MATHEMATICAL MODELLING OF THERMAL STATE IN UNDERGROUND MINING

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ABSTRACT
The effect of temperature in underground mines is related to the geothermal gradients of rocks overlying the mining excavation. This may exceed the standards of comfort for human beings to work in an underground environment thus causing thermal discomforts and associated risk. In order to evaluate the influence of high ventilation temperatures on mine workers a mathematical model has been developed based upon the concept of heat transfer from the rock mass to the air flow in the underground environment. This model has been validated in the Noves Corvo underground copper mine, Portugal.

KEYWORDS: geothermal gradient, rock mass thermal properties, human comfort, underground mining environment

1. INTRODUCTION

Thermal comfort is defined as the state of mind in which satisfaction is expressed with the thermal environment. The thermal human comfort is not exclusively a function of air temperature, but also of other parameters including mean radiant temperature, air velocity, humidity, activity level and clothing's thermal resistance. Practical thermal human comfort evaluation is carried out by evaluating PMV (Predicted Mean Vote) and PPD (Predicted Percentage of Dissatisfaction) indices. Another interesting method is to use the PPD as a function the operative temperature (t_o) as shown in Figure 1.

The PMV-PPD index has now been suggested by the International Standard Organization ISO (DIS 7730) as a standard for evaluating moderate thermal environments. It has been recommended to use the following limits:

$$-0.5<PMV<0.5$$

$$PPD<10\%$$

The recommendations outlined above are applied to PPD-t_o graph shown in Figure 1, to verify the human thermal comfort between 19 ºC and 26 ºC of operative temperature or approximately 17 º to 30 ºC dry temperature (Navarro Torres et al., 2005). This paper outlines a mathematical model that has been developed that allows the determination of the air temperature in the underground atmosphere influenced mainly by the thermal properties of rock strata. The mathematical model has been validated in the Neves Corvo underground copper mine with reference to the evaluation of human thermal comfort standards.

2. INFLUENCE OF THERMAL COMFORT IN UNDERGROUND MINING

2.1. *SOURCES OF HEAT IN UNDERGROUND MINING*

The common sources of heat in mining are initial temperature of the intake surface air, adiabatic compression of downcast air, temperature added to the air flow by ventilating fans, diesel locomotives, water infusion (thermal water), blasting, and the exposure of rock mass to the ventilating current together with human metabolism etc. In accordance with many country's standards, the threshold limits of dry bulb temperature values of human thermal comfort in underground mining are given in Table 1.

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),

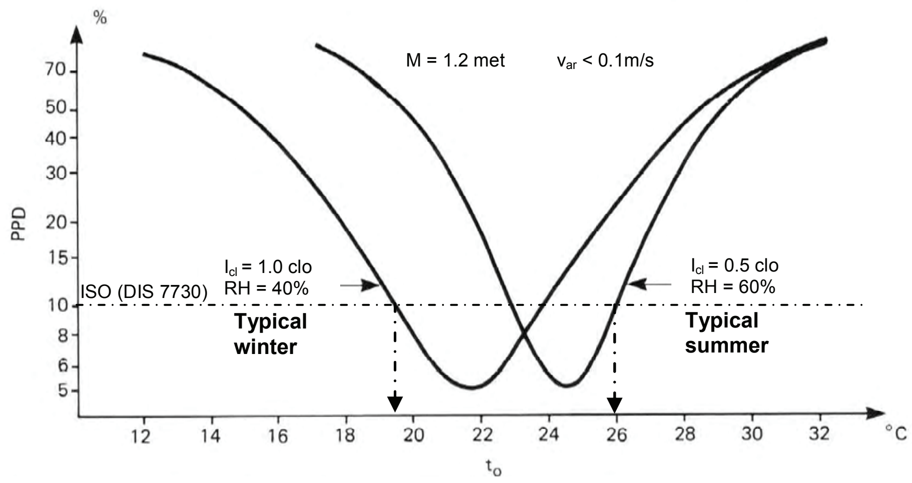

Fig. 1 PPD in function operative temperature (t_o) (Olesen, 1982).

Table 1 Threshold limit values of human thermal comfort.

