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THE ANALYSIS AND SIMULATION OF HEAT FLOW IN LONGWALL COAL FACES

ANALIZA I SYMULACJA PRZEPŁYWU CIEPŁA W PRZODKU ŚCIANY WĘGLOWEJ

The paper presents the development of two simulation models for predicting the climatic condition in mechanised longwall faces. One of these models is based on a linear heat flow concept which considers the longwall face as a semi-infinite solid consisting of three sides, viz. roof, face and floor strata, and the goaf is not considered as a continuous strata for heat emission. Heat from the goaf is carried by goaf leakage air and joins the face airflow at a few discrete points along its length. In order to consider the time of exposure of strata for heat flow purposes, the time-based development stage (referred to as the *age*) is calculated by forming rectangular elements (consistent with the finite element approach) in the roof, face and floor strata. The width of each element is equal to the web depth of the shearer and the length is equal to the incremental length considered in the simulation. The heat flow is calculated for each element separately, summed up for the increment and numerically integrated over the total length of the longwall face. Another simulation model based on a radial transient heat flow algorithm considering the longwall face in the form of a cylindrical tunnel has been developed and in this case a representative age has been calculated from the ages of all the elements of an increment.

In both models the contribution by machinery and other sources to heat and moisture levels, viz. the shearer, the armoured flexible conveyor (*AFC*), coal being conveyed, goaf leakage air etc. have been duly considered. Extensive field investigations have been carried out in five longwall panels of five coal mines to validate these simulation models. A satisfactory correlation has been obtained for both the models, therefore either of these models may be used to predict the climatic conditions in longwall faces.

Key words: strata heat flow, heat emission from machinery and other sources, climatic conditions in longwall faces

Środowisko pracy na przodku ściany węglowej urabianej mechanicznie jest jednym z ważniejszych podsystemów warunkujących wydajność pracy, wielkość produkcji oraz bezpieczeństwo górników. Dlatego też dokładne przewidywanie warunków klimatycznych i odpowiednio zaprojektowany system wentylacyjny są tak ważne przy planowaniu i projektowaniu prac w wysokoproduktywnych ścianach. W tym celu niezbędny jest niezawodny model symulacyjny do wykorzystania przez

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projektantów i inżynierów w kopalni dla zaprojektowania wygodnego miejsca pracy w rejonie prac ścianowych i zapobiegania problemom, które mogą pojawić się w przyszłości.

Główne zagadnienia związane z opracowaniem modelu symulacyjnego przedstawiono poniżej:

- przodek ściany ograniczony jest z trzech stron (czoło, spąg, strop). W czwartej części są zroby, zawierające wydobyty materiał różnych kształtów i wymiarów;
- cześć powietrza wlotowego przedostaje się do zrobów i przechodzi z powrotem do przodka z różnych odległości oraz poprzez chodnik powrotny;
- w trakcie pracy wrębiarki cienka warstwa węgla odrywana jest od czoła ściany, świeżo oderwane warstwy stropu i spągu poddawane są działaniu powietrza wentylacyjnego i wskutek przesuwania się podpór, jedna warstwa oderwana ze stropu i jedna oderwana ze spągu w pobliżu krawędzi zrobu będzie do tych zrobów wpadać. Wiek poszczególnych warstw wystawionych na działanie powietrza wentylacyjnego w różnych etapach procesu będzie różny;
- w przodku ściany znajdują się także inne źródła ciepła i wilgoci:
  - wrębiarka, zarówno w czasie pracy jałowej, jak i w trakcie wcinania,
  - przenośnik pancerny *AFC*, zarówno pusty, jak i załadowany,
  - pokruszony węgiel transportowany przenośnikiem.

W artykule zaprezentowano dwa modele symulacyjne do prognozowania warunków klimatycznych w przodku urabianym mechanicznie. Jeden z modeli opiera się na zasadzie liniowego przepływu ciepła. Przodek ściany traktowany jest jako otwór prostokątny, a równanie przewodzenia ciepła w prostokątnym układzie współrzędnych dla stałej wartości współczynnika przenikania temperatury skał ma postać następującą:

$$\frac{1}{a}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial t^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{Q'}{K}$$

gdzie: K — przewodnictwo cieplne skały [w/m°C],
a — współczynnik przenikania temperatury skał [m^2/s],
Q' — ciepło wewnętrzne wytworzone w ciele stałym

Równanie to zostało odpowiednio zmodyfikowane i przodek ściany przedstawiany jest jako ciało stałe w połowie nieskończone, mające trzy boki: czoło, spąg i strop. Zroby nie są traktowane jako warstwa ciągła dla emisji ciepła. Ciepło płynące od zrobów przenoszone jest przez powietrze wydostające się ze zrobów i łączy się z powietrzem na przodku w kilku dyskretnych punktach na długości przodka. W celu uwzględnienia czasu ekspozycji danej warstwy na przepływające ciepło oblicza się jej wiek poprzez wygenerowanie elementów prostokątnych (zgodnie z metodą elementów skończonych) w czele, spągu i stropie. Szerokość poszczególnych elementów równa jest głębokości wrębu ścianowego, a długość równa jest przyrostowi długości przyjętemu na potrzeby symulacji. Przepływ ciepła obliczany jest oddzielnie dla każdego z elementów, sumowany dla całego przyrostu i następnie numerycznie całkowany po długości całkowitej przodka.

