

# **Heat from Fragmented Rock, Explosives and Diesel Equipment in Blind Headings of Underground Mines**

by

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## **Abstract**

Modern mining industries focus on system efficiency much more than before. Simulation programs for ventilation networks and thermal environments are gaining momentum. However, it is difficult to achieve correct results for thermal environments through simulation programs. One of the reasons for this is the inaccurate estimation of heat from blind headings.

In blind headings, the heat transferred from fragmented rock, explosives and diesel equipment to the air could make the thermal environments much more complex. In order to verify the heat load, *in situ* measurements were carried out in Hishikari Mine.

According to the air temperature variation with time, a new method for determining the heat load from fragmented rock and explosives is introduced in this paper. The heat from diesel equipment is also discussed. The theoretical calculation results showed good correlation with *in situ* measurements.

**Keywords:** Heat, Fragmented rock, Explosives, Diesel equipment

## **1. Introduction**

Simulation programs for ventilation networks and thermal environments are widely used by most modern mining companies<sup>1-6</sup>). However, the simulation programs are still facing difficulties in obtaining correct simulation results. There are a number of parameters that control the flow of strata heat into mining airways<sup>7</sup>). Additionally, when the strata surface is wet, the heat transfer scenario could be more complex.

The authors<sup>8</sup>) have carried out a sensitivity analysis on parameter changes in the simulation for thermal environments. They concluded that wetness fraction is one of the most important parameters influencing the simulation results.

Besides wetness fraction<sup>9-11</sup>), significant heat from explosives, fragmented rock and diesel equipment could also impact the thermal environments of blind headings<sup>12</sup>). Macpherson<sup>7</sup>) taught how to calculate the total heat from explosives and fragmented rock. However, the research on heat

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load from fragmented rock and *in situ* measurements of air temperature variation after blasting have never been carried out before.

In this research, *in situ* measurements of air temperature variation with time after blasting were carried out. Heat load which was transferred from fragmented rock, explosives and diesel equipment are discussed in detail based on these measurements.

## 2. Experimental Setup

### 2.1 Measuring method

In order to verify the heat load from the fragmented rock, diesel equipment and explosives in an actual blind heading, the *in situ* measurements were carried out in Hishikari Mine which is an underground mine during February 12th, February 13th, March 25th, March 26th, March 27th and March 28th in 2013.

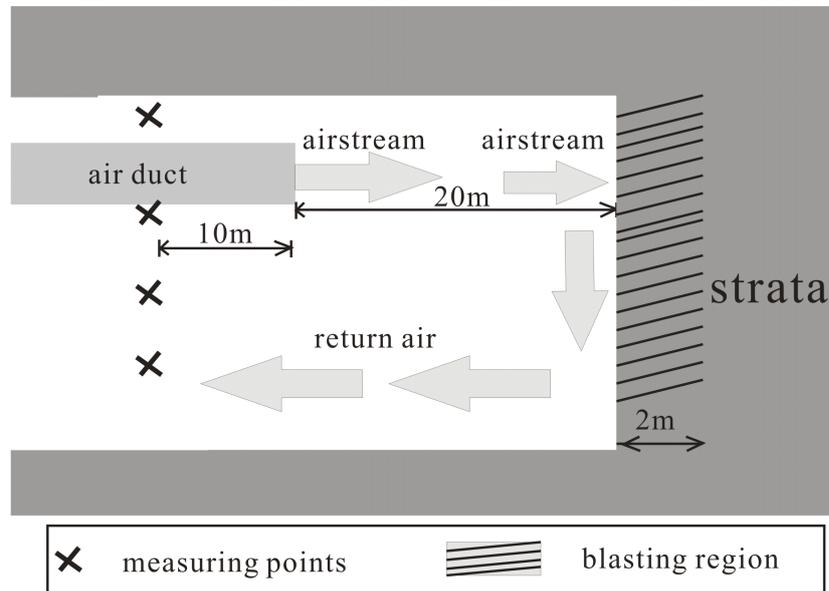
The airway had a cross-sectional area of 21.6m<sup>2</sup>. An air duct (80 cm diameter) was being installed in the roof of the airway which was producing a volume airflow of 7.73m<sup>3</sup>/s.

