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UNSTEADY FLOW OF GASES IN A MINE VENTILATION NETWORK — A NUMERICAL SIMULATION

NIEUSTALONY PRZEPŁYW GAZÓW POŻAROWYCH W KOPALNIANEJ SIECI WENTYLACYJNEJ — SYMULACJA NUMERYCZNA

In this article the authors present two methods of describing the flow of air and fire gases in ventilation networks. Both methods make use of the approximation of one-dimensional flow. The more detailed model treats air as a compressible medium and is based on the complete set of mass, momentum and energy conservation equations. The second model discounts the influence of temporary derivatives of pressure, density and velocity on the course of the phenomena researched, which results in a simpler description. The authors have applied identical fire and fire gas transport models, as well as a similar model of heat exchange with the rock mass. These methods have led to the development of computer programmes. Subsequently, we compared the results of calculations of non-stationary states caused by fires in headings ventilated by an upward current and a downward current for a single mesh networks. The data obtained are of a similar nature, although they do differ in terms of quantity. In one of the examples a more detailed model provided for the reversal of flow, while according to the quasi-static description the direction was maintained. Finally, the authors offer an interpretation of the findings and the prospective applications of the detailed description.

Key words: mining, ventilation, fires, flows dynamic, monodimensional flow, computer simulation

W artykule przestawiono dwie metody opisu przepływu powietrza i gazów pożarowych w sieciach wentylacyjnych. Obie metody stosują przybliżenie jednowymiarowego przepływu. Dokładniejszy model traktuje powietrze jako medium ściśliwe i jest oparty o pełną postać równań zachowania masy (11), pędu (12) i energii (19). Drugi z modeli pomija wpływ pochodnych czasowych ciśnienia, gęstości i prędkości na przebieg badanych zjawisk, co prowadzi do prostszego opisu (22) i (23). Zastosowano identyczne modele ogniska pożaru i transportu gazów pożarowych (4), a także podobny model wymiany ciepła z górotworem (8), uwzględniający nagrzewanie się skał (9, 10). W ognisku pożaru zachodzi proces spalania węgla w dopływającym powietrzu. Równania opisujące ognisko określają współzależność między produkcją ciepła, zużyciem tlenu wzrostem temperatury płonącego węgla i temperaturą wypływających gazów.

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Omawiane metody znalazły zastosowanie w programach komputerowych. Przeprowadzono obliczenia zmian przepływu w sieci jednooczkowej spowodowane pożarem w jednym z wyrobisk. Rozpatrywano przypadki pożaru w nachylonych wyrobiskach zarówno dla przewietrzania prądem wznoszącym (rys. 1, tab. 1), jak i schodzącym (rys. 4, tab. 3). Dla wyeliminowania wpływu zmian punktu pracy wentylatora przyjęto charakterystykę o stałym spiętrzeniu ($H = 350$ [Pa]). Warunki początkowe dobrano tak, by depresja naturalna była bliska zeru. W modelu quasi-statycznym początkowo gęstość była identyczna we wszystkich wyrobiskach, a dla drugiej metody opisu początkową temperaturę ścian wyrobisk dobrano tak, by dopływ ciepła był pomijalnie mały.

W miarę rozwoju pożaru wzrastała temperatura palącego się węgla i gazów wypływających z ogniska, a malało stężenie tlenu. Wraz ze wzrostem temperatury malała również gęstość gazów płynących z ogniska do szybu wydechowego. Powodowało to wzrost wartości wyrażenia (24) nazywanego depresją pożaru i w efekcie przyrost wydatku płynącego w sieci (rys. 2). Rozkład wydatków w oczku, przedstawiono na rysunku 3. Na drodze od szybu wlotowego do pożaru według modelu quasi-statycznego wydatek był stały, a dla drugiej metody opisu w szybie wdechowym nieznacznie malał wskutek wzrostu gęstości z głębokością, następnie pozostawał stały w poziomej bocznicy 2–3, potem nieznacznie wzrastał w nachylonej do góry bocznicy 3–4. W ognisku pożaru następował skokowy wzrost wydatku, głównie wskutek ogrzania gazów, a także wskutek dopływu produktów spalania węgla. Gazy pożarowe były chłodzone przez ściany wyrobisk. Efekt chłodzenia miał dużo większy wpływ na wzrost gęstości i spadek wydatku objętościowego niż malejąca głębokość w bocznicy 4–5 i szybie wydechowym. Porównanie temperatur ogniska pożaru, gazów pożarowych w ognisku i na wylocie szybu wydechowego zamieszczono w tabeli 2. Proces ustalania się przepływu trwał dłużej dla modelu płynu ściśliwego i zmierzał do wyższych wartości mocy, wydatku i temperatur. Otrzymane przebiegi mają podobny charakter, różnią się jednak pod względem ilościowym. Pożar w prądzie schodzącym (rys. 4 i tab. 3.) początkowo działa hamująco na przepływ, później wzrost ciągu naturalnego w szybie wydechowym powoduje przyrost wydatku (rys. 5). Także w tym przypadku wielkości porównywane w tabeli 2 są większe dla modelu przepływu płynu ściśliwego, z wyjątkiem niższej temperatury na wylocie szybu wydechowego. Różnice te mają wpływ na rozkłady wydatków objętościowych (rys. 6). W trzecim przykładzie, dla pożaru w prądzie schodzącym i niższym spiętrzeniu wentylatora ($H = 160$ [Pa]) dokładniejszy model przewidywał odwrócenie przepływu, podczas gdy według opisu quasi-statycznego kierunek został zachowany (rys. 7). Wyjaśnienie przyczyn rozbieżności i interpretacja wyników wymaga dalszych badań.