Country	Dry temperature (ºC)	Country	Dry temperature (ºC)
U.S.A.	30	France	28 (Effective)
Australia	27	South Africa	27.5
Belgian	30 (Effective)	Brazil	30
Portugal	31	Zambia	32

diesel equipments (Δt_d), excavation of rocks with the use of explosives (Δt_e), thermal water (Δt_w) and human metabolism (Δt_h) outlined in equation (1):

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

With increasing mining depths, the influence of the thermal properties of the rock mass becomes more important. Therefore, the goal of the present research is to develop a mathematical model to assess the influence of the transference of geothermal energy to underground atmosphere through Δt_r.

2.2. DEVELOPMENT OF A MATHEMATICAL MODEL OF HEAT TRANSFER OF GEOTHERMAL ENERGY TO UNDERGROUND ATMOSPHERE

At a certain depth h_{tc} from the surface defined as the thermal neutral zone (15 m according to Hartman et al., 1992; 20 to 40 m indicated by Vutukuri et al., 1986) where the temperature of rock masses varies during the year as a function of the changes of surface air temperature. Figure 2 illustrates the rock temperatures increases gradually with depth. The temperature of any rock mass at depth t_{hr} can be calculated by the following equation:

$$t_{hr} = t_{zn} + (h + h_{zn}) / g_g \quad (2)$$

$$\Delta t_g = (h_1 - h_{zn} \pm L \sin\alpha) / g_g \quad (3)$$

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

The value of Δt_g represents the temperature increase in the rock mass due to the geothermal energy in degree C (ºC), h_1 is the initial depth of the underground mining opening measured from the surface (m), L is the length of the underground opening (m) and 'α' is the inclination of the opening (º), $+\alpha$ when the gradient is descending and $-\alpha$ when it is ascending as shown in Figure 2.

For the purpose of developing the mathematical model for calculating Δt_r, the use of the heat transfer formulae of gas flow in pipes can be applied to underground openings. The heat propagation from one point to another point takes place in three distinct ways: conduction, radiation and convection. In most cases, the three processes occur simultaneously (Gomes de Azevedo, 1995) and therefore the amount of heat "q" supplied to a rock mass "m" and specific heat C_e, when the temperature increases from t_1 to t_2 (Figure 2) is given by the following general equation 4:

$$q = m C_e (t_2 - t_1) = m C_e \Delta t \quad (4)$$

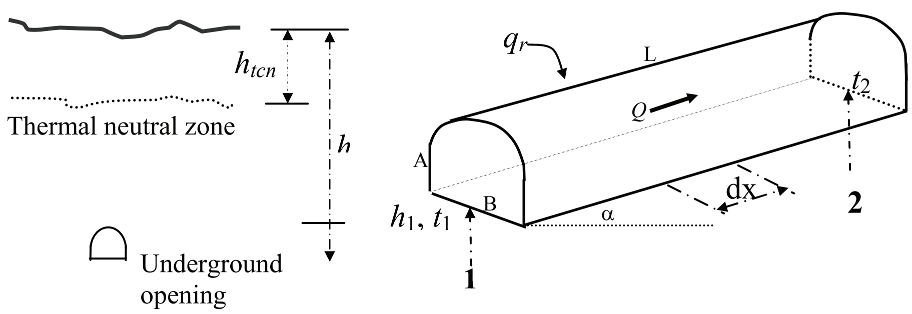

Fig. 2 Thermal neutral zone and elementary parameters of an underground opening.

For the air flowing in the underground mining openings this equation can be expressed as a function of the air flow Q as follows:

$$q_r = 1000\,\rho_a\,C_e\,Q\,\Delta t_r = 1000\,\rho_a\,C_e\,Q(t_2 - t_1) \qquad (5)$$

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 air flow (m^3/s) and
Δt_r the variation of temperature from t_1 to t_2 influenced by heat of rock mass (Figure 2).

The heat emitted from the rock mass and received by the ventilation air of the underground opening can also be given in terms of coefficient of heat transference λ (Holman, 1983) according to the equation 6:

$$d_q = \lambda\; P\, \mathrm{dx}(T_p - T_m) \qquad (6)$$

where;
T_p, T_m are the temperatures of rock wall and air mixture respectively in the particular position dx (ºC),
λ is the coefficient of transference of heat of the rock mass the air mixture (W/m^2 ºC) and P the perimeter of the underground opening (m).

