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SHEARER CONTROL ALGORITHM AND IDENTIFICATION OF CONTROL PARAMETERS

ALGORYTM STEROWANIA KOMBAJNEM ŚCIANOWYM I IDENTYFIKACJA PARAMETRÓW STERUJĄCYCH

This paper describes the concept of controlling the advancement speed of the shearer, the objective of which is to eliminate switching the devices off to the devices in the longwall and in the adjacent galleries. This is connected with the threshold limit value of 2% for the methane concentration in the air stream flowing out from the longwall heading, or 1% methane in the air flowing to the longwall. Equations were formulated which represent the emission of methane from the mined body of coal in the longwall and from the winnings on the conveyors in order to develop the numerical procedures enabling a computer simulation of the mining process with a longwall shearer and haulage of the winnings. The distribution model of air, methane and firedamp, and the model of the goaf and a methanometry method which already exist in the *Ventgraph-Plus* programme, and the model of the methane emission from the mined longwall body of coal, together with the model of the methane emission from the winnings on conveyors and the model of the logic circuit to calculate the required advancement speed of the shearer together all form a set that enables simulations of the control used for a longwall shearer in the mining process. This simulation provides a means for making a comparison of the output of the mining in the case of work using a control system for the speed advancement of the shearer and the mining performance without this circuit in a situation when switching the devices off occurs as a consequence of exceeding the 2% threshold limit value of the methane concentration. The algorithm to control a shearer developed for a computer simulation considers a simpler case, where the logic circuit only employs the methane concentration signal from a methane detector situated in the longwall gallery close to the longwall outlet.

Keywords: mine ventilation, methane hazard, longwall mining, controll of shearer operation, monitoring system

W pracy opisano koncepcję układu sterowania prędkością posuwu kombajnu, którego celem jest eliminacja wyłączeń napięcia zasilania urządzeń w ścianie i chodnikach przyległych związana z przekroczeniem progu 2% stężenia metanu w prądzie powietrza wypływającym z wyrobiska ścianowego lub 1% w powietrzu dopływającym do ściany. Dla opracowania procedur numerycznych umożliwiających

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symulację komputerową procesu urabiania kombajnem ścianowym i odstawy urobku podano związki opisujące emisję metanu z urabianej calizny węglowej ściany i z urobku na przenośnikach. Razem z już istniejącymi w programie *Ventgraph-Plus* modelem rozpływu powietrza, metanu i gazów pożarowych, modelem zrobów i modelem metanometrii, model emisji metanu z urabianej calizny ściany, model emisji metanu z urobku na przenośnikach i model układu kalkulacyjnego obliczającego wymaganą prędkość posuwu kombajnu tworzą zestaw umożliwiający wykonanie symulacji sterowania kombajnem ścianowym w procesie urabiania. Symulacja ta pozwala na porównanie wydajności urabiania przy pracy z układem sterowania prędkością posuwu kombajnu i wydajności urabiania bez tego układu, gdy występują wyłączenia napięcia zasilania z powodu przekraczania progu 2 % stężenia metanu. Algorytm sterowania kombajnem utworzony dla symulacji komputerowej obejmuje prostszy przypadek, gdy układ kalkulacyjny wykorzystuje sygnał stężenia metanu tylko z metanomierza w chodniku nadścianowym w pobliżu wylotu ściany.

Słowa kluczowe: wentylacja kopalń, zagrożenie metanowe, ściana wydobywcza sterowanie pracą kombajnu, system monitoringu

1. Introduction

The longwall system is currently the basic system used for mining coal beds in Polish mines. In coal mines facing the hazard of methane explosions application of the monitoring system is compulsory. In case of exceeding the limit values of methane concentrations, namely the 2% threshold limit value of methane concentration in the air stream flowing out from the longwall, or 1% in the air stream flowing into the longwall such system has to initiate an emergency shutdown of all local electrically powered devices. Restarting those devices is preceded with a long and complicated procedure proving that the safe conditions have been restored. The soureces of this hazard are mainly the methane released from the longwall coal face, the crushed coal and from the adjacent goaf. We know how the methane concentration in the air stream flowing out from the longwall depends on the intensity of mining, i.e. the mass rate at which the coal is mined, and this in turn depends on the advancement speed and the shearer web and height of mining (Krause, 2009). It may be assumed that the methane concentration in this air stream increases as the mining progresses, apart from fluctuations in the methane concentration caused by lack of uniformity in the methane bearing capacity of the mined bed, or variations in the volumetric air flow through the longwall heading and other accidental factors. If we react to an increase in methane concentration recorded by the methanometer in the stream of air flowing through the longwall and reduce the speed of coal mining, it is possible to avoid exceeding the two-percent threshold value during switching the devices off and maintain continuity of the mining operations. This method is implemented by making continuous measurements of the methane concentration and checking the changes in the values. This is carried out by a person with a portable methanometer who walks at a distance of several metres from the shearer. When the shearer moves towards the air stream in the longwall, the person executing the measurement of methane concentration walks in front of the shearer, while for movement of the shearer in the direction opposite to the air stream, the person measuring the methane concentration walks behind the shearer. In such a case the methane concentration measured by a methanometer includes methane which is released from the freshly uncovered coal body and also from the winnings being hauled. If the measured methane concentration increases and there is a risk that the 2% limit could be reached, the person carrying out the measurements informs the shearer operator of the necessity of reducing the mining speed. If the measured methane concentration has a decreasing tendency, the person performing the measurement informs the shearer operator that the mining speed may be increased. The hazard of switching the devices off resulting from the automatic methanometry, which measures the methane concentration in the air stream that flows from the longwall, is considerably reduced in this way.

