Temperature Determination in Hydrotechnical Works as a Variable of the Energy Change Between Air and Environment

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Abstract: Hydroenergetic works represent the major climate and ventilation problems in the rooms where they are made. The air temperature of these rooms is determined by two elements: the warmth that emanates from the massif, especially in great depths, and the humidity of air, which is seldom close to saturation. This paper studies these two elements solving the problem of parameter interaction (temperature - humidity) from an analytical point of view. The analytically obtained equations are experimentally validated through a case study.

Key words: - mass transfer coefficient, humidity balance, temperature variation on lineal meter per hydro technical work, hydro-energetically installations, real gases, convection coefficient.

1 Thermal Energy – Temperature Interaction

1.1. Introduction

Both the mining works for preparation and the hidrotechnic ones have an axial delimiting area, close to the semispherical one. The semispherical surface temperature becomes more important for convective surrounding this energy change between air and wall, as an exterior environment for air, contributes to establish the climate conditions and air flow calculation for these works.

The wall temperature for these works may be measured by special thermometers, for future estimations or recalculations. For the design phase, this (temperature), may be obtained by solving the differential equation of the conduction of an object, infinite cav limited by the spherical area, to the law of heat conduction heat transfer law of the massif and air cooling.

A spherical area S, with a radius r_0, is considered, where there is an air circulation of a temperature T_a. T_r, (figure 1) is for the exterior environment temperature, $T_a < T_r$ and a radius r.

The solid environment is supposed to be uniform and isotropic, having the temperature independent physical constants λ, c, ρ. Where :

λ the thermal conduction coefficient, in $\frac{W}{m \cdot {}^0C}$;

c – the specific heat of the rock massif, in $\frac{J}{kg \cdot K}$;

ρ – the rock massif density, in $\frac{kg}{m^3}$.

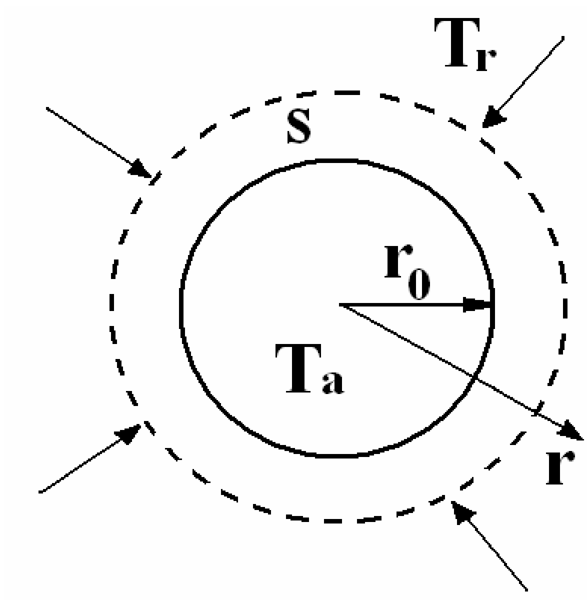

Fig.1 The air receives the temperature from the environment

There are no heat sources inside the considered area. The temperature variation of the sphere now depends on the radius r and on the period of time t.

1.2 Results and discussion

The one-dimensional differential equation of conduction through the sphere is:

$$\frac{\partial T}{\partial t} = a \cdot \left[\frac{\partial^2 T}{\partial r^2} + \frac{2}{r} \cdot \frac{\partial T}{\partial t} \right] \tag{1}$$

Equation (1) may also be written as:

$$\frac{\partial (r, T)}{\partial t} = a \cdot \frac{\partial^2 (r, T)}{\partial r^2} \tag{2}$$

where a is the thermal diffusion, in $m^2 \cdot s^{-1}$.

The domain for independent variables is for t = 0, $T = T_r$, and respectively for t > 0, $T \to T_r$, when $r \to \infty$.

The contour equation between the wall and the air is:

$$-\lambda \cdot \frac{\partial T}{\partial r}\Big|_{r=r_0} + \alpha \cdot (T - T_a)_{|r=r_0} = 0 \tag{3}$$

where α the contour convection coefficient.

The heat change is unstable, and the air temperature is modified by the theory:

$$T_a = \Delta T \cdot e^{-\omega t} \tag{4}$$

where:

ω is the frequency of the periodic oscillation of the atmospheric temperature;

ΔT – the amplitude of air temperature modifications;

t – the considered period of time.

