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## SIMULATION OF FLOW OF FIRE GASES IN A VENTILATION NETWORK OF A MINE WITH A APPLICATION OF MATHEMATICAL MODELS OF A DIFFERENT COMPLEXITY IMPLEMENTED IN THE VENTGRAPH SOFTWARE

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### 1. Introduction

The state of the flow of air in a network of headings may be determined based on the measurements or can be compared using model or simulation tests based on submitted mathematical models, which are constructed at various degrees of simplification. For forecasting the process of the ventilation of a network of mine headings, the simulation method is particularly useful, for it enables the forecasting of numerous disturbances of air flow, such as for example a subterranean fire [2], the sudden breakout of gases and rocks [1], the influx of methane that is caused by a rock mass crump [3], as well as for assessing the inertisation of the atmosphere of gobs [4, 5]. The above-mentioned issues are resolved by means of the numerical method based on the system of VENTGRAPH computer programmes, which enable the forecasting of ventilation processes under normal conditions and in emergency situations, such as a fire, and are characterised by considerable calculation possibilities, and ease of programme usage as well as interpretation of the results of the calculations [6].

Presently, only those programmes with functions that are similar to those of VENTGRAPH are used around the world, while international circles of ventilation specialists show a considerable demand for such software. On the other hand, attempts at more complex modelling, for example the usage of a full three-dimensional description and numerical fluid

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mechanics methods (CFD) for an entire network, are premature, which is due to the insufficient calculation capacity of modern computer equipment. As regards the development of the methods of forecasting situations as brought about by a subterranean fire, it is important to use CFD methods for local flow issues, which will contribute to the improvement of the new POŻAR module, and also help gain an understanding of its limitations. Interesting results concerning this issue have been presented in the work conducted by P. Skotniczny [8].

The monograph [7] show, in detail, a complex mathematical model of the fire focus, which takes into consideration the flow of the mix of humid air and gases with the simultaneous exchange of heat along the flow routes of fire gases. A significant element regarding the verification of the correctness of this selection is the comparison of those solutions describing the phenomena in question, which are obtained for the broadest possible spectrum of mathematical models with a diverse degree of simplification.

We shall present an example of forecasting the process of ventilation as caused by an open subterranean fire in operational heading of mine that is ventilated by upward air currents. This will enable a qualitative analysis of changes in the flow rate of the mix of air and fire gases, and also the verification of the possibility of reversing the air currents that ventilate the longwalls. The results obtained are shown in the form of time graphs of the changes in the observed parameters.

## **2. Comparative research — assumptions and fire parameters**

It has been assumed that comparative tests shall be performed by simulating the propagation of fire gases in a network of headings based on two variants of one dimensional models describing the course of the fire and its impact on the propagation of the mix of air and fire gases within the network of mine headings. The first of these, further names as “wet” takes into consideration the flow of the mix of humid air and gases with the simultaneous exchange of heat with the rock mass that is caused by the flow of fire gases. The second, named as “dry”, neglects the effect of humidity. Both models use a mix of steady and unsteady equations. Mass and momentum conservation equations are steady. Dynamics of the fire, transport of contaminants and heat exchange with strata are treated as unsteady. This approach is called quasi-static.

Such simplification is justified because the response of the ventilation system to buoyancy caused by the development of the fire and ventilation activities that are connected to the extinguishing of the fire is decidedly more rapid than the process of transporting fire gases.

Before proceeding to comparative tests, a region was selected in mine *M* (Fig. 1). Data for the example were obtained by using the ventilation measurements that were performed along with the database that it was based on and elaborated thereof, concordant with the standard of the VENTGRAPH system. It should be added here that the comparative tests made use of the identical data concerning the structure of the network of headings and parameters describing the flow of air.

