An Investigation on the Underground Cooling by Air Current

By

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1. Introduction

It is well known that the ventilation of mines developed in the rock mass, which has a high temperature, with the air which is cooler than the ground temperature is one of the effective means to cool the mine. Indeed, not a few analytical studies have been conducted on the theory of heat exchange between mine air current and the rock mass around it. But the effectiveness of ventilation for the underground cooling and the most effective method are not yet fully known. Looking over several analytical investigations made up to date, it seems as though they are repeating similar discussions on the same subject, and we shall point out the differences among them.

Dr. Heise and Dr. Drekopf carried out an analysis on the periodical change of temperature in the rock around an airway on the assumption that the wall temperature is subject to a periodical variation which is given as a known function.[1] This investigation has proven to be very useful for us for it was one of the first theoretical studies made pertaining to underground air temperature and developed a concept of a heat balance mantle. The assumption in this analysis, however, cannot be said sufficient as it will be discussed later.

To analyse the heat exchange with heat transfer across the wall of airways taken into consideration is far more troublesome than to analyse it taking only the heat conduction in the rock mass into consideration. Dr. Maegawa made an analysis about thirty years ago on the periodical temperature change in a thick hollow cylinder, assuming that the air in the cylinder was subject to a stationary periodical temperature change and that heat exchange took place across the inner wall.[2] About the same time, Dr. Kumabe carried out an analysis on the two-dimentional unsteady heat transmission in a hollow cylinder assuming that the air temperature in the cylinder was given as a general function of time.[3] He has reduced a formula that gave the variation in temperature distribution along a radius of the cylinder with time. These two investigations, although they were not conducted for the purpose of solving the underground cooling problem, have presented a material aid to the authors.

Recently, Dr. W. De Braaf has studied on the variation in the rock temperature with time on the assumption that the wall temperature keep constant.[4] Although this investigation stands on the same simple assumption as that of Dr. Heise and Dr. Drekopf, it surpasses what have ever been published up to date by mining engineers because it deals with variation in rock temperature with time. Mr. K. Amano has published three theses[5] treating the temperature change of air current with time in which the authors of this paper have found some errors.

All the investigations described above are based on the assumption that the temperature of air or wall at a point under consideration is constant or is subject to a steady periodical change. Such an assumption may be inevitable to make the analysis possible, but it is not enough for the discussion of underground cooling by air current, because the very problem into which we aim to inquire is to clarify the variation of the air temperature with the distance travelled as well as time. The authors have, therefore, proceeded to study the theory of heat transmission in a system composed of an airway and a rock mass around it aiming to clarify the cooling effect of air current. A strict analysis of the theme, however, is almost impossible as the succeeding explanation shows and the authors have given up the idea of a strict analysis this time, but have instead endeavored to reach a solution of this problem by means of an approximate calculation.

It is assumed in this paper that airways are horizontal; that the heat transmission in the system takes place owing to the heat conduction in the rock mass, movement of air, and the heat transfer across wall surface; that the change of air temperature with the distance travelled is due to the heat exchange between the rock mass and air current; and that in the air current or on the wall surface there appears no evaporation or condensation of water.

2. Theoretical Consideration

2.1. Equations of Heat Transmission

The temperature of the air is denoted as:	Θ °C,
the specific heat of the air under constant pressure:	C_p kcal/kg °C,
the specific weight of the air:	γ_a kg/m^3,
the thermal conductivity of the air:	λ_a kcal/m hr °C,
the mean air velocity:	w m/hr,
the temperature of the rock:	θ °C,
the wall temperature:	θ_w °C,
the thermal conductivity of the rock:	λ_g kcal/m hr °C,

the specific heat of the rock: C kcal/kg °C,
the specific weight of the rock: γ_g kg/m^3,
and the heat transfer coefficient of the wall surface: α kcal/m^2 hr °C.

Define r and z in the direction of the radius and the axis of an airway. An assumption is made here that 1 and 2 are two sections, dz m apart on a horizontal circular airway, r_1 in radius, in which air flows with velocity w m/hr.

Considering the heat transmission in an air current, the following equation is formed on the assumption that the air temperature in a section is regarded as uniform:

$$\frac{\partial\Theta}{\partial t}+w\frac{\partial\Theta}{\partial z}=\frac{\lambda_a}{C_p\gamma_a}\frac{\partial^2\Theta}{\partial z^2}+\frac{2\alpha}{C_p\gamma_a r_1}(\theta_w-\Theta)\,. \tag{1}$$

As for the heat conduction in the rock mass around the airway, the well known Equation (2) is established:

$$\frac{\partial\theta}{\partial t}=\frac{\lambda_g}{C\gamma_g}\left(\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}+\frac{\partial^2\theta}{\partial z^2}\right),\qquad r\geqq r_1\,. \tag{2}$$

Let the initial condition of Eq. (1) as Θ is a function of z only when $t=0$, and the boundary condition of the equation as Θ is constant when $z=0$; whereas the initial condition of Eq. (2) as $\theta=\theta_0$ (the ground temperature) when $t=0$, and the boundary condition of the equation as:

$$\frac{\partial\theta}{\partial r}=\frac{\alpha}{\lambda_g}(\theta_w-\Theta)\,,\qquad \text{for}\quad r=r_1\,. \tag{3}$$

To solve the simultaneous Equations (1) and (2) under all the initial and boundary conditions and to express the air temperature Θ and the rock temperature θ as functions of distance z and time t respectively are very difficult if not impossible.

