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# Heat flow assessment in an underground mine: An approach to improve the environmental conditions

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**Abstract**
The generation of heat in underground spaces due to working activities is a factor that influences production and productivity rates. This paper analyses the heat generation in an underground mine and provides a number of approaches to enhance the ventilation conditions using electrical, instead of diesel machines. This assessment has been carried out using theoretical equations and modelling software. Investigations prove that sensible and latent heat would be reduced by around 50% and 84% respectively if the change were applied in the case study. This reduction on heat input to the ventilation system would improve the workplace environment because of lower effective temperatures and gas concentrations, which would result in better safety conditions and higher employee efficiency.

*Keywords*: mine ventilation, health and safety, efficiency, heat generation, mining equipment.

# Evaluación de los flujos de calor en una mina subterránea y enfoque para mejorar sus condiciones ambientales

**Resumen**
La actividad minera en espacios subterráneos genera un aporte de calor al sistema de ventilación que tiene influencia en los niveles de producción y productividad. Este artículo analiza y cuantifica las fuentes de calor en una mina subterránea y propone una alternativa de mejora de las condiciones ambientales mediante un cambio de los equipos diésel por maquinaria eléctrica. Este análisis se apoya en varias expresiones teóricas y programas para modelizar la ventilación. Los resultados muestran una reducción del calor efectivo y aparente del 50% y 84%, respectivamente, una vez aplicados los cambios de equipos en el caso estudiado. La reducción del calor en el sistema de ventilación permitiría una mejora de las condiciones en el lugar de trabajo debido a una menor temperatura efectiva y del nivel de contaminantes, incrementado el nivel de eficiencia de los trabajadores y mejorando el nivel de seguridad.

*Palabras clave*: ventilación subterránea; seguridad y salud; eficiencia; maquinaria minera; generación de calor.

## 1. Introduction

Heat flow is an important aspect associated to underground mine ventilation, on which mining equipment has a significant impact. As the work goes deeper and the mine evolves, factors such as temperature and humidity become crucial to keep acceptable environmental conditions and fulfil the legal requirements. Besides, efficiency rates and safety levels are also influenced by this factor. Many studies have been carried out regarding gases generated by diesel engines [1,2] and the incidence of temperature in underground mines [3-5].

The reduction of heat flow in these cases is usually focused on optimising the efficiency of the refrigeration system and cutting down its operating costs through an improvement of the current systems [6-10], but this important issue has not been approached when trying to change the mining equipment. Diesel equipment has an overall

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efficiency of about one third of the electrical units. Hence, the usage of fuel will produce approximately three times as much heat as electrical machines for the same mechanical work output [11]. Moreover, the combustion process generates harmful pollutants that have to be controlled, especially in the mining sector where the conditions are quite adverse in terms of health and safety [12].

Apart from the type of energy source, there are other important factors that affect the underground air temperature; for instance, the outer climate, the area's geological factors or the method used for mineral extraction [13].

This paper determines these different heat inputs in an underground potash mine by means of empirical equations and modelling software. After this, the heat flow contribution of electrical and diesel equipment is compared in order to expose an alternative to improve the environmental conditions in an underground infrastructure. The procedure followed is:

- Determination of the heat contribution of each source in the case study.
- A comparison of the situation using electrical energy instead of diesel trucks and loaders.

## 2. Heat input measurement methodology

The data used in theoretical equations and modelling software have been provided by mine staff, and measured in situ between 2008 and 2014 or extracted from bibliography in the case of the initial iterations with the software. The equipment features have been obtained from the manufacturer's data.

First, the airflow behaviour has been determined using Vnet. Fig. 1 is a scheme of the model achieved by means of the software. These initial results will be used to know the climatic conditions of the airways and the heat sources (strata heat, equipment and fragmented rock).

### *2.1. Strata heat*

Heat emission from the strata depends on the type of rock, the exploitation method and depth and length of the airways. However, the amount of heat transmitted decreases over time, the working faces being where the greatest transmission takes place. Sometimes, strata heat can be obtained using empirical methods based on other similar mines [11]. Unfortunately, there is no such information in this case.