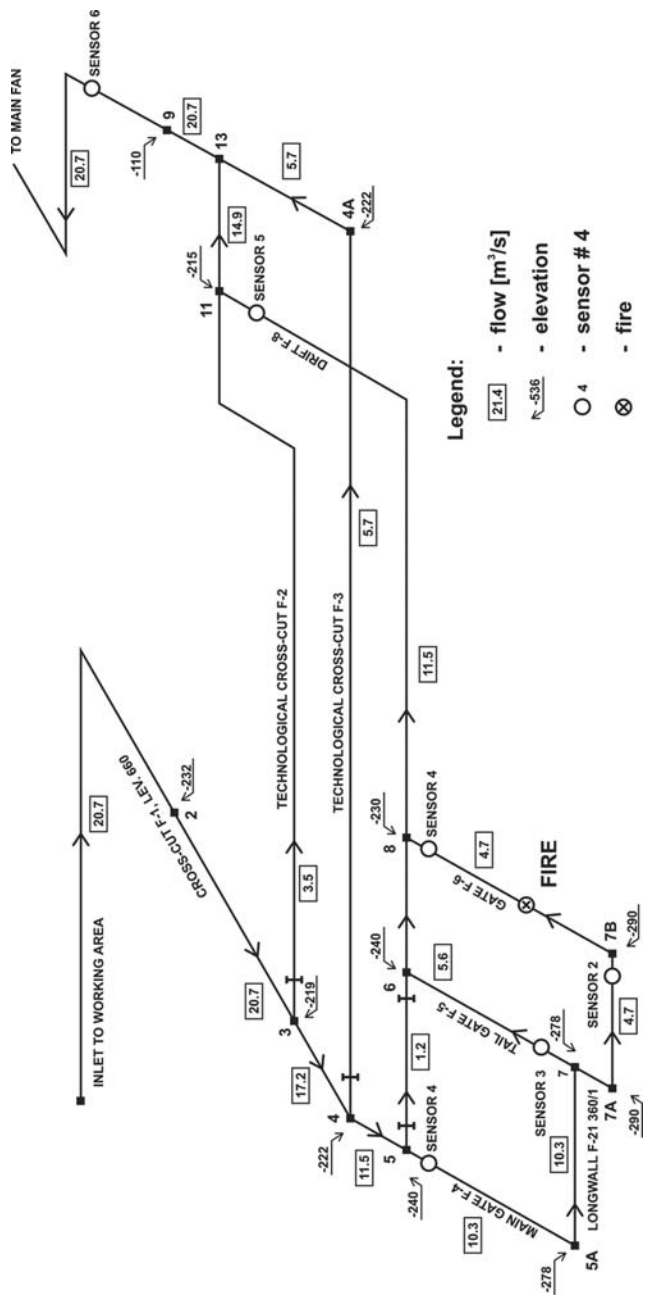


Fig. 1. Isometric scheme of the mining area of lingwall F-21, bed 360/1

Due to the considerable quantity of data that may be obtained when a fire in a complex network is simulated, various ways of presentation have been applied:

- the results of the simulations shall be presented in graphical form on a fragment of the isometric scheme of the ventilation network covering the respective area in question. On these diagrams, we shall mark the routes that are used by fire gases with thick red lines. An observation of these routes will make it possible to assess the propagation of fire gases and delimit the area at risk (due to space limitations, these images will not be included in this paper);
- in addition, we shall present time graphs of the changes in the flow rate of air and fire gases and the changes in other significant parameters impacting the flow of fire gases, e.g.
  - the temperature of the focus of the fire,
  - the temperature of the mix of air and fire gases at a selected point of the heading,
  - the density of the mix of air and fire gases at a selected point of the heading,
  - the humidity of the mix of air and fire gases at a selected point of the heading,
  - the concentration of oxygen in the mix of air and fire gases at a selected point of the heading,

As regards the hazard that is caused by the fire, the stability of the air flow directions is of key importance, while in the case of methane mines, changes in the flow rate alone may be of considerable significance. During a subterranean fire, the range of the smokiness in the mine depends, to a considerable extent, on the structure of the ventilation network, which is closely connected with the dissection of the deposit and the location of the production zones in the mining area, as well as with the stability of directions of flow of air.

An analysis of the headings with descending flow shows that the location of the fire does in fact impact the directions of the flow and the scale of the changes in the flow rate of the fire gases. If we assume that the location of the fire is at the entrance to an inclined heading, we shall be faced with a fire that will generate the greatest additional value of fire depression for the existing flow conditions (inclination, flow rate, and length of the ventilation route).

In order to satisfy the above assumption, during simulations that utilise the computer programme POŽAR we adopted the following parameter values of the fire focus model in the calculations:

- maximum fire intensity  $\psi = 5$  (on a scale of “1 to 10”),
- maximum length of the fire zone  $l = 35$  metres,
- time constant of fire escalation  $\tau = 1200$  s.

In addition, coal was adopted as the type of fuel for headings in the longwall region.