Using this particularisation, replacing the relation (4) in (3), the contour equation becomes:

$$-\lambda \cdot \frac{\partial T}{\partial r}\Big|_{r=r_0} + \alpha \cdot \left(T - \Delta T \cdot e^{-\omega t}\right)_{|r=r_0} = 0 \tag{5}$$

For the heat change equation through conduction the Laplace transformation is applied (1) obtaining:

$$\frac{a \cdot d^2 p}{dr^2} - s \cdot p + r \cdot T_r = 0 \tag{6}$$

The equation (6) is a nonhomogenous linear equation with second degree constant coefficients depending on the unknown p.

It is considered that $p = r \cdot F$, where F is the image of T.

The homogenous equation with constant coefficients has the following format:

$$\frac{a \cdot d^2 p}{dr^2} - s \cdot p = 0 \tag{7}$$

for which the solution is:

$$p = c_1 \cdot e^{\sqrt{\frac{s}{a}} \cdot r} + c_2 \cdot e^{-\sqrt{\frac{s}{a}} \cdot r} \tag{8}$$

Finally, the final image of T is:

$$F(r,s) = \frac{T_r}{s} - Bi \cdot \frac{\left(\frac{T_r}{s} - \frac{\Delta T}{s + \omega}\right) \cdot e^{-\sqrt{s} \cdot \left(\frac{r}{r_0} - 1\right) \cdot \frac{r_0}{\sqrt{a}}}}{Bi \cdot \frac{r}{r_0} + r \cdot \sqrt{\frac{s}{a}} + \frac{r}{r_0}} \tag{9}$$

where $Bi = \frac{\alpha \cdot r_0}{\lambda}$ is the Biot criterion.

In order to convert the image into original the operational calculus tables are used obtaining the following criterial relation:

$$T = T_r - \frac{Bi \cdot T_r}{Bi + 1} \cdot \frac{r_0}{r} \cdot \left\{ Erfc \cdot \frac{\left(\frac{r}{r_0} - 1\right)}{2\sqrt{F_0}} - e^{\left(\frac{r}{r_0} - 1\right)(Bi+1)} \cdot \right.$$

$$\left. \cdot e^{F_0 \cdot (Bi+1)^2} \cdot Erfc \cdot \left[\sqrt{F_0} \cdot (Bi + 1) + \frac{\frac{r}{r_0} - 1}{2\sqrt{F_0}} \right] \right\} + \tag{10}$$

$$+ \frac{Bi \cdot \Delta T}{Bi + 1} \cdot \frac{r_0}{r} \cdot \left[\frac{\sqrt{F_0}}{\sqrt{\pi \cdot t}} (Bi + 1) \cdot I_1 - \frac{F_0}{t} (Bi + 1)^2 \cdot I_2 \right]$$

where Erfc is the error function with the known expression:

$$\mathrm{Erfc}\,x = 1 - \frac{2}{\sqrt{\pi}} \int_0^x e^{-x^2}\,dx$$

For $r = r_0$, this function will allow to find the value of the temperature of the spherical wall of the executed work:

$$T_p = T_r - \frac{Bi \cdot T_r}{Bi + 1} \cdot \left(1 - e^{x^2} \cdot \mathrm{Erfc}\,x\right) + \Delta T \cdot \cdot Bi \cdot \sqrt{F_0} \cdot \left(\frac{I_1}{\sqrt{\pi \cdot t}} - x \cdot \frac{I_2}{t}\right) \quad (11)$$

where:

$$x = \sqrt{F_0} \cdot (Bi + 1)$$

The first integral may be written:

$$I_1 = \int_0^t \frac{e^{-\omega \cdot (t-T)}}{\sqrt{T}}\,dT = 2 \cdot e^{-\omega \cdot t} \cdot \sum_{n=0}^{\infty} \frac{\omega^n \cdot t^{\frac{2 \cdot n + 1}{2}}}{n! \cdot (2n+1)} \quad (12)$$

The second integral may be written:

$$I_2 = \int_0^t e^{-\omega \cdot (t-T)} \cdot e^{b^2 T} \cdot \mathrm{Erfc}\left(b\sqrt{T}\right) dT = = 1 - \frac{2 \cdot b\sqrt{T}}{\sqrt{\pi}} \sum_{n=0}^{\infty} (-1)^n \cdot \frac{b^{2 \cdot n}}{n! \cdot (2n+1)} \cdot T^n \quad (13)$$

where:

$$b = \frac{\sqrt{a}}{r_0} \cdot (Bi + 1)$$

The dimensional form of the wall temperature of the spherical area is obtained analogically with the hypothesis that the temperature of the air T_a is invariable in time.