Hence the heat capacity of the air flow per unit time (W/K) in this airway is

$$C_f = F \cdot \rho_a \cdot C_a = 7.73 \text{ m}^3/\text{s} \times 1.20 \text{ kg/m}^3 \times 1005 \text{ J/(kg.K)} = 9370 \text{ W/K} \dots \dots \dots (1)$$

where  $F$ =volume flow of air (m<sup>3</sup>/s),  $\rho_a$ =air density (kg/m<sup>3</sup>),  $C_a$ =specific heat capacity of air.(J/(kg.K)).

**Figure 1** illustrates the location of the air duct and the measuring points near the heading. The distance between the measuring points and the face of the heading was 30 meters on February 13th.



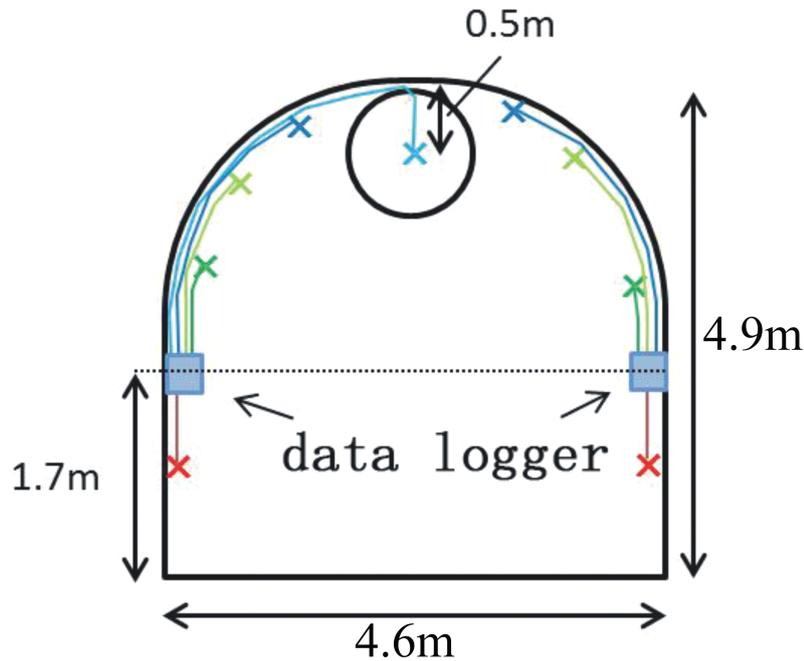
**Fig. 1** Side view of the airway that illustrates the location of the air duct and measuring points.

The distance increases as the heading advances although the distance between the duct end and the face is maintained almost constant. A blast may cause damage to the data loggers and sensors. Hence the measuring points were 30 meters from the end of the blind headings. The sensors had to be installed about one meter from the surface of the airway, because diesel equipment had to move through the center of the airway. The blind heading would advance about two meters in each blasting as shown in **Fig.1** and **Table 1** shows the characteristics of the diesel equipment.

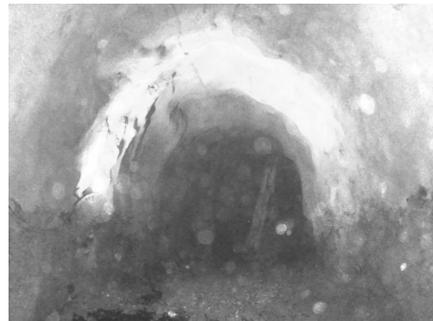
**Table 1** Characteristic of the heavy machine.

|                         | output(kW) | engine displacement (cc) |
|-------------------------|------------|--------------------------|
| scaffolding machine     | 110        | 4000                     |
| jumbo machine           | 74.9       | 7098                     |
| LHD<br>(Load-Haul-Dump) | 144        | 6700                     |
| power shovel            | 28.5       | 2189                     |

Data loggers and thermocouples of Type K (diameter is 0.5mm) were used for these measurements. The measuring interval of the data loggers was set to 30 seconds. The thermocouples were installed in nine locations of a cross-section (**Fig.2**). One of them was employed to measure the air temperature in the air duct (**Fig.2**).