Whillier [14] exposed an equation method that defines two expressions depending on the time since the tunnel was opened. If it has been open for more than 30 days, eq. (1) is used to determine the radial heat flow.

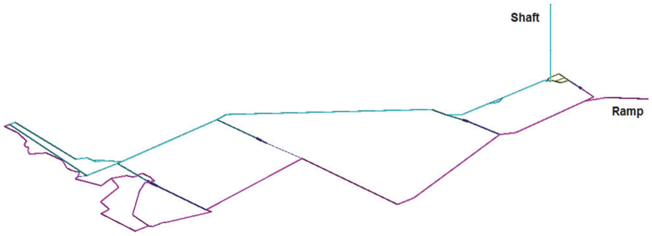

Figure 1 Modelling scheme of the mine using Vnet.
Source: Authors.

$$q = 3{,}35 \cdot L \cdot k^{0.854} \cdot (VRT - \theta d) \qquad (1)$$

Where q is heat flow from the strata (W); L is length of the tunnel (m); k is thermal conductivity of the rock (W/m·ºC); VRT is virgin rock temperature (ºC); θd is mean dry bulb temperature (ºC). Meanwhile eq. (2) is applied if the advance has taken place within the last 30 days.

$$q = 6 \cdot k \cdot (L + (4 \cdot DFA)) \cdot (VRT - \theta d) \qquad (2)$$

Where L is the length of the drift dug over the last 30 days (m), which cannot be greater than the length advanced in the last month; DFA is daily face advance (m). The main problem from eq. (1) is to find out the period that heat is transferred from the strata to the air until thermal equilibrium is achieved. This setback has been solved by modelling the strata behaviour using ClimSim. The software takes into account the heat flow transferred to the air by radiation and convection methods, determining the heat flow of a circular tunnel for a certain homogenous rock. Heat flow determination is based on the radial heat conduction from Fourier's equations, expressed in polar cylindrical coordinates (W/m$^2$).

$$k[\frac{r\,\partial^2\theta}{\partial r^2} + \left(\frac{\partial\theta}{dr}\right) + \frac{1}{r}\left(\frac{\partial^2\theta}{\partial\emptyset^2}\right) + r\frac{\partial^2\theta}{\partial z^2}] = r\rho C\frac{\partial\theta}{\partial t} \qquad (3)$$

Heat transfer can be either from the strata to the air or from the air to the strata depending on where temperature is higher, this continues until there is thermal equilibrium. When airways have been open for a long time, a phenomenon called "thermal flywheel" could arise, transferring heat from the air to the strata during the day and the opposite at night [15].

Fig. 2 explains the ClimSim functioning. First, the climatic variables have to be calculated or measured. Once the initial model is built, it has to be compared with real measures to validate it, applying iterations as many times as necessary to achieve a proper model.

After several iterations, rock conductivity and diffusivity were obtained, 6 W/mºC and 5.55 m$^2$/s·10$^{-6}$ respectively. According to the manual, values are considered acceptable when there is a difference of around ±1 ºC between modelled and measured mean values, between 2008 and 2014 in this case. Moreover, the iterations have been carried out in two different zones and four periods of the year in order to achieve more reliable results. Table 1 displays the temperature difference once the modelling is correctly adjusted.

On the other hand, Fig. 3 details the effective temperatures, calculated according to Spanish law (RGNBSM, itc 04.7.02), te = 0.9·tw + 0.1·td, where te is effective temperature, tw wet temperature, and td dry temperature.

Subsequently, base modelling has been used to calculate the length of the tunnels giving heat to the airways, changing the variables within the software called "age in" and "age out", which take into account the time since the tunnel was opened, until the sensible heat reaches a value of zero. In this case, the contribution of sensible heat to the airways is near zero after approximately one year.