The analytically obtained result with the equation (11) is only theoretical. Thus, an experimental check is imposed, starting from primarily data of a hydrotechnical work.

The two integrals I_1 şi I_2 will be applied only with the firs terms, without affecting the precision of the calculus:

$$\Phi_p = \frac{T_p - T_a}{T_r - T_a} = 1 - \frac{Bi}{Bi + 1} \cdot \left(1 - e^{x^2}\ \mathrm{Erfc}\,x\right) \quad (14)$$

$$I_1 = 2 \cdot e^{-\omega t} \cdot \left(\sqrt{t} + \frac{\omega}{3} \cdot t^{1.5} + \frac{\omega}{10} \cdot t^{2.5} + \ldots\right)$$

$$I_2 = e^{-\omega t} \cdot \left(t - \frac{4}{3} \cdot \frac{b}{\sqrt{\pi}} \cdot t^{1.5} + c \cdot \frac{t^2}{2} + \ldots\right)$$

where:

$$\omega = \frac{2 \cdot \pi}{24} = 0.2616\,;$$

$$c = \omega + b^2\,;$$

$$\sqrt{a} = \sqrt{10^{-6}}\,;$$

$$t = 8 \quad \text{hours.}$$

The relations (11) and (14) represent the criterial expressions in Fo and Bi.

The criterial equation (11), for the slightly widened invariable Bi is described in Figure 2, and the adimensional temperature may be obtained from the monogram in Figure 3.

For the ongoing hydrotechnical works which may be assimilated as semispherical, the ventilation is always made under the action of secondary fans depression, the air speed being reduced. Resulting a convection coefficient α with small values and in consequence the criterion Bi is found between the limits $Bi = 1 \div 8$.

On the other hand the hydrotechnical work is permanently advancing, thus the time t in the Fourier criterion may be from several hours to at the very most 24 hours. In consequence, the Fourier criterion has reduced values $Fo = 0.01 \div 0.1$.

The use of graphs in figure 2 and figure 3 is practically reduced to determining the temperature of the wall for the hydrotechnical work depending on the two criteria.

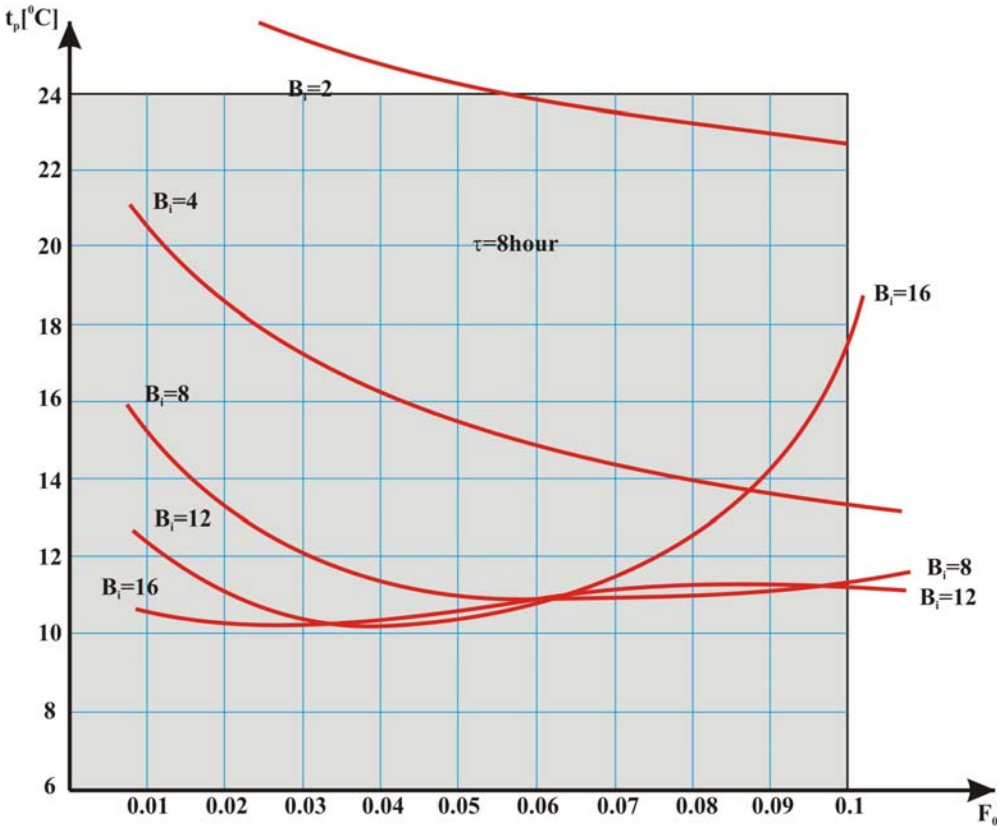

Fig.2 Hydrotechnical wall temperature variation depending on the two criteria Fo si Bi

