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Thermal State and Human Comfort in Underground Mining

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1. Introduction

The human metabolism is accompanied by heat generation, with the body temperature remaining constant near 36.9°C and in contact with surrounding atmospheric temperature; people have cooler or hotter sensations.
When people are exposed to a temperature greater than the threshold limits, it causes physiological effects expressed as follows: loss of interest in people's activities, taking frequent rests or breaks, a desire to quickly complete the task, irritability, reduced concentration and reduction in sensitivity.
A prolonged exposure of people to unfavourable thermal conditions inevitably leads to increase in body temperature and consequently producing physiological effects that affect the work efficiency. Figure 1 shows a relationship between work efficiency and effective temperature and air, wet temperature and air velocity. It may be noted that the prolonged exposure of a worker to temperature exceeding 42°C may even cause death.

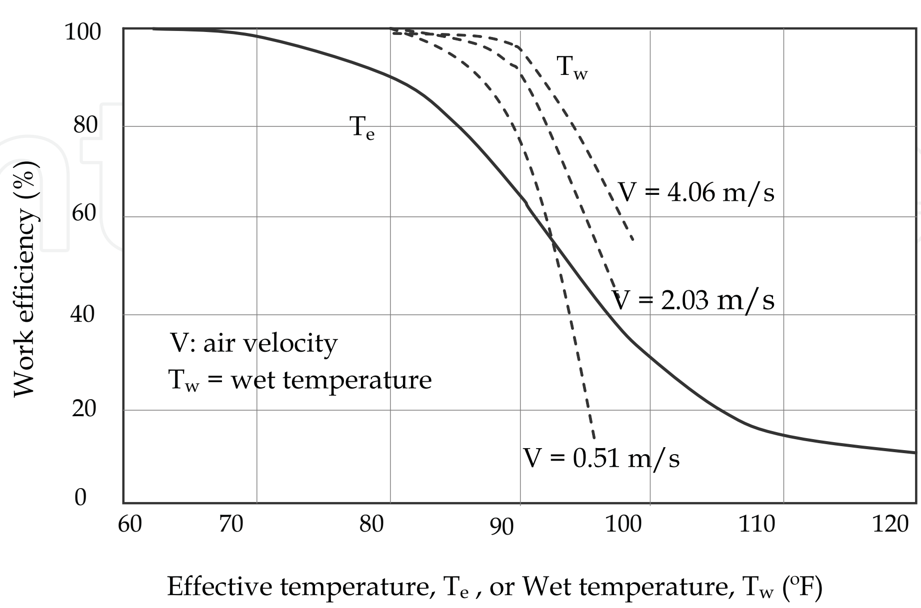

Fig. 1. Effect of temperature on work efficiency (Navarro, 2003, Ramani, 1992)

The temperature of intake air due to its passage through an underground opening gradually increases due to depth and the length of air travel through underground opening. The main cause of heat transfer to air flow in underground atmosphere is due to thermal properties of virgin rock, known as geothermal gradient. Other sources of heat to the air in underground atmosphere are air auto-compression, diesel emission, explosive detonation, human metabolism and influx of thermal water.

2. Mathematical model of heat transfer

The total variation of temperature in an underground environment Δt_{total} can be calculated by including the variation of temperature from air auto-compression Δt_a, thermal properties of rock Δt_r, heat emission from diesel equipments Δt_d, heat due to breaking of rocks with the use of explosives Δt_e, human metabolism Δt_h and thermal water Δt_w as outlined in equation (1):

$$\Delta t_{total} = \Delta t_a + \Delta t_r + \Delta t_d + \Delta t_e + \Delta t_h + \Delta t_w \quad (1)$$

With increasing mining depths, the influence of the thermal properties of the rock mass becomes more important (Navarro et al, 2008). Based on equation (1), the total underground atmosphere temperature T_2, will be expressed by equation (2), as a function of surface temperature t_s or underground opening initial temperature T_1.

$$T_2 = t_s + \Delta t_{total} \quad \text{or} \quad T_2 = T_1 + \Delta t_{total} \quad (2)$$

2.1 Surface air temperature

It is well known that the surface air temperature varies with the seasons and is subjected to regional variations according to local weather conditions, so that the temperature variation is influenced by the ventilation current temperature in underground openings.

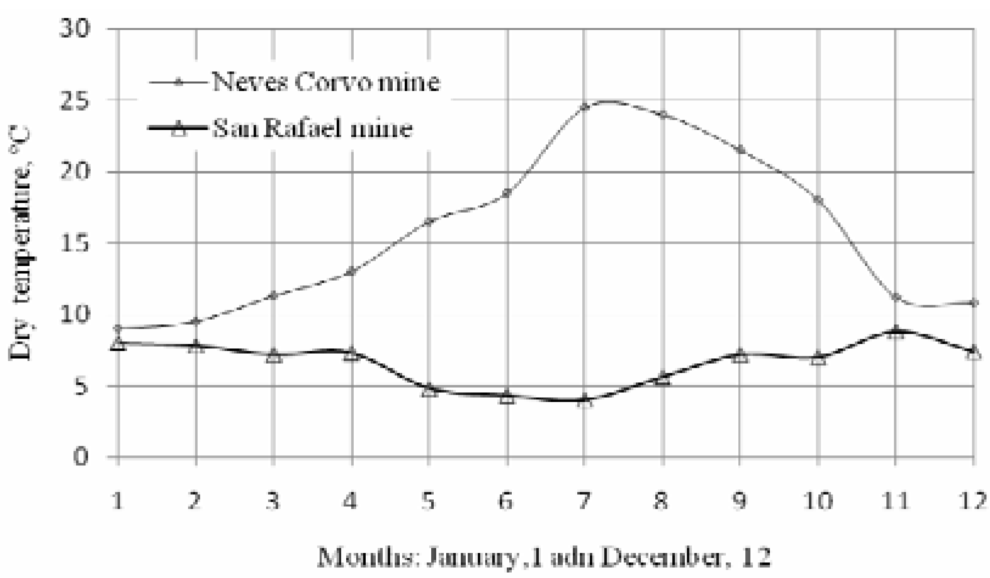

Fig. 2. Typical surface air dry temperature in Neves Corvo and San Rafael mines

Figure 2 indicates that average monthly surface temperature in Neves Corvo mine was maximum 24.5ºC in July, minimum 9.0ºC in January and mean being 15.6ºC and in San Rafel mines was maximum temperature was 8.8ºC in November, minimum 4ºC in July and mean being 6.61ºC. Surface air temperature variation throughout the year can be better illustrated with monthly average temperature measured in Neves Corvo and San Rafael mines (Figure 2). Neves Corvo mine is located in Portugal in North Hemisphere at 20º latitude and at altitude of 800m, but San Rafael mine located in Perú in South latitude at the altitude of about 4500 m. Temperature trend in Neves Corvo mine is similar to the metalliferous mines in Portugal with maximum variation range of 15 °C and temperature tendency in San Rafael mine is typical of the South American Andes with maximum variation range of 4.0 °C. Average dry bulb temperature measured in Neves Corvo mine stopes located at depth between 750 m to 770m, compared with variation of external dry bulb temperature, observed clearly the influence of outside temperature in underground openings (Figure 3). Therefore, the maximum temperature on the hottest month will be critical.

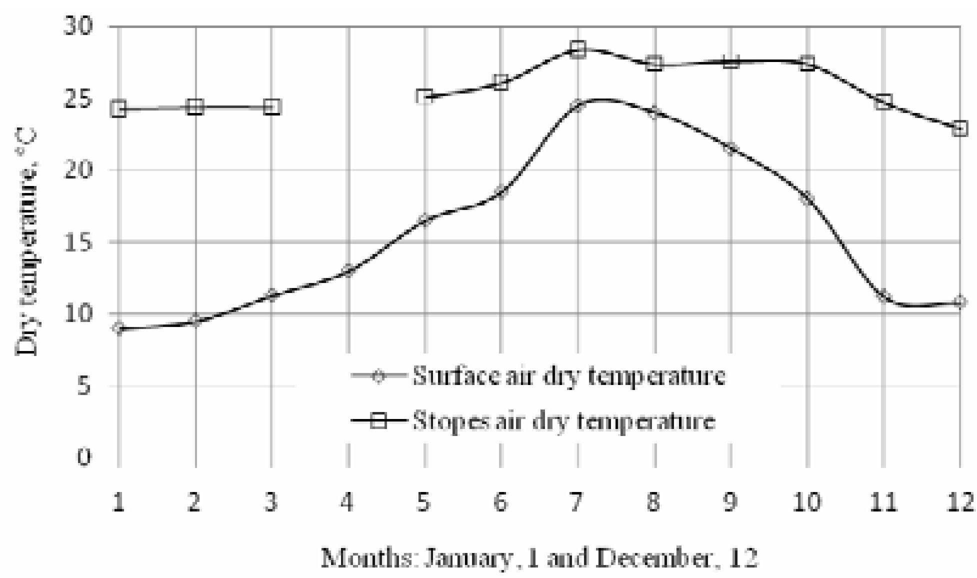

Fig. 3. Surface air temperature influencing underground openings air temperature

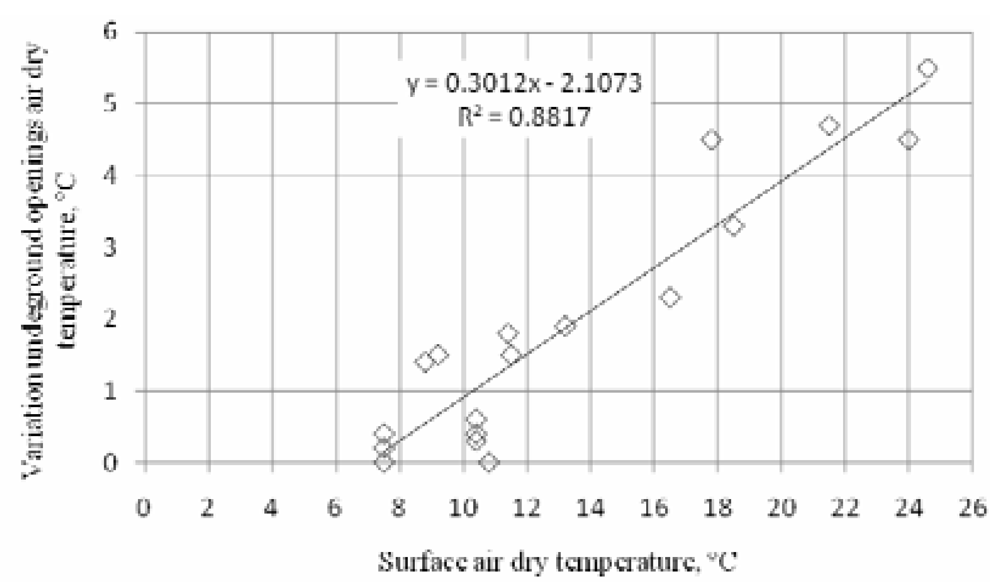

Fig. 4. Underground temperature variations as a function of surface air temperature

The surface air temperature can influence the temperature of air flow in the atmosphere of underground openings, since these are more than 7 °C, as in the Neves Corvo mine (Figure 4). This result indicates that during winter times or in mines located at large altitudes, such as the South America Andes, the outside temperature has little or no influence on the temperature of underground openings.

