Heat Balance Determination Methods for Mining Areas in Underground Mines - A Review

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Abstract.

Mine operation in presence of aerological hazards is a challenging issue for mine ventilation services. Increasing depth of exploitation and growing level of mechanization, due to the demand for intensification of extraction, makes it even more difficult regarding thermal hazard. As air temperature is a decisive factor shaping underground thermal working conditions it is extremely important to predict its value. This task determines the possibility of carrying out works in regions with the highest thermal hazard, where, due to the applicable regulations, it is necessary to use air conditioning to ensure appropriate working conditions for people. To determine the required cooling capacity for mining regions, it is crucial to identify the individual heat sources, as well as to define the amount of heat they generate. For this purpose, heat balances need to be set, taking into account the mentioned issues. The main goal of this paper is a presentation of methods available in the literature for determining the thermal balances of mining areas. The article also presents and characterizes the most important heat sources in underground mines. In addition, methods of determining heat fluxes from individual sources were indicated, as well as potential difficulties in the applicability of the above-mentioned methods for mining areas heat balances determination, in which, due to the current depth of exploitation, the thermal hazard is the most important natural hazard that determines the possibility of mining works.

1. Introduction

In the underground mining plants, a growing tendency is observed associated with deteriorating thermal working conditions. An important factor affecting this phenomenon is the constantly increasing depth of mineral exploitation and connected rock mass primary temperature increase. Undoubtedly, when considering the influence of factors shaping the microclimate underground, which is a workplace for miners, the most important seems to be air temperature, next to air humidity, and air movement. Thermal hazard is of the greatest importance due to the comfort, or even possibility of people work in the underground environment. Hence, it is becoming more and more important among natural hazards in underground mines.

The mine air temperature depends on many factors, such as the abovementioned depth of exploitation and the associated primary rock temperature, but also atmospheric air temperature, the volume of extraction, ventilation intensity, or the power of machines and devices working in mining excavations. Therefore, it is very important to identify heat sources and the amount of heat generated by them. Accurate determination of heat balances of mining areas, both existing and planned, is of great significance.
Taking into consideration that the increase of air temperature in mining excavations caused by existing heat sources is extremely significant from thermal working conditions point of view, the key is to know the processes of heat exchange between them and the air flowing in the workplace, as well as between them and miners themselves. Heat exchange can occur in three basic ways: through heat conductivity, convection, and radiation [1–4]. These phenomena usually do not occur separately in conditions of an underground mine.

Heat conduction consists of transferring energy from one material medium to another during their direct contact [1, 2, 4], or inside the medium, from places with a higher temperature to places with a lower temperature [2]. This process can take place in solids, liquids, and gases. In the case of solids, heat conduction is a result of crystal lattice vibration as well as free electrons movements if the solid is an electric conductor. Longitudinal, rotational, and vibrational movements are the cause of heat transfer in liquids and gases as an indirect action through the transfer of kinetic energy.

Convection (lifting) occurs when there is a movement of macroscopic parts of fluid or gas at different temperatures and densities [1, 3, 4]. Convection consists of four phenomena that are interrelated [2]:

- heat conduction from the solid surface to directly adhering gas or fluid particles,
- adsorption and maintenance of this heat by the particles, which results in an increase in their temperature,
- movement of higher energy particles to lower temperature areas, which results in the exchange of some of this energy,
- energy transport through the medium flow.

Thermal radiation is based on the transfer of energy through the quantum of electromagnetic radiation [1–4]. In the previously described phenomena of heat exchange, the presence of a material medium in energy transfer was necessary. Unlike the previous two, thermal radiation can occur without its presence, thus also in a vacuum [1, 2, 4]. The radiation temperature of solids, liquids, and some gases is caused by the fact that part of their internal energy (or enthalpy) is converted into electromagnetic wave energy. Sending energy through waves is called the phenomenon of radiant emissions. At absolute zero, all bodies are capable of emitting electromagnetic radiation, also known as thermal radiation.

In underground mines, heat exchange between the air flowing through excavations and the uncovered plane of the rock mass or other thermal-loaded elements takes place constantly. Heat flow occurs as a result of conductivity in such a solid wall and then in the boundary layer, while in the excavation air stream also by convection [1, 2, 4]. Heat exchange is the most intense in the air stream [2], where unlike to the boundary layer, convection, conduction, and sometimes also radiation, occur simultaneously. These phenomena, called complex heat exchange, is found in many technical problems of heat exchange [1, 2, 4]. The heat exchange between the solid surface and the flowing liquid is called heat transfer.