Drugi model symulacyjny wykorzystuje algorytm promieniowego, nieustalonego przepływu ciepła. Przodek traktowany jest jako cylindryczny tunel. Model został opracowany po zmodyfikowaniu algorytmu tak, by uwzględniał on drogi powietrza (McPherson 1986). Podstawowe równanie przewodnictwa ciepła przyjmie postać jak we wzorze (14).

W modelu promieniowym strumień ciepła obliczany dla danego odcinka wymaga podania jednej liczby określającej wiek skały i nie obejmuje obliczania przepływu ciepła z odrywanych warstw. Dlatego też reprezentatywny wiek został obliczany na podstawie wieku wszystkich elementów w ramach przyrostu. Podobnie jak w poprzednim modelu, przepływ ciepła obliczany jest także dla przyrostu długości, a wynik jest numerycznie całkowany po całkowitej długości przodka.

W obydwu modelach uwzględniono wpływ ciepła i wilgotności dostarczanych przez maszyny oraz inne źródła: wrębiarkę, przenośnik opancerzony, przenoszony węgiel, powietrze ulatniające się ze zrobów itp. W celu walidacji modeli przeprowadzono szerokie badania w terenie w pięciu polach ścianowych w pięciu kopalniach węgla, z uwzględnieniem następujących warunków pracy:

- wszystkie maszyny włączone i trwa wybieranie wrębiarką,
- wszystkie maszyny na przodku pracują bez obciążenia przez krótki czas,
- wszystkie maszyny na przodku pracują bez obciążenia przez dłuższy czas.

Oprócz badań cieplno-higrometrycznych, wszystkie dane niezbędne do symulacji zostały zgromadzone w czasie badań w terenie. W obydwu modelach uzyskano zadowalający poziom korelacji, tak więc każdy z tych modeli może być wykorzystywany do prognozowania warunków klimatycznych w regionie przodka ścianowego.

Słowa kluczowe: przepływ ciepła w warstwie, wydzielanie ciepła przez maszyny i inne źródła, warunki klimatyczne w regionie przodka ścianowego

1. Introduction

The thermal environment is an important subsystem in any mining activity, having bearing on safety, the comfort of miners and ultimately, productivity. This assumes a greater importance in longwall workings where intensive extraction and transportation activities geared for highest production rates are concentrated in a very small space. The accurate predication of climatic conditions and appropriate design of the ventilation system are essential in the planning and design of high production longwall districts. Thus there is a great need for a reliable simulation model in order to help to make sound and informed decisions which will have a significant influence in the long term on the level of production costs.

A number of models have previously been put forward by different researchers, viz. Goch and Patterson (1940), Starfield and Dickson (1967), Starfield and Bleloch (1983), McPherson (1986), Banerjee and Chernyak (1985), Stephanov et al. (1985), Nowak et al. (1997) and others for predicting heat flow in mine airways. These models assume mine airway to be a cylindrical tunnel and use a radial heat flow algorithm for predicting the heat flow into the mine's air. A few models have been developed by Starfield (1966a, 1966b), Voss (1971), Longson and Tuck (1985) for predicting heat flow into mine workings, i.e. stopes and longwall panels. It has been observed that due to the complexity of the geometry in actual mine workings, it is difficult to model the heat flow accurately and therefore the number of models suggested by different researchers are limited.

Keeping the above points in view, an attempt has been made to develop an accurate simulation model to predict the heat and moisture transfer in longwall faces. The major problems encountered during the development of this simulation model are as follows:

- the longwall face is bounded by three sides, viz. roof, floor and face. The fourth side is the goaf, which contains caved materials of different shapes and sizes;
- a part of the intake air leaks into the goaf and rejoins the face air flow at different distances along the face as well as near the return gate;
- when the shearer cuts coal, a thin slice of coal is removed from the face, fresh strips of roof and floor strata are exposed to ventilation air and due to the advance of the power supports, one strip of the roof and floor strata near the goaf edge becomes part of the goaf. The ages of all the strips in the roof and floor exposed at different sequences of cutting differ;
- other sources of heat and moisture are also present in the face, viz:

- the shearer while idling as well as when cutting the coal,
- *AFC* (Armoured Flexible Conveyor), when running empty as well as in a loaded condition,
- Broken coal conveyed on *AFC*.

After incorporating all the above parameters, the simulation model has been developed and it has been validated in five different longwall faces in three operating conditions:

- face machinery running and coal cutting is in progress,
- face is idle for a short period,
- face is idle for a long period.

2. Development of models for heat flow from strata

Two computer simulation models have been developed for predicting the heat flow from strata. The first model has been formulated considering the longwall face as a semi-infinite solid and using the concept of linear heat flow analysis. This model uses the elemental approach for the calculation of heat flow from strata, viz. the roof, face and floor are considered separately for an incremental length of longwall face. In addition, another computer simulation model has been developed after incorporating some changes into unsteady state radial heat flow algorithm for airways (McPherson 1986).

2.1. Linear heat transfer model

The general heat conduction equation representing heat flow in three dimensions in rectangular co-ordinates for a constant value of thermal conductivity is given by

$$\frac{1}{a}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}+\frac{Q'}{K} \tag{1}$$

where:

K — thermal conductivity of rock [w/m°C],
a — thermal diffusivity of rock [m²/s],
Q' — internal heat generation in the solid element.