**Fig. 2** Cross section of the airway that illustrates the installation of data loggers and thermocouples.

**Figure 3** shows duct and measuring points. **Figure 4** shows the shape of the blind heading before a blasting. **Figure 5** shows the shape of fragmented rock after blasting.

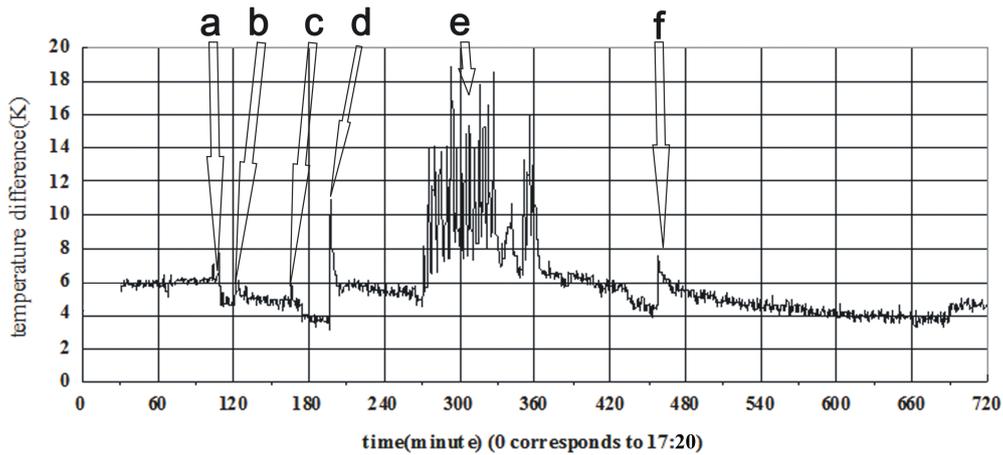
**Fig.3** Location of the sensors.**Fig.4** Blind heading before a blasting.



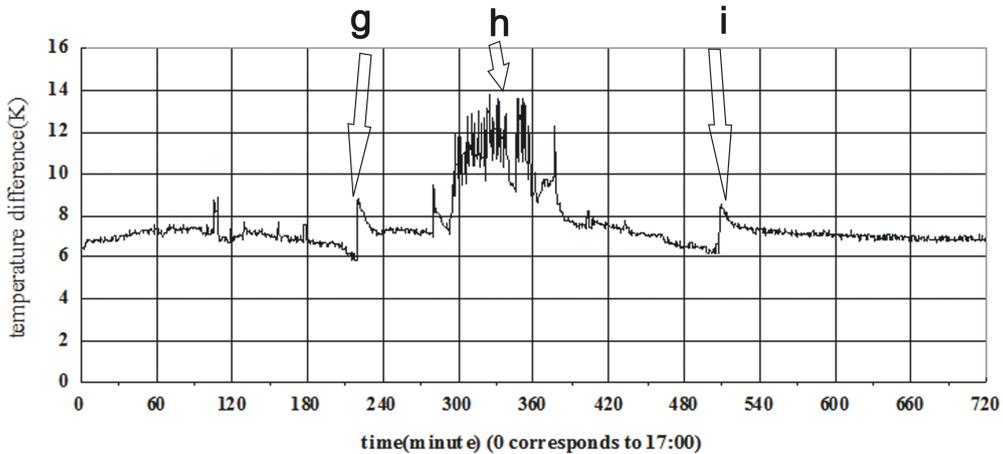
**Fig.5** Shape of fragmented rock after blasting.

## 2.2 Introduction of the measured results

The measured results of air temperature variation with time are shown in **Fig.6** and **Fig.7**. In this paper, the temperature difference indicated in all figures means the temperature difference between the temperature obtained as the average measured results of the eight thermocouples and air temperature in the air duct. ( $\theta_f - \theta_i$ ), where  $\theta_f$  = measuring data of the air temperature (K) and  $\theta_i$  = air temperature in the air duct (K).



**Fig.6** Measurement result of the variation of air temperature with time (February 12th and 13th).



**Fig.7** Measuring result of the variation of air temperature with time (March 28th and 29th).

The Operation process is introduced as shown below.