Moreover, as a part of an environmental thermal comfort assessment in deep underground mines, it is necessary to consider the surface temperature, because this is the initial temperature, t_1, of intake air to underground openings.

For similar conditions of Neves Corvo mine and at 750 m depth, variation in underground openings temperature, Δt_s, will be calculate by equation (3), based on surface air temperature, t_e.

$$\Delta t_s = 0.301 t_e - 2.107 \tag{3}$$

2.2 Heat transfer due to air auto-compression in vertical underground openings

Auto-compression process occurs during the air descent through the underground openings and due to its own compression. The mathematical model is deduced considering the equilibrium condition, air properties and the influenced of by vertical forces (Figure 5) expressed by air equilibrium condition as follows:

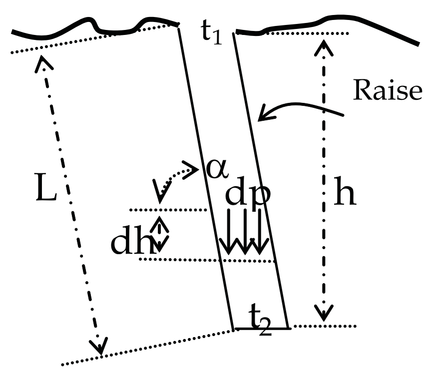

Fig. 5. Air auto-compression in inclined raise layout

$$g.dh - dp / \rho_a = 0 \tag{4}$$

Where, g is gravity, dh is depth differential, dp is pressure differential, ρ_a is air density. By substituting specific gravity γ and specific volume v *in* equation (4) the following expression is obtained:

$$dh = dp / \gamma = vdp \tag{5}$$

In adiabatic process $p.v^k =$ constant, when k is air adiabatic coefficient and differentiating results in equation (6) as follows:

$$v.dp + k.p.dp = 0 \tag{6}$$

Clapeyron equation $p.v = R.t_2$, where R is universal gases constant and t_2 is compressed air temperature, the following differential equation results:

$$p.dv = R.dt_2 - v.dp \tag{7}$$

Using equations (5), (6) and (7) equation (8) is obtained as follows:

$$dh + k(R.dt_2 - dh) = 0 \tag{8}$$

Integrating the equation (8) obtains the following expression (9) where *C* is constant:

$$(1-k)\int dh + k.R\int dt_2 = (1-k)h + k.R.t_2 + C = 0 \tag{9}$$

Rearranging equation (9), the temperature t_2 is obtained as follows:

$$t_2 = \frac{(k-1)h}{k.R} - C \tag{10}$$

For initial values *h*=0 and *t*=*t1*, the constant *C*=0, then *C*=-t_1, the adiabatic equation 9 result in equation 11 as follows:

$$\Delta t_a = t_2 - t_1 = \frac{(k-1)h}{k.R} \tag{11}$$

With numerical values of constant of perfect gases (R=29.27 kgf-m/kg-ºK) and average air adiabatic index (1.302) the final equation is obtained as follows:

$$t_2 - t_1 = 0.0098h \tag{12}$$

In general condition depth h will be expressed as a function of underground opening length L (m) and inclination α (º), as $h=LSin\alpha$ and finally, the temperature increase due air auto-compression Δt_a (ºC) results in following equation (Navarro Torres, 2003):

$$\Delta t_a = t_2 - t_1 = 0.0098L\sin\alpha \tag{13}$$

That means, when α=90º (vertical raise) for each 100 m air temperature increases by in 0.98ºC, for 200 m 1.96ºC, for 300 m 2.94ºC, for 400 m 3.92ºC, for 500 m 4.9ºC, for 650 m 6.37ºC, for 800 m 7.84 ºC and for 1000 m 9.8ºC. Therefore when α=0º (horizontal underground opening) auto-compression temperature is zero (Figure 6)

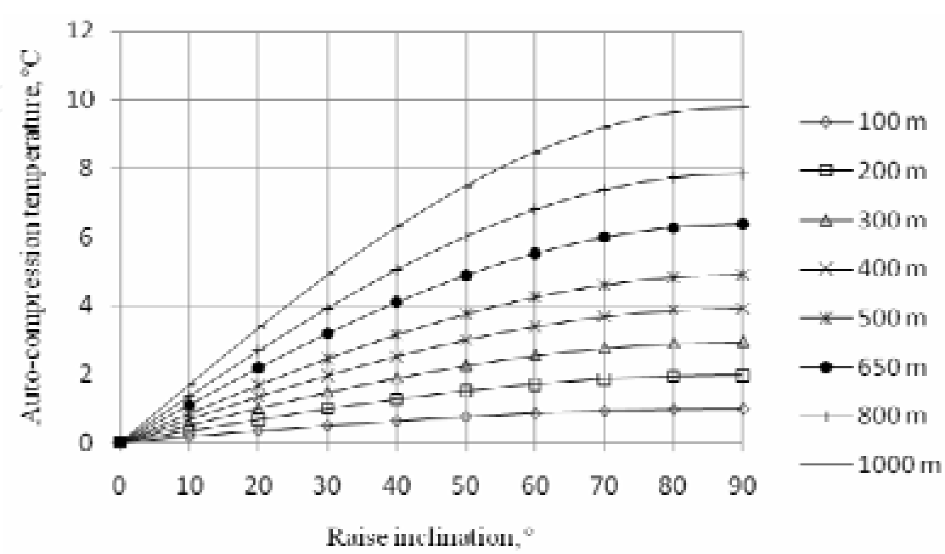

Fig. 6. Variation of auto-compression temperature with raise inclination

2.3 Heat transfer of thermal properties of rock mass to underground atmosphere

At a certain depth h_n from the surface defined as the thermal neutral zone (15 m according to Ramani 1992; 20 to 40 m indicated by Vutukuri & Lama, 1986) the temperature of rock masses varies during the year as a function of the changes of surface air temperature. The temperature of any rock mass at depth t_{hr} and underground atmosphere air temperature variation Δt_r can be calculated by the following equations:

$$t_{hr} = t_n + \frac{(h - h_n)}{g_g} \tag{14}$$

$$\Delta t_g = \frac{h_1 - h_n \pm L \sin\alpha}{g_g} \tag{15}$$

where; t_{hr} is the rock temperature at depth h (ºC), t_n is the temperature of the rock mass above the thermal neutral zone (ºC), h depth of mining excavation below the surface, h_n is the depth of the thermal neutral zone (m) and g_g geothermal gradient of the rock mass (m/ºC).

In order to obtain the mathematical model for the calculation of heat transfer of thermal properties of rock mass, use of the heat transfer formulation of gas flow in pipes can be applied to underground openings.

Heat spreads from one point to another one in three distinct ways: conduction, radiation and convection. In most cases, the three processes occur simultaneously and therefore the amount of heat "q" supplied to a body of mass "m" and specific heat C_e, when the temperature increases from t_1 to t_2 is given by the general equation (16):

$$q = m.C_e(t_2 - t_1) = m.C_e.\Delta t \tag{16}$$

For the air flowing in the underground openings this equation can be expressed in function of the circulating air volume Q through:

$$q_r = 1000\rho_a.C_{e.}Q.\Delta t_r = 1000.\rho_a.C_e.Q.(t_2 - t_1) \tag{17}$$

Where q_r is the heat received by the air from the rock mass (W), ρ_a the air density (kg/m^3), C_e the specific heat of air (kJ/m.ºC), Q the flow of air (m^3/s) and Δt_r the variation of temperature from t_1 to t_2 (Fig. 7). The heat coming out of the rock mass and received by the ventilation air in the underground environment can also be expressed in terms of coefficient of heat transfer λ (Holman, 1983) according to the equation (17):

$$dq = \lambda.P.dx(P_p - T_m) \tag{18}$$

Where T_p and T_m are the temperatures of rock wall and air mixture in the particular position x (ºC), λ is the coefficient of heat transfer between the rock mass and the air mixture (W/m^2.ºC) and P is the perimeter of the section of the underground opening (m). The total heat q_r transferred (W) can be calculated by using equation (19) as follows:

$$q_r = \lambda.P.L.(T_p - T_m)_{average} \tag{19}$$

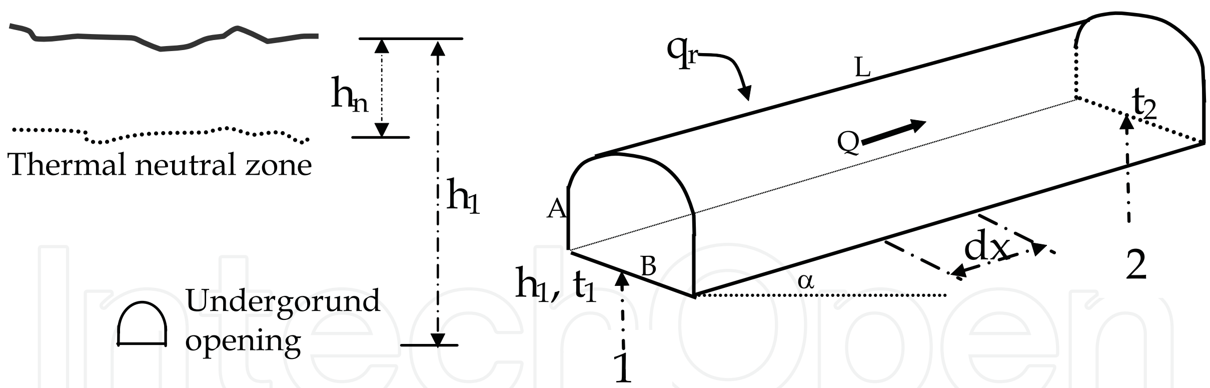

Fig. 7. Layer of rock influenced by external temperature and elementary parameters of an underground opening