### 3. Results of the calculations — the fire in the upward air current

The region of mine *M*, an isometric scheme of which is shown in figure 1 was considered. The point of the fire was located in a heading, in which air is conducted along a rise. An analysis of the structure of the connections and the functions of headings in the area indicates that the impact of the eruption of the fire should be analysed at the beginning of gallery F-6, through which the used air is channelled away from longwall F-21, bed 360/1. The location of the fire in the gallery is marked with a circle (Fig. 1). The parameters describing the flow in gallery F-6 are as follows: flow rate 4.7 m<sup>3</sup>/s, flow velocity 2.10 m/s, air density 0.37 kg/m<sup>3</sup>, heading length 800 m, cross-sectional area 12.7 m<sup>2</sup>, inclination  $\alpha = 4$  deg. (elevation difference 60 m).

In the area in question, in order to monitor the course of the phenomenon during simulation, we installed sensors registering the changes in the following physical values in the branches: quantitative flow rate of air and fire gases, temperature of the fire focus located in gallery F-6, temperature of the flowing mix of air and fire gases, oxygen — concentration, density of the flowing mix of air and fire gases, humidity of the flowing mix of air and fire gases. Table 1 and Figure 1 show the locations of sensors in the individual branches of the network.

TABLE 1

**The locations of sensors in the individual branches of the network**

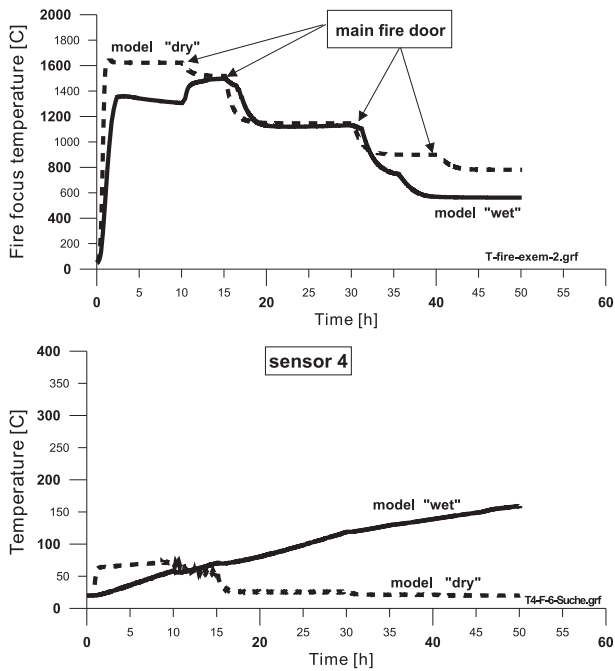
Node		Name of heading	Sensor no	Quantity of air volume stream, m <sup>3</sup> /s
entry point	exit point			
5	5A	Main Gate F-4	1	10.6
7A	7B	Gate	2	4.7
7	6	Tail gate F-5	3	5.6
Fire	8	Gate F-6	4	4.7
8	11	Drift F-8	5	11.5
13	Outlet	To the main fan	6	20.7

In the course of the simulation, the forecast values of the changes in the aforementioned parameters describing the flow of air and fire gases were registered on the computer's hard drive. These data were used to elaborate the time charts, which are shown in the successive figures for selected headings. For the adopted point of the fire, the simulation was conducted for at least 50 hours, while in the course of the simulation, changes were made in the ventilation conditions, i.e. the flow of air reaching the fire focus was limited by the construction of a basic stopping that was located upstream of the fire focus. The simulation of the construction

of the basic stopping was conducted in a number of stages. However, this was performed with a fixed time constant (3600 sec.):

- construction was started in the 10th hour of simulation, stopping resistance  $10 \text{ kg/m}^2$ ,
- in the 15th hour, the resistance of the stopping was increased to  $100 \text{ kg/m}^2$ ,
- in the 30th, the resistance of the stopping was increased to  $300 \text{ kg/m}^2$ ,
- in the 40th, the resistance of the stopping was increased to  $500 \text{ kg/m}^2$ .

The simulation of the construction of the stopping in a number of stages was aimed at verifying the impact of throttling the air flow on the course and the development of phenomena in the fire focus and the changes in the distribution of temperature, humidity, and volume stream of the flowing mix of air and fire gases.