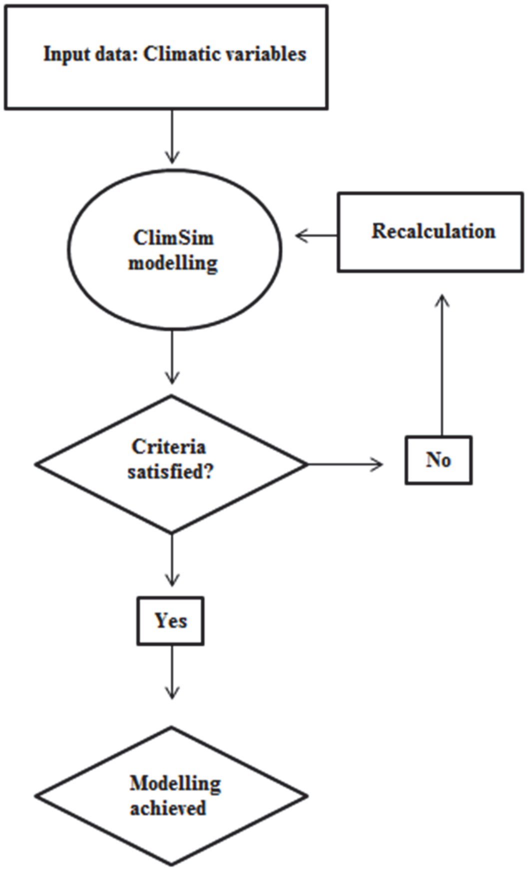

Figure 2 Scheme of the ClimSim functioning based on the user's manual explanation.
Source: Authors.

Table 1.
Temperature comparison of two points from the ventilation layout.

| Period | Dry bulb temperature ºC | | | Wet bulb temperature ºC | | |
|---|---|---|---|---|---|---|
| | Measured | ClimSim | Difference | Measured | ClimSim | Difference |
| **Point 1** | | | | | | |
| Overall | 24 | 21.62 | 2.38 | 17 | 15.96 | 1.04 |
| January | 19 | 17.60 | 1.40 | 11 | 12.07 | -1.07 |
| April | 25 | 23.07 | 1.93 | 18 | 15.87 | 2.13 |
| June | 30 | 27.80 | 2.20 | 22 | 20.65 | 1.35 |
| October | 27 | 24.95 | 2.05 | 19 | 17.77 | 1.23 |
| **Point 2** | | | | | | |
| Overall | 26 | 25.45 | 0.55 | 17 | 17.93 | -0.93 |
| January | 26 | 20.90 | 5.10 | 14 | 12.40 | 1.60 |
| April | 28 | 26.20 | 1.80 | 18 | 18.81 | -0.81 |
| June | 31 | 30.70 | 0.30 | 23 | 22.62 | 0.38 |
| October | 31 | 27.95 | 3.05 | 21 | 19.75 | 1.25 |

Source: Authors.

After that, it has been calculated theoretically to corroborate the modelled values, giving an average variation of only 9.97% both ways. Table 2 and Fig. 4 detail the behaviour of the strata heat using ClimSim.

## 2.2. *Mechanized equipment*

The exploitation method determines the heat contribution from the equipment to the ventilation system, there being a huge difference in terms of heat generation between the usage of diesel and electrical energy. Fig. 5 describes the steps to determine the heat input generated by electrical machines.

On the other hand, the efficiency of diesel machines is, approximately, 1/3 that of the electrical equipment and produces either sensible or latent heat, whereas the electrical

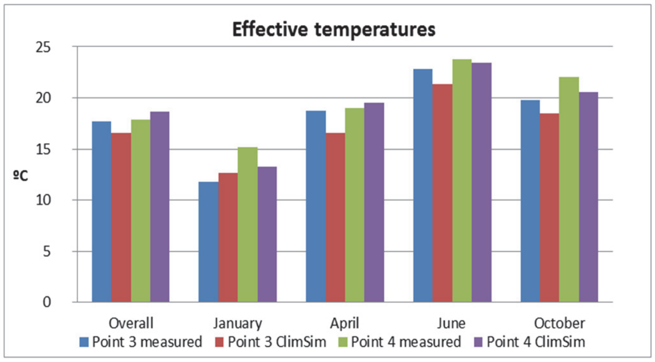

Figure 3 Comparison of the effective temperatures modelled and measured in situ.
Source: Authors.