Using equation (19) the average temperature of the rock mass may be given by equation (20) and (21):

$$T_p = \frac{1}{2}\left\{ t_1 + \left(t_1 + \frac{h_1 - h_n \pm L.\sin\alpha}{g_g} \right) \right\} \tag{20}$$

$$T_m = \frac{t_1 + t_2}{2} \tag{21}$$

By substituting equations (20) and (21) in equations (17) and (19) the following expression is obtained:

$$\left[\frac{\lambda.P.L}{2}\right]\left[\frac{h_1 - h_n \pm L.\sin\alpha}{g_g} + t_1 - t_2\right] = 1000.\rho_a.C_e.Q.(t_2 - t_1)$$

Finally the variation of temperature from t_1 to t_2 (Δt_r) may be expressed as follows:

$$\Delta t_r = t_2 - t_1 = \frac{\lambda.P.L.(h_1 - h_n \pm L.\sin\alpha)}{g_g(\lambda.P.L + 2000.\rho_a.C_e.Q)} \tag{22}$$

Resulting equation (22) is an innovative mathematical model developed for heat transfer of thermal properties of rock mass to underground openings (Navarro, 2003).
In raises or in any vertical underground openings, $h_1 = 0$, and the length which influences the temperature due to geothermal gradient is $L\ Sin a - h_n$ and a =90°, thus, resulting in the following equation:

$$\Delta t_r = t_2 - t_1 = \frac{\lambda.P.(L - h_n)^2}{g_g\left[\lambda.P.(L - h_n) + 2000.\rho_a.C_e.Q\right]} \tag{23}$$

The coefficient of heat transfer λ is calculated as a function of the thermal conductivity K (W/m°C) which is the non-dimensional coefficient of Dittus and Boelter N_{db} and the diameter of section d (m); for horizontal and inclined underground openings $d = (B + A)/2$, where B is the width of the section (m) and A its height (m):

$$\lambda = \frac{k.N_{db}}{d} \quad (24)$$

The relation of Dittus and Boelter co-efficient N_{db}. (Holman, 1983) was studied in detail by Petukohov for gases (air) that derived the following equation:

$$N_{db} = \frac{\frac{f}{8}\mathrm{Re}_d.\mathrm{Pr}}{1.07 + 12.7(\frac{f}{8})^{0.5}(\mathrm{Pr}^{0.67} - 1)} \quad (25)$$

Where R_{ed} is the Reynolds number (non-dimensional), given by:

$$R_{ed} = \frac{V.d}{\mu} \quad (26)$$

in which V is the average velocity of air (m/s), d the underground opening diameter (m) and μ the kinematic viscosity of air (Kg/m.s). In addition, f is the friction coefficient of the underground opening walls (Kg/m^3), P_r is the Prandtl number (non-dimensional) calculated by:

$$P_r = \frac{\rho_a.C_e.\mu}{K} \quad (27)$$

Air properties at atmospheric pressure will be determined based in temperatures (Table 1).

2.4 Heat transfer from diesel equipment

The equipments used in underground work generate the heat transfer to the ventilation current in underground atmosphere as follows:

1. Mobile diesel and electrical equipments, such as jumbo drills, trucks, LHDs, pumps, locomotives, etc.
2. Electrical and non-mobile equipments (fans, lighting, pumps, hoists, stations or transformer substations, etc.).

For the mobile and non-mobile equipments used in underground work, diesel equipments contributes significantly to heat transfer to the air flow in underground atmosphere. Diesel engines fuel consumption for mining equipment is 0.24 kg/kWh, with a calorific value of 44 MJ/kg (Vutukuri & Lama, 1986), so the total energy released is 0.24x 44x10^3 KJ/kWh = 10560 kJ/kWh = 176 kJ/mink = 2.9 kJ/s.KW = 2.9 kW/kW. Of the total 1kW energy release, (34%) is converted into mechanical energy and 1.9 kW (66%) is exhausted to air flow of underground atmosphere. This energy is not totally transferred to the air flow, because it depends to the effective time for which the equipment used, so it is different for each condition of underground work and the value is around 0.9 kW (31%).

Diesel equipment heat exhaust q_{ed} (KW) can be expressed by equation (28) as follows:

$$q_{ed} = f_m.f_t.q_d.P_d \quad (28)$$

Where q_d is the equivalent energy released by diesel fuel (2.9 kW/kW),
P_d is the equipment engine (kW),
f_m is mechanical efficiency and
f_t is equipment utilization efficiency.

T (ºK)	ρ a(kg/m³)	C_e (KJ/kg.ºC)	ν(kg/m.s) x10-5	μ(m²/s)x 10-6	K(W/m.ºC)	Dif.Térm. (m²/s)x10-4	P_r
100	3.6010	1.0266	0.6924	1.923	0.009246	0.02501	0.770
150	2.3675	1.0099	1.0283	4.343	0.013735	0.05745	0.753
200	1.7684	1.0061	1.3289	7.490	0.01809	0.10165	0.739
250	1.4128	1.0053	1.488	9.49	0.02227	0.13161	0.722
300	1.1774	1.0057	1.983	16.84	0.02624	0.22160	0.708
350	0.9980	1.0090	2.075	20.76	0.03003	0.2983	0.697
400	0.8826	1.0140	2.286	25.90	0.03365	0.3760	0.689
450	0.7833	1.0207	2.484	31.71	0.03707	0.4222	0.683
500	0.7048	1.0295	2.671	37.90	0.04038	0.5564	0.680
550	0.6423	1.0392	2.848	44.34	0.04360	0.6532	0.680
600	0.5879	1.0551	3.018	51.34	0.04659	0.7512	0.680
650	0.5430	1.0635	3.177	58.51	0.04953	0.8578	0.682
700	0.5030	1.0752	3.332	66.25	0.05230	0.9672	0.684
750	0.4709	1.0856	3.481	73.91	0.05509	1.0774	0.686
800	0.4405	1.0978	3.625	82.29	0.05779	1.1951	0.689
850	0.4149	1.1095	3.765	90.75	0.06028	1.3097	0.692
900	0.3925	1.1212	3.899	99.30	0.06279	1.4271	0.696
950	0.3716	1.1321	4.023	108.2	0.06525	1.5510	0.699
1000	0.3524	1.1417	4.152	117.8	0.06752	1.6779	0.702
1100	0.3204	1.160	4.44	138.2	0.0732	1.969	0.704
1200	0.2947	1.179	4.69	159.1	0.0782	2.251	0.707
1300	0.2707	1.197	4.93	182.1	0.0837	2.583	0.705
1400	0.2515	1.214	5.17	205.5	0.0891	2.920	0.705
1500	0.2355	1.230	5.40	229.1	0.0946	3.262	0.705
1600	0.2211	1.248	5.63	254.5	0.1000	3.609	0.705
1700	0.2082	1.267	5.85	280.5	0.105	3.977	0.705
1800	0.1970	1.287	6.07	308.1	0.111	4.379	0.704
1900	0.1858	1.309	6.29	338.5	0.117	4.811	0.704
2000	0.1762	1.338	6.50	369.0	0.124	5.260	0.702
2100	0.1682	1.372	6.72	399.6	0.131	5.715	0.700
2200	0.1602	1.419	6.93	432.6	0.139	6.120	0.707
2300	0.1538	1.482	7.14	464.0	0.149	6.540	0.710
2400	0.1458	1.574	7.35	504.0	0.161	7.020	0.718
2500	0.1394	1.688	7.57	543.5	0.175	7.441	0.730

Table 1. Air properties at atmospheric pressure (Holman, 1983, Navarro, 2003)

Based on equation (28), the temperature variation of air due to exhaust from the diesel equipment Δt_d (ºC) can be quantified by the following equation:

$$\Delta t_d = \frac{f_m . f_t . q_d . p_d}{\rho_a . C_e . Q} \tag{29}$$

It may be noted that the exhaust heat from the diesel engines to the underground atmosphere is from the local equipment use only.

2.5 Heat transfer from explosive blasting

The blasting process of explosive in underground environment generates heat that is transferred to the surrounding rock mass and to the ventilation current of the underground atmosphere.

Heat released by blasting q_e (kW) can be calculated by equation (30), based on calorific energy of explosive E_e (kJ/kg), and explosive quantity daily used q_e (Kg/day). For example, the calorific energy of ANFO is 3900 kJ/kg and the dynamite 60% varying between 4030 to 4650 kJ/kg.

$$q_e = \frac{E_e.q_e}{86400} \tag{30}$$

The thermal influence due to blasting Δt_e (ºC) can be quantified by equation (31) as follows:

$$\Delta t_e = \frac{E_e.q_e}{86400.\rho_a.C_e.Q} \tag{31}$$

Similar to diesel exhaust heat, the heat due to explosive detonations influences the local atmosphere only.