2. 2. Approximate Calculation

Taking all the necessary conditions described above into account, the authors propose the following way as a method of approximate calculation of the temperature change of air current with distance.

The distance travelled and time elapsed are divided into small sections respectively, and the temperature of air current in question is found by integrating the results of approximate calculations of the wall and air temperatures of each section. These calculations are carried out under the following assumptions.

It is assumed that the wall temperature is constant in each division of distance although, strictly speaking, it is a function of both distance and time (assumption 1), and that the air temperature is constant in each division of time although it is a function of both time and distance (assumption 2). As a matter of course, according to the initial condition, the wall temperature is constant throughout the airway at the instant the ventilation is started, while according to the boundary condition, air of constant temperature is supplied continuously through the entrance of the airway.

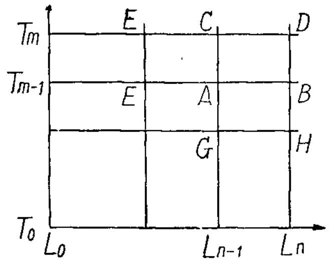


Fig. 1.

Let the distances from the entrance of an airway and the points along the airway in one section where the ventilation begins be $L_0, L_1, L_2, \cdots$, and the instant when the ventilation is started be T_0 and the points at which time is divided be $T_1, T_2, \cdots$. Now, taking distance on abscissa and time on ordinate, as shown in Fig. 1, any point at any time is represented by a point in this figure. Therefore, the interval $L_n - L_{n-1}$ is represented by $ABDC$ for the time interval $T_m - T_{m-1}$ in Fig. 1. The details of the method are as follows.

(a) According to the assumption 1, the wall temperature is taken as constant for the interval AB, so that the temperature at the point B is to be determined from Eq. (1) by putting $\frac{\partial \Theta}{\partial t} = 0$ and neglecting the first term in the right side.

$$\Theta_B = \theta_w - (\theta_w - \Theta_A) \exp \{-2\alpha(Z_B - Z_A)/C_p \gamma_a r_1 w\} . \tag{4}$$

(b) From the assumption that the air temperature during the time interval AC is taken as constant, the wall temperature at the point C can be presumed in the following manner.

It is assumed here that a circular airway, r_1 in radius, is driven into the rock mass having a uniform temperature and the rock mass is cooled continuously by passing air current with a constant temperature Θ_A through the entrance of the airway. Now, taking into consideration the heat transmission around the airway and neglecting the third term in Eq. (2) and put $v = \theta - \Theta_A$, we obtain:

$$\frac{\partial v}{\partial t} = \kappa \left(\frac{\partial^2 v}{\partial r^2} + \frac{1}{r} \frac{\partial v}{\partial r} \right), \tag{5}$$

where

$$\kappa = \lambda_g / c \gamma_g .$$

In order to solve Eq. (5), we need one additional boundary condition besides the initial as wellas boundary conditions described above. Assuming that the rock temperature at a point, r_2 m apart from the axis of the airway in radial direction, is so close to the ground temperature θ_0 even after t hours have elapsed since the beginning of the ventilation, we can put $\theta_{r_2} = \theta_0$.

Now, we divide v into two parts, v_1 and v_2, which satisfy the conditions shown in Table 1.

Table 1.

	v_1	v_2
Equations	$\frac{d^2v_1}{dr^2}+\frac{1}{r}\frac{dv_1}{dr}=0.$ ......(a)	$\frac{\partial v_2}{\partial t}=\kappa\left(\frac{\partial^2 v_2}{\partial r^2}+\frac{1}{r}\frac{\partial v_2}{\partial r}\right).$ ...(b)
For $r=r_1$	$\frac{dv_1}{dr}=hv_1, \quad h=\alpha/\lambda_g.$	$\frac{\partial v_2}{\partial r}=hv_2, \quad h=\alpha/\lambda_g.$
For $r=r_2$	$v_1=v_0.$	$v_2=0.$
For $t=0$		$v_2=v_0-v_1.$

v_1 and v_2 are found by solving Eq. (a) and (b) in the table, taking into consideration the necessary conditions, as follows:

$$v_1 = v_0\{1+hr_1 \log (r/r_1)\}/\{1+hr_1 \log (r_2/r_1)\}\,, \tag{6}$$

$$v_2 = 2r_1hv_0 \sum_{n=1}^{\infty} \frac{u_0(\alpha_n r)\, u_0(\alpha_n r_1) \exp(-\kappa\alpha_n^2 t)}{r_2^2\alpha_n^2 u_1^2(\alpha_n r_2) - r_1^2(\alpha_n^2+h^2)\, u_0^2(\alpha_n r_1)}\,, \tag{7}$$

where

$$u_0(\alpha_n r) = \frac{J_0(\alpha_n r)}{J_0(\alpha_n r_2)} - \frac{Y_0(\alpha_n r)}{Y_0(\alpha_n r_2)}\,,$$

and α_n are possitive roots of the following equation:

$$\alpha_n u_0'(\alpha_n r_1) = h u_0(\alpha_n r_1)\,.$$

Therefore, the solution of Eq. (5) becomes:

$$\frac{\theta-\Theta_A}{\theta_0-\Theta_A} = \frac{1+hr_1 \log r/r_1}{1+hr_1 \log r_2/r_1} + 2r_1h \sum_{n=1}^{\infty} \frac{u_0(\alpha_n r)\, u_0(\alpha_n r_1) \exp(-\kappa\alpha_n^2 t)}{r_2^2\alpha_n^2 u_1^2(\alpha_n r_2) - r_1^2(\alpha_n^2+h^2)\, u_0^2(\alpha_n r_1)}\,. \tag{8}$$