As the internal heat generation in a normally operating longwall face is zero, i.e. $Q' = 0$, equation (1) reduces to Fourier's heat conduction equation.

$$\frac{1}{a}\frac{\partial T}{\partial t}=\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2} \tag{2}$$

For applying the above equation, longwall face is considered as a rectangular opening within the strata with four sides, viz. roof, face, floor and caved goaf. The first three sides contribute heat and moisture to the ventilating air all along the length of the face. The fourth side is the caved goaf consisting of broken rock at some distance behind the face air flow, i.e. to the rear of the power support. The following assumptions have been made to model the strata heat flow in the longwall face:

- heat flow along the axis of the opening is negligible,
- the roof, face and floor are considered separately (referred to as *slabs*),
- the roof, face and floor strata do not contribute to heat flow prior to their exposure to the air stream,
- except for the goaf, the strata units are homogenous and isotropic.

This is a case of heat flow in semi-infinite solid. The governing equation for a one-dimensional heat flow in semi-infinite solid (Carslaw and Jaegar 1956), using $T(x,t)$ to denote the temperature at a distance x from the exposed surface at time t is

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{a}\frac{\partial T}{\partial t} \tag{3}$$

Solving equation (3) subject to initial and boundary conditions.

1. $T(x,0) = VRT$ for all values of x.
2. $T(x,t) = VRT$ for all values of t as $x \rightarrow \infty$.

The heat flux from rock to air is given by balance equation

$$K\frac{\partial T}{\partial x} = H(T_s - DBT) \tag{4}$$

where:

K — thermal conductivity of rock [W/m°C],
H — overall heat transfer coefficient [W/m²°C],
$T_s = T(0,t)$ — rock surface temperature [°C],
DBT — dry bulb temperature of air [°C],

The solution to the above equation (4) can be expressed algebraically in a closed form and is given by

$$\frac{T_x - DBT}{VRT - DBT} = Erf(X) + \exp\left(Bi + \frac{Bi^2}{4X^2}\right)Erfc\left(X + \frac{Bi}{2X}\right) \tag{5}$$

where:

T_x — temperature of rock at distance x from exposed surface [°C],

$$X = \frac{x}{2\sqrt{at}}$$

a — thermal diffusivity of rock [m²/s],
t — time or age [s],
$Erf(X)$ — error function given by Gauss's error integral

$$= \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2} dX$$

$$= \frac{2}{\sqrt{\pi}} \left(\frac{X}{1} - \frac{1}{\angle 1} \cdot \frac{X^3}{3} + \frac{1}{\angle 2} \frac{X^5}{5} \ldots \right) \tag{6}$$

Erfc(*X*) — complementary error function = 1 – *Erf* (*X*).

Simplifying equation (5) to obtain the rock surface temperature, i.e. T_x at $x = 0$

$$\frac{T_s - DBT}{VRT - DBT} = \exp\left(H^2 \cdot \frac{\alpha t}{K^2} \right) Erfc\left(H \cdot \frac{\sqrt{\alpha t}}{K} \right) \tag{7}$$

The dry surface temperature can be calculated by the balance equation

$$Q = H(T_{\text{dry}} - DBT)$$

where:

T_{dry} — dry surface temperature [°C].

But, in practice, the strata surface is wet and in addition to this dust suppression sprays are used while the shearer is cutting the face. In order to evaluate the effect of moisture, a wetness factor, *W* is used,

$$W = \frac{\text{area of wet surface}}{\text{total area}}$$

At the wet surface a sensible heat transfer (*SENWET*) and a latent heat transfer (*QLAT*) will occur such that the algebraic sum of these two is equal to the strata heat supplied to the wet surface, q_w.

$$q_w = SENWET + QLAT \tag{8}$$

All the above three components (longson and Tuck 1985) are evaluated as

$$q_w = AKW \frac{\partial T}{\partial x} \tag{9}$$

$$SENWET = AHW(T_{\text{wet}} - DBT) \tag{10}$$

$$QLAT = \frac{AWEL\{P_{\text{sat}}(T_{\text{wet}}) - P_w\}}{Baro} \tag{11}$$

where:

A — heat flow area [m^2],
E — mass transfer coefficient [kg/m^2sPa],

L — latent heat of evaporation of water [J/kg],
$P_{sat}(T_{wet})$ — saturated vapour pressure at wet surface temperature (T_{wet}) [Pa],
P_w — actual vapour pressure [Pa],
$Baro$ — barometric pressure [Pa],

The various terms of equation (8) are evaluated with the help of equations (9), (10) and (11). An initial value of T_{wet} is assumed and it is iteratively corrected till the equilibrium condition in equation (8) is satisfied.

Finally, the total heat flow (*TOTHET*) and total moisture (*TMOIST*) addition from the strata for a particular slab are given by

$$TOTHET = AH(1-W)(T_{dry} - DBT) + AHW(T_{wet} - DBT) + AWEL\frac{\{P_{sat}(T_{wet}) - P_w\}}{Baro} \tag{12}$$

$$TMOIST = \frac{QLAT}{L} \tag{13}$$

The total face is divided into a number of incremental lengths. The heat flow values from all the slabs present in an increment are added to obtain the total heat flow for an incremental length of the face. Such calculations are repeated and the results are numerically integrated along the total length of the longwall face.