Prezentowany w artykule model jednowymiarowego nieustalonego ściśliwego przepływu gazów o zmiennym składzie w warunkach wymiany ciepła z górotworem umożliwia prowadzenie symulacji komputerowych służących do wyznaczenia zmiennych w czasie charakterystyk stacji wentylatorowych w warunkach rozwoju pożaru podziemnego, określenia charakterystyk ciągu naturalnego zarówno podczas występowania pożaru podziemnego, jak i w normalnych warunkach eksploatacji, a także poszukiwania rozwiązań wykazujących cechy chaosu deterministycznego.

Słowa kluczowe: górnictwo, wentylacja, pożary, dynamika przepływów, jednowymiarowy przepływ, symulacja komputerowa

1. Introduction

Forecasting phenomena occurring in the operational functioning of the ventilation network of an underground mine — in particular when the normal operation is disrupted by an underground fire and a method of computer simulation is to be applied, requires the formulation of complex mathematical models and the adoption of appropriate boundary and initial conditions. The Ventgraph system of computer programmes (Dziurzyński et al. 1998) makes use of a quasi-static mathematical model to represent the flow of air and fire gases in a network of mine headings and goafs. An interesting issue, which enables the further development of simulation programmes, concerns the attempt to formulate a mathematical model taking into consideration the flow of the mixture of air and gases as a compressible medium. Once a solution for a complex ventilation network is determined, it will be possible to compare the results of simulations obtained on the basis of mathematical models with differing degrees of complexity.

Transient states of air propagation in the mine ventilation network, brought about by the occurrence of an underground fire, are processes for which it is necessary to consider the influence and interaction of numerous phenomena, such as the development of the fire, the dissemination of fire gases, the exchange of heat between the rock mass and the atmosphere of the mine, the occurrence of a thermal depression, or the delayed response of the network to changes in flow conditions brought about by the inertia and compressibility of air.

The authors of the present article have considered two methods of describing the phenomena that occur, based on an approximation of one-dimensional flow, which differ as regards assumptions concerning the properties of air and the nature of dynamic processes:

1) a compressible fluid variable flow model, and
2) a quasi-static incompressible fluid flow model.

In each of the above we may distinguish four interacting models:

- of air flow in the ventilation network, or more precisely the model of flow in branches (headings), for which the boundary conditions are determined by node models that take into account the operation of fans and stoppings, and also the influx of gases from the fire,
- of heat exchange with the rock mass,
- of the propagation of changes in air composition brought about by the consumption of oxygen at the fire,
- the fire itself.

Furthermore, in the present article we have presented a comparison of results obtained using the methods of description outlined herein. Approximate solutions arrived at using computer calculations have been presented in the form of diagrams and tables.

2. Mathematical ventilation-network flow models

In mine headings, and in particular in long galleries connected into a single network, we may apply the one-dimensional flow model. Various forms of equations for this model have been presented in literature concerning fluid mechanics (Prosnak 1971), specific applications in mining aerology (Dziurzyński, Tracz, Trutwin 1987), and also flow modelling in pipeline networks (Fox 1977).

In the course of research carried out by the Institute of Strata Mechanics, a number of different models were applied (Dziurzyński 1998a) in order to assess the influence of fire gases on the state of ventilation of ventilation networks. A common feature of these models was the method of modelling the transport of gas and heat exchange with the rock mass, which was based on equations that will also be made use of in the description outlined later in this paper. Differences in the two methods concerned the degree of simplification of the description of unsteady flow.

The simplest model assumed that processes connected with the dissemination of fire gases are slow to such an extent that it is only necessary to calculate successive stationary states taking into consideration changes in the variations of ventilation pressure resulting from the propagation of combustion products and the exchange of heat with the rock mass. One study (Tracz 1987) demonstrated this by means of a method based on an analysis of the frequency characteristics of mathematical models, that in the event of the propagation of outburst gases the differences between this description and the more detailed models are insignificant for the phenomenon in question, thereby justifying the utilisation of the quasi-static model in programmes used for forecasting the effects of gas outbursts (Dziurzyński, Tracz, Trutwin 1987a) and the influence of underground fires on the state of ventilation (Dziurzyński et al. 1992).

A more complex model (Dziurzyński, Tracz, Trutwin 1985) took into consideration the inertia of air movement on the assumption of incompressibility. Additionally, attention was given to the adaptation of the 'distributed constants' model based on the assumption that air undergoes transformations similar to the isentropic. Therefore flow dynamics can be described by equations of mass and momentum conservation, with the simplified form of the energy equation being used solely to determine the influence of heat exchange with the rock mass on the temperature of the fire gases. Developments in computer efficiency has made possible the application of the full form of the one-dimensional flow model, in which the following simplifications are the most important:

- usage of average values for the cross-section of the heading, which is justified when:
  - changes in the state of the arrangement along the axis of the branch are considerably slower than the time required for conditions in the cross-section of the heading to settle,
  - we can omit phenomena caused by inhomogeneous distributions in the cross section of the branch (e.g. reversed flow-currents during a fire);
- the assumed absence of thermal conduction and diffusion along the axis of the heading.

In comparison with the model in which the assumption of transformation approximating to isentropic coexists with the equation of heat exchange with the rock mass and factors allowing for losses caused by resistance to motion, the description of the phenomenon becomes more coherent at the expense of a somewhat greater complexity of calculations. Just as a comparison of solutions for flows with a constant and variable density makes it possible to distinguish phenomena connected with the compressibility of air, so the model which allows for the full gas-state equation and a more detailed balance of energy enable comparisons to be made. This model differs only slightly from that proposed in another study (Zhao Yihui et al. 1989).

It is to be expected that in the future the one-dimensional model will be replaced with a three-dimensional description that will utilise the tools of Computational Fluid Mechanics (known in English under the abbreviation CFD) (Wala, Yingling, Zhang 1996; Branny 1998). During the implementation stage of CFD methods the model presented herein may turn out to be useful for the initial assessment of the accuracy of solutions.