Another way of reducing the risk of switching the devices off in cases when the admissible methane concentration level is exceeded is by recording the parameters of the mining cycle (methane concentration, mining speed, switching off power) and by using that information to program the advancement speed of the shearer in the subsequent mining cycles.

2. Control of the longwall shearer

This paper describes the concept of a shearer control system (Fig. 1), where the person executing the methane concentration measurements in the vicinity of the shearer is replaced by an automatic system, which comprises: stationary methanometers (6) installed along the longwall, which together with methanometers in the air stream flowing in (8) and flowing out (7) from the longwall provide the information on methane concentration to the logic circuit (5). This data is entered as input data to the programme that implements an algorithm calculating the desired advancement speed of the shearer, and reducing this speed when an increase in methane concentration is ascertained, as measured by any of the methanometers (in the air stream, flowing out of the longwall or in the air that flows in towards the longwall, or flowing out from the

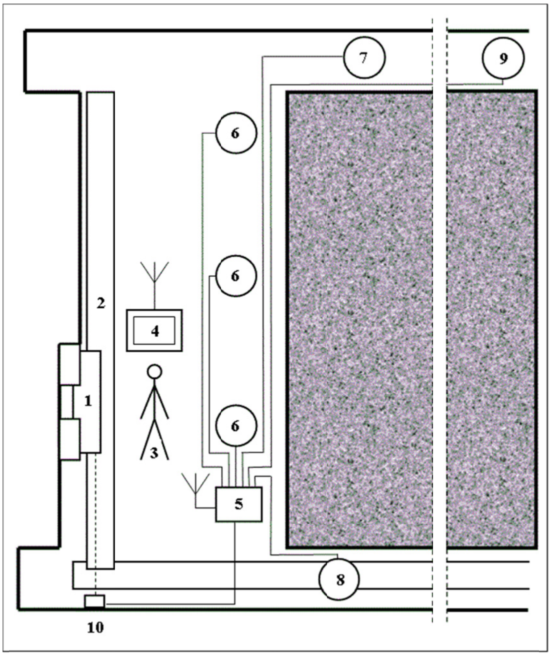

Fig. 1. Control system of longwall shearer
1 – a shearer, 2 – armored face conveyor, 3 – shearer operator, 4 – readout panel, 5 – logic calculation system, 6 – methane detectors in the longwall, 7 – methane detector in gallery at outlet from longwall, 8 – methanometer in gallery at longwall inlet, 9 – methane detector at the end of the ventilation gallery, 10 – position meter of the shearer in the longwall

longwall or from the air stream flowing towards the longwall, or measured by even one of the methanometers distributed along the longwall) and increasing the mining speed, when all methanometers indicate (concurrently) that the measured concentration values are being decreased. The value of the calculated speed is transmitted via a wireless system to the readout panel (4) of the shearer operator (3). The operator sets up the advancement speed shown on the panel screen of the shearer using control elements on the apparatus box of the shearer or on the remote control of the shearer. Verification of the concept presented by executing numerical simulations allows an assessment of its properties. The computer simulation of the longwall with an operator using the shearer requires formulating a few mathematical models:

- model of methane emission from mined coal face,
- model of methane emission from crushed coal on the AFC and the belt conveyor,
- model of the goaf adjacent to the longwall heading,
- model of methane distribution in the mine ventilation system,
- model of methanometry,
- model of calculation system.

The Mine Ventilation Laboratory of the Strata Mechanics Research Institute of the Polish Academy of Sciences has been studying issues of computer simulation for the ventilation system of a mine for many years. The *Ventgraph-Plus* programme which was developed there enabled the distribution of air, methane and firedamp in the network of the underground galleries to be calculated. In the following years the programme was supplemented by an air flow model in the goaf and the possibility of installing virtual sensors of the air flow, barometric pressure, methane concentration and concentration of components of fire gases (Dziurzyński, 1999), and in 2001 work was started on the numerical modelling of a longwall with an operating shearer (Dziurzyński et al., 2001). The longwall model developed at that time assumed that a shearer was mining at a constant speed and in a single direction. In the following years the model was developed further to include the operation of the shearer according to the specified schedule, with mining taking place in both directions and with standstills of the shearer and of the conveyors (Blecharz et al., 2003). At present the developed longwall model and control algorithm of a longwall shearer applies to the case when the speed of the mining advancement of the shearer depends on the methane concentration measured by a methanometer in the longwall gallery close to the longwall outlet.

3. Model of methane emission from the wall with an operating shearer

The process of mining the body of coal with the use of a longwall shearer is accompanied by the distribution of methane emissions from the mined body of coal and from the hauled coal which may vary over time. In the paper (Dziurzyński et al., 2001) a mathematical model was presented of methane emission from the mined coal face specified by Tarasow and Kołmakow (1978) and the mathematical model of methane emission from the crushed coal on the conveyor belt, based on the results of the work of Drzęźla and Badura (1980).