2.1.1. Elemental approach and consideration of age

Consideration of representative age is rather complicated in an incremental length of a longwall face. Therefore, an approach consistent with the finite element method has been adopted for this purpose. In this case the face is considered as a single slab and the face span consists of rectangular elements of exposed surfaces in roof and floor slabs (Fig. 1). The width of each element in the roof and floor slabs is equal to the web depth of the shearer and the length of each element is equal to the incremental length. The age of the element depends upon the cutting rate and the rate of face advance. For this purpose, a starting time and the location of each cutting sequence are used. The machine cuts in both directions of its traverse across the face. The age of the roof and floor elements exposed by cutting are evaluated by knowing the cutting direction (either from intake gate to return gate or vice versa), the momentary distance of the shearer from the intake gate and the cutting speed of the shearer. If shearer is idling, the non-operating time of the shearer is also considered and in this case the age of the last element of the cut is equal to the idling time of the shearer. The age of the face slab in a particular incremental length is equal to the age of the roof or floor element adjacent to it. It has been assumed that the power supports are advanced as soon as face cutting is completed. Power support advancement introduces a fresh row of elements near to the face and suppresses the same number of elements at the rear. For a particular increment, the ages of all elements are calculated at their centres and all other parameters are assumed to remain constant

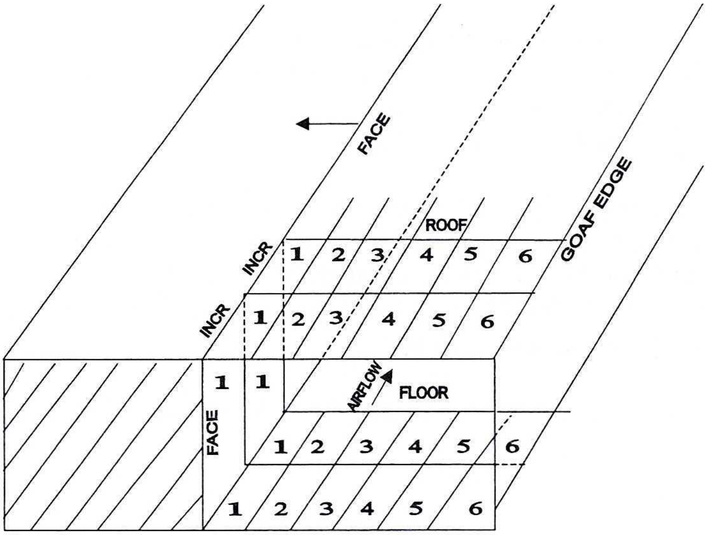

Fig. 1. Generation of elements in the roof, face and floor slabs for computation of heat and moisture contribution in a longwall face
1—6 — elements generated in the roof, face and floor depending upon the depth of cut and span of the longwall face

Rys. 1. Generowanie elementów warstw stropu, czoła i spągu do obliczania wpływu ciepła i wilgotności w rejonie przodka

within an element and any changes are applied at the boundaries between adjacent elements. Heat flow and moisture additions are calculated for all the elements of an increment and added together to give the total contribution from the incremental length. For the given inlet conditions as well as the heat and moisture addition, the outlet conditions for the increment are calculated, which become inlet conditions for the next increment. The computation is repeated for the entire length of the face segment. The schematic view of the concept is also presented in Fig. 1.

2.2. Radial heat flow transient model for longwall face

The radial transient-heat flow model for a longwall face is developed with certain modifications of the unsteady state heat transfer for airways (McPherson 1986). At first a few important steps of this model are presented and subsequently the modifications introduced in the model are discussed. There are certain symbols common to both the linear and the radial heat flow transient models, and these are not redefined in this section.

The general equation for conductive radial heat transfer is given by

$$\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} = \frac{1}{a}\frac{\partial T}{\partial t} \qquad (14)$$

In order to apply the above equation in general cases of heat transfer in mine airways, the radial distances and time are expressed as dimensionless numbers.

Dimensionless radius — $r_d = \dfrac{r}{r_a}$

where:

r_a — effective radius of the airway [perimeter/2π].

Dimensionless time = $Fo = \dfrac{at}{r_a^2}$ (referred to as the Fourier number).

Putting the value of r and t in equation (14)

$$\frac{\partial^2 T}{\partial (r_d \cdot r_a)^2} + \frac{1}{r_d \cdot r_a} \cdot \frac{\partial T}{\partial (r_d \cdot r_a)} = \frac{1}{\alpha} \frac{\partial T}{\partial \left(\dfrac{F_o r_a^2}{a} \right)} \tag{15}$$

Since r_a and α are constant equation (15) can be rewritten as

$$\frac{\partial^2 T}{r_a^2 \partial (r_d)^2} + \frac{1}{r_d \cdot r_a^2} \cdot \frac{\partial T}{\partial r_d} = \frac{1}{a\left(\dfrac{r_a^2}{a} \right)} \cdot \frac{\partial T}{\partial F_o}$$

The r_a^2 and α terms cancel, giving the radial heat conduction equation as

$$\frac{\partial^2 T}{\partial (r_d^2)^2} + \frac{1}{r_d} \cdot \frac{\partial T}{\partial r_d} = \frac{\partial T}{\partial F_o} \tag{16}$$

The solution of equation (16) has been introduced by Carrier (1940), Goch and Patterson (1940), and Carslaw and Jager (1956) with the boundary conditions:

1. $T = VRT$ when $t = 0$ for all $r > r_a$ ($r_d > 1$).
2. $T \to VRT$ when $r \to \infty$ for all F_o.

Heat flux from rock to air can be expressed by

$$K \frac{\partial T}{\partial r} = q = H(T_s - DBT) \tag{17}$$

In the above equation L.H.S. represents heat flux in the rock and the R.H.S. represents the same flux convected to air.