Putting $r=r_1$ in Eq. (8), we get Eq. (9) which gives the rate of change in the wall temperature.

$$\frac{\theta_w-\Theta_A}{\theta_0-\theta_A} = \frac{1}{1+hr_1 \log (r_2/r_1)} + \sum_{n=1}^{\infty} \frac{2r_1hu_0^2(\alpha_n r_1) \exp(-\kappa\alpha_n^2 t)}{r_2^2\alpha_n^2 u_1^2(\alpha_n r_2) - r_1^2(\alpha_n^2+h^2)\, u_0^2(\alpha_n r_1)}\,. \tag{9}$$

Eq. (9) thus reduced gives the wall temperature of a rock mass at any time under the assumption that an air current of constant temperature is supplied continuously. Actually, though, as the air temperature varies with time, we cannot derive the wall temperature of the point C directly from Eq. (9). For this reason, we further assume that the temperature distribution in the rock mass along a radius at any time is equal to an imaginary temperature distribution in the rock mass, which is presumed to be cooled by constant supply of air of the same temperature as that of the present air temperature Θ_A and reached at the instant the wall surface temperature coincides with $(\theta_w)_A$, (assumption 3).

The time t' which may be required for the temperature to reach the wall temperature can be found from Eq. (9). Consequently, the wall temperature at the point C can also be determined from the same Eq. (9) by putting $t=t'+T_{m+1}-T_m$.

(c) The wall temperature at the point A and B are determined by applying the method described in (b) to the adjacent section $GHBA$.

(d) The air temperature at the point A can be obtained by applying the method described in (a) to the other adjacent section $EACF$.

(e) Because the determination of the wall temperature and the air temperature within any section can be made in successive order from the neighboring sections, the calculation may be started from the first sections on the oz-axis and ot-axis for which both the wall and air temperature are determined by the initial and boundary conditions respectively. The calculations in the sections along the both axes in turn can be started from the original point. In this way, the wall temperature and the air temperature of every section can be determined.

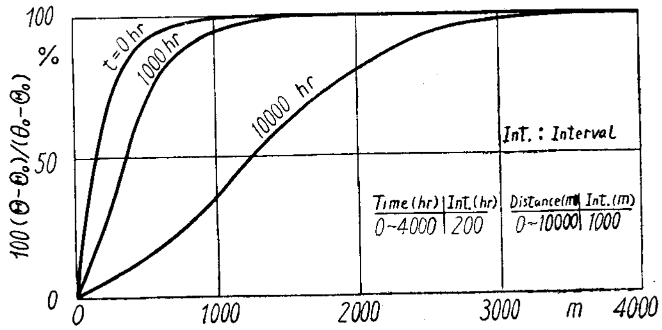


Fig. 2. The fineness of the divisions, I.

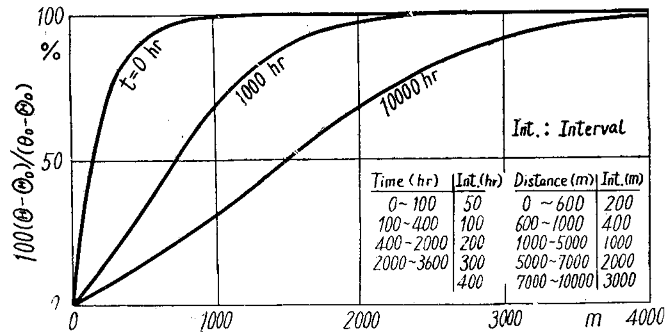


Fig. 3. The fineness of the divisions, II.

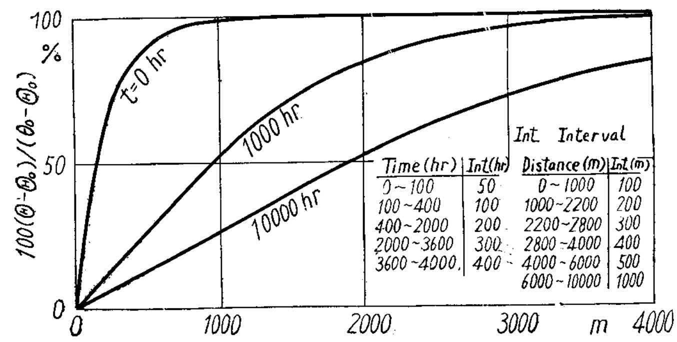


Fig. 4. The fineness of the divisions, III.