2.6 Heat transfer due to human metabolism

The heat transfer of human metabolism in not significant and can be ignored (Hartman et al., 1997), for example 800 workers in normal working conditions leads to a total release of 192 kW (65000 BTU/hr), energy corresponding to each worker being 0.25 kW.

Thus, when the number of people or workers in an underground environment is large, temperature increase by human metabolism Δt_h (ºC) can be expressed by equation (32), where q_h is the human heat release and it is a function of effective temperature (kW/person) and, n is the total number of human involved.

$$\Delta t_h = \frac{q_h.n}{\rho_a.C_e.Q} \tag{32}$$

2.7 Heat transfer from underground water

Two sources of water are encountered in mining: Groundwater or Mine water. All ground water, especially from hot fissures and natural rock reservoirs, is a prolific source of heat in mine workings. Since water and heat are both derived from the surrounding rock or geothermal sources, the water temperature will approach or even exceed the rock temperature.

The water transfers its heat to the mine air, mainly by evaporation increasing the latent heat of the air.

The total heat gain from hot underground water in open channel flow q_w (kW) can be calculated from the equation (33):

$$q_w = F_{tw}.c_w(t_{tw} - t_a) \tag{33}$$

Where F_{tw} is weight flow rate of thermal water (kg/s)
C_w is specific heat of water (4.187 kJ/kg°C), and
t_{tw} and t_a are water temperatures at points of emission and exit from the mine airway in (°C), respectively.

The thermal influence of underground ventilation air flow can be calculated by equation (34) as follows:

$$\Delta t_w = 4.187 \frac{F_{tw} \cdot (t_{tw} - t_a)}{\rho_a . C_e . Q} \tag{34}$$

3. Case studies of heat transfer in underground mining

3.1 Case study in Portuguese Neves Corvo mine

Vertical underground opening

The Neves Corvo mine is an operating underground copper and zinc mine in the western part of the Iberian Pyrite Belt which stretches through southern Spain into Portugal. The mine uses both bench and fill and drift and fills underground stoping methods. The copper plant has treated a maximum of 2.0 mt per annum of ore and in 2007 it was upgraded to treat up to 2.2 mt of ore per annum.

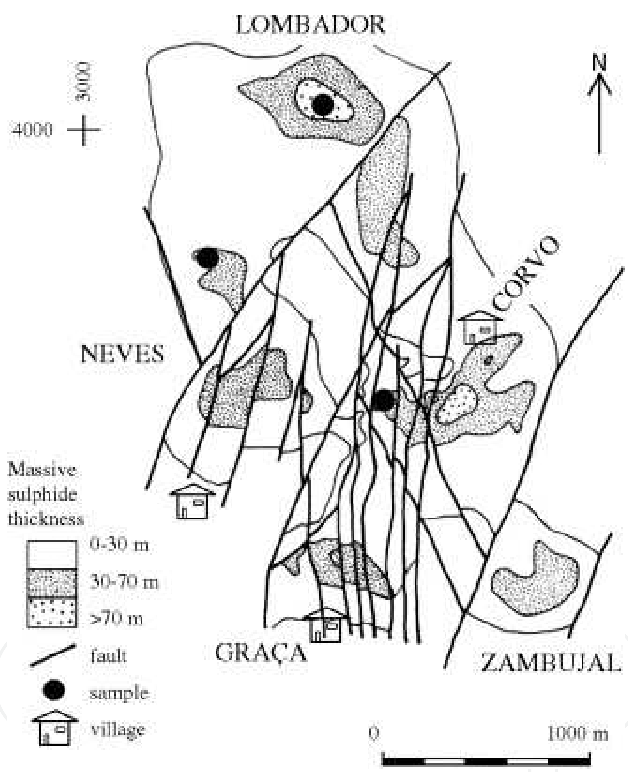

Fig. 8. Map of the Neves Corvo area showing the massive sulphide ore bodies Neves, Corvo, Gracia and Zambjal, main faults and the exploratory boreholes (Moura, 2005)

The ore bodies of the underground Neves Corvo copper mine (Fig. 8) were formed in a volcanic sedimentary submarine environment possibly linked with an intercontinental rift and, third order pull apart basins, not far from the collision zone and located in geological formations between Volcanic Lavas (V1) and Volcanic Sediments (V2). The V1 is composed of black shale/schist and has same silicfication but generally less than V2 volcanic. The V2 has a compact vitreous due the high quantity of silica (Riolitic) showing schistosity and alteration from Chlorite (Lobato, 2000).Mining areas are located between +200m and -450m, and they are referred to 0 level, equivalent to 0 m datum and transport level equivalent to -550m level (Fig. 9). The total length of underground vertical shafts, inclined and horizontal openings is about 80 kilometres.

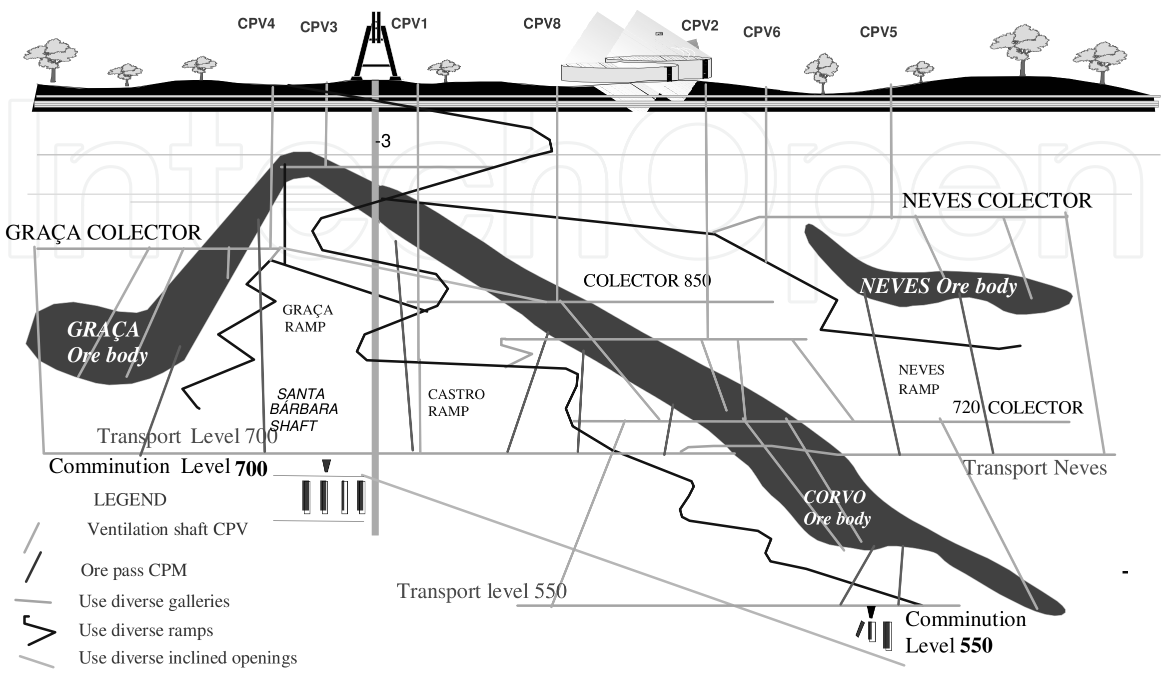

Fig. 9. Neves Corvo underground mine cross section (Navarro, 2003)

The air temperature in underground stopes of Neves Corvo mine is moderate averaging between 20ºC to 33ºC and in isolated areas in critical condition reaching 42ºC
For applying the mathematical model a vertical underground opening the CPV3 shaft shown in Figure 10, was selected (Navarro Torres, et al, 2008). This shaft was constructed using a raise boring machine from the depth of 1222.40m level to 973.64m level with a length of 248.76m and a diameter of 4.2 m (perimeter 13.19 m and 13.85 m^2 in cross section area).
The wall friction factor corresponded to 0.0362 kg/m^3 with an average air velocity measured in July 2000 of 11.84 m/s and average exterior temperature of 24.61 ºC (Figure 2 and Figure 3). Average airflow resulted in 164.03 m^3/s calculated based on air velocity measured, as indicated in Figure 11.