The temperature gradient may also be expressed in dimensionless form, G where

$$G = \frac{\partial T}{\partial r} \frac{r_a}{(VRT - DBT)} \tag{18}$$

Rearranging the equation

$$\frac{\partial T}{\partial r}=\frac{G(VRT-DBT)}{r_a} \tag{19}$$

Putting the value of $\frac{\partial T}{\partial r}$ in equation (17) and rearranging, it gives

$$T_s=\frac{K}{r_a H}G(VRT-DBT)+DBT \tag{20}$$

In order to find out the dry surface temperature, T_{dry} from equation (20) the dimensionless temperature gradient, G is calculated by Gibson's algorithm (McPherson 1986). The heat flux from the dry surface is calculated by

$$q_d=\frac{KG}{r_a}(VRT-DBT) \tag{21}$$

Similar to the previous model the total heat at the wet surface is given by

$$q_w = SENWET + QLAT \tag{22}$$

The value of q_w is calculated by using the concept of *Pseudo-base temperature* (T_b) given by McPherson (1986).

Thus, the different terms of equation (22) are calculated as follows:

$$q_w=\frac{KG}{r_a}(VRT-T_b) \tag{23}$$

$$SENWET = H(T_{wet} - DBT) \tag{24}$$

$$QLAT=\frac{EL\{P_{sat}(T_{wet})-P_w\}}{Baro} \tag{25}$$

The calculation of *SENWET* and *QLAT* involves assuming a value of T_{wet} and correcting it interactively till equation (22) is satisfied. Total heat transfer, Q for the incremental length of the roadway is given by

$$Q = 2\pi r_a\, INCR\ \{SENDRY(1 - W) + Wq_w) \tag{26}$$

Total moisture is calculated in a similar manner to the previous model.

The above model is modified in such a way that it is suited to longwall face geometry. In the radial transient model it is assumed that all the four sides of the longwall face, i.e. the roof, face, floor and the caved goaf, are contributing heat and moisture all along its length. It is considered that the packed goaf is contributing heat and moisture in a similar manner as the other three sides. In addition, the goaf return air, which is rejoining at a few discrete points, is also an additional source of heat and moisture. For calculation of the heat flux an equivalent radius is taken for the longwall face opening. This is taken as perimeter/2π. In the linear heat flow model (as discussed in the previous section) the age of each parallel strip in a 10 m increment is calculated, heat flow from each strip being calculated separately and integrated for the increment. In a radial model the heat flux is calculated in a section and requires a single figure for the age, as it does not have any provision for calculating heat flow from strips. Thus, the average age for all parallel strips of an increment is calculated and used by the model. In order to calculate the average age for a particular increment, the ages of all elements of an increment are calculated as per the linear heat flow model. The average age is computed as per the weighted average method:

$$\text{Average age} = \frac{\Sigma A_i Age_i}{\Sigma A_i} = \frac{\Sigma W_i \cdot INCR \cdot Age_i}{\Sigma W_i \cdot INCR} = \frac{\Sigma W_i Age_i}{\Sigma W_i} \tag{27}$$

where:

A_i — area of the element [m^2], ($i = 1, 2, 3, \dots n$, i.e. number of elements in an increment),
W_i — width of each element [m],
$INCR$ — incremental length [m], (it is constant for all elements).

3. Heat from machinery and other sources

3.1. Shearer

For estimating the power requirement by a shearer to cut coal specific energy requirements are determined in the laboratory in a special coal rig and in the field by power transducers (CMRI 1992). In addition, a few other characteristics of working seams may also be investigated. The two specific energy terms (field and laboratory specific energy) are related as follows:

$$FSE = \frac{0.04A^{0.53}(1232 + D)}{DEP^{0.29} C^{0.92} D} \tag{28}$$

where:

FSE — field specific energy to cut coal [MJ/m^3],
A — laboratory specific energy [MJ/m^3],
DEP — depth of working [m],
C — frequency of cleats [m^{-1}],
D — operating seam thickness [m].

Power required by a shearer to cut coal is given by

$$P_c = FSE \cdot \text{Volumetric cutting rate } (m^3/s) \cdot 1000 \tag{29}$$

where:

P_c — power required by shearer to cut coal [kW].

The volumetric cutting rate is the product of the cutting speed of the shearer [m/s], the depth of cut [m] and height of longwall face [m].

In reality, part of the cutting power is used to break the coal and to create new surfaces and is transferred into the coal. The second part is converted into heat and is calculated as

$$P_{\text{cht}} = P_c\,(1 - \eta_m \cdot \eta_g) \tag{30}$$

where:

η_m — efficiency of the motor used for cutting (generally 0.9),

η_g — efficiency of the gearing mechanism used for coal-cutting by the shearer (generally 0.85).

Some of this heat, P_{cht} will be transferred directly to the air as heat from the machine body and some will be taken up by the cooling water. It has been assumed that each will take an equal share (Whittaker 1979). The part that goes into the cooling water, which is discharged as a dust suppression spray, will then be added to the coal on the conveyor.

The total power requirement by a shearer (P_4) is calculated as

$$P_4 = P_c + P_h \tag{31}$$

where:

P_h — actual power required by the haulage unit of the shearer [kW].

The actual haulage power, P_h in the field situation is given by

$$P_h = K_{mf} \cdot P_{th}$$

where:

P_{th} — theoretical power required for traction and gravity [kW],

K_{mf} — maintenance factor for a particular shearer.