Tarasow and Kołmakow assumed that a shearer mining the longwall generates a cracking zone with a length of 10 to 20 m in front of it, resulting in an increased methane outflow directly in front of the shearer. This outflow increases as the shearer approaches a given point, and then decreases once such a point is passed. Such a theoretically derived course of the methane emission rate (density of volume stream) has been confirmed by the results of measurements (Fig. 2) published by Tarasow and Kołmakow (1978).

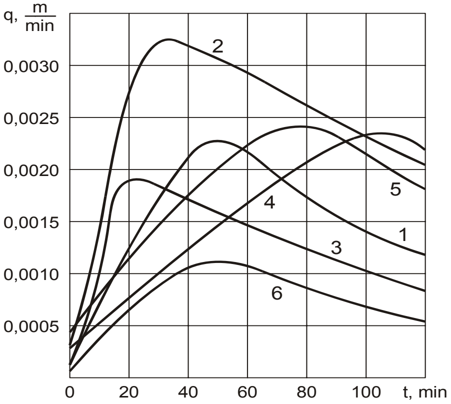

Fig. 2. Speed profiles of methane emission rate in the impact zone of the shearer measured for different coal beds (according to Tarasow and Kołmakow, 1978)

It may be noticed that the actual profiles of the speed at which methane is released are similar to the triangular profile. Hence the triangular profile was assumed for the requirements of numerical modelling, as shown in Fig. 3. This profile is characterised by a small number of parameters. They include: the initial q_p and the maximum $q_{\max}$ methane volume flow from a surface unit of longwall body of coal, the mining time of the cracking zone T_k and the stabilisation time of methane emission after uncovering a new body of coal surface T_{ust}.

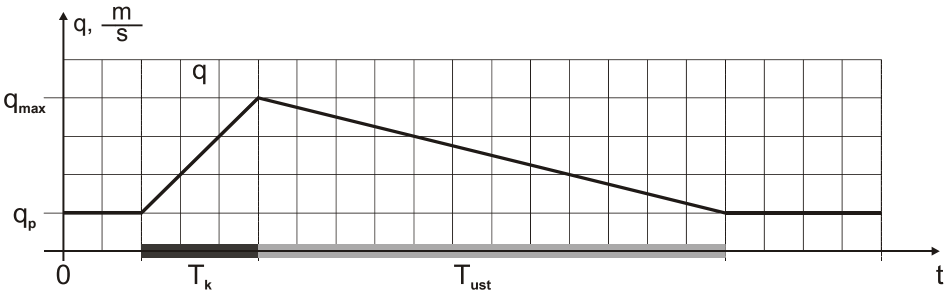

Fig. 3. Depiction of the actual profile of the speed of methane emission in the impact zone of the shearer with a triangular course

This form of profile has been adopted in the numerical model which illustrates the methane emission from a longwall mined with the use of a shearer operating at a constant advance speed and in one direction (Blecharz et al., 2003).

In practice the shearer moves at a variable speed, depending on current conditions, or may have stoppages mine in either direction along the longwall. The conveyors can also stop when the shearer is stationary. This gave rise to the necessity of developing a new model, which would allow for such movement of the shearer and of the conveyors. The model of methane emission presented in Fig. 4 was adopted for the coal face of a longwall mined with the use of a shearer:

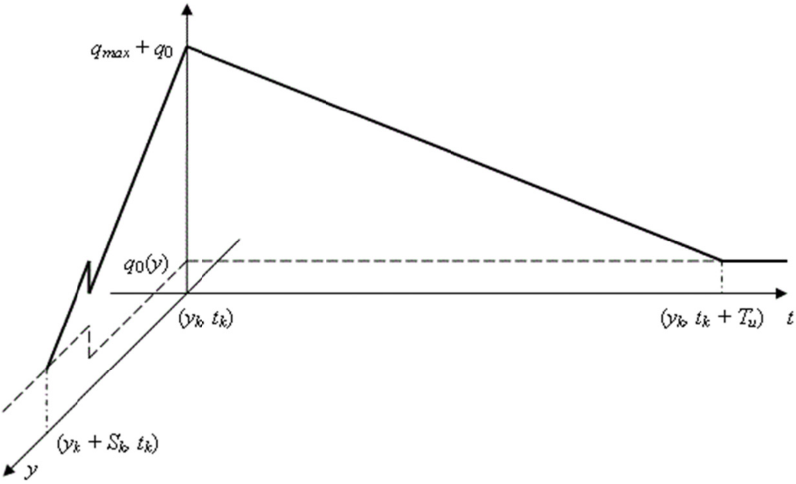

Fig. 4. Change in density of a methane stream from the longwall coal face in front of a shearer (y axis) and from the uncovered surface of the body of coal behind the shearer (t axis)

Denotations (Fig. 4):

y_k — position of the shearer in the longwall at time t_k,
S_k — length of the cracking zone in front of the shearer,
T_u — stabilisation time of methane emission after uncovering a new surface of the longwall body of coal,
$q_{\max}$ — the highest value of density of methane stream during mining,
$q_0(y)$ — initial value of density of methane stream.

The adoption of the initial value of the methane stream density $q_0(y)$ as a function of the location of y in the longwall enables modelling the variable gas bearing capacity along the longwall.