**Fig. 2.** Changes of the temperature of fire focus and gases produced by the fire

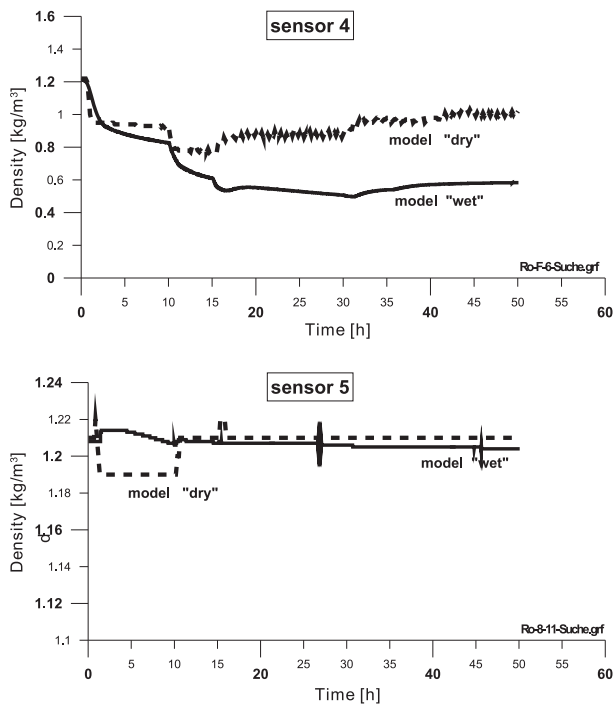
The down chart in Figure 2 shows the changes in the temperature of the fire focus that were obtained based on calculations for two models. The dotted line represents the results of the calculations for the “dry” model, while the solid line shows the results for the “humid” model.

When observing the course of the changes in the temperature of the fire focus, we see the impact of the respective ventilation manoeuvres performed (construction of the basic stopping), which led to a limitation of the fire and the zone of smokiness.

The up graph in Figure 2 shows the changes in the temperature of the flowing mix of air and fire gases, as registered by one of the sensors of the monitoring system, which were located in the headings that were used for the movement of fire gases.

When observing the obtained results of the changes in the temperature of the flowing mix of air and fire gases along the route of passage of gases, we see that — based on the “dry” model — following the construction of the basic stopping, there occurs a fall in the temperature. As regards the simulation using the “humid” model, we observe a slow but constant rise in the temperature. Due to the transfer of heat to the side walls of the heading, we observe a fall in the temperature of moving fire gases.

In the successive graphs in Figure 3 we show the changes in the density of the flowing mix of air and fire gases, as registered by the successive sensors that were located in the headings that were used for the movement of fire gases.



**Fig. 3.** Changes of the fire gas density, location at sensors 4 and 5

In the successive graphs (Fig. 4) we show the changes in the density of oxygen of the flowing mix of air and fire gases, as registered by the successive sensors that were located in the headings that were used for the movement of fire gases.

In the collective graph (Fig. 5) we show the changes in the relative humidity of the flowing mix of air and fire gases as registered by the sensor that are located in the headings that are used for the movement of fire gases.