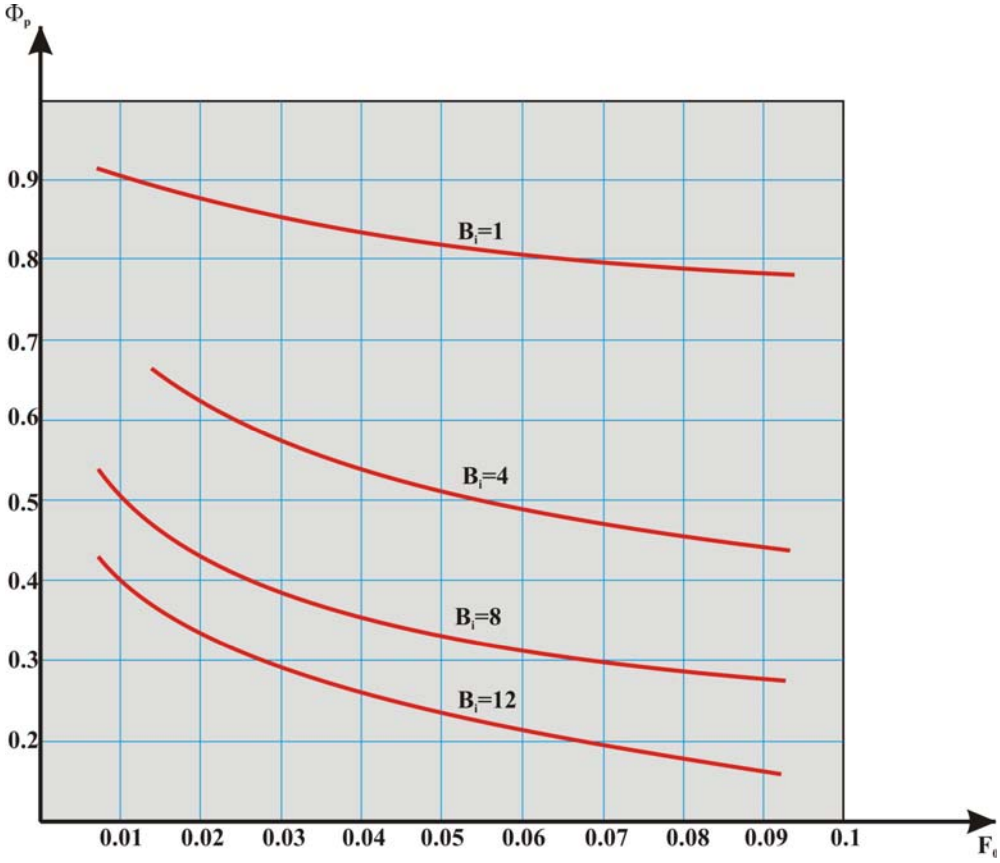

Fig.3 The adimensional temperature according to Fo si Bi criteria

2. The influence of moisture on air temperature in underground rooms

2.1. Introduction

Comfort, in some mining activities or productive hydro energetic activities rooms, is highly influenced by the air humidity. Humidity influences the physiology of organisms and produces negative effects on technical installations in these rooms.

Air pressure, in these rooms, does not significantly oscillate, being almost the same as the atmospheric pressure outside. When works are being executed at a higher depth, signify changes of pressure occur. Due to the lowered pressure in these rooms, the evaporation of water vapours is possible even at lower temperatures than the one corresponding to the barometric pressure.

2.2 Calculus Method

Air humidity is calculated by the following known relation:

$$x = 10^{-3} \cdot d = 0{,}622 \cdot \frac{\varphi \cdot f(t)}{B - \varphi \cdot f(t)} \left[\frac{\text{kg vapour}}{\text{kg dry air}}\right] \qquad (15)$$

where:
B - is the barometric pressure;
φ - relative humidity;
f(t) - the pressure of the saturated vapours at temperature t.

But when almost reaching the condensation point, water vapours will no longer respect the Perfect Gas Law, thus they cannot be considered real, leading to the several equations.