2.1. One-dimensional variable compressible fluid flow model

The ventilation system of the mine may be treated as a network of headings called *branches*. Branches are connected with each other in *nodes*. Places where air is absorbed by the network or returned to the atmosphere are called *boundary nodes*. Due to effects connected with the compressibility of air, the network will most often be mapped on an open canonical diagram (Czeczott 1957).

In the ventilation duct we may distinguish a line known as the *duct axis*. To each point of the axis we may assign a co-ordinate s and a flat area constituting the cross-section of the duct.

The state of flow in the duct is represented by the mass or volumetric flow rate and the following average quantities — velocity v, density ρ,static pressure p and mass oxygen concentration C_{O_2}

Air flowing in the headings accords to the ideal gas law:

$$p = \rho R T \tag{1}$$

where:

R — gas constant,
T — gas temperature.

The internal energy of gas e [J/kg] is, in turn, determined by the expression:

$$e = C_V T = \frac{1}{\kappa - 1} \frac{p}{\rho} \tag{2}$$

where:

$\kappa = \frac{C_p}{C_V}$ isentropic coefficient,

C_p, C_V — specific heat at a constant pressure and volume, respectively [J/(kg K)].

Changes in the composition of air occur exclusively at the seat of the fire, as a result of the combustion processes.

Air neither gives up nor absorbs humidity from the environment.

The propagation of changes in the composition of air caused by combustion processes at the fire is brought about by transport in a stream of air; we are not taking into consideration the influence of diffusion along the axis of the heading and assuming that the settling time of concentrations in air in a direction transverse to the axis is negligible.

The mass in a unit of volume of one of the components of air, i.e. oxygen, is designated by ρ_{O_2} [kg/m^3]. Thus, the mass concentration of oxygen C_{O_2} is determined by the formula:

$$C_{O_2} = \frac{\rho_{O_2}}{\rho} \tag{3}$$

In accordance with the adopted assumptions, we may also write down the equation of continuity for ρ_{O_2}. This equation, once we have used the equation of continuity for ρ (11), leads to a dependence defining changes in the distribution of oxygen concentration brought about by transport with a flow velocity of v:

$$\frac{\partial C_{O_2}}{\partial t} + v\frac{\partial C_{O_2}}{\partial s} = 0 \tag{4}$$

The above equation is written down in a characteristic form, and thus we may solve it applying the method of characteristics.

The flow is of a turbulent nature, with the resulting pressure loss gradient in [Pa/m] fulfilling the dependence:

$$j = \lambda \frac{F}{4A}\frac{\rho|v|v}{2} \tag{5}$$

where:

$A = A(s)$ — cross-section area [m^2],
$F = F(s)$ — section circumference of resistance coef ficient λ [m].

The influence of energy losses at stoppings and other structures disturbing flow is represented by the pressure loss w_T [Pa]. The simplified description assumes that this leads to step changes in pressure distribution $\Delta p = -w_T$. Due to the lack of alternative models, it was accepted that the following dependence is also valid for unsteady states:

$$w_T = r_T(\rho)|Q|Q = r_T|Av|Av \tag{6}$$

where:

Q — is the volumetric flow rate.

The operation of fans leads to the occurrence of a step change in the distribution of static pressure $p(s)$ by the value:

$$\Delta p = H(Q) \tag{7}$$

in accordance with the appropriate characteristic. As in the case of stoppings, it has been assumed that characteristics elaborated for stationary flow are also valid for transients.

The influence of the gravitational field which, in the event of changes in air density caused by the exchange of heat, is responsible for the occurrence of the phenomenon of natural ventilation pressure, is taken into account.

The influx of heat takes place exclusively as a result of the influence of the fire and thermal exchange with the rock mass; we are omitting heat conduction along the axis of the heading and assuming that the settling time of air temperatures in a direction transverse to the axis is negligible. The quantity of heat exchanged through the surface of the heading in a unit time is determined by the appropriate form of Newton's equation (Staniszewski 1979):

$$q_{SK} = k\{T(s,t) - \theta(s,t)\} \tag{8}$$

where:

T — air temperature present in the equation of state (1) [K],
θ_0 — temperature of the surface of the heading [K],
k — coefficient of heat penetration [W/m^{2}K].

Overall, the coefficient k is the function of temperature differences and flow velocities (Staniszewski 1979).

It has been accepted that in order to assess the quantity of air exchanged with the rock mass the simplified model of this media is sufficiently accurate. It is assumed that the heading is cylindrical, the rock mass is homogenous, the distribution of temperatures is axially symmetrical, and that changes therein in the direction of the heading are negligible to such an extent that for each section it is sufficient to treat the phenomenon as being flat. Under such assumptions, the equation of thermal conduction will take the following form:

$$\frac{\partial \theta}{\partial t} = \frac{\lambda_S}{\rho_S c_S'} \frac{\partial^2 \theta}{\partial r^2} \tag{9}$$

with the boundary condition given by the dependence:

$$\lambda_S \left.\frac{\partial \theta}{\partial r}\right|_{r=r_0} = -k(T - \theta_0) \tag{10}$$

where:

r — distance from the axis of the heading,
r_0 — co-ordinate of the area of the heading,
$\theta = \theta(r)$, $\theta = \theta(r_0)$, while λ_S [W/(mK)], c_S [J/(kgK)] — coefficient of heat conduction and the specific heat of the rocks, respectively.

It was assumed that air mixes completely in the nodes, the nodes neither generate, nor store mass or energy (an exception is the node representing the influence of the fire).