2.3. Discussion on the Approximate Calculation

(1) The fineness of the division of time and distance.

In the approximate calculation, it is a matter of course that the finer the division, the more accurate the result obtained. To what extent of fineness the division should be made depends upon actual individual case.

For example, the relations between the rate of air temperature rise ψ and the distance z along the airway (see 3.2.) obtained from the calculations based upon rough, medium, and fine divisions, I, II, III, are as shown in Fig. 2, 3, 4, assuming that $r_1=2$ m, $w=7200$ m/hr, $\alpha=10$ kcal/m^2 hr °C, $\lambda_g=2.0$ kcal/m hr °C. It is noticed in these figures that there is considerable difference between the results of I and II, however, it appears that only a small difference is noticed between those of II and III. In order to obtain an accurate result, finer divisions than III is preferable, but we are compelled to satisfy ourselves with the division III because the calculation with finer divisions than that requires enormous time and effort.

(2) On the process of determining wall temperature.

Comparing the temperature distribution in the rock in a real case with that in an imaginary case in which the rock is cooled by air current of constant temperature, it is noted that the air and wall temperature, the temperature gradient in the laminar sublayer in contact with the wall surface, and the temperature of the part of the rock beyond a sufficient distance from the wall surface of the former are equal to those of the latter because the heat transfer coefficients of both the airways are equal. But it is felt that the temperature distributions of both the rock masses may be somewhat different. The temperature distribution determined experimentally in the rock mass around East 2nd Level, Yotsuyama Coal Mine, by Mr. D. Miyazaki, is shown in Fig. 5 with a solid line.[6] This actual survey has been conducted 62,000 hours after the level was driven. The hydraulic mean radius of the level was about 2 m, and the mean air velocity was 7200 m/hr and the ground temperature of 40°C was noted at the time of the survey. As the level is driven in sandstone, estimating that $\kappa=0.002$ m^2/hr, $\lambda_g=1.0$ kcal/m hr °C and $\alpha=10$ kcal/m^2 hr °C, and introducing $\Theta=23$°C, $\theta_w=23.36$°C, we can find, by making use of the Curve E in Fig. 7 which is drawn on the basis of Eq. (9), that the imaginary time t' for this level is about 50,000 hours. Substituting t by t' obtained above in Eq. (8) and putting $r_2=100$ m (see 2.3. (3)), the theoretical temperature distribution in radial direction can be calculated as shown with a dotted line in Fig. 5. Since there is not much difference between the actual and the theoretical temperature distributions shown in Fig. 5, our method of estimating wall temperature may be allowed.

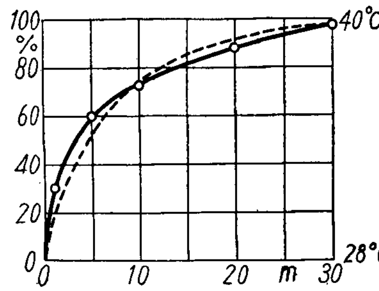


Fig. 5. The temperature distribution in the rock around East Second Level, Yotsuyama Coal Mine.

(3) The depth where no more temperature change is recognized.

It is evident that the more terms in the series in Eq. (9) are taken, the more accurate the results obtained will be, but at the same time the operation will become more troublesome and at last it will be impossible. Therefore, we shall consider whether or not it is possible to perform accurate calculation to serve a practical purpose using a few number of terms sufficient to make the operation possible. Experience and scrutiny show that more terms are needed as the ratio r_2/r_1 increases or time t decreases.

Doubtless, the cooling reaches deeper part in a semi-infinite body, on the surface of which heat transmission takes place, than in an infinite body with a cylindrical opening, on the surface of which heat transmission takes place. As the analysis of heat transmission in the former is far easier than that in the latter, we shall find the depth x_t where cooling effect is hardly recognized in a semi-infinite body for the purpose of determining r_2 for an infinite body.

Taking direction x normal to the surface of the semi-infinite body and assuming $\theta=\theta_0$ for $t=0$ and $\frac{\partial\theta}{\partial x}=h(\theta-\Theta)$ for $x=0$, we can derive the following Equation (11) by solving the fundamental Equation (10).

$$\frac{\partial\theta}{\partial t}=\kappa\frac{\partial^2\theta}{\partial x^2}, \tag{10}$$

$$\left.\begin{aligned}\frac{\theta-\Theta}{\theta_0-\Theta}&=\phi\left(\frac{x}{2\sqrt{\kappa t}}\right)+e^{hx+h^2\kappa t}\left\{1-\phi\left(\frac{x}{2\sqrt{\kappa t}}+h\sqrt{\kappa t}\right)\right\},\\ \phi(y)&=\frac{2}{\sqrt{\pi}}\int_0^y e^{-y^2}dy.\end{aligned}\right\} \tag{11}$$

Now, let us find the relation between x and t so that the ratio almost equal to a unity.

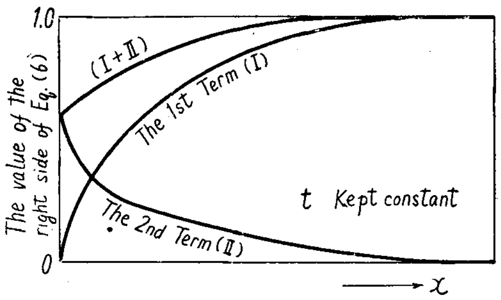


Fig. 6.