In this paper, identification of the heat source in the underground mine workings has been made. Methods for heat balance determination in underground mines were reviewed with respect to ways of heat exchange and the differences and similarities in the approach for determining the amount of heat transferred to the air from individual energy source has been pointed. Potential difficulties in the application of the considered methods by ventilation services to determine the thermal balances of planned and existing mining departments were also indicated.

2. Heat sources in underground mine
In underground mining excavations, there are plenty of heat sources that significantly affect the mine air temperature. Identification of its types is very important in terms of determining
the amount of heat generated in particular. Depending on the conditions in which the mining operations take place, such as the depth of the deposit, and the associated mining technology suitable for these conditions, the amount of heat generated by the single source can be different.

However, the most important heat balance components in underground mines include heat from the rock mass, heat from machines and devices working in excavations, vaporization of moisture heat, and heat exchanged with excavated material [1, 4–6]. What is more in [2, 7, 8] authors pointed also the importance of heat generated due to air compression in the field of gravity.

2.1. Heat from the rock mass
The primary temperature of rock mass is a decisive factor influencing the temperature of the air in underground mining excavations. In many publications, [5, 9–14], as the main driving force for heat flow from the rock mass, the difference between its primary temperature at a given depth and the air temperature in the excavation is pointed. It is a fact, then, that heat flux from rocks to air is proportional to this difference [5, 7]. As can be seen in [15], air temperature in deep copper ore mine may vary from 35 to 39 °C, while primary rock temperature at the current depth of exploitation it is around 45 °C [16]. Calculating the total heat flow requires additional information on airflow rate and the heat transfer area. The size of the excavation is particularly important because the difference between the inlet and outlet air temperature increases when the overall heat transfer area increases [5], which is connected to the surface of the excavation sidewalls, roof, and floor.

It should be noted that the amount of heat coming from the strata in the conditions of the underground mine is partially reduced due to the presence of other heat sources [6]. Mine air temperature increase caused by other sources contributes to reducing the amount of heat exchanged in the air-strata system.

2.2. Heat from machines and devices
The heat generated by the machines and devices installed in the underground mining excavations, both electrically and diesel driven, is also of great importance. All of them, starting from rock breaking and moving machines, through transformers, fans, and ending with lights, are transferring all input power, via useful effect, into heat [7, 14, 17, 18]. It is assumed that all electricity "consumed" underground, except that supplied to equipment in the exhaust air currents and cooling equipment, is converted into heat [6, 19] that heats the mine air. The calorific value of the fuel consumed underground is treated in the same way, it all passes into the mine air in the form of heat.

The value of heat stream generated by the machines and devices depends on its power, their efficiency, and methods of converting the energy supplied to them into other forms, as well as on the way the equipment is loaded over time [1, 2, 6, 9, 20]. The highest machine power and the more the machine is loaded over time, the more heat is generated.

Considering the efficiency, an electric engine properly selected for a specific application is characterized by a similar value of power consumed and the value of useful power. However, diesel engine power consumed, by taking into account the calorific value of the fuel consumed, is several times higher than the useful power. Machines powered by diesel engines are emitting three times more heat than those powered by electric engines of the same useful power [1, 2, 6, 9, 17, 21].

In the case of Diesel engines, 30% of heat is emitted because of heating the engine, a large part is emitted with the exhaust gases, while useful energy turns into heat through friction processes [1, 2, 6, 7, 9, 17, 21]. During the operation of the material-moving devices transporting the material uphill part of the energy driving is turned into potential energy, while energy driving the material-breaking devices is turned into surface energy [1, 6, 9], as a result of fragmentation
and thus the creation of new surfaces. The value of surface energy depends on the degree of fragmentation and is hard to estimate.

2.3. Heat of moisture vaporization
The exploitation of mineral resources is inextricably accompanied by water. Water may be derived from the surrounding the excavations rock mass, or from technological processes as support for drilling of blasting holes, for preventing dust when excavating materials generating large amounts of it, and for back-filling [7, 8].