It was accepted that fire gases are created in an area called the *fire focus or the seat of the fire*. This may be located in one of the branches of a network which we may imagine as comprising two branches in series connected with a special node, known as the *fire focus node*. Mine air flowing in from one branch feeds the fire with oxygen, whilst heat and combustion products flow into the other branch. When analysing the complex process of the exchange of mass and energy in the fire, we shall consider the following phenomena:

- Oxygen loss, brought about by the process of combustion of coal and changes in oxygen concentration in the mixture of air flowing through the area covering the fire focus connected to it.
- Emission of heat as a result of the process of combustion of coal in the fire focus.

A detailed description of the focus model has been presented in studies (Dziurzyński 1998a).

2.2. Equations of the model of one-dimensional flow in the branches of a ventilation network

When deriving a system of equations for the model of one-dimensional flow, the authors made use of the following studies: (Fox 1977; Puzyrewski, Sawicki 1987). In the present publication it will be discussed briefly. Within the area defined by the ares of sections for points with co-ordinates s and $s + \delta s$ and the part of the rock-surface limiting the duct between these sections we shall effect a balance of the streams of mass, momentum and energy, taking into consideration the changes that occur in these quantities over a period of time δt. At this point, the energy balance equation must be discussed in greater detail for the pertinent section of the heading. In accordance with the first law of thermodynamics, the quantity of heat flowing in from the sides of work is equal to the resultant of inflowing and outflowing streams of energy, increased by the appropriate terms dependent on work carried out and the velocity of energy changes of air contained in the analysed area. Having passed $\delta s, \delta t \rightarrow 0$, we may write down the appropriate differential equations, which accord to the principles of conservation of:

mass

$$\frac{\partial \rho}{\partial t} + v \frac{\partial \rho}{\partial s} + \rho \frac{\partial v}{\partial s} = -\frac{\rho v}{A} \frac{dA}{ds} \tag{11}$$

momentum

$$\rho \left\{ \frac{\partial v}{\partial t} + \frac{\partial v}{\partial s} \right\} + \frac{\partial p}{\partial s} = -\left(j + \rho g \frac{dz}{ds} \right) \tag{12}$$

and energy

$$\frac{1}{\kappa - 1} \left\{ \frac{\partial p}{\partial t} + v \frac{\partial p}{\partial s} \right\} - \frac{1}{\kappa - 1} \frac{p}{\rho} \left\{ \frac{\partial \rho}{\partial t} + v \frac{\partial \rho}{\partial s} \right\} = \left\{ \frac{q_{SK} F}{A} + v \left(\rho g \frac{dz}{ds} + j \right) \right\} \tag{13}$$

where:

s — co-ordinate measured along the axis of the duct [m],
g — gravitational acceleration [m/s^2],
$z = z(s)$ — height of a point of the axis with a co-ordinate s [M],
p — average static pressure [Pa],
q_{SK} — intensity of heat exchanged through the walls of the duct (calculated from equations 8 and 9) [W/m^2],

and

- volumetric rate of flow [m^3/s]

$$Q = Q(s,t) \tag{14}$$

- average flow velocity [m/s]

$$v(s,t) \overset{\text{DEF}}{=} Q / A \tag{15}$$

- mass flow rate [kg/s]

$$G = G(s,t) \tag{16}$$

- average air density [kg/m^3]

$$\rho(s,t) \overset{\text{DEF}}{=} G / Q \tag{17}$$

- isentropic acoustic velocity [m/s]

$$c = \sqrt{\kappa \frac{p}{\rho}} \tag{18}$$

In order to proceed from the system of equations to the form presented above, it was necessary to adopt simplifying assumptions concerning average quantities (Puzyrewski, Sawicki 1987), (*inter alia* Coriolis' coefficient equating to unity).

The energy balance equation (13), once the density derivatives are replaced with the appropriate expressions from equation (11), may be written down in the following form:

$$\rho c^2 \frac{\partial v}{\partial s} + \frac{\partial p}{\partial t} + v \frac{\partial p}{\partial s} = c^2 \frac{\rho v}{A} \frac{dA}{ds} + (\kappa - 1) \left\{ \frac{q_{SK} F}{A} + v \left(\rho g \frac{dz}{ds} - j \right) \right\} \tag{19}$$

The above system of equations may be reduced to the so-called "characteristic" form (Rożdiestwienskij, Janienko 1978) and may be resolved by applying the method of characteristics (Fox 1977; Zhao Yihui et al. 1989)

2.3. Quasi-static one-dimensional incompressible fluid flow model

In order to arrive at a solution for the system of equations (cf. point 2.1.) with distributed constants for a network made up of many headings, it is necessary to use computers with very high calculational capacities. A Study by (Dziurzyński et al. 1987) contains solutions for a system of equations with distributed constants for a ventilation network comprising a few dozen headings. Results obtained were compared with solutions arrived at for simplified models, and their practical usefulness thus established. In calculations effected for an actual ventilation network it is often unnecessary to have solutions for all flow parameters in all points of the network. For example, from the point of view of the work safety of miners, a knowledge of the distribution of gas concentrations during the movement of, e.g., fire gases constitutes important information. In this connection we adopt additional assumptions simplifying the equations, thanks to by which means we may speed up and facilitate the reaching of effective solutions.

We continue to analyse the quasi-static model, in which in order to determine the propagation of air in a network of headings it is sufficient to adopt a system of equations for the stationary state, whilst in order to determine the distribution of concentrations of components of a mixture we take into consideration the temporal derivative in the equation of continuity.