The right side of Eq. (11) is a unity for $t=0$, or it converges into a unity for $x\to\infty$. As we are discussing a case in which t is not zero, x must mathematically be infinite to make the right side of Eq. (11) equal to a unity. The values of the terms in the right side of the equation vary with x as shown in Fig. 6. It is noted from this figure that the first term in Eq. (11) increases with x and approaches a unity, while the second term approaches zero, and the left side of the equation becomes almost equal to a unity as soon as the depth x becomes so great the first term of the right side becomes almost equal to a unity. Let x_t be the depth x when the above mentioned state is realized, namely:

$$\phi\left(\frac{x_t}{2\sqrt{\kappa t}}\right) \simeq 1 . \tag{12}$$

To obtain an accuracy to four places of decimals, we can write it as

$$x_t/2\sqrt{\kappa t} \geqq 3 , \tag{13}$$

or

$$r_2 \geqq r_1 + 6\sqrt{\kappa t} . \tag{14}$$

As for the infinite rock mass with a cylindrical opening, we suggest to use Eq. (14) to find r_2, the distance from the center of an airway where almost no influence of air current is effected.

For the reason stated above, Eq. (14) is a safe assumption.

For example, it will be admitted to take $r_2 = 12$ m, for $t < 800$ hours, $r_2 = 30$ m, for $800 \text{ hr} < t < 6000$ hr and $r_2 = 100$ m for $t > 6000$ hr, assuming $\kappa = 0.003 \text{ m}^2/\text{hr}$.

3. Results of Calculation

3.1. Conditions Employed

Since the usefulness of the results depends much on the conditions selected, we have paid great attention to determine the conditions to be employed in the approximate calculation.

Thermal conductivity and thermal diffusivity of the rock: As the thermal conductivities of several rocks are nearly uniform in magnitude, it is taken as $\lambda_g = 1$ kcal/m hr °C, a representative value. Assuming $\gamma_g = 2500 \text{ kg/m}^3$, $C = 0.2$ kcal/kg °C, we get $\kappa = \lambda_g / c\gamma_g = 0.002 \text{ m}^2/\text{hr}$. In order to present a datum for adjustment of the results of calculation for the different values of λ_g, a set of calculation has been carried out for $\lambda_g = 2$ kcal/m hr °C, $\kappa = 0.004 \text{ m}^2/\text{hr}$.

Specific weight and specific heat under constant pressure of air:

$\gamma_a = 1.2 \text{ kg/m}^3$, $C_p = 0.24$ kcal/kg °C.

Radius of airway: $r_1 = 1, 2, 3$ m.

Air velocity: $w = 3600, 7200, 14400$ m/hr for $r_1 = 1$ m,
$w = 3600, 7200, 14400$ m/hr for $r_1 = 2$ m,
$w = 7200, 14400$ m/hr for $r_1 = 3$ m.

Heat transfer coefficient: The heat transfer coefficient is shown as a function of the Reynolds' number, of the coefficient of friction ξ, and of the dimension of the airway and so on. The function for the underground airways, however, has not yet been fully established. The authors have carried out theoretical and experimental studies on this problem, and have obtained the following equation:

$$\alpha = \lambda_a \xi w / 8\nu , \tag{15}$$

where ν is the kinematic viscosity of air. In our calculation, Eq. (15) has been adopted.

Putting $\xi=0.03$, $\lambda_a=0.02$ kcal/m hr °C, $\nu=3600\times1.5\times10^{-5}$ m²/hr in Eq. (15), we have decided the heat transfer coefficient for each case as shown in Table 2. In order to present data for adjustment of the results of calculation for different values of α, two sets of calculation have been worked out for the values of α: one set with a half the value and another with a quarter of the value described above.

Coordinating what have been described above, the conditions employed in our calculations are tabulated in Table 2.

Table 2.

	r_1 (m)	w (m/s)	α (kcal/m²hr°C)	h (m⁻¹)	λ_g (kcal/m²hr°C)	$\kappa\times10^3$ (m²/hr)	Q (m³/min)
A	1	1	5	5	1	2	188
B	1	2	10	10	1	2	377
C	1	4	20	20	1	2	754
D	2	1	5	5	1	2	754
E	2	2	10	10	1	2	1510
F	2	4	20	20	1	2	3020
G	3	2	10	10	1	2	3390
H	3	4	20	20	1	2	6790
I	2	2	5	5	1	2	1510
J	2	2	2.5	2.5	1	2	1510
K	2	2	10	5	2	4	1510

3. 2. Calculation

As a preliminary work, the change of wall temperature with time has been calculated for every condition, assuming the air temperature is kept constant. The results are as plotted in Fig. 7. Dividing time and distance in the same manner as the fine divisions III (see 2. 3. (1)), and making use of Fig. 7, the temperature change of air