The total heat q_r transferred (W) can be calculated through:

$$q_r = \lambda\, P\, L\,(T_p - T_m)_{average} \qquad (7)$$

Combining the equation 4 with the parameters illustrated in the Figure 2 results in

$T_p = \{t_1 + [t_1 + (h_1 - h_{zn} \pm \mathrm{L}\sin\alpha)/g_g]\}/2$ and

$T_m = (t_1 + t_2)/2$

Applying the above values to equations 5 and 7, results in equation 8 as follows:

$$\left[(\lambda PL\,)/2\right]\left[(h_1 - h_{zn} \pm L\,sin\alpha)/g_g + t_1 - t_2\right] = 10^3 \rho_a\, C_e\, Q(t_2 - t_1) \qquad (8)$$

Finally the variation of temperature from t_1 to t_2 enables to calculate Δt_r as follows:

$$\Delta t_r = t_2 - t_1 = \frac{\lambda\, P\, L(h_1 - h_{tcn} \pm L\sin\alpha)}{g_g(\lambda\, P\, L + 2000\,\rho_a\, C_e\, Q)} \qquad (9)$$

In raises or any vertical underground openings, h_1=0, and the length which influences the geothermic degree is L Sinα - h_{zn} and α +, thus giving:

$$\Delta t_r = t_2 - t_1 = \frac{\lambda\, P(L\sin\alpha - h_{zn})^2}{g_g\left[\lambda\, P(L\sin\alpha - h_{tcn}) + 2000\,\rho_a\, C_e\, Q\right]} \qquad (10)$$

The coefficient of heat transfer λ is calculated as function of the thermal conductivity K (W/m.ºC), the non-dimensional coefficient of Dittus and Boelter 'Nu_d' 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):

$$\lambda = \frac{K\, Nu_d}{d} \qquad (11)$$

The relationship of Dittus and Boelter factor Nu_d (Holman, 1983) was studied in detail by Petukhov for gases (air) who arrived with the following equation:

$$Nu_d = \frac{\frac{f}{8}\mathrm{Re}_d\,\mathrm{Pr}}{1.07 + 12.7(\frac{f}{8})^{0.5}(\mathrm{Pr}^{0.67} - 1)} \qquad (12)$$

where;
Re_d is the Reynolds number (non-dimensional quantity) given by:

$\mathrm{Re}_d = V\; d/\mu$,

where;
V is the average air velocity (m/s),
d is the underground opening diameter (m) and
μ is the kinematic air viscosity(Kg/m.s).
f is the friction coefficient of the underground opening walls (Kg/m^3),

Pr is the Prandtl number (a non-dimensional quantity) calculated by;

$Pr = C_e \mu / K$.

The physic-chemical air properties are obtained in thermodynamic tables (Navarro Torres et al., 2005).

2.3. MATHEMATICAL EXPRESSIONS OF HEAT TRANSFER OF OTHER SOURCES

The mathematical expression for the temperature variation from air auto-compression Δt_a (ºC) developed (Navarro Torres et al., 2005) resulted in equation 13 as follows:

$$\Delta t_{ha} = 0.0098\ L \sin\alpha \tag{13}$$

where;
L and α are the well or shaft length (m) and inclination (º), respectively (Figure 3).

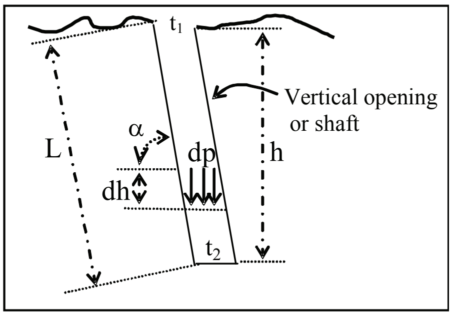

Fig. 3 Auto-compression scheme.

The temperature variation of air due to exhaust from the diesel equipment Δt_a (ºC) can be quantified by the following equation:

$$\Delta t_{ed} = \frac{f_m\, f_t\, q_d\, p_d}{\rho_a\, C_e\, Q}$$

where;
$f_m \cdot f_t$ are the mechanical and energy combined factors,
q_d is the equivalent energy of fuel diesel (2.9 KW/KW) and p_d is the engine power (KW) (Vutukuri et al., 1986).
c_e is the explosive heat liberated (KJ/kg),
e_u is the explosive energy calorific value (example for ANFO is 3900 KJ/kg and for dynamite 60% varied between 4030 to 4650 KJ/kg

The thermal influence due to blasting Δt_e (ºC) can be quantified in equation 15.

$$\Delta t_{ex} = \frac{c_e\, e_u}{8640\, \rho_a\, C_e\, Q}$$

The influence of the underground atmospheric temperature by thermal water Δt_w is obtained by in situ measurements and the human metabolism Δt_h is neglected because actually it is not important because normally underground mines are mechanized.

