Thermal control in mine openings

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Abstract
Thermal control systems of pits and ore mines, in which the energy sources are arranged arbitrarily lengthwise of openings are under investigation. Optimal distances between sources are determined from the measure of energy savings for conditioning of mine air. The location regularities of energy sources during the constant and variable air flow in mine opening are established.

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Central scheme of thermal control is usually used in mines and pits when energy source, e. g. calorific installation is arranged at the beginning of mine openings chain [1,2,3]. Such arrangement of main calorific installation when using heat storage openings (HSO) is economically unsound. The control scheme when the air heating apparatus is arranged at the end of HSO network is less energy-consuming [4]. In this investigation we considered more general case, where calorific installation is arranged arbitrarily lengthwise of air heading, defined there optimum quantity and order necessary for achieving of an objective– the minimum of energy and economical costs for thermal control. The results of earlier studies [4,5] show that it is possible to obtain the reduction of total energy intensity of thermal control system by arranging of conditioning units along the length in a successive order (in general case HSO can be used).

The arrangement of electric power plants along the length makes sense when this condition is satisfied:

$$N_0 - \sum_{i=1}^{n} N_i > 0 \text{,kW,} \tag{1}$$

where N_0 — the power of electric power plant for conditioning arranged at the beginning of air heading, kW; N_i — the power of i-th electric power plant arranged lengthwise, kW; n — the total quantity of plants throughout the air heading.

The arrangement of electric power plants (EPP) along the length is economically sound when this condition is satisfied:

$$E_0(\tau) - \sum_{i=1}^{n} E_i(\tau) > 0, \text{ rub/y,} \qquad (2)$$

where $E_0(\tau)$— total expenses involved in thermal control when arranging EPP at the beginning of air heading, rub/y; $E_i(\tau)$ — same when arranging EPP along the length, rub/y; τ — running time, hrs.

Conditions (1) and (2) give the possibility to select energetic and cost-effective method of control due to arranging of EPP, in particular there quantity and way of arrangement along the air heading. For this purpose two questions must be considered:

1) while using “n” EPP instead of one central plant, what value “n” must be taken for minimum energy intensity of thermal control system;

2) what l_n/L ratio must be taken for minimum energy intensity of system, where l_n — the distance between EPP, L — the total length of air heading (for face – face length, for mine – the length of air heading with intake air etc.)

For responding to these questions let us compose the objective function using the equation (1):

$$f' = N_0 - \sum_{i=1}^{n} N_i, \text{kW,} \qquad (3)$$

and test it for maximum. It is obviously that:

$$\sum_{i=1}^{n} N_i = Gc_\mathrm{p}(t_1 - t_\mathrm{conc.area}) + Gc_\mathrm{p}(t_2 - t_\mathrm{conc.area}) + Gc_\mathrm{p}(t_3 - t_\mathrm{conc.area}) + \ldots$$
$$\ldots + Gc_\mathrm{p}(t_i - t_\mathrm{conc.area}) + \ldots + Gc_\mathrm{p}(t_\mathrm{n} - t_\mathrm{conc.area}), \qquad (4)$$

$$N_0 = Gc_\mathrm{p}(t_o - t_\mathrm{out}), \text{kW,} \qquad (5)$$

where G — rate of flow, kg/s; c_p — heat capacity of air; J/kg °C; t_0 — air preheat (cooling) temperature after central EPP determined by back heat calculating, °C; t_out – outside air temperature, °C; $t_\mathrm{conc.area}$ — air temperature at the end of air heading on concerned area °C; t_i — temperature after spacing of i-th EPP, °C.