This factor (K_{mf}) has been studied for different shearers in India and its value increases when the state of maintenance of the shearer is poor and the shearer becomes older. P_{th} (theoretical power required for traction and gravity) can be determined by using the concept of a free body diagram of mechanics and is given by

$$P_{th} = \frac{h_s \cdot m \cdot g(\mu \cos\alpha \pm \sin\alpha)}{\eta_{mh} \cdot \eta_{gh} \cdot 60} \tag{32}$$

where:

h_s — cutting speed of the shearer [m/min],

M — mass of the shearer [t],

α — inclination along the face [deg.],

η_{mh} — fractional efficiency of the shearer haulage motor (generally 0.9),

η_{gh} — fractional efficiency of the haulage gear box of the shearer (generally 0.85),

μ — sliding rail friction (value is generally 0.3).

The sign is positive when the shearer is cutting up the gradient and it is negative when the shearer is cutting downhill. The shearer generally moves over the top race of the Armoured Flexible Conveyor (*AFC*), therefore all the electrical power spent for haulage goes as heat to mine air because of the friction of the shearer shoes. Heat due to the shearer, the cut coal and the water interact in a complex manner and there are chances of duplication unless these sources are analysed minutely. The heat flow pattern around a shearer is given is Fig. 2.

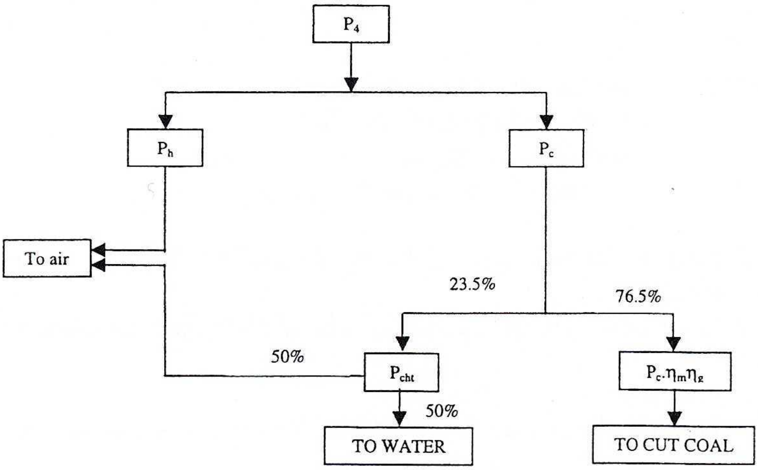

Fig. 2. Schematic chart of heat flow pattern around shearer

Rys. 2. Schemat przepływu ciepła wokół wrębiarki

3.2. Armoured Flexible Conveyor (*AFC*)

The heat given out by the *AFC* can be calculated by using the equation used for designing belt conveyor installations, but with the following modifications:

I. Velocity in the *AFC* is interpreted as the effective speed of the *AFC* and is calculated as

$$ECS = SPDAFC \pm \frac{SPDMC}{60} \tag{33}$$

where:

ECS — effective speed of *AFC* [m/s],

SPDAFC — *AFC* chain speed [m/s],

SPDMC — cutting speed of shearer [m/min].

The sign is positive when direction of the *AFC* chain movement is opposite to the direction of cutting of the shearer or otherwise. This affects the load distribution in the *AFC*.

II. Load distribution in *AFC* is confined to part of its length between the shearer and the discharge point, and its rate is given by

$$CUTRMC = \frac{SPDMC \cdot DEPTCU \cdot HTF \cdot \rho_r}{60} \tag{34}$$

$$RLODR = \frac{CUTRMC}{ECS}$$

where:

- $CUTRMC$ — cutting rate of the shearer [kg/s],
- HTF — height of the longwall face [m],
- ρ_r — density of coal [kg/m^3],
- $RLODR$ — load distribution rate in the AFC [kg/m].

III. Coefficient of friction is much higher in *AFC* and its value has been taken as 0.33 (as per *AFC* manual).

IV. The mass of rotating parts consisting of chains and flights are taken directly from *AFC* manual.

The following formulae are used to calculate the power consumption by the *AFC*:

$$P_{AFC} = P_e + P_1 + P_g \tag{35}$$

where:

- P_e — power required to run *AFC* in empty condition [W],
- P_1 — power required to run the load (coal) against chain friction [W],
- P_g — power required to raise the load against gravity [W].

The different components of the total power are derived separately by using the concept of the free body diagram of mechanics. Each individual component is calculated as follows:

$$P_e = rm_1 Lg\mu V\cos\theta \tag{36}$$

$$P_1 = rm_2 gL\mu\cos\theta \tag{37}$$

$$P_g = rm_2 Lg\sin\theta \tag{38}$$

where:

- rm_1 — mass of rotating components [kg/m],

L — length of *AFC* [m],
μ — coefficient of friction
V — effective speed of *AFC* [m/s],
θ — gradient of roadway (it is negative for a dipping conveyor and positive for a rising conveyor),
g — acceleration due to gravity [m/s^2],
rm_2 — coal flow rate (same as cutting rate of shearer = *CUTRMC*) [kg/s].