Water evaporation is possible by changing the enthalpy of both the rock and air, as well as water in the excavation [1, 2, 9]. The complexity of the processes taking place at that time does not make it possible to easily estimate the exact increase in humidity. An increase in specific humidity at the expense of air enthalpy causes a decrease in its temperature.

When the mine air is in direct contact with the mine water of constant temperature the air can be heated, cooled, moisturized, or dehumidified [1, 2, 9]. If the water temperature is higher than the temperature of the dew point the evaporation of water occurs, while condensation of water occurs when the dew point temperature is higher than the temperature of the water.

2.4. Heat from excavated mineral deposit
The volume of production is affecting both the heat flow and temperature rise [5]. The more material is excavated, the more virgin surfaces are exposed and more heat is loosed by the mined material.

The amount of heat loosed by the mined material depends most of all on its mass and the difference in temperature between it and the mine air [1, 2, 9]. As the works of Voss’s [22] and Waclawik’s [1] implies the only 70% of heat flux, calculated taking into account the above-mentioned factors, is flowing into mine air.

2.5. Heat generated due to the auto-compression
Mine air pressure in underground mining excavations is higher than the atmospheric air pressure. When the air is flowing from the atmosphere through shaft or decline, either naturally or because of ventilation applied, specific thermodynamic changes occur, especially polytropic transformation [2]. The reason for the temperature increase is the conversion of potential energy into thermal energy [7, 8, 14, 17, 18]. At the same time, heat present due to geothermal gradient and radiometric decay in the surrounding rock leads to heat transfer from the rock to the air on the transport route in the shaft [20]. With the compression of air during its transport down into the mine increase in its temperature is associated, while during its transport up, because of decompression, temperature decreases.

3. Heat balance determination methods
3.1. Heat from the rock mass
There are many theoretical methods used to estimate heat transfer processes occurring in underground airway and to predict mine air temperature [1, 2, 5, 10, 19, 21, 23–27]. To estimate these phenomena usually Fourier’s Law of Heat Conduction is used [1, 2, 10, 19, 21, 28]:

\[ q = -\lambda A \frac{dT}{dx} \]  

where: \( q \) – heat flux, W; \( \lambda \) - thermal conductivity of the material, W/m °C; \( A \) - area through which heat flux passes, \( m^2 \); \( T \) – temperature, °C; \( x \) – distance, m.

Constructing model of heat exchange between rocks and the air flowing through the excavation is associated with certain simplifying assumptions [6, 24].
In [1, 6] authors assumed that rocks are a continuous, layered heterogeneous, and isotropic body. Energy is transferred in rocks by thermal conductivity. This process is one-dimensional and takes place in the direction perpendicular to the walls of the excavation. Rock temperature is a variable in time, as well as in space, in the direction perpendicular to the walls of the excavation and parallel - changes along the length of the excavation. On the other hand, the air temperature changes only along the length of the excavation. In this case, the density of the heat flux exchanged between air and rocks on the length of one meter of the excavation is determined by the formula [1, 6]:

$$q_s = \lambda q^*_s F_s (\vartheta_o - T_a)$$

(2)

where: $q_s$ - density of the heat flux, W/m; $q^*_s$ - dimensionless rock temperature gradient, 1/m; $F_s$ - area of exposed rock per unit length of the excavation $m^2/m$; $\vartheta_o$ - virgin rock temperature, °C; $T_a$ - air temperature in the excavation, °C.

Based on the same assumptions Szlązak et al. [29] proposed the equation of heat balance determining the relationship between rock and air temperatures at the sidewall surface, supplemented with the effect of thermal radiation and moisture transfer from rocks:

$$q = \lambda \frac{\partial \vartheta}{\partial r} \bigg|_{r=r_1} = \alpha (\vartheta_{ew} - T_a) + R (\vartheta_{ew} - \vartheta_{ewr}) + f l \epsilon (p_{ww} - p_w)$$

(3)

where: $\vartheta$ - temperature of the rock, °C; $r$ - radius of the excavation, m; $\alpha$ - heat transfer coefficient, W/m²K; $\vartheta_{ew}$ - average effective sidewall temperature, °C; $R$ - heat transfer coefficient by radiation, W/m²K; $\vartheta_{ewr}$ - surface temperature, to which the sidewall with temperature $\vartheta_{ew}$ emits radiation, °C; $f_l$ - the degree of moisture in the perimeter of the excavation (averaged); $\epsilon$ - mass transfer factor (moisture), kg/m²sPa; $p_{ww}$ - vapour pressure in the saturated state at the rock surface temperature, Pa; $p_w$ - water vapor pressure of the air in the excavation, Pa.