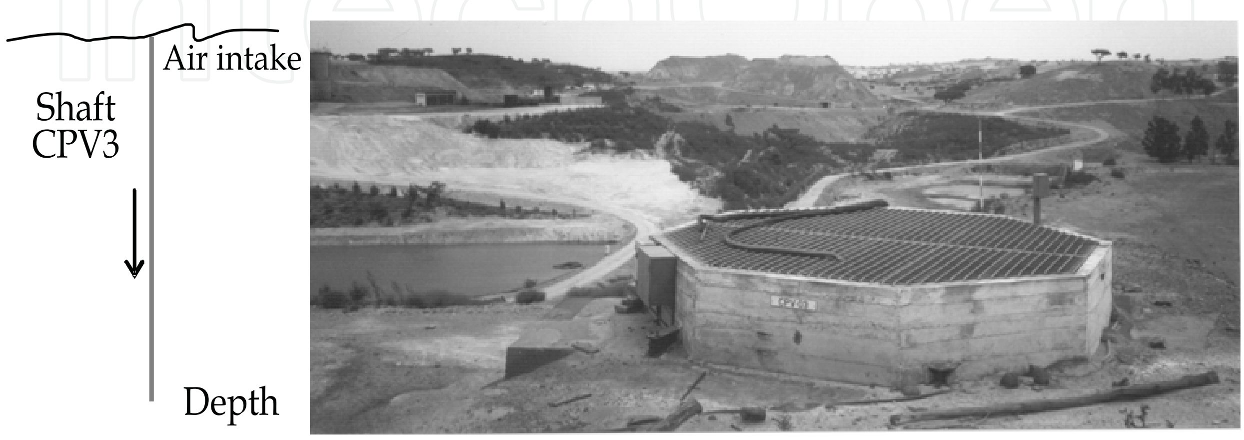

Fig. 10. Scheme and photograph of shaft CPV3

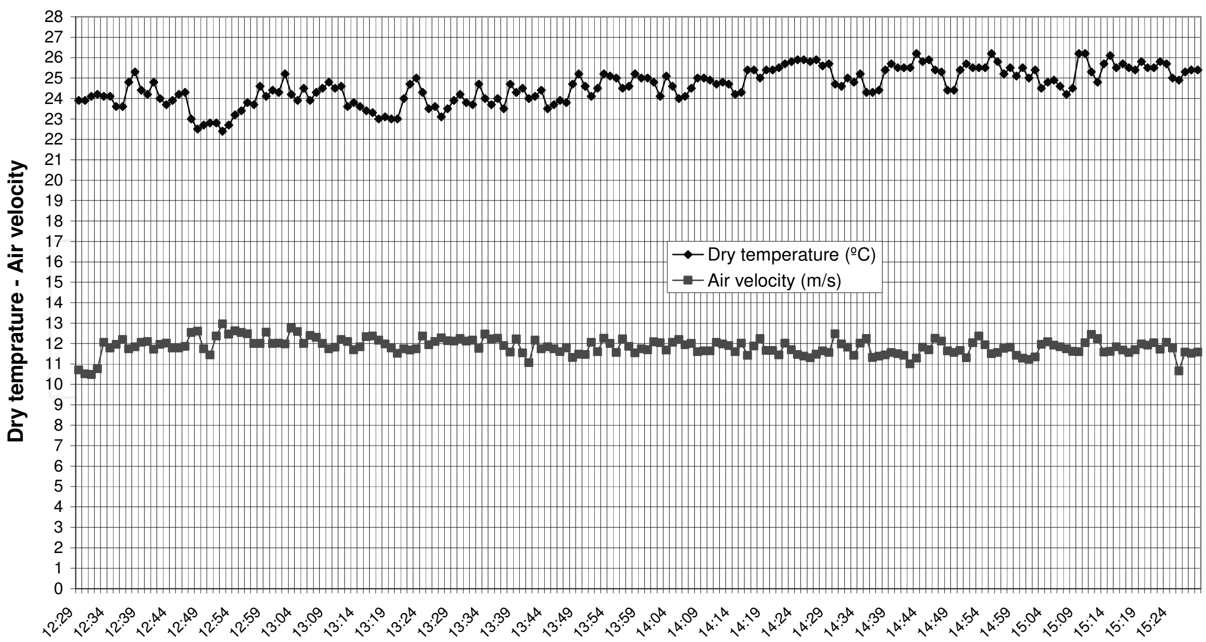

Fig. 11. Intake dry temperature and air velocity measured by Data LOGGER DL20K

The air temperature in CPV3 shaft is not influenced by the temperature rise due to diesel equipments (Δt_d), explosives (Δt_e), thermal water (Δt_w) and human metabolism (Δt_h). Therefore, only auto-compression (Δt_a) and geo-thermal properties of rock (Δt_r) were considered for the validation of the proposed model.
The physio-chemical properties of air shown in Table 2 extracted from Table 1 for 24.4ºC enabled the calculation of the Prandtl number P_r, Reynolds number Re_d, related to Dittus and Boelter number N_{db} and coefficient of heat transfer λ, by applying equations (27), (26), (25) and (24), respectively as shown in Table 3.

ρ_a (kg/m^3)	C_e (kJ/kg.ºC)	μ (m^2/s)	K(W/m.ºC)
1.1888	1.0056	16.48 x10^{-6}	0.026

Table 2. Physio-chemical air properties at 24.4 ºC (Navarro, 2008).

P_r	R_{ed}	N_{bd}	λ (W/ m^2.ºC)
0.709	3.02 x 10^6	5162.02	76.106

Table 3. Coefficient of heat transfer and previous values calculated

Finally using the geothermal gradient as 30.3 m/ºC for the rock mass (g_g) for the Neves Corvo mine (Fernández-Rubio. *et al.*, 1990) and using 30.0m as the depth of thermal neutral zone in the developed mathematical model in equation (23), the temperature rise of rock mass ($\Delta t_r = t_2 - t_1$) is calculated as 2.65ºC. Applying these values to equation (13), the temperature increase due to air auto-compression can be obtained as 2.38ºC. Then the total increase of the air temperature during the air flow in the shaft CVP3 results in 5.03ºC (Fig. 12), calculated by following simplified equation:

$$\Delta t_a + \Delta t_r = 0.0098.L + \frac{0.033(L-30)^2}{2.38.Q + L - 30} \tag{34}$$

Obviously, when airflow is decreased, the total temperature increment (auto-compression + geothermal properties of rock + temperature due to depth increase) significantly raises the total temperature increment (Fig. 12).

By applying equation (2) to equation (34), the underground atmosphere's temperature of CPV3 shaft T_2 in Neves Corvo mine as a function of airflow quantity Q is represented by equation (35) given below and illustrated in Figure 13 for the average surface temperature 15.65ºC (maximum 24.5ºC, minimum 9ºC and mean 15.65ºC).

$$T_2 = t_s + 2.44 + \frac{1579.25}{2.38Q + 248.76} \tag{35}$$

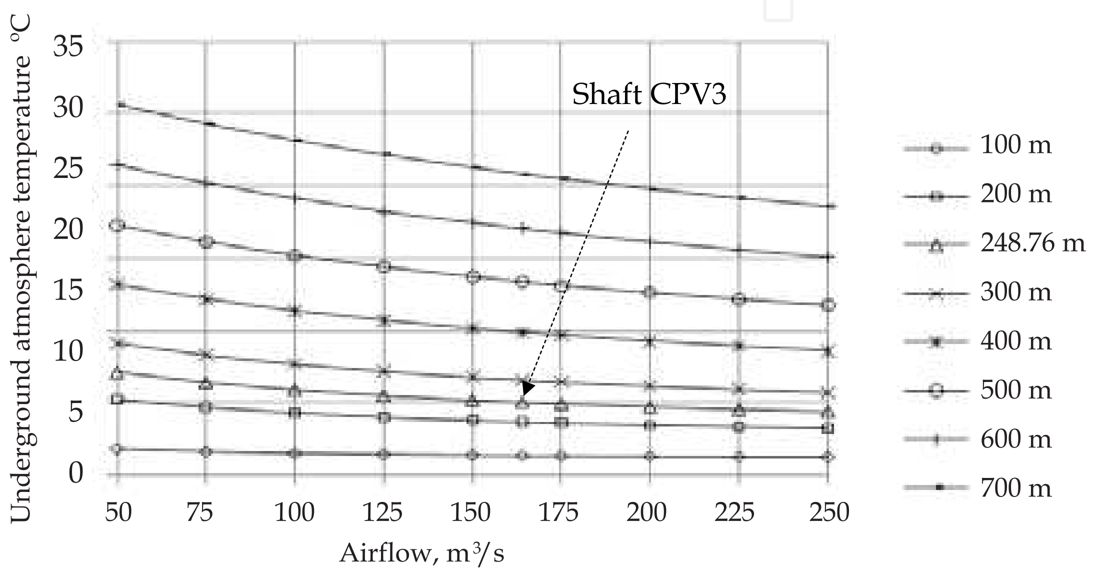

Fig. 12. Total increases in temperature due to auto-compression and geothermal properties of rock as a function of shaft depth and airflow in shaft CPV3

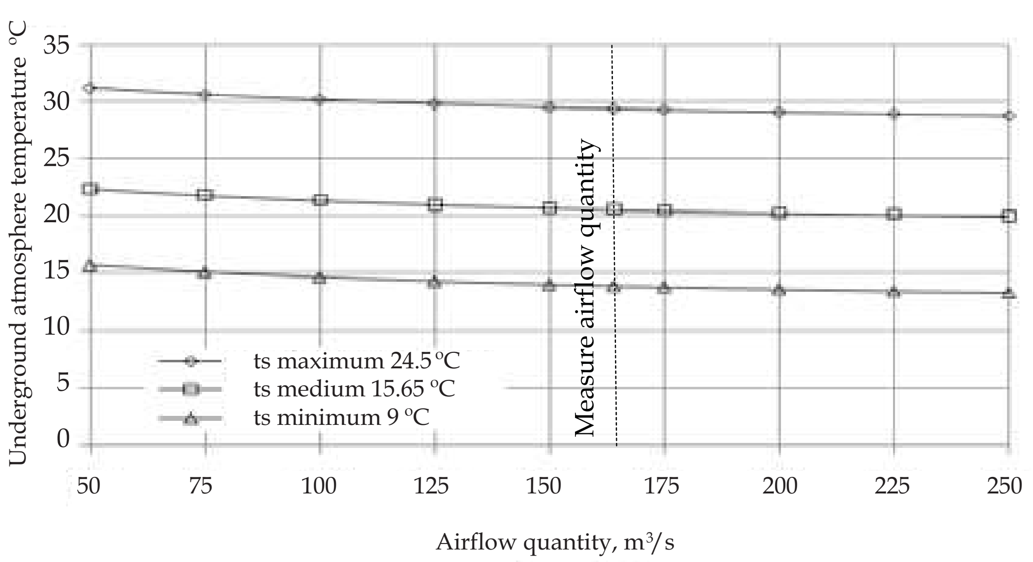

Fig. 13. Underground atmosphere temperature influenced by auto-compression and thermal properties of rock and airflow quantity in CPV3 shaft

It may be observed that a slight increase in the underground atmospheric temperature, results in slight decrease in the air flow. The average values measurement with Data LOGGER DL20K of ROTRONIC in the air shaft intake with a thermo/hygrometer Casella in the shaft (Fig. 14) was 29.52ºC in the shaft bottom and 24.61ºC in the intake, therefore the difference is 4.91ºC.The comparison the results show a total variation of temperature (Δt_{total}) between the mathematical model and measured temperature in CPV3 shaft is only 0.12ºC.