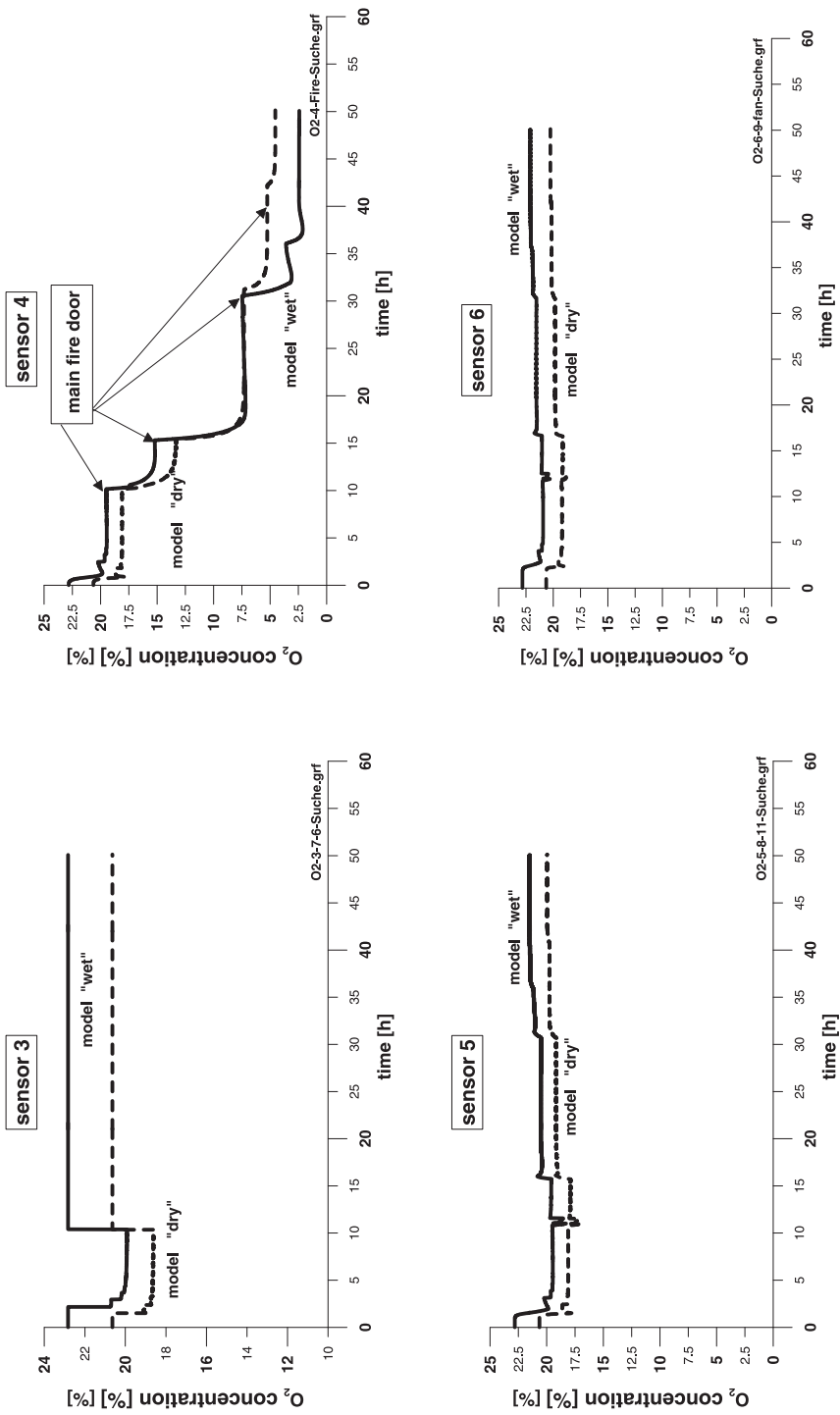


Fig. 4. Course of the changes in the concentration of oxygen, location at sensor 3



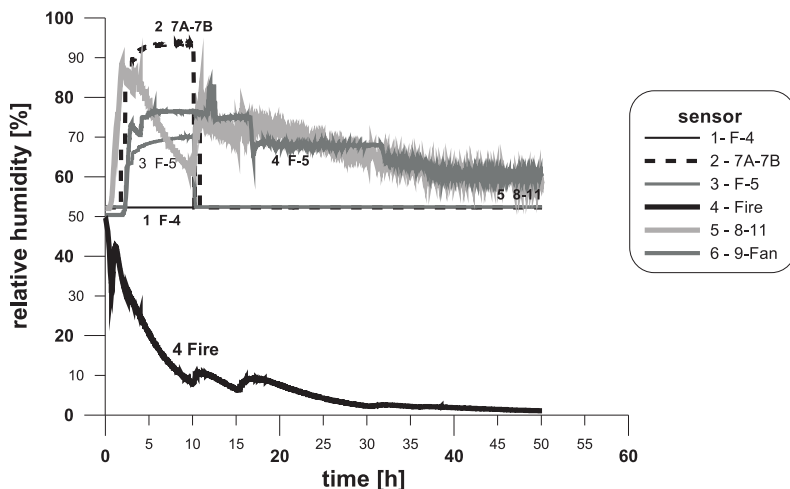


Fig. 5. Changes of the relative humidity location at all the sensors

Graphs in Figure 6 show the changes in the flow rate of the flowing mix of air and fire gases, as registered by the sensor that was located in the headings that were used for the movement of fire gases.