- The first measurement which was conducted on 12th and 13th February, 2013:
  - 17:20, measurement started
  - 17:20~19:15: hole drilling by mining jumbo
  - 19:20~20:10: explosive filling
  - 20:40: blasting (mass of fragmented rock: 58.4ton mass of water gel explosive used: 44.4kg)
  - 21:45~23:15: fragmented rock loaded by LHD
  - 23:15~24:30: explosive filling
  - 24:59: blasting (mass of fragmented rock: 48.4ton, mass of water gel explosive used: 17.2kg)
- The second measurement which was conducted on 28th and 29th March, 2013
  - 20:40 blasting (mass of fragmented rock: 49.6.4ton, mass of water gel explosive used: 41.8kg)
  - 22:15~24:00 fragmented rock loaded by LHD
  - 24:00~24:45 explosive filling
  - 25:25: blasting (mass of fragmented rock: 63.4 ton mass of water gel explosive used: 21.3kg)

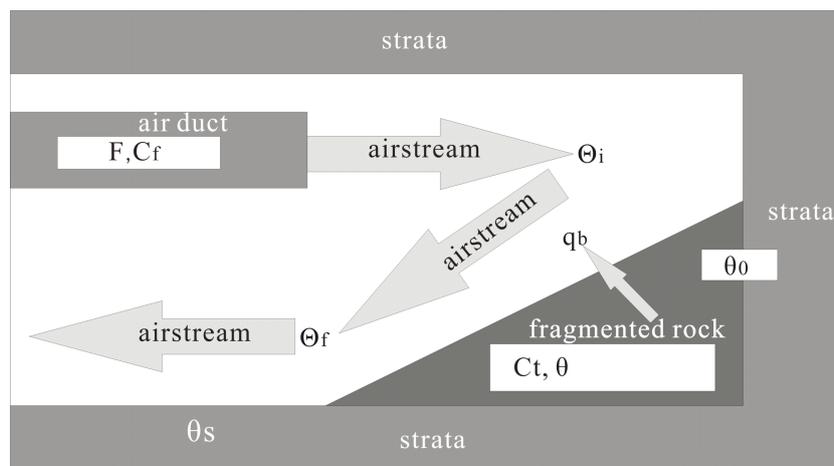
The brief discussion of the measured results is shown below(a~i means the operation as shown in **Fig.6** and **Fig.7**):

- a. air temperature increased due to the moving of mining jumbo. Air temperature decreased due to the mining jumbo exit from the area.
- b. air temperature increased due to the moving of scaffolding machine.
- c. air temperature increased due to the moving of scaffolding machine. Air temperature decreased due to the mining jumbo exit from the area.
- d. air temperature increased due to the blasting at 20:40.
- e. air temperature increased due to the moving of LHD
- f. air temperature increased due to the blasting work at 24:59
- g. air temperature increased due to the blasting at 20:40.
- h. air temperature increased due to the moving of LHD
- i. air temperature increased due to the blasting at 25:25.

### 3. Heat from Fragmented Rock

#### 3.1 Theoretical analysis on heat from fragmented rock

When a pile of fragmented rock surface is exposed to a ventilating airstream and there is a temperature difference between the rock and the air, then heat transfer will take place<sup>7)</sup> as shown in **Fig. 8**. This figure also shows the parameters employed in the analysis.



**Fig.8** Side view of the airway that illustrates the parameters employed in the research.

The heat capacity of the fragmented rock is given by:

$$C_t = v_g \cdot \rho_g \cdot c_g \quad \dots\dots\dots(2)$$

where  $C_t$ =heat capacity of the fragmented rock (J/K),  $v_g$ =volume of the fragmented rock( $m^3$ ),  $\rho_g$ =rock density ( $kg/m^3$ ) and  $c_g$ =specific heat capacity of fragmented rock (J/(kg.K)).