Table 2
Behaviour of the strata modelled by means of ClimSim.

| Age in (days) | Age out (days) | Sensible heat (kW) | Latent heat (kW) | Months the tunnel has been open |
|---|---|---|---|---|
| 30 | 0 | 17.93 | 33.72 | 1 |
| 90 | 60 | 6.00 | 27.28 | 3 |
| 182 | 152 | 2.64 | 25.97 | 6 |
| 365 | 335 | 0.13 | 25.08 | 12 |
| 730 | 700 | -1.85 | 24.43 | 24 |

Source: Authors.

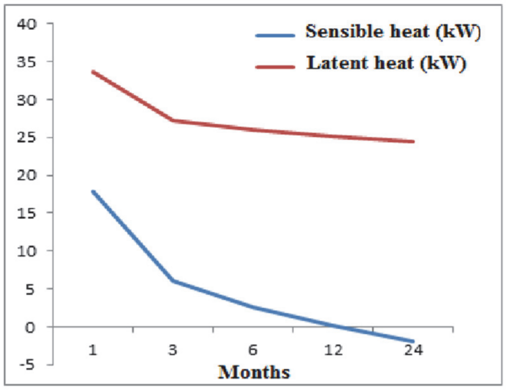

Figure 4 Behaviour of the strata heat, either sensible or latent.
Source: Authors.

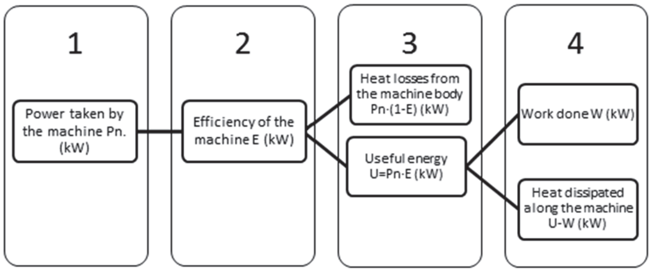

Figure 5 Scheme of the heat generated by electrical machines.
Source: Authors.

equipment only produces sensible heat. The three main heat sources are: 1) radiator and body of the machine, 2) combustion gases, and 3) movement and friction due to the usage of the machine [11]. Its quantification can be achieved considering a ratio of 0.3 litres of diesel per 1 kW per hour, with a calorific value of 34000 kJ/litre, and producing a heat generation of 2.83 kW for each kilowatt of mechanical output.

Each litre of fuel consumed produces around 1.1 litres of water due to combustion gases [16]. However, this value could be several times higher because of the refrigeration system. Some in situ analyses have pointed out that this ratio could vary from 3 to 10 litres per litre of fuel consumed, depending on the power and maintenance [17]. The following equation determines the total heat generated, which comprises latent and sensible heat.

$$qc = c \cdot \frac{Ec}{100} \cdot PC \tag{4}$$

Where qc is heat emitted by the combustion (kW); c is combustible (l/s); Ec is combustion efficiency (%); and PC is combustible calorific value (kJ/l). McPherson [11] gives some references for combustion efficiency (95%), and the rate of liquid equivalent per litre of fuel (5). This last parameter is necessary to calculate the quantity of water generated by the combustion.

$$W = c \cdot \frac{Ec}{100} \cdot r \tag{5}$$

Where W is water generated (l), and r is rate of liquid equivalent. After determining the water generated, the latent heat is obtained by taking into account a standard value of the water latent vaporization heat, 2450 kJ/kg, and an equivalency of 1:1 litre-kilogram of water.

$$ql = \lambda w \cdot W \tag{6}$$

Where ql is latent heat (kJ), and λw is water latent vaporization heat (kJ/kg). Finally, sensible heat can be obtained by deducting latent heat from the result in eq. 4. Later on, the figures were transformed to kW in order to compare the values for 8 hours of work.