An analysis of the results that were obtained shows that in the area in question there occurs a reversal of the initial direction of the flow of air. The fire in the upward air current causes a reversal of the lateral air current in gallery F-5. Following the occurrence of this reversal, the fire gases reach the focus of the fire. An example is the phenomenon of the reversal of the lateral current, known from W. Budryk's theory, in which the initial direction is restored by the erected basic stopping. The graphs show the changes in the physical parameters of the flowing mix of air in the successive headings of the analysed ventilation area. The courses of the changes in the individual parameters show certain discrepancies, depending on the model shown:

- The temperature of the fire focus is determined based on the humid model prior to construction of the basic stopping (stage 1) is 1494°C, while for the dry model it totals 1622°C, (more than 8%), while after 50 hours (stationary state) it equals 561°C, while for the dry model it totals 780°C, which gives a difference of 39% with respect to the humid model. The limitation of the influx of the volume stream of air causes a decrease in the temperature of the fire focus.
- The temperature of the incoming mix of air and fire gases as registered by sensor 4 in gallery F-6, as determined for both models, differs considerably. The results of the calculations of the changes in the temperature of the flowing mix of humid air and fire gases that were obtained show a slow increase in the temperature of the flowing air. This is caused by the influx of heat that is generated in the fire focus, which is limited by the construction of the basic stopping.