For this hypothesis we are going to take into consideration E. Schmidt’s equation:

$$v = \frac{R \cdot T}{p} - \frac{b}{\left(\frac{T}{100}\right)^{n_1}} - p^2 \cdot \left[\frac{c}{\left(\frac{T}{100}\right)^{n_2}} - \frac{d}{\left(\frac{T}{100}\right)^{n_3}}\right] \qquad 16)$$

where:
v is the specific volume;
T – the absolute temperature of the moist air;
p – the pressure of the moist air;
R – nature constant of the moist air;

The exponents n_1, n_2, n_3 are coefficients determined from specialty literature.

Clapeyron Equation for dry air is the following:

$$p_a \cdot V = m_a \cdot R_a \cdot T \qquad (17)$$

Moreover, the natural air stream or the air circulating through the ventilation system is in contact with certain open areas of water or with very humidified walls or walls on to which water a thin layer of water may be flowing. When water vapours reach a temperature below the condensation point they condense on the contacted areas. The condensed quantity is negatively influencing the machineries and the equipment.

In this paper, the influence of air humidity over the temperature of the areas traversed by the air stream and the value of the convective coefficient between air and the objects bounding its flow. The value of this coefficient is very little known, thus we consider that its determination is useful both for those who work in such climate conditions and for the designers of ventilation systems.

where:
m_a is the dried air mass;
R_a – dried air nature constant;
p_a – the partial pressure of the dried air;
V – moist air volume;

The humidity level results from the two equations:

$$x = \frac{p_v}{p_a} \cdot \left\{1 + \frac{b \cdot v_v^{-1}}{\left(\frac{T}{100}\right)^{n_1}} + p_v^2 \cdot v_v^{-1} \cdot \left[\frac{c}{\left(\frac{T}{100}\right)^{n_2}} + \frac{d}{\left(\frac{T}{100}\right)^{n_3}}\right]\right\} = \frac{m_v}{m_a} \cdot \frac{R_v}{R_a} \qquad (18)$$

where index "v" it refers to water vapours, and index "a" to dry air.

It appears a coefficient that can be calculated knowing the values of a, b, c, d and m from literature and parameters p_v and v_v from diagrams and tables.

$$x = 0.622 \frac{\varphi \cdot f(t)}{B - \varphi \cdot f(t)} \cdot \left\{1 + \frac{b \cdot v_v^{-1}}{\left(\frac{T}{100}\right)^{n_1}} + p_v^2 \cdot v_v^{-1} \cdot \left[\frac{c}{\left(\frac{T}{100}\right)^{n_2}} + \frac{d}{\left(\frac{T}{100}\right)^{n_3}}\right]\right\} \qquad (19)$$

In relation (19) we neglect the last term of the parentheses, this doesn’t influence with relevant errors. So we obtain:

$$x = 0.622 \cdot \frac{\varphi \cdot f(t)}{B - \varphi \cdot f(t)} \cdot \left(1 + \frac{b \cdot v_v^{-1}}{\left(\frac{T}{100}\right)^{n_1}} \right) \qquad (20)$$

2.3 Problem Solving

From the specialty literature we know $b = 0.9172$ and $n_1 = 2.82$, and for $t = 20^0 C$, the searched correction coefficient has the value:

$$1 + \frac{b \cdot v_v^{-1}}{\left(\frac{T}{100}\right)^{n_1}} = 1 + \frac{0.9172 \cdot 57.8^{-1}}{\left(\frac{293}{100}\right)^{2.82}} = 1.01$$

In order to observe the modifications of air humidity on a hydro technical work length $\Delta y = 120\,\text{m}$ with a certain flow, on an area S, perimeter P and radius R_0, measurements have been made on both ends of the hydro technical work and the values have been inserted into table 1. It has been considered that the air is in a state close to saturation.

Temperature variation on lineal meter of air is obtained using the relation:

$$\Delta T = \frac{r}{c_p} \cdot \frac{\Delta x}{\Delta y} = \frac{2500 \cdot 10^3}{1011.6} \cdot \frac{0.00057}{120} = 0.01173 \frac{{}^0C}{m} \qquad (21)$$

where: r is the evaporation latent heat.

The simplifying hypothesis, has been taken onto consideration, where there are no other sources to contribute to the change of temperature.

The convection coefficient is another very important parameter for air contacting open areas of water or moist walls.

A.N. Şcerban considers the criterial equation:

$$Nu = \xi \cdot A \cdot Re^m \qquad (22)$$

Be it the case of turbulent ventilation we may consider $\xi = 1$, taking into account Nu and Re:

$$\alpha = 2.44 \cdot \frac{\dot{m}^{0.8} \cdot P}{S} \qquad (23)$$

where:

$\dot{m}$ is the air flow in kg/s;

P – hydro technical work perimeter in meters;

S – cross section of the hydro technical work in m^2.