3. MATHEMATICAL MODEL VALIDATION IN A PORTUGUESE MINE

3.1. ROCK MASS AND UNDERGROUND OPENINGS

The Neves Corvo mine belongs to the Mining Society of Neves Corvo S.A. (Somincor) and is a subsidy of the Lundin Mining Corporation. Neves-Corvo 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 mine has been a significant producer of copper since 1989. 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.

The ore bodies of the underground Neves Corvo copper mine shown in Figure 4 are formed between 354 and 354.5 millions years ago 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 silicification 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).

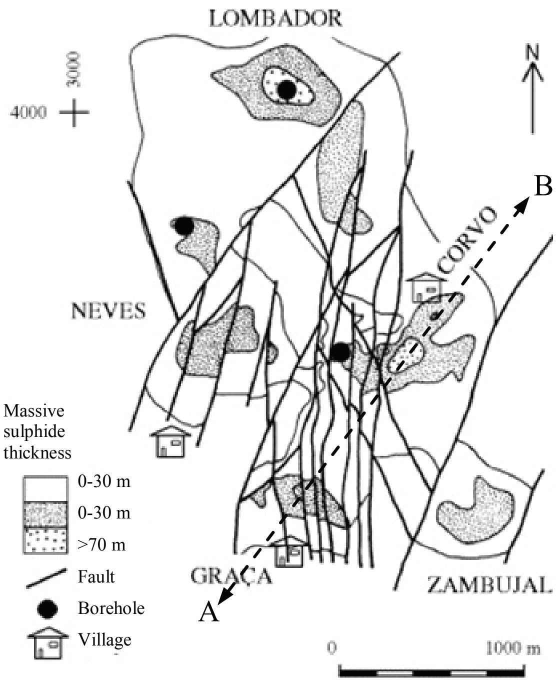

Fig. 4 Map of the Neves Corvo area showing the massive sulphide ore bodies Neves, Corvo, Gracia and Zambjal, with main faults and the location of exploratory boreholes (Moura, 2005).

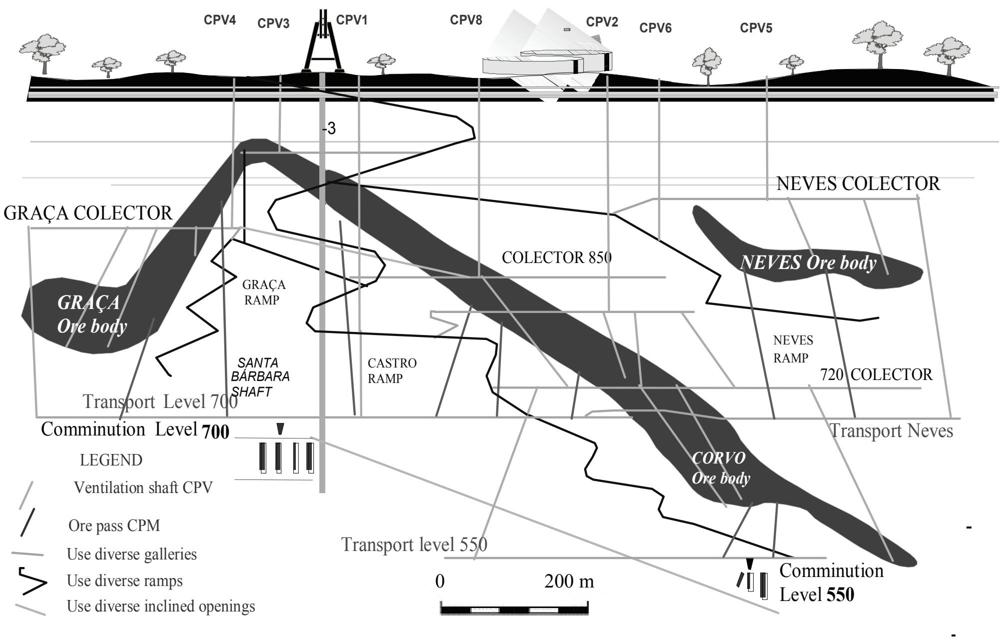

Fig. 5 Neves Corvo underground principal openings, vertical section A-B 30º northeast (Navarro Torres et al., 2005).