The distribution and profile of the speed of methane emission, as shown in Fig. 4, are described by the following relations:

$$(t = t_k) \wedge (y > y_k + S_k) \Rightarrow q_{\mathrm{CH}_4} = q_0(y) \tag{1}$$

$$(t = t_k) \wedge (y_k \le y \le y_k + S_k) \Rightarrow q_{\mathrm{CH}_4} = \frac{q_{\max}}{S_k}(S_k + y_k - y) + q_0(y) \tag{2}$$

$$(y = y_k) \wedge (t > t_k + T_u) \Rightarrow q_{\mathrm{CH}_4} = q_0(y) \tag{3}$$

$$(y = y_k) \wedge (t_k \le t \le t_k + T_u) \Rightarrow q_{\mathrm{CH}_4} = \frac{q_{\max}}{T_u}(T_u + t_k - t) + q_0(y_k) \tag{4}$$

The adopted description of the methane emission from the body of coal in the longwall indicates the spatial and time dependencies of methane emission during mining, as shown in Fig. 5.

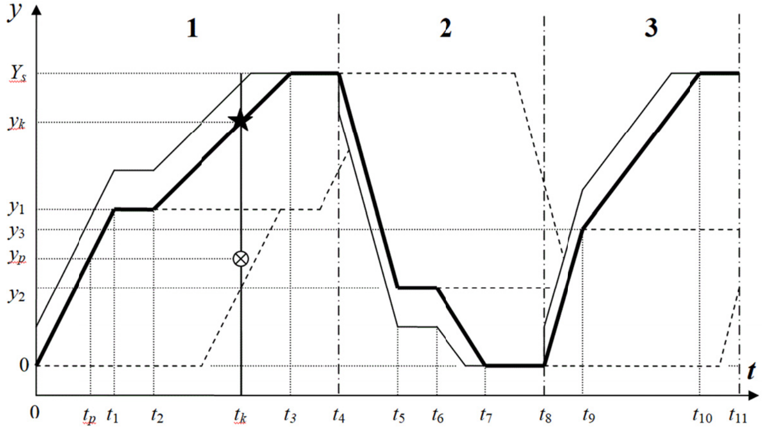

Fig. 5. Zones of different density of the methane stream from the body of coal at the longwall mined with the use of the shearer at variable speeds of shearer and periods of standstill.
Bold line – route of the shearer; Continuous thin line – cracking zone in front of the shearer; Thin dashed line – stabilisation time of methane emission after uncovering of a new surface of longwall body of coal

Denotations (Fig. 5):

Y_s — longwall length,
y_k — location of shearer at time t_k,
y_p — location of a point at the longwall for which a calculation is made of the density of methane volume stream
$y_{0,1,2,3}$ — location of the shearer at time $t_{0...11}$ of speed change of the shearer,
t_3, t_{10} — stationary time of the shearer at the end of the longwall and standstill until time t_4, t_{11},
t_7 — time of the shearer stoppage and the beginning of the longwall and standstill until time t_8,
t_4, t_8, t_{11} — time of completion of the subsequent mining cycle and commencement of the subsequent one.

Figures 4 and 5 give rise to the relations specified below for the methane volume flow from a unit surface (outflow speed) $q_{CH_4\,ks}$ from the mined longwall with the use of a shearer:

Denotations:

t_p — time when the shearer was in position y_p in the current mining cycle,
t_{pp} — time when the shearer was in position y_p in the preceding mining cycle,
v_k — speed of the shearer advance,
v_{kp} — initial speed of advancement of the shearer,
v_{ko} — speed of advancement of the shearer calculated by the logic circuit,
v_{ps} — current speed of the armoured face conveyor,
v_{psp} — speed of the armoured face conveyor,

v_{pt} — current speed of the belt conveyor,
v_{ptp} — speed of the belt conveyor,
t_{pk1}, t_{pk3} — standstill time of the shearer after reaching the end of the longwall when mining upwards along the longwall,
t_{pk2} — standstill time of the shearer after reaching the beginning of the longwall when mining downwards along the longwall,
w — movement direction of the shearer: $w = 1$ – movement up (towards the end of) the longwall, $w = -1$ – movements down (towards the beginning of) the longwall,
sm — power off binary signal from the methanometer, $sm = 1$ – power off.

From Fig. 5 the standstill time of the shearer $t_{pk1} = t_4 - t_3$, $t_{pk2} = t_8 - t_7$, $t_{pk3} = t_{11} - t_{10}$.