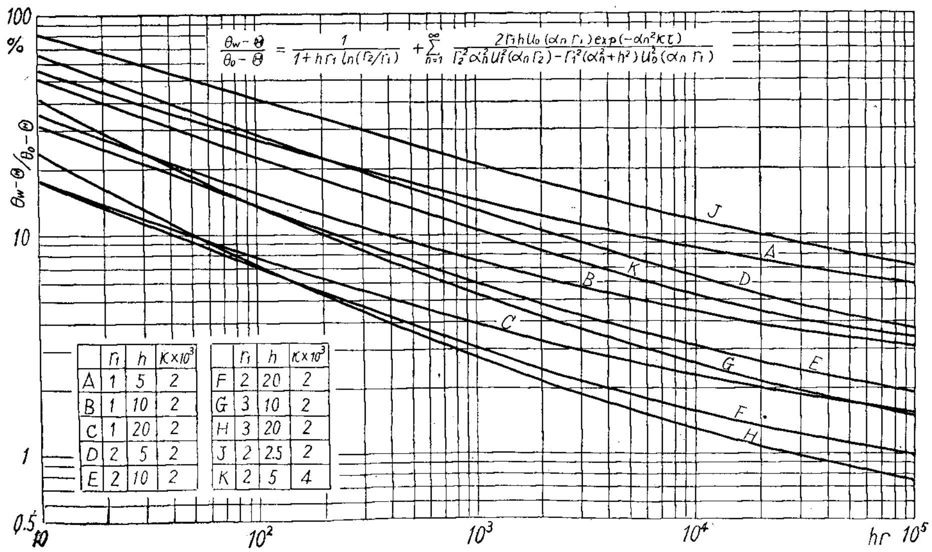
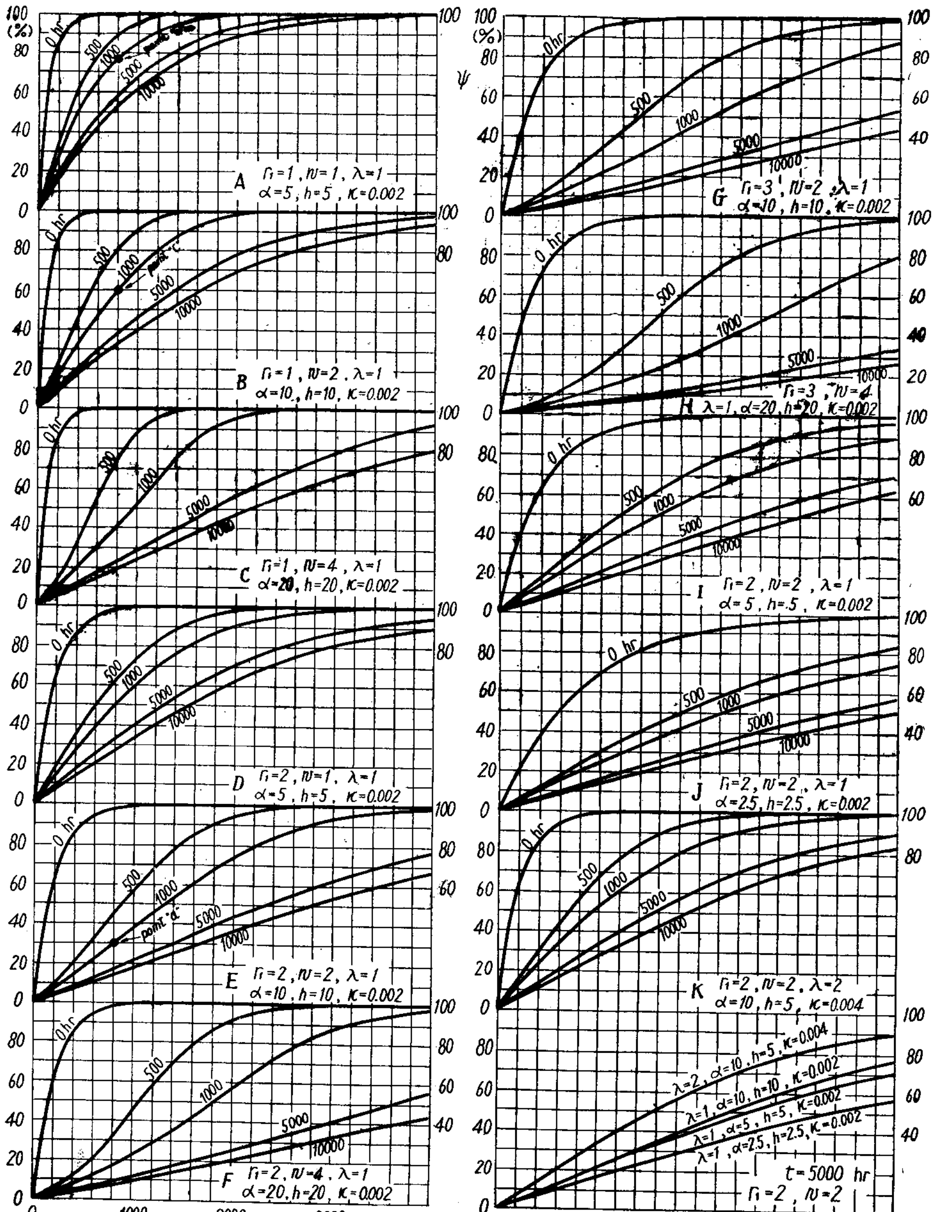


Fig. 7. The change of wall temperature with time.