If η_{AFC} is the fractional efficiency of the *AFC* motors, the fraction of total power appearing as heat (P_{ht}) is given by

$$P_{ht} = \frac{P_1}{\eta_{\mathrm{AFC}}} - P_g \tag{39}$$

The P_{ht} has two components:

$$P_{ht} = P_{\mathrm{lin}} + P_{\mathrm{spot}} \tag{40}$$

where:

P_{lin} — fraction of total heat appearing as a linear source along the length of the *AFC* due to friction — $P_e + P_l$

P_{spot} — fraction of total heat appearing as a point source at the two ends of the *AFC* drive motors — $P_{\mathrm{ht}} - P_{\mathrm{lin}}$

3.3. Conveyed coal on the *AFC*

When coal is transported from the cutting machine position to the outbye, its temperature drops and heat is released to the mine air. It comprises two components, that of the original strata and heat from the breaking process. While cutting, the spraying water also wets the coal. The temperature of the cut coal below the face machine (Tu) has been estimated (Verma 1984) and is given as

$$Tu = 0.72\ VRT + 8.2 \tag{41}$$

The temperature drop of the cut coal during its transit from the cutting position has been calculated by the following equation (Fiala et al. 1985):

$$\Delta T = 0.0024 L_d^{0.8} (Tu - WBT\,(\mathrm{inlet})) \tag{42}$$

where:

ΔT — temperature drop of cut coal from the shearer cutting position to discharge point of *AFC* [°C],
L_d — length of *AFC* loaded with coal [m],
WB (inlet) — wet bulb temperature of inlet air [°C].

3.4. Goaf leakage air at longwall coal face

In India most longwall faces are worked by the *retreating method*. In a retreating longwall face part of the intake air from the main gate bypasses the face and moves to the goaf. Most of this goaf leakage rejoins the main body of the air current. In the similar situation of a retreating face at Wolstanton Colliery (United Kingdom) the study indicates that the goaf leakage air re-emerges within the last 20 m of the longwall face (Browning and Burrell 1980).

A detailed investigation carried out by the Central Mining Research Institute in many retreating longwall faces has enabled an average figure for design purpose to be arrived at (CMRI 1993). Although these figures can be variable and site-specific, it has been found that an average of 30% of the intake air to the panel leaks into the goaf and the remainder flows along the face. Of this 30%, about 21% rejoins at the tail end and the remaining part (9% of panel intake) leaks back to the face nearer to the return gate. As the goaf is nearly at *VRT*, this air can be a major source of heat and should therefore be taken into account. For the climatic simulation models an average figure for the goaf leakage is taken and it is assumed that 9% of the intake air joins the face through the goaf edge at two points, i.e. 3/4 and 7/8 of the length of the face measured from the intake gate (Fig. 3).

The temperature of this rejoining goaf air depends upon the temperature of the inlet air (dry bulb and wet bulb) to the goaf and the *VRT* of the place. The above three parameters are studied in field conditions to establish if any relationship exists between them. The final relationship established is given by

$$\text{Temp} = \text{Temp (inlet)} + 3.3922\{1 - \exp(-0.24(VRT - \text{Temp (inlet)})\} \tag{43}$$

where:

Temp and Temp (inlet) are *DBT*/*WBT* in °C of goaf return air rejoining and goaf intake air respectively.

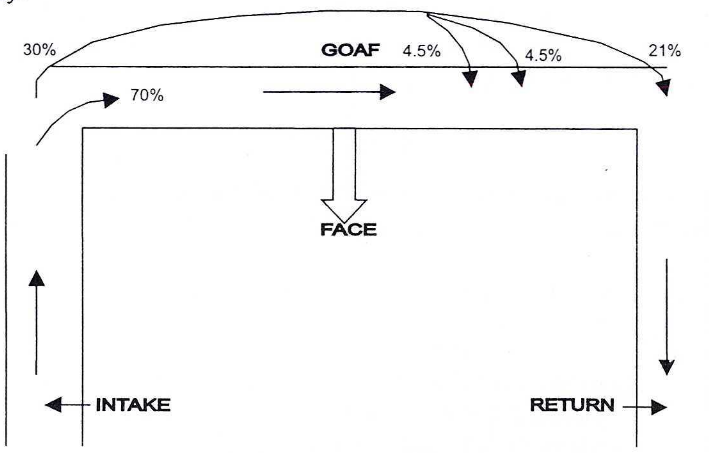

Fig. 3. Average goaf leakage pattern in a longwall face

Rys. 3. Średni przebieg wycieków powietrza ze zrobów

In the case of *DBT* the correlation coefficient is 0.985 and in case of *WBT* it is 0.973. The above relationship is used in the simulation model to calculate the *DBT* and *WBT* of goaf return air rejoining the face airflow, when the temperature of the goaf intake air and *VRT* at the beginning of the face are given.

4. Development of thecomputer program and validation of the models

The models were coded in the form of a computer program having a main module and several sub-routines. The different major steps followed in the simulation are given below:

Step 1: Compute enthalpy, mixing ratio and other thermodynamic properties of the inlet air at the beginning of the longwall face using dry bulb temperature, wet bulb temperature and barometric pressure.

Step 2: Compute age gradient of all the cuts from starting ages and direction of cutting.

Step 3: Compute ages of all the elements in the incremental length, generate fresh row of elements while cutting and suppress the elements in roof and floor after power support advancement.

Step 4: Compute surface heat transfer coefficient and heat given out by the machinery both spot and linear heat sources (shearer, *AFC*, conveyed coal etc.) present in the incremental length.

Step 5: Calculate the value of error function from Gauss's error integral; surface temperature of all the elements present in the incremental length, sensible and latent heat given out by all elements of the increment and cumulative heat load.