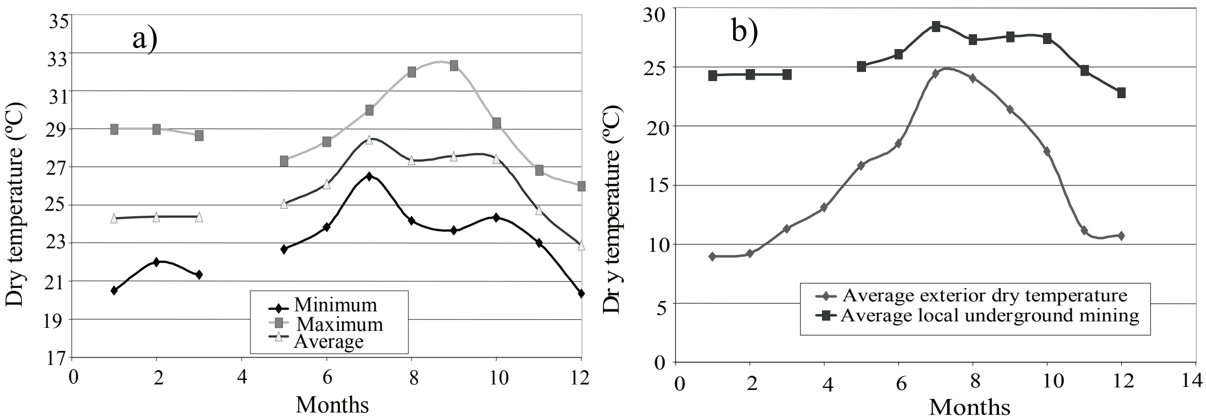

Fig. 6 Temperature variation in local underground mining (a) and compared with exterior temperature (b) (measured during 1998 to 2000, by (Navarro Torres et al., 2005)).

The underground openings excavated for exploitation in Graça, Corvo and Neves ore bodies are located between + 200 m and - 450 m, and they are referred to 0 level, equivalent to 0m datum and transport level equivalent to - 550m level as shown in Figure 5. The total length of underground vertical shafts, inclined and horizontal openings is about 80 kilometres.

The air temperature in underground stopes of Neves Corvo mine is moderate averaging between 20 ºC to 33 ºC and in isolated areas in critical condition reaching 42 ºC. Surface temperature behaviour is more variable compared to underground temperature in stopes as indicated in Figure 6.

3.2. VALIDATION IN CPV3 SHAFT

For the validation of the mathematical model, the CPV3 shaft shown in Figure 7 was selected. This shaft was constructed using a raise boring machine from the depth of 1222.40m level to 973.64m level with a length of 248.76 m and a diameter of 2 m (perimeter 14.86 m and 13.85 m^2 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 6). Average airflow resulted in 164.03 m^3/s as indicated in Figure 8.

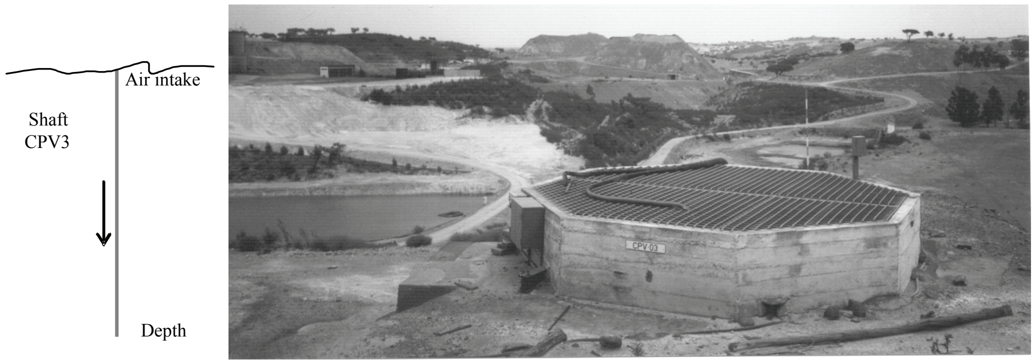

Fig. 7 Scheme and photograph of shaft CPV3.