Here, it is assumed that the heat load lost from the fragmented rock to the air is proportional to the difference in temperature between the fragmented rock and surrounding air. It may be stated as

$$-C_t \cdot d\theta / dt = A \cdot (\theta - \Theta_f) \quad \dots\dots\dots(3)$$

where  $\theta$ =average temperature of the fragmented rock at certain time ( $^{\circ}C$ ),  $A$ = proportional coefficient (W/K),  $\Theta_f$ =air temperature when the heat transfer is taking place ( $^{\circ}C$ ).

Integrating equation (3) and applying an initial condition as  $\theta = \theta_0$  when  $t = 0$ . The equation can be converted to

$$\int_{\theta_0}^{\theta} \frac{-C_t}{A(\theta - \Theta_f)} d\theta = \int_0^t dt \quad \dots\dots\dots(4)$$

Then

$$(\theta - \Theta_f) = (\theta_0 - \Theta_f) \exp(-A / C_t \cdot t) \quad \dots\dots\dots(5)$$

or

$$A / C_t = - \frac{\ln \frac{\theta - \Theta_f}{\theta_0 - \Theta_f}}{t} \quad \dots\dots\dots(6)$$

Heat load lost from the fragmented rock to the air is given as

$$q_b = -C_t \cdot \frac{d\theta}{dt} \quad \dots\dots\dots(7)$$

where  $q_b$ =heat load lost from fragmented rock to the air (W)

Substituting for equation (3) and (5) in equation (7), then

$$q_b = C_t(\theta_0 - \Theta_f) \cdot (A / C_t) \exp(-A / C_t \cdot t) \quad \dots\dots\dots(8)$$

or

$$q_b = (\theta_0 - \Theta_f) \cdot A \cdot \exp(-A / C_t \cdot t) \quad \dots\dots\dots(9)$$

Equation (9) shows the heat load lost from fragmented rock may be subject to exponential decay.

### 3.2 In situ research on heat load from fragmented rock

Heat from explosives and fragmented rock in the blind heading was removed by the ventilation system. Hence the air temperature will increase.

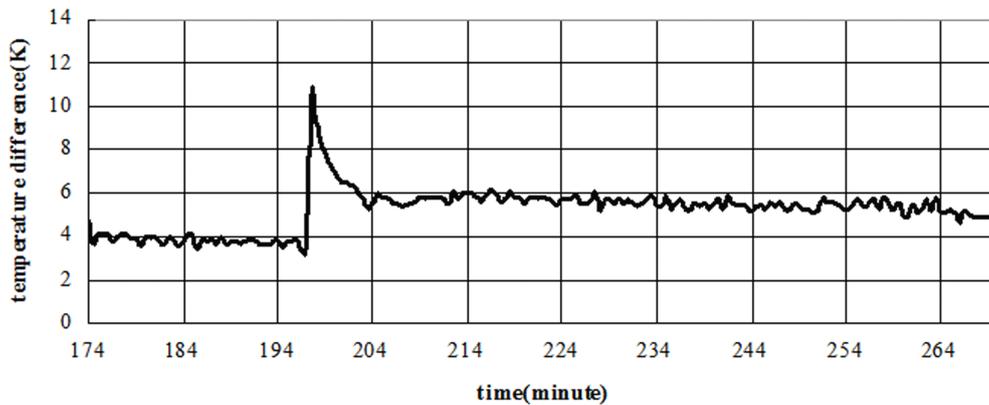
**Figure 7** shows the variation of the air temperature could become less obvious than **Fig.6** as the distance between the sensors and the blasting increases from 30m(**Fig.6**) to 78m(**Fig.7**). Hence the research on the heat from explosives and fragmented rock is going to be conducted by analyzing the data of area d in **Fig.6** as shown in **Fig. 9**.

Before 197 minutes, the air temperature difference was stable at about 4K. The increase can be considered to be caused by the strata heat. Hence the strata heat before a blasting around the measuring area is

$$q_{r0} = C_f \cdot (\Theta_{f0} - \Theta_i) = 37500 \text{ W} \dots\dots\dots(10)$$

where  $q_{r0}$ =strata heat before the blasting (W),  $C_f$ =heat capacity of air in per unit time (W/K) as shown in equation (1),  $\Theta_{f0}$ =stable air temperature before blasting (K),  $\Theta_i$ =air temperature at the exit of the air duct (K), here  $\Theta_{f0}-\Theta_i=4 \text{ K}$ .