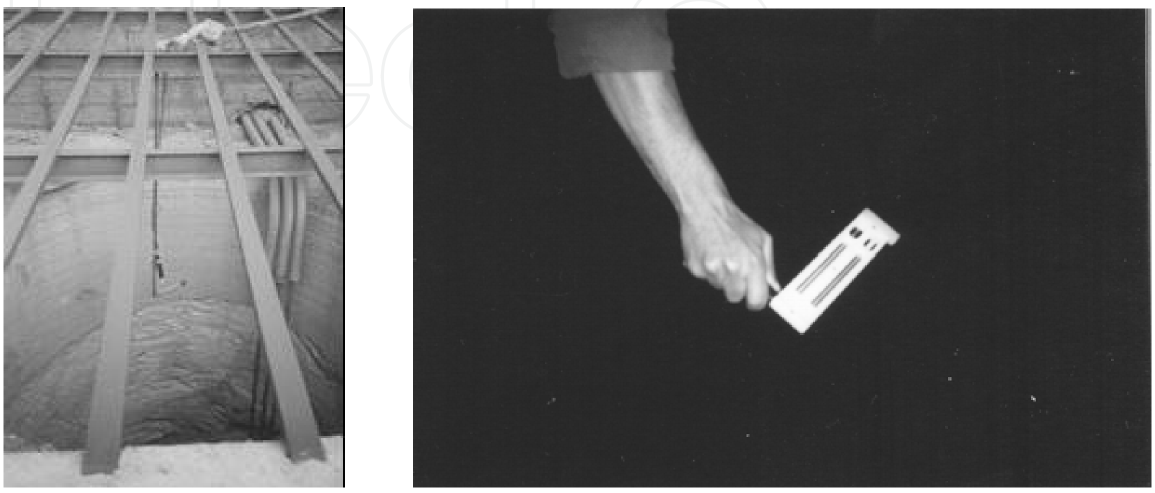

Fig. 14. Measurements with Data LOGGER DL20K and thermo/hygrometer Casel

3.2 Case study in Peruvian San Rafael tin mine

Sub-horizontal underground opening

The San Rafael mine belongs to the Peruvian company MINSUR S.A. and is located Southwest of the San Bartolomé de Quenamari mountain (altitude 5299 m), in the Department of Puno in the Eastern Mountains of Southern Peru. It is geographically located in the coordinates of 70°19' longitude West and 14°14' latitude south. This mine is the only producer of tin in Peru and ore production is 2500 tons per day, with 5.23% of tin (Sn). Geology of San Rafael mine involves silts and quartzite rocks of the tertiary Sandia formation with the intrusion of two granites. In the neighborhood there are rocks of the superior Paleozoic age. In the Sandia formation silts have dark gray colors with muscovite in the cleavage plans and the quartzites are intercalated with silts (Fig. 15).
The mineralized veins and ore bodies are located in the intrusive ore body of San Rafael along the NE – SW direction, with a length of 800 m to 1000 m, a width of 300 m and depth of up to 2000 m. These ore bodies have widths of 4 m to 30 m, lengths of 30 m to 180 m and heights of 60 m to 610 m, and in general have prismatic forms. The main existing minerals are cassiterite, stanhite and chalcopyrite.
The main access from surface is through 4523m ramp that communicates to 3825m level, constituting the principal infrastructure of underground transport, as well as the ventilation circuit (Fig. 16).
Figure 17 presents the clean air temperatures with normal trend until the level 3950 m (17ºC), but in 3850m level, where a variation is only 100 m, temperature increases to 34ºC, thus showing the effect of thermal water. A forecast for air temperature in the 3850m level without the influence of hot water leads to 20ºC for the air flow of 8.11m^3/s.

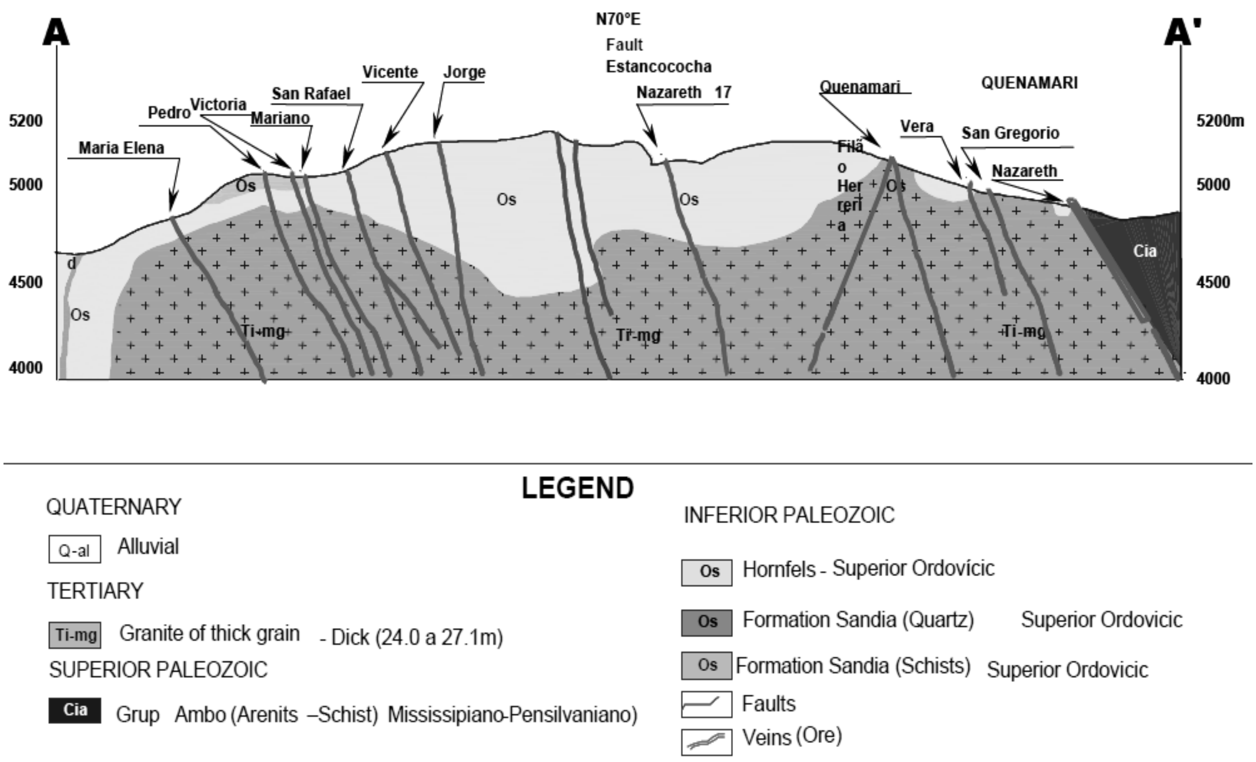

Fig. 15. Geological section with zones of mining in San Rafael along the direction N 70º E

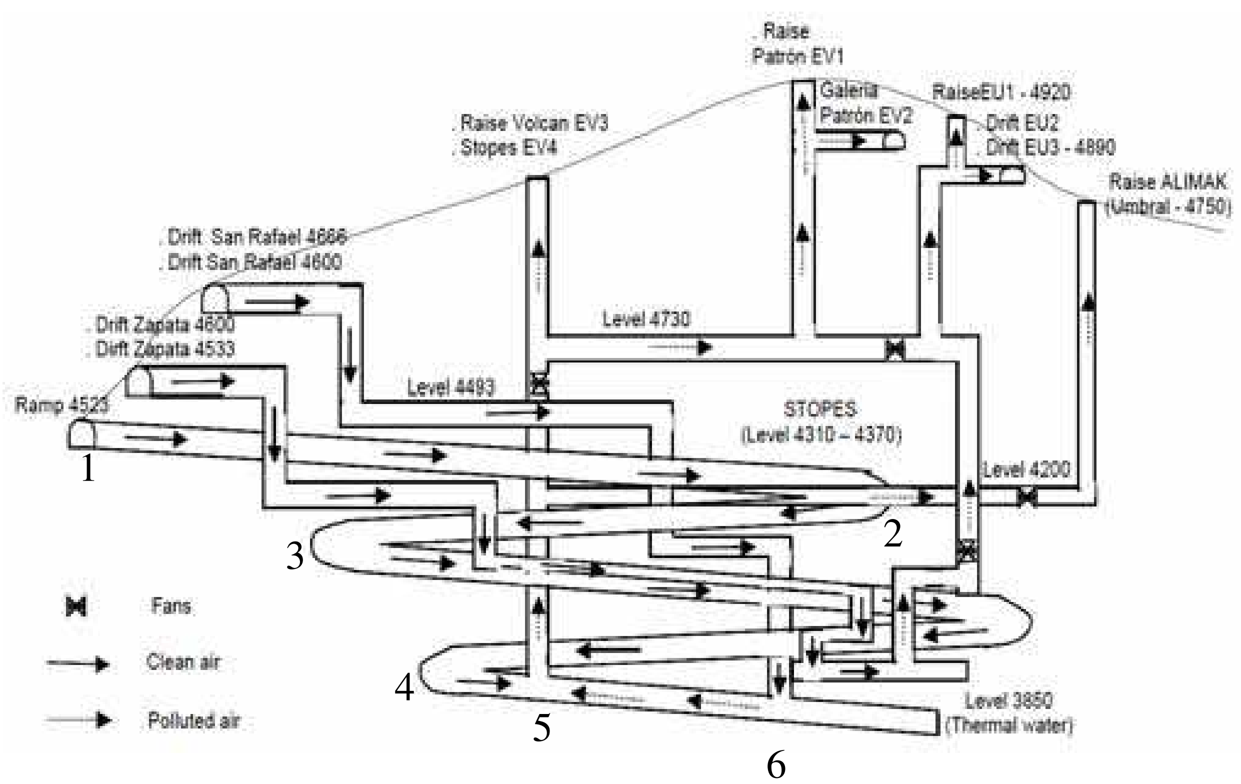

Fig. 16. General project of the underground environment of San Rafael mine (Navarro, 2001)