Step 6: Add goaf air flow with heat and moisture if joining in this incremental length.

Step 7: Compute the thermodynamic properties of air at the end of incremental length and it becomes the inlet condition to the next increment.

Step 8: Repeat the steps 4 to 7 till the end of the longwall face.

5. Validation of the models

Extensive field observations were carried out to identify the nature, magnitude and pattern of heat and moisture transfer at five mechanised retreating longwall panels:

1. Panel 3/3 of No.16 bottom seam in Moonidih Colliery.
2. Panel W9of the Borachak seam in Dhemomain Colliery.
3. Panel PH3of Hatnal seam in Seetalpur Colliery.
4. No. 1 panel of No. 1 seam-top section of GDK11A Colliery.
5. 6^{th} panel of top seam middle section in VK7 Colliery.

Thermo-hygrometric measurements were taken at the beginning as well as at the end of each longwall face. These measurements were continued for a period of time, so that results could be analysed under different conditions of face working. The thermo--physical measurements were taken in three different operating conditions of the face:

1. All the face machinery running and face cutting in process.
2. All the face machinery idling for a short period (less than 4 hrs).
3. All the machinery in the face idle for a long period (more than 4 hrs).

In addition to the thermo-hygrometric measurements, all other relevant data required for the simulation were also collected in the field.

In order to test the quality of predictions produced by the program, the simulation models were run in the above three conditions of observation. A comparative study was prepared between the predicted outlet conditions at the longwall faces and observed outlet conditions for all the face operating levels for all the collieries and is presented in Table 1.

TABLE 1

Correlation of outlet environmental conditions in the longwall faces

TABLICA 4

Korelacja warunków otoczenia „na wyjściu" w przodku ścianowym

Colliery	Operating conditions of the longwall panel	Predicted outlet temperature at the end of longwall face by using linear heat flow model		Predicted outlet temperature at the end of longwall face by using radial transient model		Observed outlet temperature of longwall face	
		DBT [°C]	*WBT* [°C]	*DBT* [°C]	*WBT* [°C]	*DBT* [°C]	*WBT* [°C]
Moonidih	A	33.52	28.92	33.84	29.48	33.50	29.00
	B	30.08	28.08	30.62	27.54	30.10	27.20
	C	28.67	26.24	29.26	26.65	28.80	26.30
Dhemomain	A	32.56	28.85	32.68	29.29	32.50	29.00
	B	29.34	27.04	29.80	27.42	29.50	27.20
	C	28.85	26.41	28.38	26.53	27.90	26.40
Seetalpur	A	33.31	30.09	33.49	30.45	33.50	30.50
	B	31.54	29.60	31.89	29.89	31.50	29.70
	C	29.88	28.49	30.28	28.73	30.00	28.50
GDK11A	A	32.22	28.43	32.09	28.67	32.40	28.70
	B	28.73	26.41	28.04	26.61	27.90	26.50
	C	26.63	25.00	26.90	25.58	26.80	25.90
VK7	A	32.02	27.81	32.01	28.03	31.90	28.30
	B	27.84	26.00	28.09	26.20	27.70	26.10
	C	26.64	25.48	26.88	25.62	26.50	25.50

A — All the face machinery running and face cutting in process.
B — All the face machinery idling for a short period (less than 4 hrs).
C — All the machinery in the face idle for a long period (more than 4 hrs).

6. Discussion and Conclusion

It may be observed from Table 1 that the maximum deviations between the observed and predicted outlet conditions obtained by the linear heat flow model are within ±0.13°C, ±0.14°C, ±0.19°C, ±0.18°C and ±0.14°C for a dry bulb temperature, and ±0.12°C, ±0.19°C, ±0.41°C, ±0.9°C and ±0.49°C for a wet bulb temperature, but for the radial transient model the above mentioned deviations are within ±0.52°C, ±0.6°C, ±0.39°C, ±0.31°C and ±0.39°C for a dry bulb temperature, and ±0.48°C, ±0.29°C, ±0.23°C, ±0.11°C and ±0.27°C for a wet bulb temperature between different operating conditions in the case of Moonidih, Dhemomain, Seetalpur, GDK11A and VK7 collieries respectively. It can be seen that in case of the linear heat flow model the predicted outlet conditions match fairly closely with the observed dry and wet bulb temperatures except for GDK11A, where there is a difference of ±0.9°C in the wet bulb temperature, but in the majority of cases the predicted temperature is slightly less than the observed temperature.

In case of the radial transient model, the deviations are slightly greater than for the linear heat flow model, but are well within an acceptable limit. In the majority of cases, the predicted outlet conditions predicted by the radial transient model were slightly greater than the observed outlet conditions. Thus, the simulation work presented in the paper clearly indicates that the heat and moisture contribution due to strata, goaf, shearer, *AFC* and coal conveyed on the AFC are represented properly and adequately in the simulation models. Though the geometry of a longwall face suggests a linear heat flow analysis, the simulation results clearly show that the radial flow transient model can also be used to predict the outlet environmental condition of longwall faces provided appropriate radius and age factors are taken into account.

Finally, it can be concluded that the correlation is excellent in both the linear and the radial transient heat flow models, therefore either of them can be used to predict the climatic conditions of longwall faces in advance of actual workings which will help in the planning and designing of a comfortable workplace environment to achieve the required production, productivity and safety levels in longwall coal mine faces.

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