After inserting (4) and (5) in (3) following objective function is obtained:

$$f = t_0 + n \cdot t_\mathrm{conc.area} - \sum_{i=1}^{n} t_i, \text{ °C,} \qquad (6)$$

For demonstrativeness and simplicity of computation the following formula is used for determination of temperature:

$$t_i = (t_\mathrm{conc.area} - T_\mathrm{e}) \cdot \exp A(l_i - l_{i-1}) + T_\mathrm{e}, \text{ °C,} \qquad (7)$$

thereafter objective function becomes

$$f = t_0 + (t_\mathrm{conc.area} - T_\mathrm{e})\left[n - \sum_{i=1}^{n} \exp A(l_i - l_{i-1})\right], \text{°C,} \qquad (8)$$

Testing of given function for maximum gives rise to following set of equations

$$\frac{df}{dl_i} = -A \cdot \exp A(l_i - l_{i-1}) + A\exp A(l_{i+1} - l_i) = 0, \; i=1, 2, 3, \ldots, n. \qquad (9)$$

solution of which gives

$$2 \cdot l_i = l_{i+1} - l_{i-1}, \qquad (10)$$

from which if $h_i = l_i - l_{i-1}$ we obtain

$$h_i = h_{i+1}, \qquad (11)$$

which is equivalent to equation

$$l_i = il_n/n, \qquad (12)$$

where l_n — total length along which EPP are arranged, m.

Equations (11) and (12) demonstrate that the optimum arrangement of plants in concordance with energy factor is their regularly arrangement along the length, in these circumstances the function f→ max. Numerical calculations demonstrate that the plant location affects significantly total energy costs and gives the possibility to reduce them by 15÷35%.

Let us determine the source quantity, which it makes sense to arrange along the length of mine opening, with this purpose we may use the objective function of the form

$$f = t_0 + (t_\mathrm{conc.area} - T_\mathrm{e})n(1 - \exp AL/n), \quad \text{°C,} \qquad (13)$$

Testing of given function for maximum gives rise to the following equation

$$e^{\frac{AL}{n}} \cdot \left(1 - \frac{AL}{n}\right) = 1, \qquad (14)$$

which is correct when $n \to \infty$, since

$$\lim_{n\to\infty} e^{\frac{Al}{n}}\left(1 - \frac{AL}{n}\right) = 1. \qquad (15)$$

Hence the most energetic method of thermal control is using of the low-power sources arranged along the length of mine opening regularly, i.e. from physical standpoint the last equation signifies that the more sources are arranged regularly the more energy is saved.

The obtained formulas need to be extended when variable air volume in the mine opening inasmuch as the objective function is determined by the value t_i. Variable air volume is typical for rooms of the coal pits and development openings of all kinds of mines, ore mines and underground facilities of cryolithic zone. From a mathematical standpoint it is equivalent to the following formula of the unknown temperature after EPP:

$$t_i = T_\mathrm{e} + \left(t_\mathrm{conc.area} - T_\mathrm{e}\right)\exp\left[\int\limits_{l_{i-1}}^{l_i} A(l)dl\right], \text{°C}, \quad (16)$$

Following alternation is representative of rooms:

$$A(l) = A/\left(G_0 + Cl\right)^m, \text{1/m}, \quad (17)$$

After integration (16) and transformations the following correspondence is obtained

$$t_i = T_\mathrm{e} + \left(t_\mathrm{conc.area} - T_\mathrm{e}\right)\exp\left[a\left(\frac{1}{y_{i-1}^k} - \frac{1}{y_i^k}\right)\right], \text{ °C}, \quad (18)$$

where $a = A/C(m-1)$ and $y_i^k = \left(G_0 + Cl_i\right)^{m-1}$ (19)

Arguments "C" and "A" are obtained from equation:

$C = \left(G_0 - G_k\right)/L$, kg/m·s, and $A = K_\tau \cdot U/c_\mathrm{p}$, kg/m·s. (20)

Inserting (1) into (6) and testing a function for maximum the following set of equations is obtained:

$$\frac{df}{dy_i} = \exp\left[a\left(\frac{1}{y_{i-1}^k} - \frac{1}{y_i^k}\right)\right] - \exp\left[a\left(\frac{1}{y_{i-1}^k} - \frac{1}{y_{i+1}^k}\right)\right] = 0$$