Mining with movement of the shearer up the longwall ($w = 1$):

$$sm = 0 \Rightarrow v_k = w \cdot v_{ko}, \quad v_{ps} = v_{psp}, \quad v_{pt} = v_{ptp} \tag{5}$$

$$y_p < y_k \quad \wedge \quad t_k - t_p > T_u \Rightarrow q_{\mathrm{CH}_4\,ks}\left(y_p\right) = q_0\left(y_p\right) \tag{6}$$

$$y_p < y_k \quad \wedge \quad t_k - t_p \le T_u \Rightarrow q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \frac{q_{\max}}{T_u}\left(T_u + t_p - t_k\right) + q_0\left(y_p\right) \tag{7}$$

$$y_k \le y_p \le y_k + S_k \quad \wedge \quad t_k - t_{pp} \ge T_u \Rightarrow$$
$$q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \frac{q_{\max}}{S_k}\left(S_k + y_k - y_p\right) + q_0\left(y_p\right) \tag{8}$$

$$y_k \le y_p \le y_k + S_k \quad \wedge \quad t_k - t_{pp} < T_u \Rightarrow$$
$$q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \max\left[\frac{q_{\max}}{S_k}\left(S_k + y_k - y_p\right), \frac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right)\right] + q_0\left(y_p\right) \tag{9}$$

$$y_p > y_k + S_k \quad \wedge \quad t_k - t_{pp} \le T_u \Rightarrow q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \frac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right) + q_0\left(y_p\right) \tag{10}$$

$$y_p > y_k + S_k \quad \wedge \quad t_k - t_{pp} > T_u \Rightarrow q_{\mathrm{CH}_4\,ks}\left(y_p\right) = q_0\left(y_p\right) \tag{11}$$

Standstill of the shearer and conveyors due to switching off the power during mining up the longwall:

$$sm = 1 \Rightarrow v_k = 0, \quad v_{ps} = 0, \quad v_{pt} = 0, \quad t_i = t_k \tag{12}$$

t_i — time of stopping of the shearer, on Fig. 5: $i = 1$.

$$y_k \le y_p \le y_k + S_k \quad \wedge \quad t_k - t_{pp} \ge T_u \Rightarrow$$
$$q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \frac{q_{\max}}{T_u S_k}\left(T_u + t_i - t_k\right)\left(S_k + y_k - y_p\right) + q_0\left(y_p\right) \tag{13}$$

$$y_k \le y_p \le y_k + S_k \quad \wedge \quad t_k - t_{pp} < T_u \Rightarrow$$

$$q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \max\begin{bmatrix} \dfrac{q_{\max}}{T_u S_k}\left(T_u + t_i - t_k\right)\left(S_k + y_k - y_p\right), \\ \dfrac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right) \end{bmatrix} + q_0\left(y_p\right) \tag{14}$$

$$sm = 0 \Rightarrow v_k = w \cdot v_{ko}, \quad v_{ps} = v_{psp}, \quad v_{pt} = v_{ptp}, \quad t_i = t_k \tag{15}$$

t_i — start time of the shearer, on Fig. 5: $i = 2$.

Standstill of the shearer after reaching the end of the longwall:

$$y_k = Y_s \Rightarrow v_k = 0, \quad t_i = t_k, \quad w = -1 \tag{16}$$

t_i — stopping time of the shearer, on Fig. 5: $i = 3, 10$,

$$t_k = t_i + t_{pk} \Rightarrow v_k = w \cdot v_{ko}, \quad t_i = t_k \tag{17}$$

t_{pk} — standstill time of the shearer, $t_{pk} = t_{pk1}, t_{pk3}$,
t_i — start time of the shearer, on Fig. 5: $i = 4, 11$.

Mining during movement of the shearer down the longwall ($w = -1$):

$$sm = 0 \Rightarrow v_k = w \cdot v_{ko}, \quad v_{ps} = v_{psp}, \quad v_{pt} = v_{ptp} \tag{18}$$

$$y_p > y_k \Rightarrow q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \frac{q_{\max}}{T_u}\left(T_u + t_p - t_k\right) + q_0\left(y_p\right) \tag{19}$$

$$y_k \ge y_p \ge y_k - S_k \quad \wedge \quad t_k - t_{pp} \ge T_u \Rightarrow$$

$$q_{\mathrm{CH}_4}\left(y_p\right) = \frac{q_{\max}}{S_k}\left(S_k + y_p - y_k\right) + q_0\left(y_p\right) \tag{20}$$

$$y_k \le y_p \le y_k - S_k \quad \wedge \quad t_k - t_{pp} < T_u \Rightarrow$$

$$q_{\mathrm{CH}_4\,ks}\left(y_p\right) = \max\left[\frac{q_{\max}}{S_k}\left(S_k + y_p - y_k\right), \frac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right)\right] + q_0\left(y_p\right) \tag{21}$$

$$y_p < y_k - S_k \quad \wedge \quad t_k - t_{pp} < T_u \Rightarrow q_{\mathrm{CH}_4}\left(y_p\right) = \frac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right) + q_0\left(y_p\right) \tag{22}$$

$$y_p < y_k - S_k \quad \wedge \quad t_k - t_{pp} \ge T_u \Rightarrow q_{\mathrm{CH}_4}\left(y_p\right) = q_0\left(y_p\right) \tag{23}$$

Standstill of the shearer and of the conveyors due to switching off the power during mining down the longwall:

$$sm = 1 \Rightarrow v_k = 0, \quad v_{ps} = 0, \quad v_{pt} = 0, \quad t_i = t_k \tag{24}$$

t_i — stopping time of the shearer, in Fig. 5: $i = 5$.