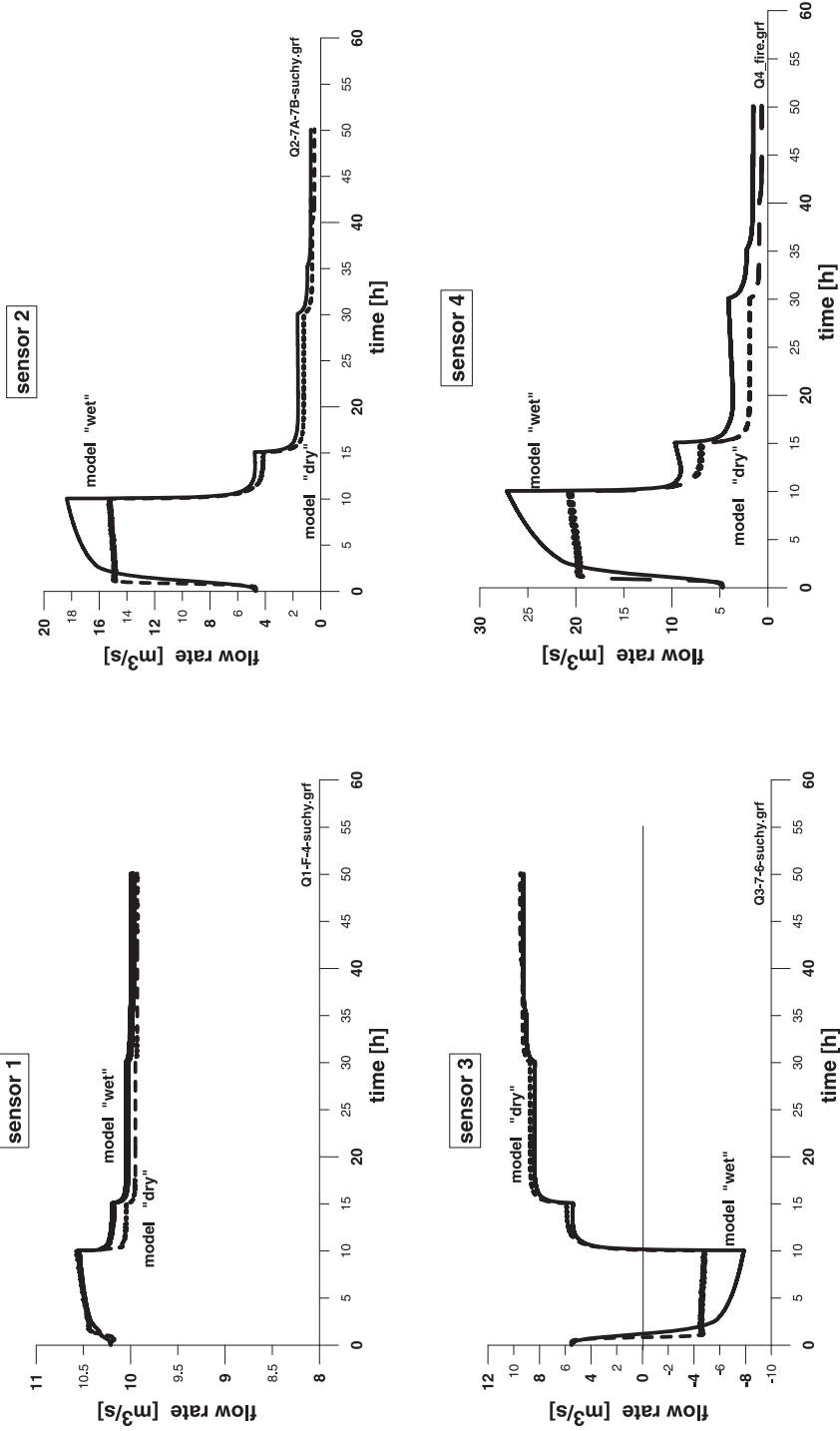


Fig. 6. Changes of the flow rate in location at sensors 1 to 4

- The densities of the flowing mix of air and fire gases, as determined for both models, differ less than the temperatures. The greatest difference concerns sensor 4, which is located in the heading behind the fire focus; this totals 34% with respect to the value of initial density.
- The concentration of oxygen in the flowing mix of air and fire gases as determined for both models is very similar. It is noteworthy that the initial value of the concentration differs, for we have adopted an air oxygen content of 21% (volumetric concentration) for the “dry” model, and 23% (mass concentration) for the “humid” model.

Changes in the volumetric flow rate of the mix of air and fire gases for both models show the greatest probability, and — what is of significance — the final flow rate state (stationary state) that was obtained for headings in which sensors 1, 2, 3, 4, 5, and 6 are located is identical. In headings where sensors 2, 3, 4, and 5 are located, during the initial phase of the development of the fire, we observe a transient state that is characterised by the occurrence of differences in the volumetric stream of mix flow. Following the construction of the stopping, these differences disappear.

#### **4. Final comments**

Detailed deliberations leading to the consideration in the equations of the mathematical model of the flow of the mix of humid air and gases with the simultaneous exchange of heat along the routes of the flow of fire gases have been presented in the monograph [7]. In order to take into consideration the flow of humid air in the network of mine headings under conditions of a developing subterranean fire, it was necessary to elaborate a mathematical model. This model contains system of numerous equations that are interconnected by parameters describing the flow of humid air and takes into consideration the following:

- 1) The mass balance in the heading fire focus, which makes it possible to determine: the density of humid and misty air; changes in the mass of air components during the combustion of fuel in the fire focus; changes in the mass of components and the density of air exiting the focus of the fire.
- 2) The heat balance for air in the focus of the fire, which makes it possible to determine: enthalpy of humid air; heat reaching the focus of the fire; heat entering from the burning fuel; heat exiting from the focus of the fire; heat accumulated in air in the focus of the fire; the temperature of air exiting the focus of the fire.
- 3) The heat balance for the focus of the fire, which makes it possible to determine: the heat from fuel combustion; the heat channelled away to the rock mass; the heat accumulated in the fuel; the temperature of the focus of the fire.
- 4) For the flow of humid air in the corridor heading: the heat channelled away to the rock mass; the enthalpy and temperature of humid air in the heading; the enthalpy and temperature of misty air in the heading.
- 5) The flow of humid air through the nodes of the ventilation network.

The objective of numerical calculations is to determine the density distribution of the humid air flowing along all of the ventilation routes. The presence of the fire causes considerable changes in the quantity of flowing air, while in extreme instances a change occurs in the direction of the air flow. For the first time, the elaborated model makes it possible to take into consideration the full impact of air humidity on the changes in the quantity of flowing air.

An important element for assessing the quality of the applied mathematical models in computer programmes is the comparison of the solutions obtained for a set of mathematical models describing the phenomena relating to the flow of hot fire gases in the network of headings, differing as regards the degree of simplification (flow model for a dry fluid or a humid one). This comparison, and the application of the results of the experiments and in situ measurements [2], have made possible the optimal development and verification of the modernised POŻAR module of the system of computer programmes VENTGRAPH.

An analysis of the results that were obtained for two different models has shown only slightly differing courses of observed air flow parameters. It is noteworthy that the best conformity will be obtained for the course of changes in the volume stream of the flowing mix of air and fire gases. The differences observed in the solutions, e.g. temperature distributions, in turn results from the adopted mathematical model. It would appear that the next step leading to the development of the presented method of determining the flow of the air mix consists in continuing fire experiments in order to gain a better understanding of the coal combustion processes in the fire focus in the event of a limited air flow.

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