There is also a mass transfer next to the heat transfer calculated using the relation no. (24):

$$\alpha' = \beta \cdot r \cdot \frac{p_v' - p_v}{t_p - t_a} \qquad (24)$$

where:

β is the evaporating mass coefficient in $\frac{kg}{m^2 \cdot h \cdot mbar}$;

p_v' - partial pressure of water vapours to the walls temperature in mbar;

p_v - partial pressure of water vapours in air in mbar;

t_p – wall's temperature in °C;

t_a – air temperature measured with a dry thermometer in °C.

If $\beta = 0.01$, is accepted in the speciality literature $\varphi > 0.8$, then the average coefficient through mass transfer becomes $\alpha' \cong 3 \frac{W}{m^2 \cdot K}$.

Table 1 - Air temperature variation

Flow and working geometry	
$\dot{m}$ [kg/s]	29.08
R_0[m]	1.59
S[m^2]	6.5
P[m]	8.19
$c_p \left[\frac{J}{kg \cdot K}\right]$	1011.6
Air humidity balance	
B[mmHg]	725.3
t_1[^{0}C]	16.4
t'_1[^{0}C]	15.58
φ_1[%]	92.3
x_1	0.0113
t_2[^{0}C]	16.0
t'_2[^{0}C]	15.9
φ_2 [%]	98.3
x_2	0.0118
Δx [m]	0.00057

The graph in Figure 4 is based on Table 1.