Such a model has been adopted in the POZAR programme, which is designed for simulating the propagation of a mixture of air and fire gases in a network of mining headings. In accordance with the assumptions adopted, the equation of state (1) has been retained, while the equations of continuity, motion and energy have taken the following forms (Dziurzyński 1985, 1998a):

equation of motion for the steady state:

$$v\frac{\partial(v\rho)}{\partial s}+\frac{\partial p}{\partial s}+g\rho\frac{dz}{ds}+w+j_{rt}\delta(s-s_{rt})=h_w\delta(s-s_w) \tag{20}$$

equation of continuity:

$$\frac{\partial(v\rho)}{\partial s}=0 \tag{21}$$

the equation of energy:

$$c_p\left(\frac{\partial T}{\partial t}+v\frac{\partial(T)}{\partial s}\right)=q_{sk} \tag{22}$$

where:

j_{rt} — pressure losses caused by local resistance (stopping) [Pa],

s_{rt} — co-ordinate of the point of occurrence of local losses,

$\delta(s-s_{rt})$ — Dirac delta function [1/m],

h_w — fan static pressure [Pa],

s_w — fan location co-ordinate,

Placing (5) in (20), taking into consideration (21) and integrating along the length of branch L_i, then following additional transformations, we arrive at:

$$(p_{1i}-p_{2i})+g\rho_{sr_i}(z_{1i}-z_{2i})+\frac{R_i}{\rho^2_{sr_i}}G_i|G_i|+w'_{Ti}=h_{Wi} \tag{23}$$

where:

$G_i=\rho_i v_i A_i$ — mass flow quantity [kg/s],

$\rho_{sr_i}=\frac{1}{L_i}\int_0^{L_i}\rho_i ds$ — average density in heading number i [kg/m^3],

$R_i=\lambda\frac{\rho_{sr}L_iF_i}{A_i^3}$ — aerodynamic resistance in heading number i [kg/m^7],

w'_{Ti} — pressure loss caused by local resistance (stopping) in heading number i [Pa],

L_i — length of heading number i [m], with indices 1 and 2 denoting the inlet and outlet of the branch, respectively.

Following integration along the length of the heading and the application of nodal and mesh equations for the network, equations (23) constitute a mathematical model of the flow of air and fire gases in the mining heading. In order to solve this system we use the Cross method (Hinsley, Scott 1951), which makes it possible to determine the distribution of mass flows of air and fire gases. The developing fire, located in one heading, generates heat that is transported along headings and changes the initial distribution of densities of the air and fire gases.

For both descriptions (presented under 2.1 and 2.2) the authors have adopted the same concentration transport, heat exchange with the rock mass, rock heating and fire focus models.

3. Examples

Computer programmes have been elaborated for both methods described (2.1 and 2.2). It should, however, be added that while the quasi-static model has been applied in the POŻAR programme of the Ventgraph system, the second programme, utilising the compressible fluid flow model is currently being tested (the first results, obtained for a single-mesh network, are given in this article).

3.1. Fire in an upward current in a single mesh network

The network in question is represented in Fig. 1. It comprises a downcast shaft, a system of horizontal and inclined headings connected in series, and an upcast shaft. In a single mesh network we may define the co-ordinate s which denotes the distance from the inlet node. For example, downcast shaft 1–2 has a length of 200 [m], and thus node 2 corresponds to $s = 200$; a description of the geometrical parameters of the network is presented in Table 1. Cross-sections in branches and the average densities, static pressures, temperatures and velocities corresponding thereto may be assigned directly to co-ordinate s.

Additional assumptions have been adopted in order to eliminate the influence of changes at the operating point of the fan and the natural ventilation pressure on results obtained. For these reasons it was assumed that the fan has a flat pressure-flow characteristic $H = 350$ [Pa], that the density of air in all headings is identical in the quasi-static model, and that for the compressible fluid flow model, the initial distribution of wall temperatures in headings is so similar to the distribution of temperatures of through-flowing air, that at the initial instant the natural ventilation exerts a negligible influence on flow. Under such conditions, the natural ventilation pressure h_N (24) is close to zero.

$$h_N = -g\int \rho dz \tag{24}$$

Calculations were started at the stationary state. Then

$$G = \rho Q = \text{const.} \tag{25}$$

TABLE 1

Structure and selected geometric parameters of the network presented in Fig. 1

TABLICA 1

Struktura i wybrane prarametry geometryczne sieci przedstawionej na rysunku 1

Branch no.	Nodes		Length [m]	Range of s [m]	$z_2 - z_1$ [m]
	inlet	outlet			
1	1	2	400	0—400	–400
2	2	3	200	400—600	0
3	3	4 (fire)	200	600—800	100
4	4 (fire)	5	200	800—1,000	100
5	5	6	200	1,000—1,200	0
6	6	7	200	1,200—1,400	200

In the compressible fluid flow model the term $\rho g = \frac{dz}{ds}$ causes density to increase along with depth z, and in the light of (25) this indicates a decrease in the value of volumetric flow rate. In consequence, the value of volumetric flow in individual branches of the network is diversified. The distribution of flows in the mesh is presented in Fig. 3. According to the quasi-static model, flow from the downcast shaft to the fire was stable, while for the second description method it slightly decreased in the downcast shaft as a result of the increase in density along with depth, and subsequently remained stable in the horizontal branch 2–3, increasing slightly in the upwardly inclined branch 3–5 and upcast shaft 6–7.