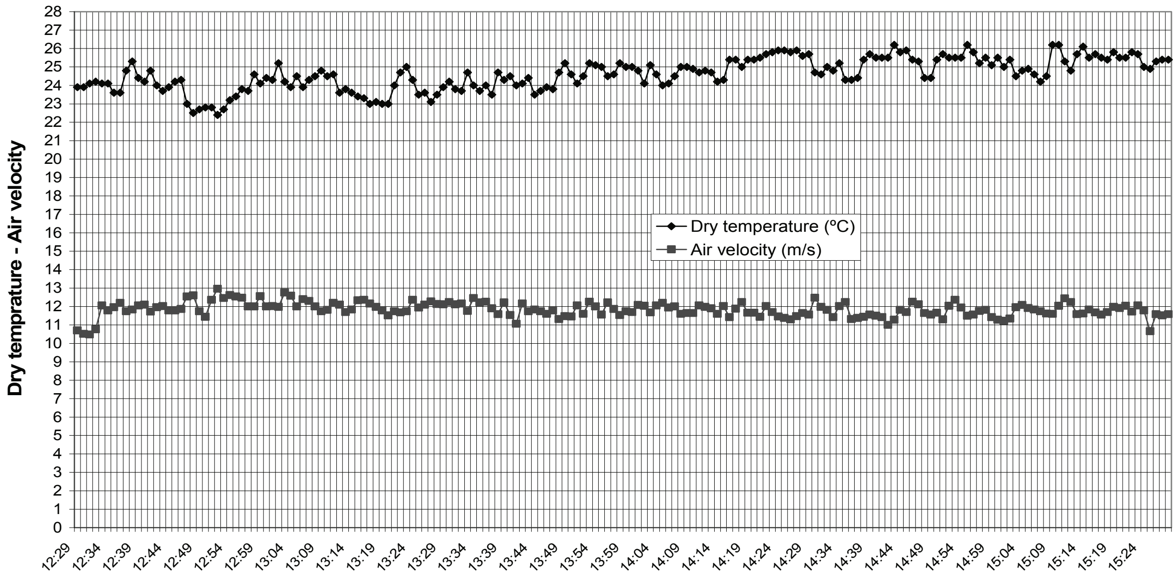

Fig. 8 Intake dry temperature and air velocity measuring by Data LOGGER DL20K.

Table 2 Physical-chemical air properties at 24.4 ºC (Navarro Torres et al, 2005).

ρ_a (kg/m^3)	C_e (KJ/kg.ºC)	μ (m^2/s)	K (W/m ºC)	Pr
1.1888	1.0056	16.48 x10^{-6}	0.026	0.709

Table 3 Coefficient of heat transfer and previous values calculated.

Re_d	Nu_d	λ (W/ m^2.ºC)
1.44 x 10^{-6}	5162.02	76.106

The air in CPV3 shaft is not influenced by diesel equipments (Δt_d), explosives (Δt_e), thermal water (Δt_w) and human metabolism (Δt_h). Therefore, only auto-compression (Δt_a) and thermal properties of rock (Δt_r) were considered for the validation of the proposed model.

The physical-geometric parameters of CPV3 shaft and physico-chemical properties of air shown in Table 2 enabled the calculation of the Reynolds number (Re_d) and the Prandtl number (Pr) by simple equations referred to before and applied to equation 12 to calculate N_{ud} as 5162.02.

It may be recalled that (Nu_d) is Dittus and Boelter coefficient. This result leads to the calculation of the coefficient of heat transfer (λ) by applying equation 12 and resulting in 76.106 W/m^{2o}C (Table 3).

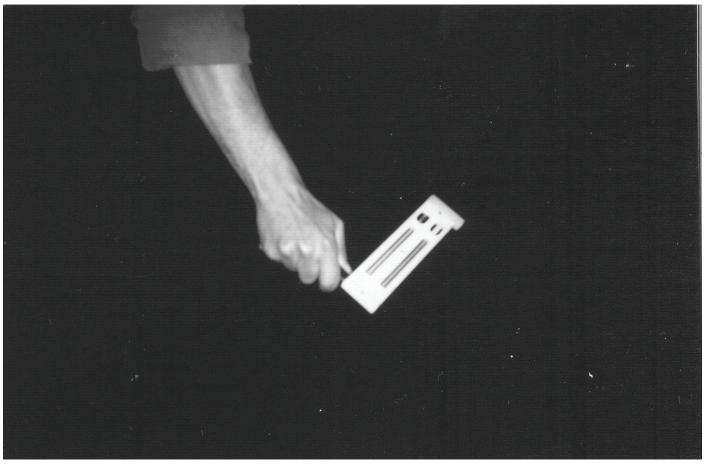

Fig. 9 Measurements with Data LOGGER DL20K and thermo/hygrometer Casella.