Whillier [30] makes the heat flux density dependent on the time that has passed since the excavation was made. If the excavation is more than 30 days old, the following formula is used to determine the heat flow along the excavation length [21]:

$$q = 3.35 s \lambda^{0.854} (\vartheta_o - T_a)$$

(4)

where: $s$ - length of the excavation, m.

Although, if the excavation is less than 30 days old, the heat flux is determined by the formula [21]:

$$q = 6 \lambda [s + (4 d_{fa})] (\vartheta_o - T_a)$$

(5)

where: $d_{fa}$ - daily face advance, m.

Using equation (5) it is important to estimate the time in which the heat is transferred from the rock mass to the air until the thermal equilibrium will be achieved. The solution for this problem may be applying the strata model with help of ClimSim software. This software assumes heat transfer by convection and radiation in homogeneous strata. The heat flow is based on the principles described by the Fourier equation expressed in terms of cylindrical coordinates (W/m²) [21].

According to [26] the heat exchanged between rocks and the air around a unit length of the circular airway of radius $r$ is given by:

$$q = 2\pi r \lambda \frac{\partial \vartheta}{\partial r} \bigg|_{r=r_1}$$

(6)
Amano [26] distinguishes the heat that is transferred from the dry wall and the heat transferred from the totally wet wall, thus introducing a non-dimensional factor $\eta$:

$$\eta = \frac{hr}{\vartheta - Ta}$$  \hspace{1cm} (7)

$$h = \frac{\alpha}{\lambda}$$  \hspace{1cm} (8)

where: $\vartheta_w$ - wall temperature, °C.

Further investigation implies need for introducing another non-dimensional factor $\eta_t$ [26]:

$$\eta_t = \frac{\vartheta_o - Ta}{\vartheta_o - \vartheta_w}$$  \hspace{1cm} (9)

Thus, heat exchanged between air and rock mass is given by general formula [26]:

$$q = 2\pi \lambda \eta \eta_t (\vartheta_o - \vartheta_w)$$  \hspace{1cm} (10)

Heat transferred from the dry wall is given by [26]:

$$q = 2\pi r \lambda \alpha (\vartheta_{wd} - T_a)$$  \hspace{1cm} (11)

where: $\vartheta_{wd}$ - dry wall temperature, °C.

While heat transferred from the totally wet wall is given by [26]:

$$q = \alpha (\vartheta_{ww} - T_a) + \alpha \left[0.622 \frac{p_{ww} - p_{ww} - p_{ww}}{p_{ww}} \lambda_w \frac{l_w}{cpa} \right]$$  \hspace{1cm} (12)

where: $\vartheta_{ww}$ - temperature of totally wet wall, °C; $p$ - total pressure of mixture, Pa; $l_w$ - latent heat of water vaporization at $\vartheta_{ww}$, J/kg; $c_{pa}$ - specific heat of air at constant pressure, kJ/kg K.

However, mathematical methods described above [1, 6, 21, 26], as well as others [2, 10, 19, 23, 24, 27] are assuming constant air temperature or that only small changes occur due airway ventilation time. On the other hand, Cheung [25] implies that this assumption is not correct. Measures taken in British coal mines show that air temperature changes up to 5°C at each point over some time equal to one week. It can be concluded, that heat emission from the rock mass varies with time [25]. Taking into consideration this fact, the strata heat transmission into the mine air can be modeled by Duhamel’s Theorem [31]. In this model it is assumed that an airway is cylindrical, rocks are homogeneous and the conduction occurs only radially.