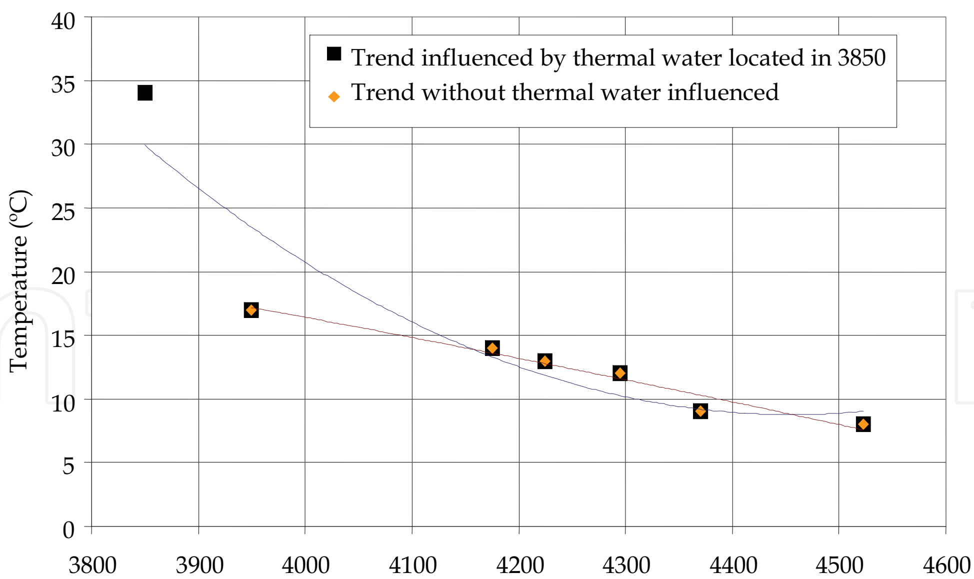

Fig. 17. Air temperature trends with and without the influence of thermal water (Navarro, 2003)

The thermal water temperature measured in the flowing water channel was 40ºC and the influence of air temperature in underground opening was up to 34 ºC (15 m^2 section). It may be observed that an increase in temperature by 12 ºC is not a normal trend of air temperatures, because it represents an increase of about 60%.

In San Rafael mine case study, the calculated geothermal gradient g_g based on equations (1) and (22) and measured data and equation (22) needed recalculation of temperatures variation due to diesel exhaust, explosive detonations and thermal water, because in local level 3850, the temperature increment due to auto-compression and human metabolism are insignificant.

Diesel equipments heat transfer Δt_d, is calculated by applying equation (29) based on combined factors of mechanical efficiency and equipment utilization efficiency ($f_m.f_t$) of 0.005 for diesel equipments used in ramp 4523(level 3850) (Table 4), air density 1.2661 kg/m^3 and specific heat of air 1.0056 kJ/kg.ºC (Table 1) and for depth local level 3850 of ramp 4523, temperature increase result is 0.85ºC.

Heat transfer Δt_e due to explosive detonation is determined by applying equation (31), based on an average of 120 kg per day ANFO, air density and air specific heat (Table 1), resulting in temperature rise of 0.52ºC.

The thermal water heat transfer calculated by applying equation (34), based on measured flow rate of 4.93 l/s of thermal water in channel F_{tw}, was 40ºC water temperatures at points of emission t_{tw} and 34ºC at the exit from the mine airway t_a; using air density and air specific heat (Table 1), result being 12ºC.

Using these results and applying equation (1) based in measured 22ºC (34ºC-12ºC) total temperature increase Δt_{total} the heat transfer of virgin rock Δt_r results in 8.63ºC.

Finally, for the following conditions d = 4.5m, f = 0.0046kg/m^3, V = 0.39m/s, P = 18m, L = 7000m, h_1 = 30m, h_n = 30m, α = 7º, Q = 8.11m^3/s (branch 6-5 Figure 15) and for physical-chemical air conditions (Table 5) and calculated Prandtl number P_r, Reynolds number Re_d, relation of Dittus and Boelter N_{db} and coefficient of heat transfer λ, is calculated applying equations (27), (26), (25) and (24), respectively as shown in Table 6, and applying equation (22) the geothermal gradient result in 59.51m/ºC or 1.68 ºC for each 100 m.

Mining operations	Equipments
Development and prospection	. 2 Jumbo Boomer H 282 of Atlas Copco, with 75 HP (55.93 KW) . 2 LHD de 5.5. Yd³ EJC, with 186.43 KW each.
Drilling long holes	. 1 Simba H-1354 de Atlas Copco, Cop – 1838, with 80 HP (59.66 KW) . 1 DTH Tunnel 60, Drillco Toolls, Topo 3 . 1 DTH Mustang A32 de Atlas Copco, with Drill Cop – 34
Mucking ins stopes	. 2 LHD de 6.5 yd³ ST100 Wagner, with 250 HP (186.43 KW) each. . 1 LHD de 3.5 Yd³ Wagner (stand by), com 185 HP (137.9 KW)
Fragmentation	. 4 hydraulic drills Kent
Ore transport by ramp	. 6 Trucks Volvo NL12, de 15 m³, with 410 HP (305.73 KW) each.
Supervision	. 27 Cars, with 89 HP (66.37 KW) each.

Table 4. Underground diesel equipment used in San Rafael mine

ρ_a (kg/m³)	C_e (kJ/kg.ºC)	μ (m²/s)	K(W/m.ºC)
1.26614	1.0056	14.07×10^{-6}	0.0248056

Table 5. Physical-chemical air properties

P_r	R_{ed}	N_{bd}	λ (W/ m².ºC)
0.710	0.125×10^6	45.08	0.248

Table 6. Coefficient of heat transfer and previous values calculated

Geothermal gradient trend of San Rafael mine based on calculated results as compared with worldwide mining district trends is shown in Fig. 18.

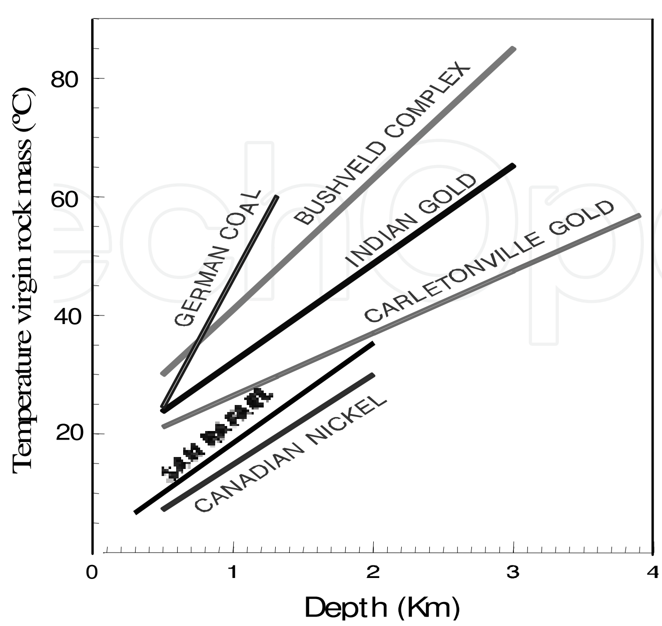

Fig. 18. Geothermal gradient of San Rafael mine compared of some worldwide mining districts (compiled by Navarro, 2001)

In Rafael mine, the intake clean air bay drifts 4666, 4600 and ramp 4523, compared with the mine deepest level at 3835 m, there is an 831 m level difference where temperature raises 21.5ºC, or about 1ºC for each 40m depth. This result indicates a variation of annual average external temperature of 6.61 ºC and at level 3850 would reach 16.70 ºC (Fig. 19), which is compatible with the trend of temperatures measured in ramp 4523. The thermal conductivity of the rock mass of the San Rafael mine is estimated as 3.25 W/mºC.

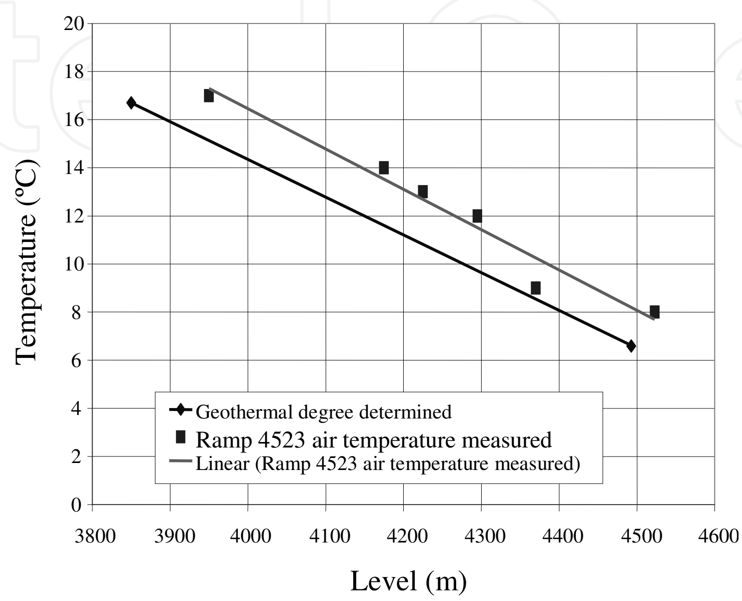

Fig. 19. Geothermal gradient determined and air temperature measured Navarro, 2003

Thermal human comfort assessment in underground openings based on International Standards Organization (ISO 7730) and American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE/55) standards, and the thermal human comfort defined based in operative ranges from 22ºC to 28ºC as shown in Figure 20.