$$y_k \geq y_p \geq y_k - S_k \quad \wedge \quad t_k - t_{pp} \geq T_u \Rightarrow$$

$$q_{\mathrm{CH}_4\, ks}\left(y_p\right) = \frac{q_{\max}}{T_u S_k}\left(T_u + t_{kp} - t_k\right)\left(S_k + y_p - y_k\right) + q_0\left(y_p\right) \tag{25a}$$

$$y_k \leq y_p \leq y_k - S_k \quad \wedge \quad t_p - t_{pp} < T_u \Rightarrow$$

$$q_{\mathrm{CH}_4\, ks}\left(y_p\right) = \max\begin{bmatrix} \dfrac{q_{\max}}{T_u S_k}\left(T_u + t_{kp} - t_k\right)\left(S_k + y_p - y_k\right), \\ \dfrac{q_{\max}}{T_u}\left(T_u + t_{pp} - t_k\right) \end{bmatrix} + q_0\left(y_p\right) \tag{25b}$$

$$sm = 0 \Rightarrow v_k = w \cdot v_{ko}, \quad v_{ps} = v_{psp}, \quad v_{pt} = v_{ptp}, \quad t_i = t_k \tag{26}$$

t_i — start time of the shearer, in Fig. 5: $i = 6$.

Standstill of the shearer once the start of the longwall is reached

$$y_k = 0 \Rightarrow v_k = 0, \quad t_i = t_k \tag{27}$$

t_i — stopping time of the shearer, in Fig. 5: $i = 7$,

$$t_k = t_i + t_{pk} \Rightarrow v_k = w \cdot v_{ko}, \quad t_i = t_k \tag{28}$$

t_{pk} — standstill time of the shearer, $t_{pk} = t_{pk2}$,
t_i — start time of the shearer, in Fig. 5: $i = 8$.

4. Model of methane emission from the armoured face and belt conveyors

The methane released from the mined coal hauled by the conveyors mixes with the stream of air in the longwall. The article (Dziurzyński et al., 2001) presented a degassing model of the crushed coal on a conveyor with exponential reduction of the volume flow from unit length of the winning, based on the results of the work of Drzęźla and Badura (1980). A more precise degassing model of crushed coal, based on the work of Airuni (1987) and making use of data provided in the work of Klebanow (1974) and Kozłowski (1972) has been presented in the paper of Dziurzyński and Krach (2001).

Fig. 6 presents the route of the shearer and the route of the crushed coal on the conveyors allowing for stationary periods of the shearer and the conveyors caused by switching off power to devices at the longwall and the longwall galleries as a consequence of exceeding the 2% threshold of methane concentration measured by any methanometer in the longwall or in the gallery at the longwall outlet (tailgate), or as a consequence of exceeding the 1% threshold of methane concentration measured by a methanometer in the longwall maingate.

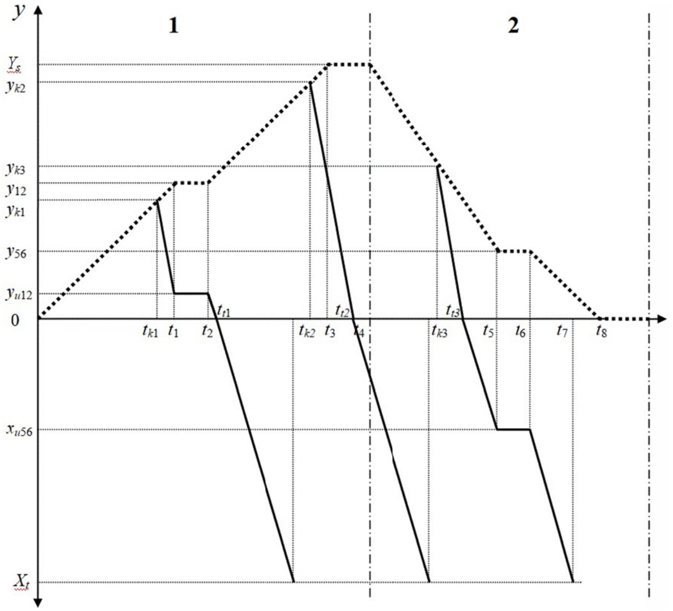

Fig. 6. Movement trajectories of the shearer and winning on the longwall conveyor and on the conveyor in the transport gallery. Bold dotted line – trajectory of the shearer movement; bold continuous line – trajectory of crushed coal on conveyors

Denotations on the figure 6:

X_t — length of haulage gallery,
Y_s — length of longwall,
y_{k1}, y_{k2}, y_{k3} — position of the shearer in longwall in time t_{k1}, t_{k2}, t_{k3},
y_{12} — position of the shearer in longwall during standstill from t_1 to t_2,
y_{u12} — position of the coal mined in time t_{k1} on the AFC conveyor in that time,
y_{56} — position of the shearer in longwall during standstill from t_5 to t_6,
x_{u56} — position of the coal on the belt conveyor in that time, mined at time t_{k3},
$t_1, t_2, t_3, t_4, t_5, t_6$ — times of change of the speed of the shearer,
t_{t1}, t_{t2}, t_{t3} — time after which coal mined in time t_{k1}, t_{k2}, t_{k3} gets to the belt conveyor in the maingate.

The following time dependencies arise from the above figure 6:

Transport time on the AFC conveyor for crushed coal from time of excavation t_s until time t_k, when the crushed coal is at a distance of y_p from the start of the longwall:

$$\tau_s = t_k - t_{ks} \tag{29}$$

where t_{ks} is the time of mining calculated from the equation

$$y_k\left(t_{ks}\right) = y_s\left(t_{ks}\right) \tag{30}$$

where

$y_k(t)$ — movement trajectory of the shearer

$y_s(t)$ — movement trajectory of crushed coal on the longwall conveyor coming from a point with coordinates (t_k, y_p).