The problem of dealing with varying in time surface temperatures has been also raised in [32] and [29]. Rock surface temperature variable has been determined by introducing the dimensionless heat flow rate, also known as the dimensionless coefficient of heat transfer. The value of function $K$ in terms of the two independent variables, Biot number (Bi) and Fourier number (Fo), can be approximated by the formula [29]:

$$K = \sqrt{\frac{1 + (1.6\sqrt{Fo})}{(1.77\sqrt{Fo}) + \left(\frac{1}{3.7}\right)\left(1 + (1.6\sqrt{Fo})\right)}}$$  \hspace{1cm} (13)

The introduction of the $K$ function allows for an explored surface temperature replacement with the virgin temperature of the rock mass. Thus, the amount of heat released from surrounding rock mass can be calculated from [32]:

$$q = KU\lambda (\vartheta_o - T_a)$$  \hspace{1cm} (14)

where: $K$ - dimensionless heat flow rate (dimensionless coefficient of heat transfer); $U$ - perimeter of an excavation, m.
### 3.2. Heat from machines and devices

The general formula for the determination of heat transferred from machines and devices is proposed by The Central Mining Institute [1]:

\[
q_m = k_n N \tag{15}
\]

where: \(q_m\) - heat flux generated by machines and devices, kW; \(N\) - power of machinery, kW; \(k_n\) - coefficient determining what part of the installed power causes the air temperature increase, \(-\).

Based on this it is also possible to calculate air temperature increase by dividing heat flux by stream of air volume, air density and specific heat of air at constant pressure [1].

To determine precisely the heat flux from machines and devices powered by Diesel engines, the key is to determine fuel consumption per hour of operation and per 1 kW of power, which is according to different authors approx. 0.25 kg/kWh [6, 9], 0.24 kg/kWh [8] or 0.30 l/kWh [7, 21]. The approaches for determination of the number of hours of Diesel-powered machines operation is given in [19]. If this information is known, heat generated in an hour of operation of each mining area can be determined, regardless of the value of machinery power installed there, based on the calorific value of the fuel. According to [1, 6, 9, 19, 33] this value for Diesel fuel is 45.6 MJ/kg and according to [8] 44 MJ/kg.

As shown in [21] total heat generated, containing latent and sensible heat, taking into account the efficiency of combustion, can be described by the following formula [21]:

\[
q_c = c \frac{E_c}{100\%} C_v \tag{16}
\]

where: \(q_c\) - heat flux generated by Diesel engines (from combustion), kW; \(c\) - fuel consumption, kg/s; \(E_c\) - combustion efficiency, \%; \(C_v\) - calorific value of the fuel, kJ/kg.

While the quantity of water generated by combustion by the formula [21]:

\[
W = c \frac{E_c}{100\%} r \tag{17}
\]

where: \(W\) - water generated, kg; \(r\) - rate of liquid equivalent, s,

is used to determine combustion latent heat [21]:

\[
q_l = lw \tag{18}
\]

where: \(q_l\) - combustion latent heat, J.

The sensible heat of combustion can be obtained by deducting latent heat from the result in eq. 16 [21].

The energy converted for heat directly in the drive of machines and devices is described by the formula [1, 6]:

\[
q_d = (N_d - N_n) k_t \tag{19}
\]

where: \(q_d\) - heat flux emitted from the drive to the environment, W; \(N_d\) - power supplied to the drive, W; \(N_n\) - useful power of the drive, W; \(k_t\) - non-uniformity of the drive operation coefficient, \(-\).

Diesel equipment heat released with exhausts gases may be estimated by the formula [8]:

\[
q_e = f_m f_t q_{cp} N \tag{20}
\]

where: \(q_e\) - heat flux emitted with exhaust gases, W; \(f_m\) - mechanical efficiency, \(-\); \(f_t\) - equipment utilization efficiency, \(-\); \(q_{cp}\) - heat generated by Diesel equipment for 1kW of power, kW/kW; \(N\) - machinery rated power, kW.
As Voss suggests [22], based on the experience with coal mines, 30% of the heat generated by machines and equipment is carried outside the excavation with the transported material. From 10% to 25% of the remaining heat is explicitly transferred to the air, and the remaining 90% to 75% implicitly through the evaporation of moisture.

In the case of machinery and devices drove by electrical engines knowledge of the total power and load factors is necessary. Zhou and others [14] state that heat gained in this way can be described by the formula:

\[
q_{em} = \frac{\phi_1 \phi_2 \phi_3 \tau R A N}{24}
\]

(21)

where:
- \(q_{em}\) - heat generated by electrical driven machinery, J/h;
- \(\phi_1\) - installation factor (ratio of motor maximum power consumption to rated power, usually 0.7), -;
- \(\phi_2\) - simultaneous factor (ratio of summarized used motor rated power to total rated power), -;
- \(\phi_3\) - load factor, usually 0.4-0.5, -;
- \(\tau R\) - machine running time per day, h/d;
- \(A\) - conversion factor equal to 3.6 \times 10^6 J/h.