Finally using the 30.3 m/ºC of the geothermal gradient for the rock mass (g_g) for the Neves Corvo mine (Fernández Rubio et al., 1990), 30.0 m depth as the depth of thermal neutral zone and using the developed mathematical model in equation 10, the influence of thermal properties of rock mass ($\Delta t_r = t_2 - t_1$) is calculated as 2.79 ºC. Applying these values to equation 13, the temperature increase due to air auto-compression can be obtained as 2.44 ºC. Then the total increase of the air temperature during the air flow for shaft CVP3 results in 5.23 ºC.

The average values measurement with Data LOGGER DL20K of ROTRONIC in the air shaft intake with a thermo/hygrometer Casella in the shaft (Figure 9) was 29.52 ºC in the shaft bottom and 24.61 ºC in the intake, therefore the difference is 4.91 ºC.

The comparison the results show a total variation of temperature (Δt_{total}) between the mathematical model and measured temperature is 0.32 ºC or an error of 1.3%.

3.3. VALIDATION IN HORIZONTAL AND INCLINED OPENINGS

The selected horizontal and inclined openings for validation the mathematical model was the access of CO570GA1 stope, Collector N0900GV and Ramp NRAM02. The access of CO570GA1stope is a sub-horizontal opening of 204.00 m length and with small 0.90 m inclination, 20.96 m of perimeter, 27.56 m^2 of section and a friction factor 0.0046 kg/m^3. In the access of CO570GA1 the mineral production was 6000tones/round (2 rounds/week) with 0.20 kg of ANFO/tonne (Coupers et al., 1998). In this locale the larger diesel equipment used is one LHD Toro 500D (204 Kw) and the measured airflow was 8 m^3/s. The variation of air temperature between the intake and exhaust of CO570GA1 underground stope was 18.6% higher influenced by the thermal properties of the rock, 36.5% for blasting and 44.9% for diesel equipment respectively and this result is similar to US underground mines (Hartman et al., 1982).

For mathematical model validation in inclined openings collector N0900GV and ramp NRAM02 a similar process for previous underground environments obtained a measurement values shown in Figure 10.

As neither any diesel equipments nor blasting activities were used in the collector N0900GV and ramp NRAM02 because the ramp is used for the ore collection from the stopes or local underground work and the collector is appointed for the ventilation system.

4. DISCUSSION ON THE MEASUREMENT AND MATHEMATICAL MODEL VALUES

The measured average total dry temperature values were compared with the calculated values by mathematical model at four underground sites as shown in Figure 8 and Table 4. It can be seen that the error in the measured and calculated values range from 10% to 80% and are under 1º Celcius (optimal error range).

Larger average total temperature variation correspond to the larger opening length, depth or presence or absence of diesel equipment and blasting using and less variation corresponding to smaller length, depth or absence of diesel equipment and blasting (Figure 11) The applicability of the mathematical model was assessed by the average total dry temperature (Δt_{total}) and not only by thermal properties of rock (Δt_r). This procedure causes some influence, but they had been considered valid.

Finally the intake and exit temperatures in underground openings will change influenced by the exterior surface temperature as shown in Figure 6.

This procedure were also applied to San Rafael Peruvian mine (Dinis da Gama et. al., 2002) for

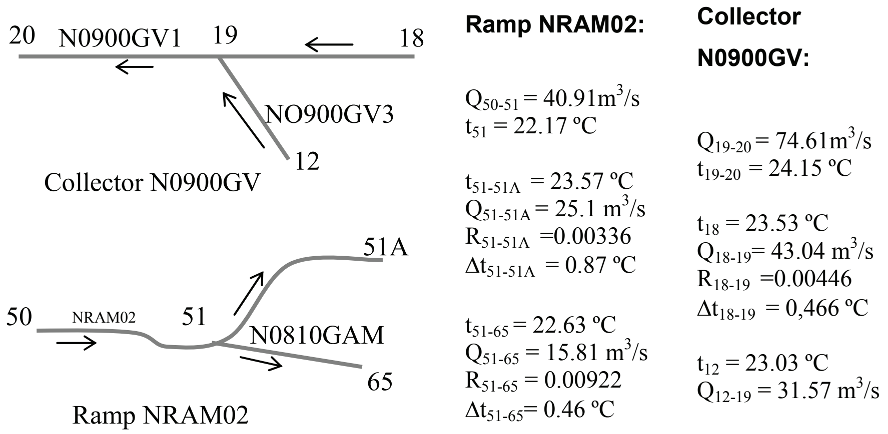

Fig. 10 Scheme and measurement average values of collector N0900GV and ramp NRAM02.