It was assumed that the source of fire gases was located mid-length through branch 3–5 (s = 600 [m]), which is ventilated by an upward current. This point has been designated as node no. 4. A time constant 300 [s] was adopted for the escalation of the fire. As the fire developed, heat transferred to the flowing air caused a decrease in density in branches 4–5, 5–6 and 6–7. The right side of expression (24), now called the *fire depression*, increased accordingly. Additional draught was generated by the fire gases in branches 4–5 and 6–7, which were ventilated by an upward current. This brought about an increase in flow, which lasted until the settlement of conditions in the fire focus and the stabilisation of wall temperatures in headings heated by the through-flowing air. The courses of changes in the volumetric flow rate in selected network branches are represented in Fig. 2. Fig. 3 shows the distribution of flows 10 hours after calculations started. In the first two examples changes in flow conditions progressed at such a slow rate that for a given moment in time, dependence (25) is satisfied fairly accurately and may be used in order to interpret the distributions of volumetric flows presented in Figs. 3 and 6. In the fire focus (s = 800 or 600 [m]) there occurred a step increase in flow, mainly as a result of the heating of gases, but also due to

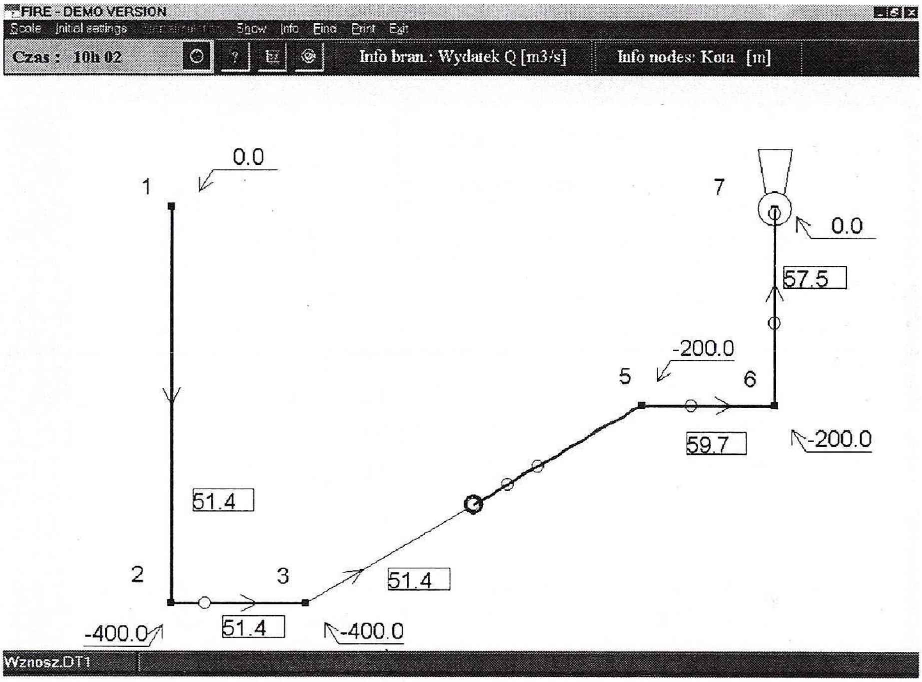

Fig. 1. Fire in an upward current — diagram of the analysed network

Rys. 1. Pożar w prądzie wznoszącym — schemat rozpatrywanej sieci

the inflow of products of coal combustion. On the way towards node 7 the density was rising and volumetric flow rate was falling. Fire gases were cooled by the walls of headings. The effect of cooling had a much greater effect on changes of density and volumetric flow than the decreasing depth in branch 4–5 and the upcast shaft.

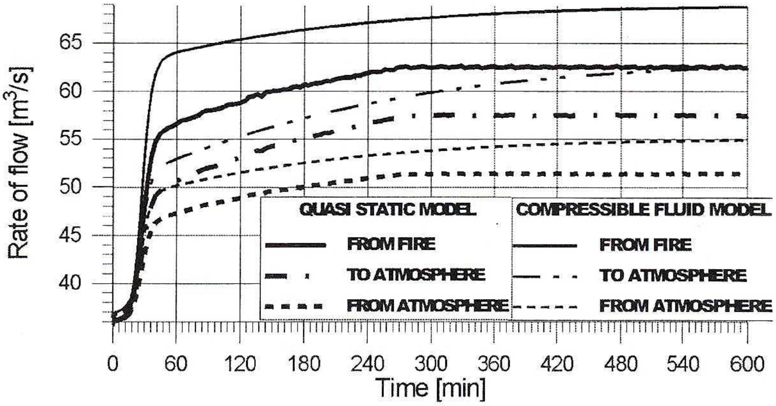

Fig. 2. Fire in an upward current — courses of changes in volumetric flows over time

Rys. 2. Pożar w prądzie wznoszącym — przebiegi zmian wydatków objętościowych w czasie

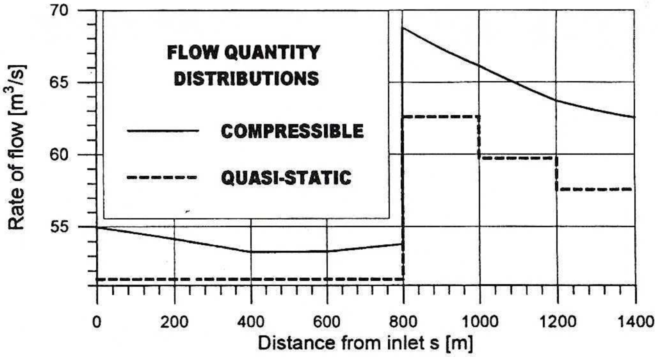

Fig. 3. Fire in an upward current — distribution of volumetric flows in network branches, at a moment $t = 10$ hours

Rys. 3. Pożar w prądzie wznoszącym — rozkład wydatków objętościowych w bocznicach sieci, w chwili $t = 10$ godzin

In Figs. 2 and 3 the differences between results obtained for the methods of description may be compared. These result from simplifications in the incompressible fluid flow model, which lead to a constant density value in individual branches and a correspondingly constant volumetric flow. The more detailed description allows for changes along the axis of the branch in quantities such as the coefficient of heat transfer k and density, which exerts an influence on volumetric flow and unitary resistance. Table 2 presents a comparison of selected quantities calculated using the quasi-static and compressible fluid flow models. In the case of compressible fluid flow, the walls of headings were subject to heating for a considerable period of time, and as a result the process of settlement of the temperature of through-flowing fire gases — and thus the