### *2.3. Fragmented rock*

When fragmented rock is exposed to the ventilation airstream and there is a difference between rock and air temperature, heat transference is generated following the expression below [11].

$$q_{fr} = m \cdot C \cdot (\theta_1 - \theta_2) \tag{7}$$

Where qfr is heat load due to rock fragmentation (kW); m is mass flow of the mineral exploited (Kg/s); C is the specific heat of the rock (kJ/kgºC); $\theta_1$ is the temperature of the rock immediately after fragmentation (ºC); and $\theta_2$ is temperature of the fragmented rock at the exit of the ventilation system (ºC). Temperature $\theta_1$ can be considered equivalent to the virgin rock temperature with enough accuracy according to McPherson [11].

## 3. Mining equipment

Tables 3 and 4 detail the current mining equipment in the case study and the features needed to determine the heat input.

Table 3.
Diesel equipment characteristics.

| Type | Quantity | Nominal power (CV) | Nominal power (kW) | Consumption (l/h) |
|---|---|---|---|---|
| Truck | 22 | 400 | 294 | 67 |
| Loader | 12 | 300 | 221 | 58 |
| Car | 64 | 100 | 74 | 14 |
| Jumbo | 3 | 90 | 66 | 14 |
| Auxiliary equipment | 6 | 88 | 65 | 14 |

Source: Authors.

Table 4.
Electrical equipment characteristics.

| Type | Nominal power (kW) | Quantity |
|---|---|---|
| Continuous haulage machine | 165 | 1 |
| | 180 | 1 |
| | 220 | 5 |
| Conveyors | 56 | 2 |
| | 110 | 1 |
| | 180 | 1 |
| | 200 | 2 |
| | 400 | 3 |
| | 600 | 6 |
| Continuous miner | 529 | 10 |

Source: Authors.

The electrical trucks and loaders chosen have very similar sizes and capacities to the diesel ones. The models used were the Scooptram ST1030 and Scooptram EST1030 for the diesel and electrical loader respectively and the MT436B and EMT35 for the trucks.

## 4. Results and discussion

The heat inputs described above are shown in Tables 5 and 6, taking into account the latent and sensible heat contribution of each source. Table 5 exposes the results for the current situation (diesel loaders and trucks), whereas Table 6 shows the results after the change proposed; electrical loaders and trucks instead of diesel ones.

Table 5.
Heat input using diesel trucks and loaders.

| Source of heat | Sensible heat (kW) | Latent heat (kW) | Contribution (%) |
|---|---|---|---|
| Machines | 11093 | 6248 | 73.8 |
| Conveyors | 1072 | | 4.6 |
| Continuous haulage machine | 145 | | 0.6 |
| Miners | 1455 | | 6.2 |
| Fragmented rock | 297 | | 1.3 |
| Strata | 1102 | 2072 | 13.5 |
| Total | 15163 | 8320 | 100.0 |

Source: Authors.

Table 6.
Heat input using electrical trucks and loaders.

| **Source of heat** | **Sensible heat (kW)** | **Latent heat (kW)** | **Contribution (%)** |
|---|---|---|---|
| Machines | 5609 | 987 | 51.8 |
| Conveyors | 1072 | | 8.4 |
| Continuous haulage machine | 145 | | 1.1 |
| Miners | 1455 | | 11.4 |
| Fragmented rock | 297 | | 2.3 |
| Strata | 1102 | 2072 | 24.9 |
| Total | 9679 | 3059 | 100.0 |

Source: Authors.

As can be deduced from tables above and Fig. 6, the main source of sensible or latent heat is the machinery itself. Overall, the change of the loaders and trucks would reduce the contribution of heat from the mining equipment by 23%, and sensible and latent heat would decrease by about 36% and 63% respectively.