Transport time on the belt conveyor in the haulage gallery of the crushed coal element which at time t_k is at a distance of x_t from the longwall:

$$\tau_{t0} = t_k - t_{x0} \tag{31}$$

where t_{x0} is the time in which a coal element is at the start of the conveyor calculated on the basis of the following equation:

$$x_t\left(t_{x0}\right) = 0 \tag{32}$$

where $x_t(t)$ — movement trajectory of an element of crushed coal on the belt conveyor coming from a point with coordinates (t_k, x_t).

Time of transport on the longwall AFC conveyor of an element of coal which at time t_{x0} was situated at the beginning of the longwall:

$$\tau_{s0} = t_{x0} - t_{kt} \tag{33}$$

where t_{kt} is the mining time of the analysed element of the coal calculated from the equation

$$y_k\left(t_{kt}\right) = y_{s0}\left(t_{kt}\right) \tag{34}$$

where $y_{s0}(t)$ — trajectory of the coal on the AFC conveyor coming from a point with coordinates $(t_{s0}, 0)$.

Transport time of the coal element at the AFC and belt conveyors from time of excavation until time t_k, at which the analysed coal element is at a distance of x_t from the beginning of the belt conveyor in the transport gallery:

$$\tau_t = \tau_{t0} + \tau_{s0} \tag{35}$$

The linear density of coal on conveyors may be calculated from the equations given by Drzęźla and Badura (1980):

Linear density of coal on the longwall conveyor equals to:

$$g_s = \rho_w z H \frac{\left|v_k\left(t_s\right)\right|}{v_s + v_k\left(t_s\right)} \tag{36}$$

where

ρ_w — density of mined coal,

z — depth of the shearer cut,

H — height of the shearer cut,

$v_k(t_s)$ — speed of the shearer advance at time t_s,

v_s — speed of the AFC conveyor.

Linear density of coal on the belt conveyor:

$$g_t = g_s \frac{v_s}{v_t} \tag{37}$$

where v_t — speed of the conveyor in the transport gallery.

If the time of transport delays for coal carried on the conveyors is known, based on dependencies provided by Airuni (1987) and used in the works of (Dziurzyński & Krach, 2001) and (Blecharz et al., 2003), it is possible to calculate the volume flow of methane relaeased from the mass unit of coal, and then, once the linear density of the crushed coal is known, from the unit length of the coal on conveyors.

Volume flow of methane released from a unit length of the coal on the AFC conveyor:

$$q_{\mathrm{CH}_4\, ps} = g_s \sum_{i=0}^{3} G_i \exp\left(-\frac{\tau_s}{\tau_i}\right) \tag{38}$$

Volume flow of methane released from a unit length of the coal on the belt conveyor:

$$q_{\mathrm{CH}_4\, pt} = g_t \sum_{i=0}^{3} G_i \exp\left(-\frac{\tau_t}{\tau_i}\right) \tag{39}$$

where: $G_i = \frac{V_i}{\tau_i}$

V_0, τ_0 — volume of desorbed gas and time constant of desorption from the volume of sorption particles
V_1, τ_1 — volume of adsorbed gas and time constant of desorption for gas accumulated at the surface of adsorption particles;
V_2, τ_2 — volume of adsorbed gas and time constant of desorption for super adsorption particles,
V_3, τ_3 — volume of adsorbed gas and time constant of desorption for filtration and adsorption particles,

where: $\tau_0 > \tau_1 > \tau_2 > \tau_3$.

Figures pertaining to the volume V_i and time constants τ_i have been given in the work of Dziurzyński and Krach (2001). The overall stream of methane flowing into the air in the longwall length unit:

$$q_{M\,\mathrm{CH}_4\, s} = \rho_{\mathrm{CH}_4} \left(q_{\mathrm{CH}_4\, ks} + q_{\mathrm{CH}_4\, ps}\right) \tag{40}$$

where

ρ_{CH_4} — methane density,
$q_{\mathrm{CH}_4\, ks}$ — methane stream volume flowing in from the unit length of the mined coal face ,
$q_{\mathrm{CH}_4\, ps}$ — methane stream volume flowing in from the unit length of the coal on the AFC conveyor.

5. Virtual methane detector

Methane that flows in to the air stream from the coal transported on the belt conveyor, methane flowing in from the coal face of the longwall and coal on the AFC conveyor and methane from the goaf form a mixture with the concentration changing over time and the length of the longwall. In this example of the numerical simulation it was assumed that the methane concentration is measured with the use of a single methane detector located in the tailgate an the longwall outlet. This methanometer triggers the emergency power shut-off signal to the devices at the longwall and in the galleries adjacent in the event of exceeding the assumed threshold value for C_w (as a rule 2%) of methane concentration in the stream of air flowing out from the longwall. Switching on the power and re-start of the shearer and of the conveyors occurs following the planned period t_p after the fall of methane concentration below the programmed value of concentration C_z lower than C_w.

$$C_{\mathrm{CH}_4}(t_k) \geq C_w \Rightarrow sm = 1\,, \quad \text{power shut-off,} \tag{41}$$

$$C_{\mathrm{CH}_4}(t_k) \leq C_z \Rightarrow t_{po} = t_k \tag{42}$$

$$t_k = t_p + t_{po} \Rightarrow sm = 0\,, \quad \text{switching on the power by the mine operation manager at the control room} \tag{43}$$

where

$C_{\mathrm{CH}_4}(t_k)$ — measured methane concentration,
C_w — methane concentration threshold at which power is switched off, generally 2%,
C_z — methane concentration, below which power may be switched on,
sm — signal of switching off power from the methanometer,
t_{po} — time delay in switching on the power,
t_k — present time.