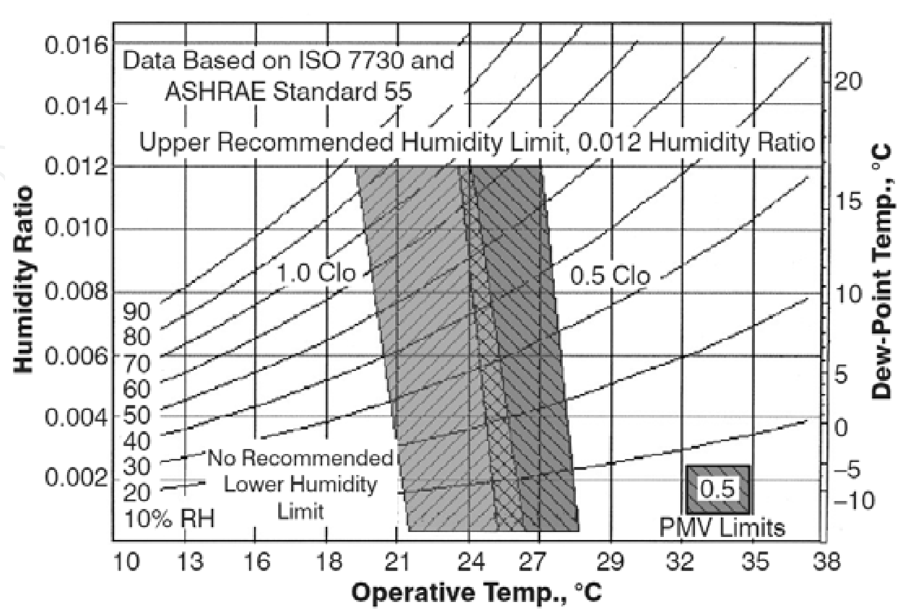

Fig. 20. ISO 7730 and ASHRAE/55 human thermal comfort standards

By applying equations (1) and (2), using the annual average external temperature as 6.61 ºC (Fig. 2), without the influence of thermal water and the physio-chemical properties of air conditions (Tables 5 and 6) the thermal condition of 4523m ramp in San Rafael mine was assessed by using equation (36)..

$$\Delta t_{total} = \frac{0.544L^2}{265.653L + 151539.88Q} + \frac{11.745}{Q} \tag{36}$$

In San Rafael mine without thermal water heat transfer, the temperature is lower than thermal comfort standards (ISO 7730 and ASHRAE/55). Figure 21 illustrates the underground opening temperatures for various air flow rates and underground opening lengths. It can be observed that when airflow increases, the underground opening temperature decreases, and on the other hand, when underground opening length increases, the change in underground air temperature is moderate.

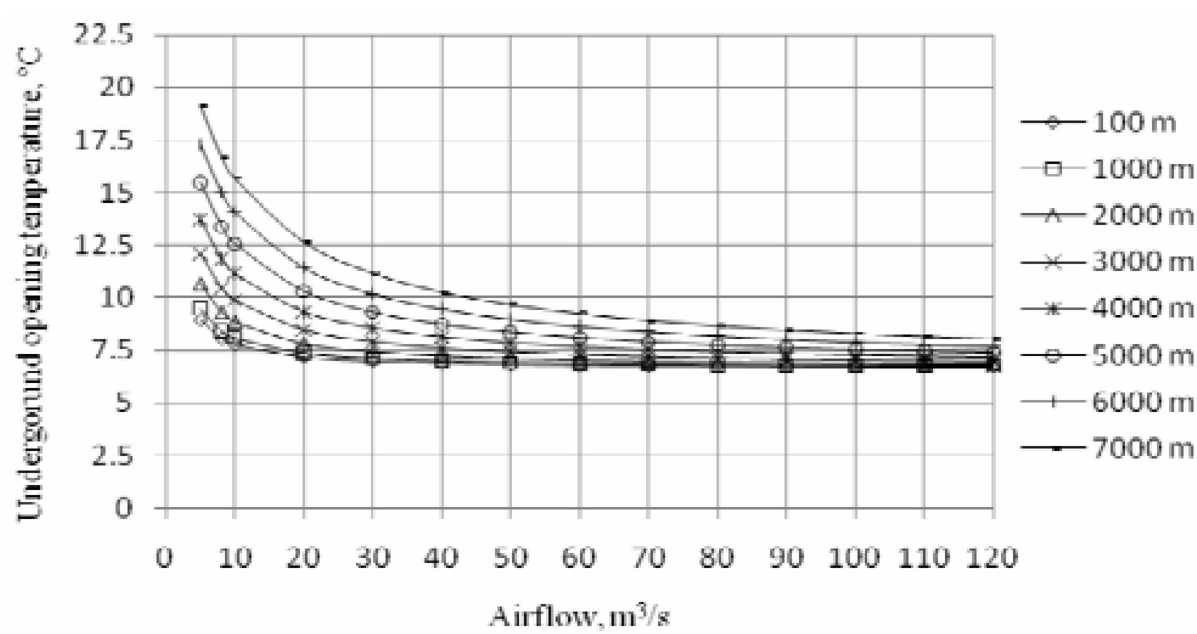

Fig. 21. Temperature total increment influenced by airflow quantity and underground openings length in San Rafael mine

For thermal human comfort assessments in underground openings it is necessary to determine the local thermal situation and that obtain increasing for the total temperature increment Δt_{total} the initial temperature in the underground opening branch *(t_1)*. In San Rafael mine measured average minimum temperature in July was 4°C and the maximum temperature in February was 7.8ºC and the average temperature was 6.16ºC a shown in Figure 2.
Underground atmosphere temperature in ramp 4523 (Level 385 m), influenced by thermal water as a function of initial temperature in local branch t_1, local length (349 m) and airflow quantity Q, will be expressed by particular equation (37) as shown in Figure 22.

$$t_2 = t_1 + \frac{1}{0.0868 + 0.142Q} + \frac{109.04}{Q} \tag{37}$$

In the locality of ramp 4523 (level 3835) where the average intake air temperature is 16.7ºC, the temperature is influenced by the heat transfer due geothermal properties of rock, diesel exhaust, explosive detonation and thermal groundwater and the human thermal comfort will be obtained for airflow quantity between 6 and 8 m^3/s (Fig. 20). When the airflow quantity are smaller than 6 m^3/s the underground atmosphere temperature increases greatly and for the flow rates higher than 8 m^3/s the surface temperature decreases gradually.

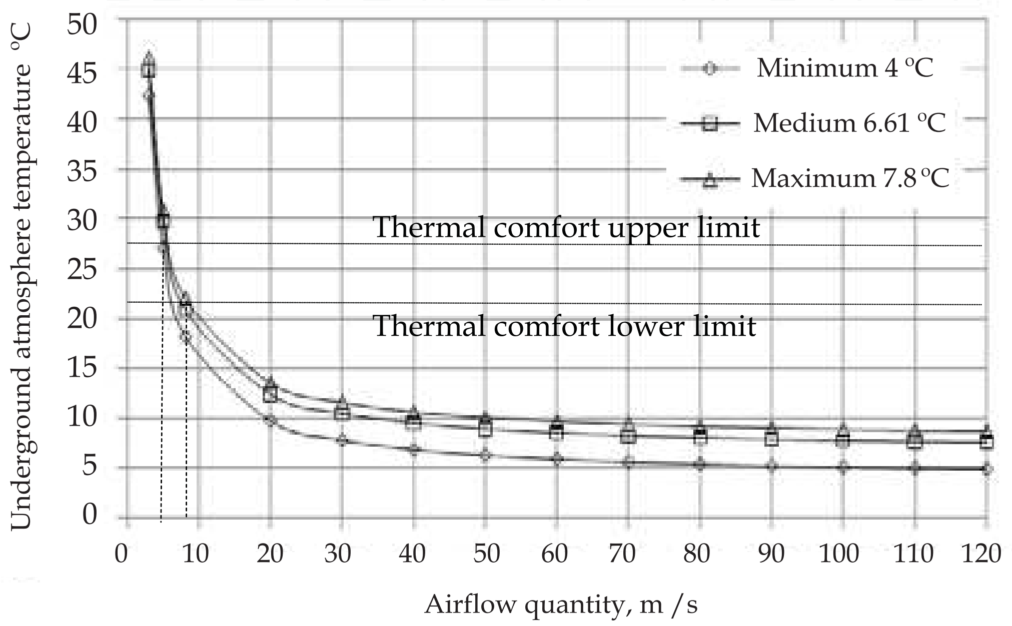

Fig. 22. Human thermal comfort situation in ramp 4523m (level 3835) of San Rafael mine

It may be noted that without the presence of thermal water there is no risk of environmental thermal discomfort, but in localities with thermal water there appears to be risk of thermal discomfort.

3. Acknowledgements

Thanks are due to Dr A. S. Atkins, Faculty of Computing, Engineering and Technology, Staffordshire University for his valuable suggestions to improve the quality of this book chapter.

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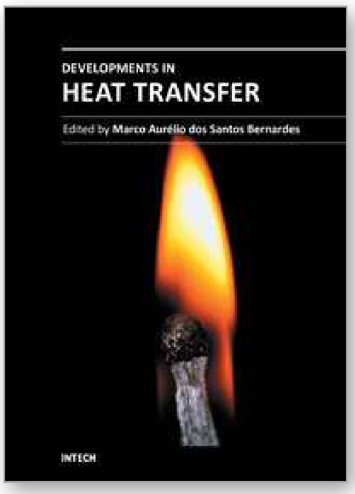

Developments in Heat Transfer

Edited by Dr. Marco Aurelio Dos Santos Bernardes

ISBN 978-953-307-569-3
Hard cover, 688 pages
Publisher InTech
Published online 15, September, 2011
Published in print edition September, 2011

This book comprises heat transfer fundamental concepts and modes (specifically conduction, convection and radiation), bioheat, entransy theory development, micro heat transfer, high temperature applications, turbulent shear flows, mass transfer, heat pipes, design optimization, medical therapies, fiber-optics, heat transfer in surfactant solutions, landmine detection, heat exchangers, radiant floor, packed bed thermal storage systems, inverse space marching method, heat transfer in short slot ducts, freezing an drying mechanisms, variable property effects in heat transfer, heat transfer in electronics and process industries, fission-track thermochronology, combustion, heat transfer in liquid metal flows, human comfort in underground mining, heat transfer on electrical discharge machining and mixing convection. The experimental and theoretical investigations, assessment and enhancement techniques illustrated here aspire to be useful for many researchers, scientists, engineers and graduate students.

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