Wagner [18], on the other hand, suggests that all the power of the machinery is absorbed completely by the ventilation air as heat, so the heat gained is described simply by the formula:

\[
q_{em} = \dot{m} \Delta H
\]

(22)

where:
- \(\dot{m}\) - mass stream of air, kg/s;
- \(\Delta H\) - change in enthalpy, J/kg.

3.3. Heat of moisture vaporization

When the humidity increase occurs at the expense of air enthalpy its temperature decreases. The energy balance of this process is described by the formula [1, 9]:

\[
c_{pa} \Delta t_a = l \Delta x
\]

(23)

where:
- \(\Delta t_a\) - air temperature decrease, °C;
- \(\Delta x\) - specific air humidity increase, kg/kg.

Thus, enthalpy needed for water vaporization can be defined as a product of the water mass stream evaporating in the excavation \(\dot{m}_s\) and latent heat of water vaporization \(l\) [6]:

\[
q_w = \dot{m}_s l
\]

(24)

In turn, the increase in specific humidity is defined as a ratio of mass stream of water evaporating in the excavation and mass stream of dry air in the excavation [6]:

\[
\Delta x = \frac{\dot{m}_s}{V \rho}
\]

(25)

To determine water mass evaporating in the excavation wetness of the excavation surface must be established. In [29] it is defined as the averaged degree of moisture in the excavation, Wacławik et al. [6] arbitrarily assume the percentage of the excavation surfaces wetness. Similarly, quantitatively on a scale from 1 to 10, the wetness of excavation surfaces is determined by Lambrechts [11], as well as in [24, 26] determined in the range from 0 to 1.

3.4. Heat from excavated mineral deposit

Before its transport, the exploited material will be partially cooled by the mine air in the heading, as well ass during transport load of heat will be transferred to the air, because of the temperature difference between air and fragmented rocks. Nixon et al. [33] simply estimate the amount of this heat by determination of total mass removed from the heading in a certain time period. In this case the heat load to the mine air is gained by multiplication of removed mass and thermal capacity of rocks.
In [21] and [20] authors make the amount of heat transferred to air from fragmented rock dependent on the rock temperature difference directly after fragmentation and after the transport at the ventilation network end:

\[ q_{fr} = \dot{m}_{fr} c_{pr} (\theta_1 - \theta_2) \]  

(26)

where: \( q_{fr} \) - heat from excavated material, kW; \( \dot{m}_{fr} \) - mass flow of excavated material, kg/s; \( c_{pr} \) - specific heat of the rock, kJ/kg °C; \( \theta_1 \) - rock temperature immediately after fragmentation (assumed as equal to virgin rock temperature), °C; \( \theta_2 \) - rock temperature at the exit of ventilation system, °C.

A similar equation for the heat released to the air by fragmented rocks during transport is described by Wagner [18]. The last term of the equation referring to the temperature difference is considered as temperature difference at the beginning and at the end of transport. On the other hand, Wacławik [1, 6, 9] defines the last part of the equation as lowering the temperature of the excavated rock in the heading under consideration.

Based on research conducted in coal mines Voss [22] stated that only 70% of heat calculated this way is transferred to the air current - 85% as latent heat, through evaporation of moisture, and 15% as sensible heat.

### 3.5. Heat generated due to the auto-compression

Auto-compression in a strict sense is not a source of heat. An increase of temperature is a result of the conversion of potential energy into enthalpy [18, 34]:

\[ (H_2 - H_1) = g(Z_1 - Z_2) \]

(27)

where: \( H \) - enthalpy of air, J/kg; \( g \) - gravitational acceleration, m/s²; \( Z \) - elevation above certain level, m.

The change in temperature may be obtained by dividing change of enthalpy \((g(Z_1 - Z_2))\) by specific heat of air at constant pressure \( c_{pa} \) [18, 34].

The heat generated due to the air compression in the shaft for specific conditions of Chinese underground mines thanks to conducted research, as shown in [14], may be calculated by use of the following equation:

\[ q_s = -0.976\dot{\bar{m}}(273 + t_i) \left[ 1 + \frac{0.0124h}{101.325 + 0.012Z} \right]^{0.286} - 1 \]

(28)

where: \( t_i \) - air temperature at the shaft inlet, °C; \( h \) - height of the mine shaft, m.