6. Model of calculation system

The calculation system computes the advancement speed of the shearer considering the value of the measured methane concentration and the speed of its change. This task is implemented by the proportional–integral–derivative controller (PID) in the logic circuit (Górecki, 1971; Węgrzyn, 1972). The diagram of the control system for the methane concentration at the longwall outlet with the calculating circuit and the control unit is shown in Fig. 7.

The output signal from the regulator is the methane concentration C_{CH_4}, measured at the tailgate at the longwall outlet. This signal is subtracted in the summing up node from the programmed signal, which in this case is the programmed value of the methane concentration $C_{\mathrm{CH}_4 zd}$, the result of which gives the error signal e.

$$e = C_{\mathrm{CH}_4\,zd} - C_{\mathrm{CH}_4} \tag{44}$$

The error signal is sent to the controller input of the proportional-integral-derivative controller (PID), implementing the following function:

$$o = wp \cdot e + wi \cdot \sum e \cdot \Delta t + wd \cdot \frac{\Delta e}{\Delta t} \tag{45}$$

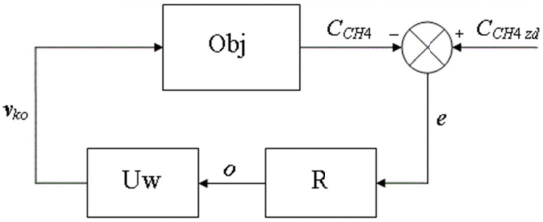

Fig. 7. System controlling the methane concentration at the outfall of the longwall mined with the use of a shearer

Denotations (Fig. 7):

Obj — control object: longwall mined with the use of a shearer with adjacent goaf, with the AFC an the belt conveyor in the haulage gallery and with a methanometer at the longwall outlet,
R — regulator,
Uw — output circuit,
C_{CH_4} — measured methane concentration,
$C_{\mathrm{CH}_4\,zd}$ — planned methane concentration,
e — error signal,
o — output signal of controller,
v_{ko} — calculated advancement speed of the shearer,

Assuming that $C_{\mathrm{CH}_4\,zd}$ = constant, the following is obtained $\frac{\Delta e}{\Delta t} = \frac{\Delta C_{\mathrm{CH}_4}}{\Delta t} = v_{\mathrm{CH}_4}$ and hence

$$o = wp \cdot e + wi \cdot \sum e \cdot \Delta t + wd \cdot v_{\mathrm{CH}_4} \tag{46}$$

where

v_{CH_4} — rate of change of measured methane concentration,
wp — gain of the proportional element,
wi — gain of the integrating element,
wd — gain of the differential element.

The gain of the proportional element is equal to the quotient of the value of the output signal of the element and the input signal of the element. Gain of the integrating element equals the quotient of the rate at which the output signal of the element increases in response to the discrete signal and the value of that signal. Gain of the differential element is a quotient of the value of the output signal of the element and the rate at which the input signal increases linearly.

The rate of change of the measured methane concentration gives the following dependence:

$$v_{\mathrm{CH}_4} = \frac{C_{\mathrm{CH}_4}(t_k) - C_{\mathrm{CH}_4}(t_k - \Delta t)}{\Delta t} \tag{47}$$

where $C_{\mathrm{CH}_4}(t_k)$ — measured methane concentration,

The output signal of the controller is sent to the input of the Uw system, which at a zero input signal of the controller gives the calculated speed of the shearer v_{ko} equal to the initial value of the speed of the shearer v_{kp}, and at a decreasing output signal of the controller, which is a response to the growing measured methane concentration, reduces the speed of the shearer being calculated.

$$v_{ko} = v_{kp}\left(\frac{o}{C_{\mathrm{CH}_4\, zd}} + 1\right) \tag{48}$$

The calculated value of the advancement speed of the shearer is transmitted to the operator's readout panel. The operator sets it up on the shearer or directly to the advancement speed control system of the shearer.

7. Summary

The above specified relations for models of a longwall mined with the use of a shearer, coal on conveyors, virtual methanometer, and the calculation circuit provided a basis for the development of numerical procedures extending the *Ventgraph-Plus* programme by the option of simulating the system that controls the advancement speed of the shearer. The objective of this system is to eliminate emergency power shut-offs and subsequent stoppages of the devices in the longwall and in the adjoining galleries caused by exceeding the 2% threshold limit value of the methane concentration in the air stream flowing out of the longwall. The extended *Ventgraph-Plus* programme enables the option of simulating the operation of the shearer with a control system, and also without it in order to make a comparison of the daily performance in both cases.

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