(%)
ψ
0 hr
500
1000
5000
10000
A ri=1 , ru=1 , λ=1 α=5 , h=5 , κ=0.002
B ri=1 , ru=2 , λ=1 α=10 , h=10 , κ=0.002
C ri=1 , ru=4 , λ=1 α=20 , h=20 , κ=0.002
D ri=2 , ru=1 , λ=1 α=5 , h=5 , κ=0.002
E ri=2 , ru=2 , λ=1 α=10 , h=10 , κ=0.002
F ri=2 , ru=4 , λ=1 α=20 , h=20 , κ=0.002
G ri=3 , ru=2 , λ=1 α=10 , h=10 , κ=0.002
H ri=3 , ru=4 λ=1 , α=20 , h=20 , κ=0.002
I ri=2 , ru=2 , λ=1 α=5 , h=5 , κ=0.002
J ri=2 , ru=2 , λ=1 α=2.5 , h=2.5 , κ=0.002
K ri=2 , ru=2 , λ=2 α=10 , h=5 , κ=0.004
λ=2 , α=10 , h=5 , κ=0.004
λ=1 , α=10 , h=10 , κ=0.002
λ=1 , α=5 , h=5 , κ=0.002
λ=1 , α=2.5 , h=2.5 , κ=0.002
t=5000 hr
ri=2 , ru=2
Z(m)

current with time has been calculated by means of the method explained in 2.2. for each condition in Table 2. Plotting the rate of air temperature rise ψ against the distance travelled and taking time as a parameter the results obtained are as shown in Fig. 8 $A \sim K$. The temperature change for any intermediate condition can be estimated in interpolation. Frequently, however, lack of data takes place to carry out interpolation. In such cases, therefore, it must be estimated without interpolation.

Example 1. Find the air temperature of a point, 800 m from the entrance of an airway, 2 m in radius, driven in the rock of 40°C, after 1000 hours from the beginning of ventilation, assuming that air of 28°C is supplied from the entrance at the rate of 2 m/s i.e. 1510 m^3/min.

Assuming $\lambda_g = 1.0$ kcal/m hr °C, $\kappa = 0.002$ m^2/hr, $\alpha = 10$ kcal/m^2 hr °C, it is found from the point "a" in Fig. 8 E, that the rate of temperature rise is 29 per cent, so the air temperature is 31.5°C after 1000 hours have passed.

Example 2. Find the air temperature of a section, 800 m from the entrance of an airway, 10 m^2 in sectional area, supported with rail arches, and ventilated at the rate of 1000 m^3/min i.e. 1.67 m/s, after 1000 hours from the beginning of ventilation, assuming that the ground temperature, the air temperature at the entrance and the kind of rock are equal to Example 1 respectively.

Estimate $\xi = 0.05$, the periphery $U = 12.6$ m and $\lambda_g = 1.0$ kcal/m hr °C, $\kappa = 0.002$ m^2/hr, $\lambda_a = 0.02$ kcal/m hr °C, $\nu = 1.5 \times 10^{-5}$ m^2/s, then we obtain

$$r_1 = 1.59 \text{ m}, \qquad \alpha = \lambda_a \xi w / 8\nu = 13.9 \text{ kcal/m}^2 \text{ hr °C}.$$

Now, from the point "b" in Fig. 8 A and point "c" in Fig. 8 B, it is found that $\psi = 78$, 59 per cent for $w = 1.0$, 2.0 m/s respectively for an airway, 1 m in radius. From the point "d" in Fig. 8 D, and point "a" in Fig. 8 E, it is found that $\psi = 50$, 29 per cent for $w = 1.0$, 2.0 m/s respectively for another airway, 2 m in radius. We can estimate

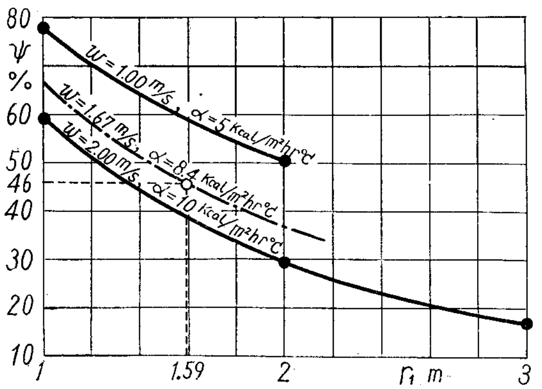


Fig. 9 A.

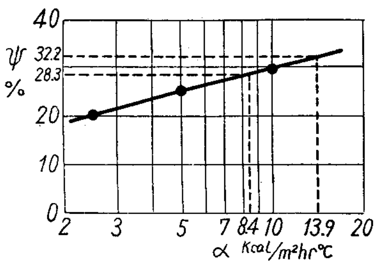


Fig. 9 B.