TABLE 2

A comparison of calculation results for both quasi-static and compressible fluid flow models

TABLICA 2

Porównanie wyników obliczeń dla modelu quasi-statycznego i płynu ściśliwego

	Fire in an upward current		Fire in a downward current	
	quasi-static	compressible	quasi-static	compressible
Fuel temp. [deg C]	1207.67	1218.1	1217.2	1227.54
Gases temp. [deg C]	79.9	98.6	88.6	112.76
Heat prod. [MW]	8.05	8.01	8.0	7.9
Oxygen conc. [%]	19.7	19.6	19.5	19.3
Gases temp. in node 6 [deg C]	46.5	53.3	46.8	43.8

density of the air — was correspondingly longer-lasting and took place at a higher temperature and lower densities. This led to more intensive flow than that calculated applying the quasi-static model. The course of changes in heat production by the fire were nearly identical.

3.2. Fire in a downward current

The second calculation example concerned a fire in a branch ventilated by a downward current (3–5 on Fig. 4, $s = 600$ [m]). Selected network data has been presented in Table 3, a comparison of results in Table 2, while the corresponding courses and distributions of flows — in Figs. 5 and 6. The state of flow for the quasi-static model stabilised after approximately five hours. According to the second model, it took twice as long to reach the steady state. The temperature of gases flowing out of the fire was lower for the quasi-static model, but at the outlet this relation changed, which fact indicates that cooling was more effective under the second method. Lower flows obtained for the quasi-static model are connected with greater densities, and thus with a lower fire depression.

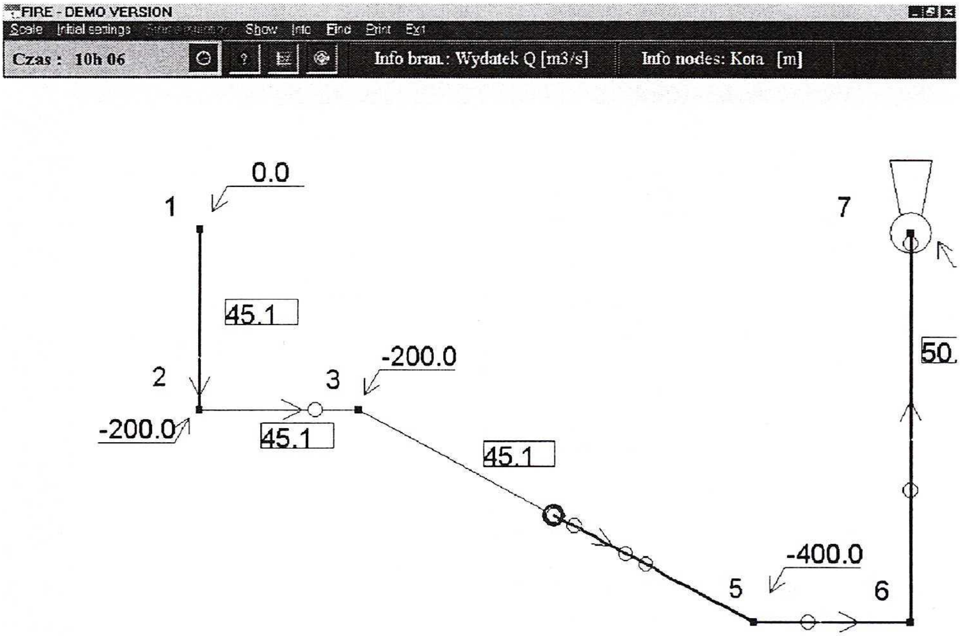

Fig. 4. Diagram of the analysed network

Rys. 4. Pożar w prądzie schodzącym — schemat rozpatrywanej sieci

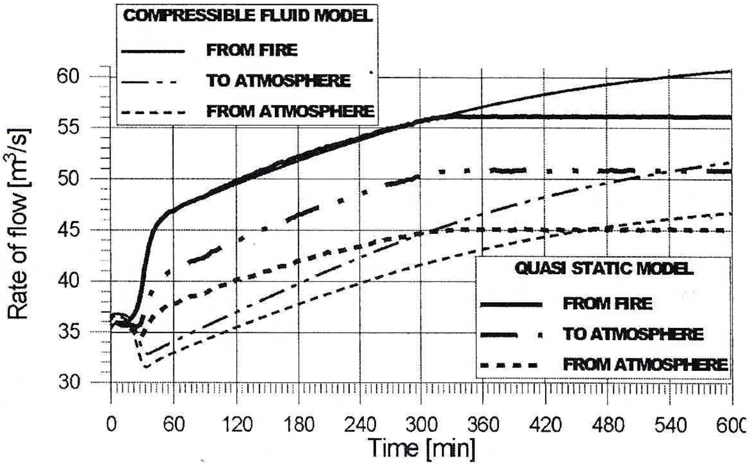

Fig. 5. Fire in a downward current — courses of changes in volumetric flows over time

Rys. 5. Pożar w prądzie schodzącym — przebiegi zmian wydatków objętościowych w czasie

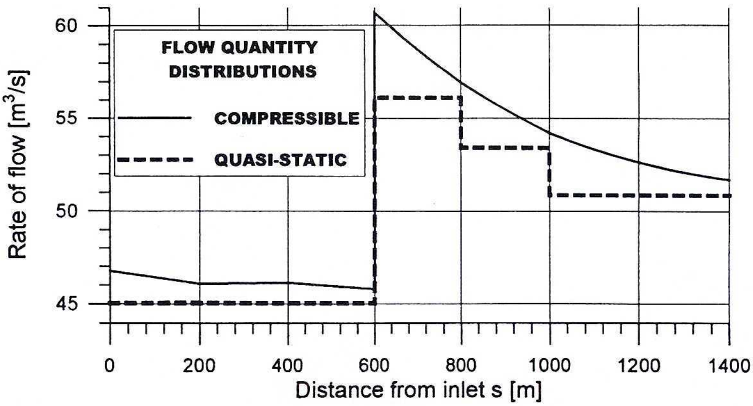

Fig. 6. Fire in a downward current — distribution of volumetric flow rates in network branches, at a moment $t = 10$ hours

Rys. 6. Pożar w prądzie schodzącym — rozkład wydatków objętościowych w bocznicach sieci, w chwili $t = 10$ godzin

In the first two examples, transient processes take place at such a slow rate that when interpreting results we may analyse the steady state equation (23), written down for mesh 1–2–3–4–5–6. Pressures in nodes 1 and 6 are identical, while the term connected with changes in kinetic energy adopts considerably lower values than the static fan head, frictional pressure loss or fire depression.

