of the GAG operation.

The graphs presented in Fig. 3 show the recorded results of measurements of following parameters:

a) air temperature behind the fire source;

b) oxygen concentration behind the fire source;

c) flux of heat generated in the fire source;

d) temperature of fire source.

e) air flow rate over the fire source.

The Fig. 4 shows the recorded results of measurements of following parameters:

a) air flow entering the mine - intake 1-76;

b) air flow entering the mine - intake 1-42; in this branch the GAG is situated;

c) air flow entering the mine - intake 1-200

d) air and gas flow returning from the mine - branch 98-1;

e) concentration of oxygen in a mixture of air and gases returning from the mine - branch 98-1.

f) concentration of oxygen in a mixture of air and gases near node 61 , 3 Level - 4 Heading .

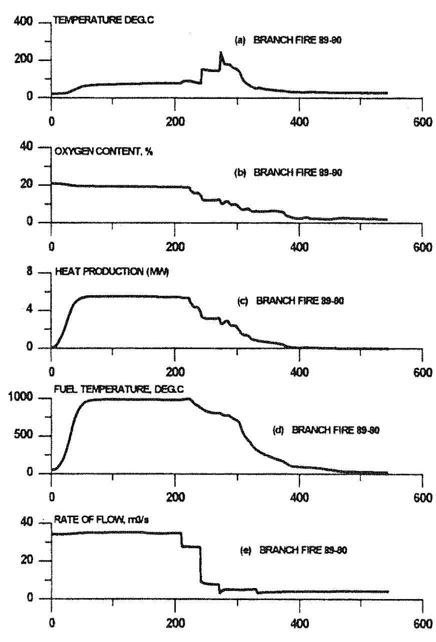

Fig. 3. Temperature in air flow, oxygen content, heat production of fire, temperature of burning material and rate of flow in branches versus time (computer simulation). Example P1

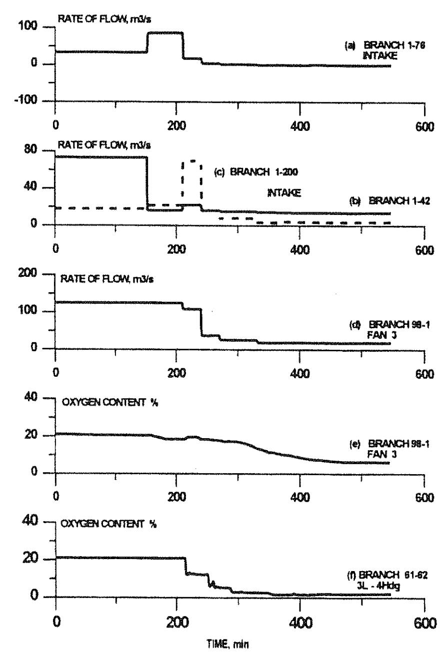

Fig. 4. Rates of flow and oxygen content in branches versus time (computer simulation)

CONCLUSIONS

The comprehensive simulations of the development of an underground fire and its extinguishing with application of the GAG inert gas generator allow the authors to draw the following general conclusions:

1. ***Application of the GAG generator in a complex network of coal mine branches causes significant changes in propagation of the air and fire gases. The presented method allows for an appropriate preparation of the most appropriate firefighting actions IN ADVANCE with the most efficient application of the GAG.***

2. ***The presented exemplary simulation carried out for a complex network of branches allows for the optimal selection of the location of stoppings in order to stop or to open gas flows along the appropriate branches. These actions were necessary for efficient extinguishing of the fire.***

3. ***Location of the GAG generator in relation to the location of the fire source significantly influences the efficiency of the firefighting action .***

4. ***The flow at the intake and in the return from the mine should not be throttled too intensively, because it may the flow reverse of gases towards the place where the GAG generator is located.***

5. ***Operation of the GAG has a significant effect on the direction of gas flows in the ventilation network. Therefore any GAG application should be thoroughly simulated and researched.***

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