$\psi=46$ per cent for $r_1=1.59$ m, $w=1.67$ m/s by interpolation as shown in Fig. 9 A using the values of ψ above mentioned. But this percentage corresponds approximately to $\alpha=8.4$ kcal/m^2 hr °C, while the value of α in this problem is 13.9 kcal/m^2 hr °C. The correction for ψ due to the difference in the value of α is found to be about 3.9 per cent from Fig. 9 B which is based upon Fig. 8 I and J. Therefore, we get $\psi \doteqdot 50$ per cent for $\alpha=13.9$ kcal/m^2 hr °C. Consequently, the temperature of the air in question is estimated to be approximately 34°C.

4. Conclusion

From the approximate calculation of the rate of air temperature change in underground airways, we have obtained several instructions concerning the cooling of underground by air current as follows.

(1) In the early days of ventilation, the temperature of air current rises rapidly with distance travelled and this accounts for feeling cool only in the vicinity of the entrance of the airway. As time goes by, however, the air temperature drops and cooling gradually proceeds farther into the inner part of the airway. It is a matter of course that the greater the quantity of air, the more rapid the decreases of temperature. Consequently, it is not impossible to bring the temperature of air current down near to that of the air supplied. But, as

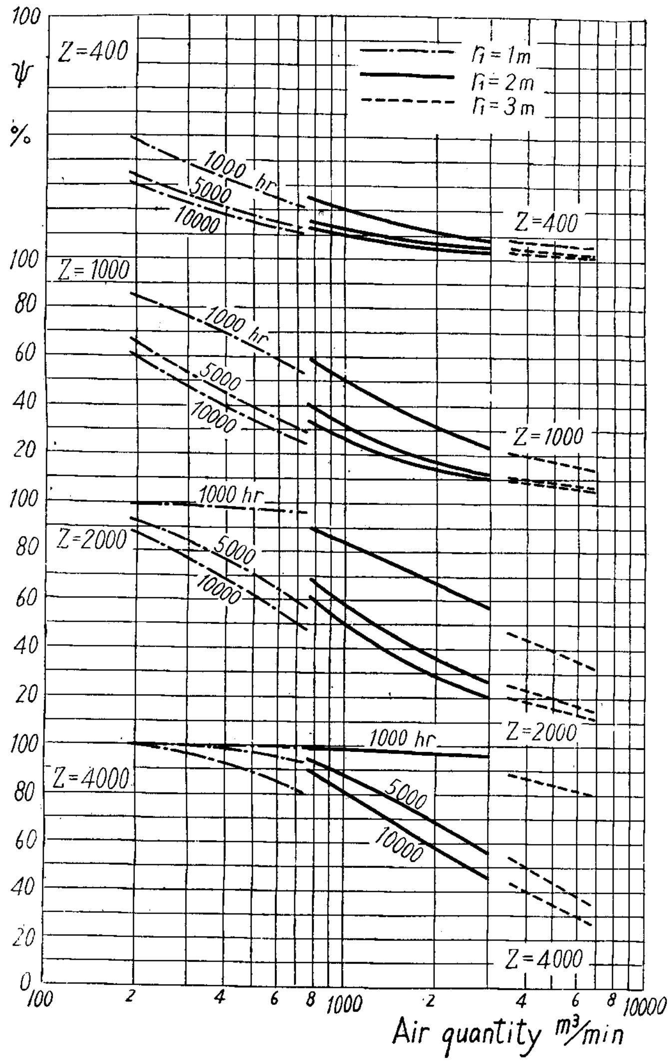


Fig. 10. The relation between the air quantity and the rate of air temperature rise ψ.

is seen in Fig. 8 and 10, the rate of cooling decreases with time passed as well as with increase in the quantity of air, and lowering of the temperature is not realized in practice merely by expending time or by ventilating greater quantity of air. It is concluded, therefore, that there is a certain limit in the applicability of the ventilation for the purpose of cooling. In short, the ventilation by which the air velocity exceeds several meters per second or such the ventilation which does not cool off the temperature of mines to a desired temperature within one year must be considered as an ineffective ventilation.

(2) As for the influences of several factors, the smaller the thermal conductivity or the heat transfer coefficient, and the higher the velocity, the more rapid the decreases of the air temperature. The heat quantity transmitted to the air decreases with decrease in the thermal conductivity or in the heat tranfer coefficient, but it grows with increase in the air velocity. Thus, efficient cooling of underground does not always mean reducing heat quantity from the rock and is contrary to what one might imagine from the "cooling".

(3) In order to promote the effect of underground cooling, such means are available: (1) increasing air volume, (ii) lowering the thermal conductivity, and (iii) lowering the heat transfer coefficient. The effectiveness of these means can be examined by Fig. 8. As to (i), discussion must also be made from the standpoint of ventilation. In order to lower the thermal conductivity, there is nothing that can be done but to line the wall surface with materials of low heat conductivity. Pertaining to the heat transfer coefficient, the authors propose a new idea: that lowering of the resistance of an airway is effective to decrease the heat transfer coefficient; consequently, it makes the cooling effective, as shown in Fig. 8 I and J. Both the measures, of course, must be discussed also from the standpoint of economy.

(4) It is usually accepted that a smaller sectional area is preferable so far as air quantity is kept constant. From the disscussion on this idea from Fig. 10, it is found that there are cases indeed where a smaller sectional area is better, but there is a few cases in which it is not so; at any rate, it is apparent that the sectional area is of little worth consideration.

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