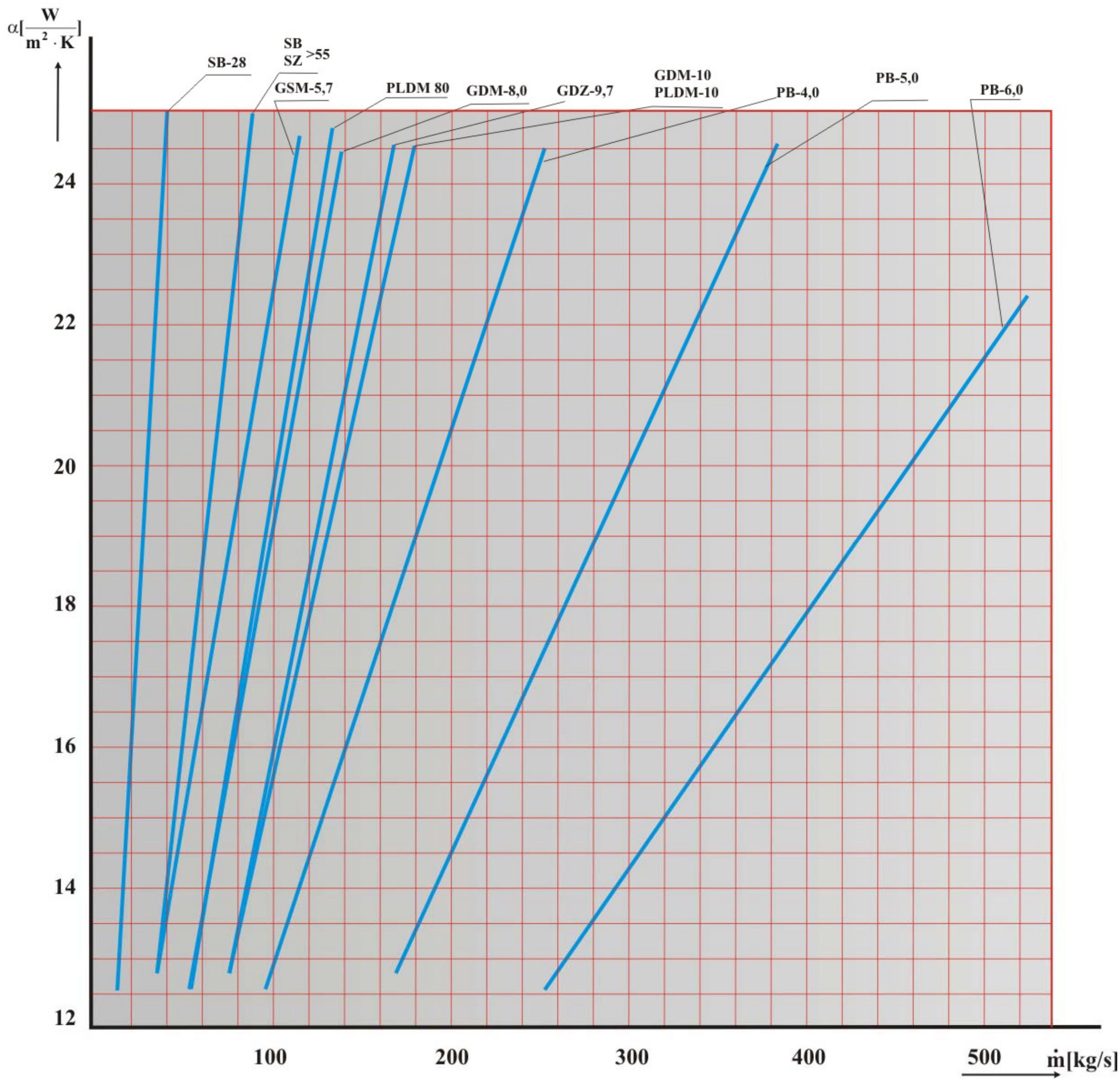

Fig.4 Convection Coefficient Dependency on the mass flow for different types of galleries/groves

Using the expression no (23) the values of the convection coefficient have been calculated and inserted into table 2.

The graph in Figure 5 has been drawn taking into consideration, the physical properties of air in the temperature interval, the speed of air comprised between $0.2 \div 8\ \mathrm{m/s}$, and the Tables 1 and 2.

The same result may also be reached by another criterial relation:

$$Nu = 0.46 \cdot Re^{0.57} \tag{25}$$

The convection coefficient α of the Nusselt criterium depends on the temperature, the physical properties of air and on the flow regime.

Explaining the relation no. (25), for hydro technical works, the following relation has been determined:

$$\alpha = 0.45 \cdot \frac{\lambda_a}{\upsilon_a^{0.58}} \cdot \frac{w^{0.58}}{d^{0.42}} = k(t) \frac{w^{0.58}}{d^{0.42}} \tag{26}$$

Where:
k(t) is a term depending only on temperature;
w – air speed in hydro technical works in m/s;
υ_a - relative sliminess of air in m^2/s;
λ_a - conduction coefficient of air, in $\frac{W}{m \cdot K}$.

Table 2. Convection Coefficient Values

Type of hydro technical work	Flow [kg/s]	Work Perimeter [m]	Cross Section [m^2]	Convection Coefficient [W/(m^2·K)]
Concrete Well	116 – 490	12.5 – 18.84	12.65 – 28.26	13.75 – 20.85
Double Metallic Grove	47 – 167	7.25 – 11.48	5.2 – 10.0	12.61 – 24.23
Inclined Planes	63 – 150	11.83 – 12.09	8 – 10	12.74 – 21.93
Winze	25 – 92	5.9 – 8.2	2.8 –5.3	14.29 – 25.64