### 4. Summary

Thermodynamic processes taking place in underground mining excavations, as a result of which there is an increase in mine air temperature, have a very complex structure. Therefore, there are many difficulties in the mathematical description of these phenomena, which would make it possible to accurately determine the amount of heat transferred from individual sources to the air. Thus, presented in this paper theoretical methods for mining areas heat balance determination are characterized by many simplifications. Although these assumptions have an impact on the estimated heat generated by a specific source, they are mandatory to assess its amount.

It should be noted that there are many similarities in the presented methods of determining heat fluxes from individual sources, and, consequently, in the heat balances of mining departments. Equations characterizing heat exchange between rock mass and air in the excavation are based on Fourier’s Law of Heat Conduction. In this approach, the most important is the value of temperature difference between the rock mass and the air, for which heat flux is proportional. However, the value of the thermal conductivity coefficient for rocks and the area
of rocks exposure taking part in heat exchange are also significant. Apart from the parameters included in the Fourier equation, attention should be paid to additional aspects indicated by the authors, constituting differences in selected methods. These include the age of the excavations, which affects the rocks’ cooled-down degree around the excavation, the moisture content, which determines what part of the heat is latent and sensible, as well as the air temperature variability along the length of the excavation.

Another similarity is manifested regarding heat transferred from machines and devices. In the case of Diesel-powered machines, the value of heat generated is received by the calorific value of fuel spend in a certain period. While for the electrically driven machines value of heat transferred to the mine air is obtained as a difference between power supplied to the drive and useful power of the drive, including non-uniformity of the drive operation. The key point of heat emission from machines and devices is the assumption that all consumed electricity power and fuel are transferred into heat.

Selected methods also take up the problem of heat transfer due to evaporation of moisture in the same way. The amount of water under phase-change is estimated arbitrarily and presented as a number or percentage scale. In the presented methods, the approach to heat exchanged with excavated material is not different. The way of determining its value is alike to the heat from rock mass determination. It is based on temperature difference directly after fragmentation, so at the beginning of transport, and at the end of the mining area, considering the mass of transported material and its specific heat. Regarding heat generated due to the auto-compression, only a few methods for heat balance determination are taking this as a source of heat, which may be the result of a purpose of the specific method related to the depth of exploitation. Potential energy converted into enthalpy has the greatest importance in the case of very deep mines, thus it is omitted when the mine is shallow.

5. Conclusions
1. Based on the observations and analysis of the literature, it can be stated that the determination of heat balances of mining areas in the conditions of underground mines is based on the procedures specified many years ago. From the point of view of the dynamically changing operating conditions, related to the increasing depth and intensification of extraction, manifested by an increase in the amount of heat given off to the air by the rock mass and mining machines, this approach may not provide accurate and satisfactory results. This implies a need for verification of presented methods through the comparative analysis of results obtained by a certain method for underground mining areas with hard thermal conditions, for example in polish copper ore mines.

2. It should be taken into account that most of the calculation coefficients used to determine heat fluxes were also obtained experimentally in laboratory or mining conditions years ago. With the primary temperature of the rock mass increase due to the increasing depth, as well as with the increasing amount of heat generated by machines, as a result of the intensification of extraction, the coefficients necessary for the calculations should be re-determined and systematically determined in the future.

3. Considering that the amount of heat coming from a specific source in the conditions of the underground mine is partially reduced due to the presence of other heat sources, attention should be paid to determine the quantitative impact of a given source on the total heat transferred to the air. Research conducted in this direction should take into account various operating conditions. The variables particularly necessary for validation are the depth of exploitation and the power of mining machines and devices operating in a given area.

4. Knowing that the heat released to the air current by the rock mass in underground workings is one of the most important sources of heat increasing its temperature, one should consider
changing the approach of determining the heat flux from this source based on the Fourier’s law of thermal conductivity. It should be remembered that heat is also exchanged due to convection and thermal radiation, and taking into account the greater depths of exploitation, it may turn out that the heat exchanged due to these mechanisms will not be negligible anymore.

5. Research conducted in the conditions of a real mining area should also be directed to determining how heat is exchanged in regions with the most severe climatic conditions. As part of the research, it is necessary to establish how quantitatively the share of conduction, convection, and thermal radiation changes in the heat transfer with the increasing primary temperature of the rock mass.

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