At 197 minutes, the air temperature increased rapidly when a blasting was carried out. The air temperature decreased immediately after the blasting. It produced  $58.4 \times 10^3 \text{ kg}$  of fragmented rock as shown in **Fig.5**. Here it is temporarily assumed the air temperature variation from 197.5 minutes to 270 minutes was caused by the heat load lost from the fragmented rock, then equation (11) can be obtained.



**Fig.9** Variation of air temperature with time from 174 minutes to 270 minutes.

$$C_f \cdot \Delta t \cdot \left( \sum_{data=1}^N (\Theta_f - \Theta_{f0}) \right) = C_r (\theta_0 - \theta) \dots\dots\dots(11)$$

where:  $\Delta t$ =time interval of the measurements,  $N$ =number of measured data from 197.5 minutes to 270 minutes,  $\Theta_{f0}$ =stable air temperature before blasting (°C). The given data are listed in **Table 2**.

**Table 2** Given data that employed in the calculation.

|            | figure         | unit |
|------------|----------------|------|
| $\Delta t$ | 30             | s    |
| $N$        | 145            |      |
| $\Theta_f$ | measuring data | K    |

The heat capacity of the fragmented rock is  
 $C_r=58.4 \times 10^3 \text{ kg} \times 837.4 \text{ J/kg.K} = 48.9 \times 10^6 \text{ J/K}$

It can be calculated from equation (11) that the average temperature of fragmented rock only decreased by 1.9 K over 72.5 minutes. In this case,  $A/Ct$  can be calculated as  $1.2 \times 10^{-5}$  from equation (6). The range of values of the exponential function  $\exp(-A/Ct.t)$  could be very close to one during these period. Hence, From equation (9) the heat load lost from the fragmented rock to the air shall nearly be seen as remain constant with respect to time. This is the reason why the air temperature decreased very slowly after 204 minutes and could be stable at about 1.6 K higher than air temperature before the blasting as shown in **Fig.9**.

Care should be taken that strata heat should be proportional to the temperature difference between air temperature and temperature of the rock temperature. Hence if the air temperature has

been changed, changes of strata heat will also take place. After the blasting, the strata heat was different from that before the blasting. Here the heat lost from the fragmented rock and strata can not be separated. However, the sum of the two kinds of heat sources can be calculated by equation (12) because it is the two heat sources jointly increased the air temperature by 5.6 K. Hence

$$q_{r1} + q_b = C_f \cdot (\Theta_{f1} - \Theta_i) = 52500 \text{ W} \dots \dots \dots (12)$$

where  $q_{r1}$ =strata heat after blasting (W),  $\Theta_{f1}$ =stable air temperature after blasting (K), here  $\Theta_{f1}-\Theta_{f0}=5.6\text{K}$ .

The area  $g$  and  $i$  in **Fig.7** also shows the air temperature after blasting could be stably higher than the air temperature before a blasting. It can be concluded it was the heat from explosives that caused the rapid increase in air temperature at 197.5 minutes. Macpherson<sup>7)</sup> also pointed out heat produced by explosives causes a peak heat load on the ventilation system.

#### 4. Heat Transfer Coefficient and the Proportional Coefficient (A)

Nusselt number for a typical airways<sup>7)</sup> is expressed as equation (13)

$$N_u = \frac{0.35 f R_e}{1 + 1.592(15.217 f R_e^{0.2} - 1) / R_e^{0.125}} \dots \dots \dots (13)$$

where  $f$ =Atkinson friction factor,  $R_e$ =Reynolds' number.

The convective heat transfer coefficient<sup>7)</sup>,  $h$  (W/(m<sup>2</sup>.K)), is given as

$$h = \frac{N_u k_a}{d} \dots \dots \dots (14)$$

where  $k_a$ =thermal conductivity of air ( $2.2348 \times 10^{-4} T^{0.8353}$  W/(m.K),  $T$  being the absolute temperature in kelvins) and  $d$ =hydraulic mean diameter (m)

The heat transfer coefficient ( $h$ ) can be calculated as 4.54W/(m<sup>2</sup>.K) by equation (14).