Furthermore, Table 7 exposes the current fleet of vehicles using diesel and the proposal, together with their heat generation and the percentage variation of both options.

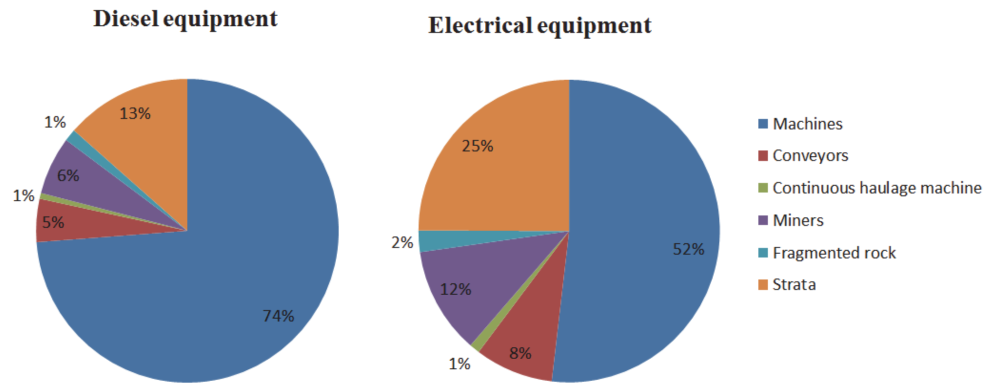

Figure 6 Percentage variation of the different heat inputs using electrical or diesel equipment.
Source: Authors.

Table 7.
Summary of the heat generated by the vehicles.

| **Type** | **Unit heat (kW)** | | **Total sensible heat (kW)** | | **Difference of sensible heat (%)** | **Total latent heat (kW)** | | **Difference of latent heat (%)** |
|---|---|---|---|---|---|---|---|---|
| | Diesel | Electrical | Diesel | Electrical | | Diesel | Electrical | |
| Truck | 450.9 | 90 | 6345 | 1984 | 68.7 | 3574 | 0 | - |
| Loader | 390.3 | 156 | 2996 | 1873 | 37.5 | 1687 | 0 | - |
| Car | 39.3 | - | 1607 | [1] | - | 905 | [2] | - |
| Jumbo | 25.1 | - | 48 | [1] | - | 27 | [2] | - |
| Auxiliary equipment | 25.1 | - | 96 | [1] | - | 54 | [2] | - |
| Total | | | 11093 | 5608 | 49.4 | 6248 | 986 | 84.2 |

[1] Only loaders and trucks are changed. Thus, other diesel using equipment is added to the total sensible heat input after applying the proposal.
Source: Authors.

The unit heat per machine is considerably reduced using electrical equipment, and the results above show a huge difference in terms of heat generation. Besides, as fuel consumption would be cut down, the generation of pollutants such as $NO_x$, CO or $CO_2$ would also decrease. Taking a ratio of 1:1 quantity of pollutants-litres of diesel burned, the generation would be minimized by 88% based on the data used.

Despite the considerable improvements of the hypothetical change, it has to be pointed out that these machines need a trolley or a cable in the majority of the cases to match the power required, reducing the flexibility of the vehicle fleet. Thus, a mixture of both kinds of equipment may be necessary. On the other hand, more research to achieve suitable batteries needs to be undertaken.

## 5. Conclusions

The usage of electrical loaders and trucks decreases the generation of sensible heat by 49.4% and latent heat by 84.2%. Overall, the contribution of heat from machines dropped from 73.8% to 51.85%. In addition, the modelling by ClimSim allowed us to observe the behaviour of strata heat in a potash mine, finding out the trend of sensible and latent heat in the airways.

Apart from the electrical engines' higher energy efficiency, less consumption of diesel would mean a drop in temperature and pollutants concentration. Therefore, ventilation requirements would be reduced and a better workplace environment could be achieved, leading to higher productivity and production rates. The usage of electrical equipment can also help to reduce the uncertainty in future mining activity due to oil price variations and more restrictive legal requirements.

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