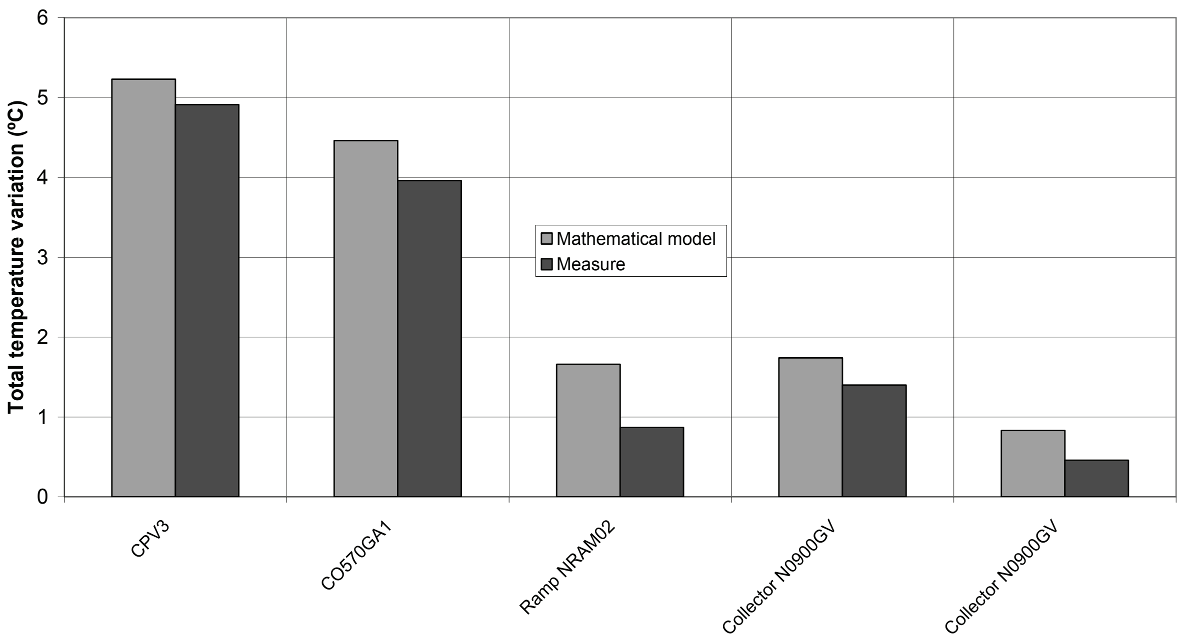

Fig. 11 Comparison of the measured and mathematical model results.

Table 4 Comparison average measure and mathematical model values.

Local	Average measure values (ºC)			Math. Model	Difference	Ratio
	Intake	Exit	Δt_{total}	Δt_{total} (ºC)	(ºC)	error
CPV3	24.61	29.52	4.91	5.23	0.32	0.94
CO570GA1	28.11	32.07	3.96	4.46	0.50	0.89
Collector N0900GV	23.53 23.03	24.15	0.87	1.66	0.79	0.52
Ramp NRAM02	22.17	23.57	1.40	1.74	0.34	0.80
		22.63	0.46	0.83	0.37	0.56

assessment of the thermal comfort environmental with very good results.

5. CONCLUSIONS

The evaluation of human thermal comfort in underground mines based on dry bulb temperature is considered as a most practical approach, although the thermal comfort depends on various other parameters including mean radiant temperature, air velocity, humidity, activity level and the use thermal resistant clothing's by the operators. In this paper the PPD (Predicted Percentage Dissatisfaction) index has been used as the function of the operative temperature and a mathematical model has been developed that allows the prediction of air temperature in the underground mining environment influenced by the geothermic gradient of the rock mass surrounding the mining excavations. This mathematical model has been validated in the Neves Corvo, Lead and Zinc mine in Portugal. The comparison between the calculated values by the developed mathematical model and the measured values, in the field, show very small variations with acceptable values for the real life situations. Following the validation of this mathematical model in Portugal, this procedure has been used in the San Rafael Mine in Peru to predict the thermal environment in the underground workings with satisfactory results.

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