It may be assumed fairly precisely that the sum of friction pressure losses and fire depression is equal to the fan head. We assumed that the head had a constant value, regardless the quantity of air flowing through the fan. Here, the natural draught

TABLE 3

Structure and selected geometric parameters of the network presented in Fig. 4

TABLICA 3

Struktura i wybrane prarametry geometryczne sieci przedstawionej na rysunku 4

Branch no.	Nodes		Length [m]	Range of s [m]	$z_2 - z_1$ [m]
	inlet	outlet			
1	1	2	200	0—200	-200
2	2	3	200	200—400	0
3	3	4 (fire)	200	400—600	−100
4	4 (fire)	5	200	600—800	−100
5	5	6	200	800—1,000	0
6	6	7	400	1,000—1,400	400

generated in branch 4–5 acted in the opposite direction to that of flow, whereas the draught in upcast shaft 6–7 was augmented by the action of the fan. Initially, the restraining influence of the draught in the branch adjacent to the fire increased more rapidly than the draught in the downcast shaft, which resulted in the positive value of expression (24) and thereby in a decrease in friction pressure loss and — in consequence — flow rate. Subsequently, the dominant influence was exerted by the draught in the shaft, leading to a considerable increase in flow rate, however to values smaller than in the case of a fire in the upward current. According to the quasi-static model, the process of flow constriction was less visible and of shorter duration.

In the third of our examples there appeared significant differences in simulation results. Under the compressible fluid flow model, if the fan head in network ventilated by a downward current is equal to 160 [Pa], flow will be reversed, while in the simpler model the initial direction of flow was maintained. Along the path from the fire to the upcast shaft, air is cooled by the walls of headings, which leads to an increase in its density and thus reduces the influence of the natural draught in the upcast shaft. On the other hand, the difference in depth between the inlet and outlet of a shaft is four times greater than in branch 4–5, and thus the natural draught in the shaft is more susceptible to changes in density. During the reversal of the direction of flow as flow velocity fell, the concentration of air in fire gases decreased and the production of heat in the fire focus fell, while the temperature of the fire gases increased. For a moment after the change of the velocity sign, an influence was exerted on the fire focus by fire gases returning from branch 4–7. Subsequently, the phenomenon had a course similar to a typical fire in an upward current, however due to the restraining influence of the fan, the flow head was less intensive. Following the change in the direction of flow, most probably as a result of the rapid change in conditions, the occurred damped oscillations, visible in Fig. 7.

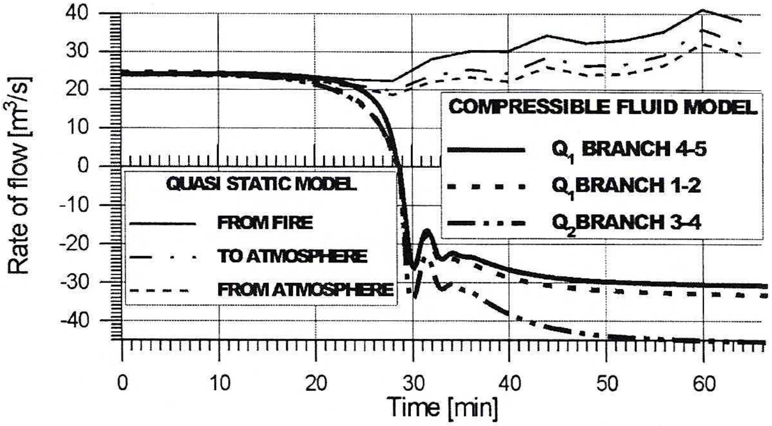

Fig. 7. Change in the direction of flow brought about by a fire in a downward current — courses of changes in volumetric flow rates over time

Rys. 7. Zmiana kierunku przepływu wskutek pożaru w prądzie schodzącym — przebiegi zmian wydatków objętościowych w czasie

The course of the process of flow reversal and interdependences between courses obtained will constitute the subject of further research.

4. Summary

Developments in computer efficiency have made it possible to apply the complete one-dimensional flow model for the analysis of phenomena occurring in mine ventilation networks. A comparison of results of exemplary calculations has been used to check the correctness of the computer programme in which the new model was utilised. The adaptation of models of heat exchange, fire gas transport and the fire focus applied in the quasi-static model has enabled the rapid supplementation of the compressible fluid flow model, so that it may now describe the process of propagation of fire gases in the ventilation network.

The compressible fluid flow model makes it possible to carry out computer simulations with the objective of:

- determining time-variable characteristics of fan stations under conditions of development of an underground fire,
- determining characteristics of the natural ventilation both during an underground fire and under normal operating conditions,
- analysing phenomena occurring during the reversal of flow as a result of the influence of the fire depression in single mesh and multi-mesh networks,
- arriving at solutions displaying features of deterministic chaos.

In further research the authors shall carry out simulations for multi-mesh networks, and also apply models of stoppings and fans with characteristics similar to actual.

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