, i=1, 2, 3, ..., n, (21)

from which entering the designations k=m-1 and x=1-m, we obtain the following correspondence:

$$y_i = \left(\frac{i}{n}\right)^{\frac{1}{x}} \cdot y_n. \quad (22)$$

After comparing (22) with (12) a substantial difference between two equations is seen. Argument h_i is determined by the formula:

$$h_i = \left(\sqrt[x]{i/n} - \sqrt[x]{(i-1)/n}\right) \cdot y_n. \quad (23)$$

Using correspondences for determination of arguments "C" and " y_i " we obtain the following correspondences for distance determination of i-th calorific installation arrangement:

$$\left(l_i/L\right) = \left[1 - \eta\left(i/n\right)^{\frac{1}{1-m}}\right]\Big/\left(1-\eta\right), \quad (24)$$

where $\eta = G_k/G_0$ — coefficient of air delivery.

Let us consider variant m=1. Returning to equation (17) after integration we obtain

$t_i = T_\mathrm{e} + \left(t_\mathrm{conc.area} - T_\mathrm{e}\right)\left(y_i/y_{i-1}\right)^\mathrm{T}$, where P=A/C, (25)

After inserting this equation into (6) and testing a function for maximum the following set of equations is obtained:

$$y_i = \sqrt{y_{i+1}y_{i-1},} \quad i = 1, 2, 3, \ldots, n. \quad (26)$$

Whence it follows:

$$\frac{l_i}{L} = \frac{1-\eta^{i/(n+1)}}{1-\eta} \quad (27)$$

As an example the variant n=2 and n=1 is considered. It is equivalent to the constant air flow in mine opening. Developing the resulting indeterminacy (0/0), we obtain numerical result:

$$\frac{l_1}{l_2} = \frac{1/3}{2/3} = 0{,}5,$$

h.e. we obtain that EPP must be arranged regularly along the length during the constant air flow in mine opening, which has been proved before. For demonstrativeness graphs of ratio $\left(l_i/l_{i+1}\right)$ varying in accordance with the coefficient of air delivery and various quantity of EPP in mine opening are given in the Figure 1.

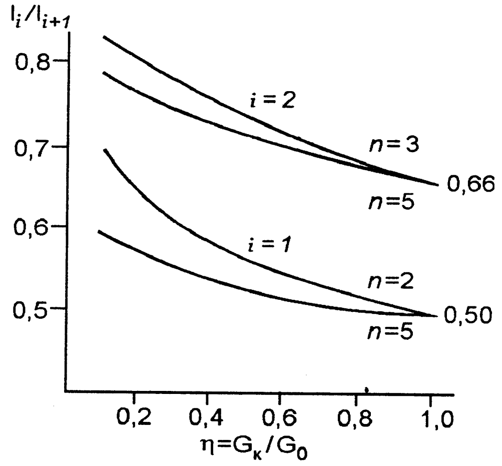

Figure . The ratio varying of lengths in accordance with the coefficient of air delivery for various quantities of calorific installations used in mine openings.

It is seen from graphs that ratio increases with the decrease of the coefficient of air delivery, h.e. EPP must be arranged irregularly along the length of mine opening and the distance of arranging the i-th calorific installation must be determined by formula (24) for obtaining the maximum energy saving.

Comparative analysis also enables to make a conclusion that assumed calculation model affects significantly on the final result – the determination of EPP arrangement principles along the length and the necessity of using of more accurate models which particularly consider the air flow variation lengthwise of mine opening. Therefore the most general model for temperature prediction in mine openings has been developed by us and what is more we have developed the mathematical model, algorithm and scheme for prediction of temperature condition in mine openings if the arranged regularly sources are available, and the sources strength and position are time-controlled.

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