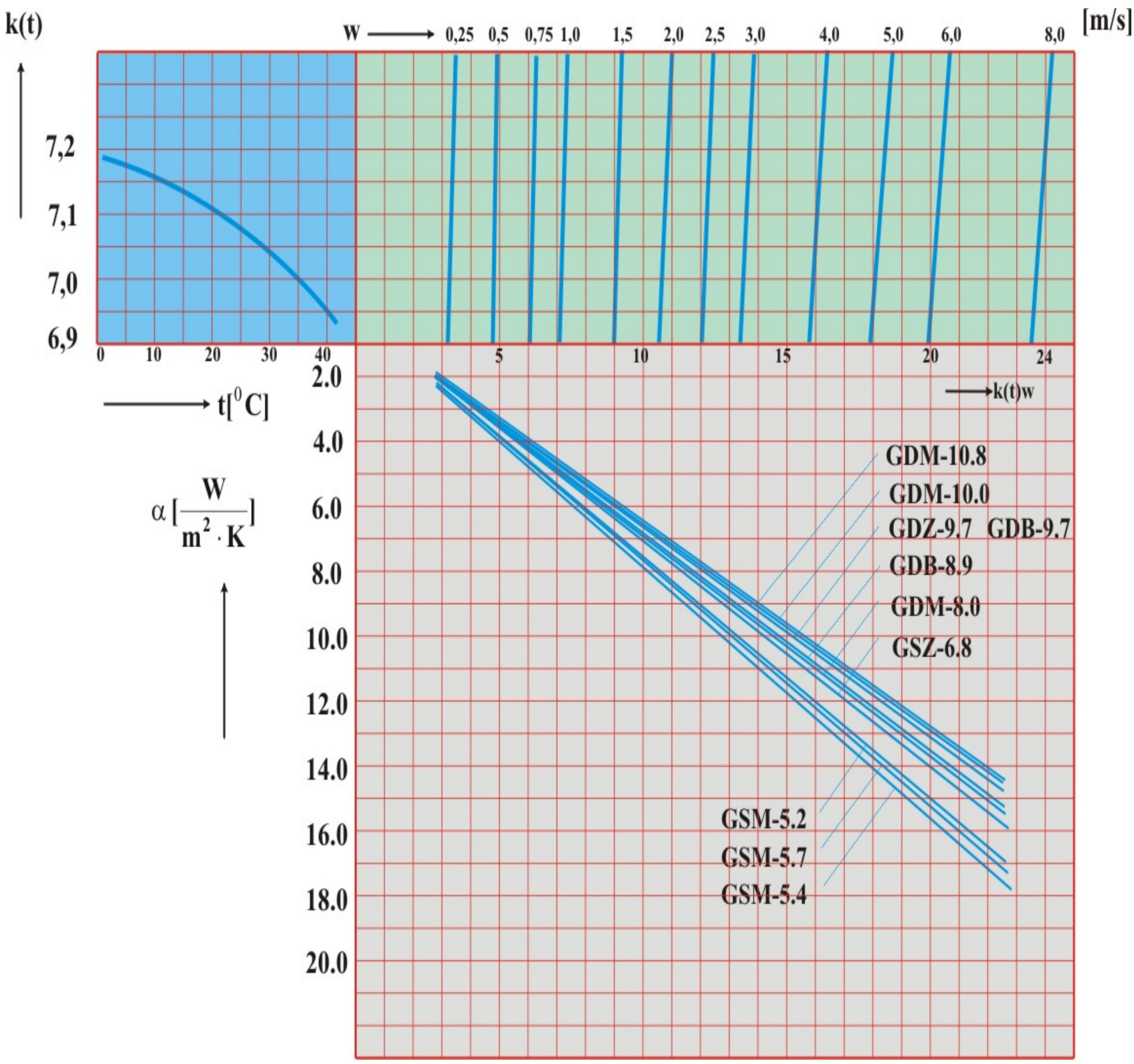

Fig.5 The convective coefficient depending on the geometry of the hydro technical work and on the mass flow

The temperature coefficient k(t) has values between the interval [2]

$$k(t) = 6.986 \div 7.1812 \frac{J}{m^{2.16} \cdot s^{0.42} \cdot K}$$

The following notes have been made in Figures 4 and 5:
GDM – double metallic gallery/grove;
GDZ – double walled gallery/grove;
GDB – double concrete gallery/grove;
GSM – simple metallic gallery/grove;
GSZ – simple walled gallery/grove;
PB – concrete well;
PLDM – double metallic inclined plane.

3 Conclusions

The underground hydroenergetics rooms should assure a climate where the activity can take place in full security conditions.

1. In order to solve special hydrotechnical problems, the amount of heat emanated from the underground massif to the circulating air through the hydrotechnical work needs to be known. Thus, a forecast of the rock massif temperature surrounding the artificial freezing pipe of water-bearing soils or for the underground access way heating in the winter may be achieved.

In these situations was solved the thermal conduction equation, for the works where the surface can be considerate spherical (equation 1). Hereunder, the temperature of the air that circulates in these works is modifying after the equation 4.

2. Solving the conduction equation, finally results a criteria equation in Fo and Bi (equation 11). Using the equation 11 was made the figure nr. 2, and so results the wall temperature value.

3. The θ_p value could be determinate very simple, using the figure nr. 3, function of the invariant Fo and Bi.

4. The convective coefficient α, at the work wall, could be obtained from the figure no. 4 function of the air mass flow and of the underground excavation type or may be taken from table 2.

5. The convective coefficient could be obtained also from the Nusselt equation, function of the temperature, speed and hydroenergetic work type, using figure nr. 5.

6. In order to simplify and unify the thermal calculations, the simplification of monogram lifting, experimental data hashing and hydrotechnical thermal processes modelling, the final formulas may be reduced to a simplified format for the stationary thermal calculations:

$$Q = k \cdot \left(T_r - T_a\right) \cdot S$$

where: k = f(t, r, λ, c, ρ, a...) is the unstationary heat change, obtained from the relation:

$$k = \alpha \cdot \phi_p = \alpha \cdot \frac{T_p - T_a}{T_r - T_a}$$

7. The value for the temperature variation per linear meter traversed by the air, according to the excess humidity influence for these works, has been calculated as follows: $\Delta t = 0.01173 \left[{}^0C \cdot m^{-1}\right]$. This value may be used for a determined length.

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