For any given type of surface and flow conditions, the heat transferred through the boundary layers is proportional to the temperature difference across those layers. In the case where there is no fragmented rock, heat passing from the surface of the rock into the main airstream can be rewritten from equation (10) to equation (15).

$$C_f \cdot (\Theta_{f0} - \Theta_i) = h \cdot s_0 (\theta_s - \Theta_{f0}) = 37500 \text{ W} \dots \dots \dots (15)$$

where  $s_0$ =surface area when there is no fragmented rock (m<sup>2</sup>),  $\theta_s$ :temperature of the rock surface(K)

The figures of the data are listed in **Table 3**.

**Table 3** Given data that employed in the calculation.

|       | figure | unit                  |
|-------|--------|-----------------------|
| $h$   | 4.54   | W/(m <sup>2</sup> .K) |
| $s_0$ | 259.57 | m <sup>2</sup>        |

$\theta_s - \Theta_{f0}$  can be calculated as 31.8 K by equation (15).

In the case where there is fragmented rock, the heat source is strata heat and heat from fragmented rock. Heat transfer coefficient is a function mainly of air velocity and the characteristics of the rock surface<sup>7)</sup>. Hence, the heat transfer coefficient can be thought almost same in the two cases.

Then equation (12) can be rewritten as

$$C_f \cdot (\Theta_{f1} - \Theta_i) = h \cdot s_1 (\theta_s - \Theta_{f1}) = 52500 \text{ W} \dots \dots \dots (16)$$

where: $s_1$ =surface area after the blasting (m<sup>2</sup>),  $\theta_s - \Theta_{f1}$ =30.2K,  $h$ =4.54 W/(m<sup>2</sup>.K).

Hence  $s_1$  can be calculated as  $382.71\text{m}^2$  from equation (16). It shall be assumed exposure of the fragmented rock added to the surface area of the heat exchange region. The  $58.4 \times 10^3$  kg blast produced a  $123.14\text{m}^2$  new surface area and a nearly constant heat source.

Now the strata heat and heat load from fragmented rock can be calculated respectively. The strata heat after the blasting is

$$q_{r1} = h \cdot s_0 \cdot (\theta_s - \Theta_{f1}) = 35600\text{W} \dots \dots \dots (17)$$

and the heat load from fragmented rock is  $q_b = 16900\text{W}$

Hence the  $58.4 \times 10^3$  kg blast can pass  $16900\text{W}$  of heat into the air.

The temperature of the rock surface only decreased by  $4.5\text{K}$ . Hence proportional coefficient  $A$  shall be stated approximately as

$$A = h \times s \dots \dots \dots (18)$$

In the case where there is no fragmented rock,  $A_0 = h \times s = 4.54 \times 259.57 = 1178.4\text{W/K}$

In the case where there is a  $58.4 \times 10^3$  kg blasting  $A_1 = h \times s_1 = 4.54 \times 382.71 = 1737.5\text{W/K}$

Hence it shall be assumed the new surface area increases proportionately with mass of fragmented rock. Hence, in the case where there is  $n$  kg fragmented rock,

$$A_n = A_0 + n \times h \times s_1 / 58.4 \times 10^3 \dots \dots \dots (19)$$

The relationship can established from equation (15) to

$$C_f (\Theta_{fi} - \Theta_i) = (A_0 + n \cdot h \cdot s_1 / 58.4 \times 10^3) (\theta_s - \Theta_{fi}) \dots \dots \dots (20)$$

where  $\Theta_{fi}$  = stable air temperature after  $n$  kg blasting (K)

The function of stable air temperature and mass of fragmented rock after blasting is,

$$\Theta_{fi} = \theta_s - \frac{(\theta_s - \Theta_i) \cdot C_f}{A_0 + n \cdot h \cdot s_1 / 58.4 \times 10^3 + C_f} \dots \dots \dots (21)$$

The trial calculation can be conducted by equation (21). The results shows if  $150$  tons of fragmented rock have been produced, the air temperature difference will be higher than  $8\text{K}$ . In order to verify the assumption and demonstrate equation (21) is correct, a future *in situ* measurement is needed.

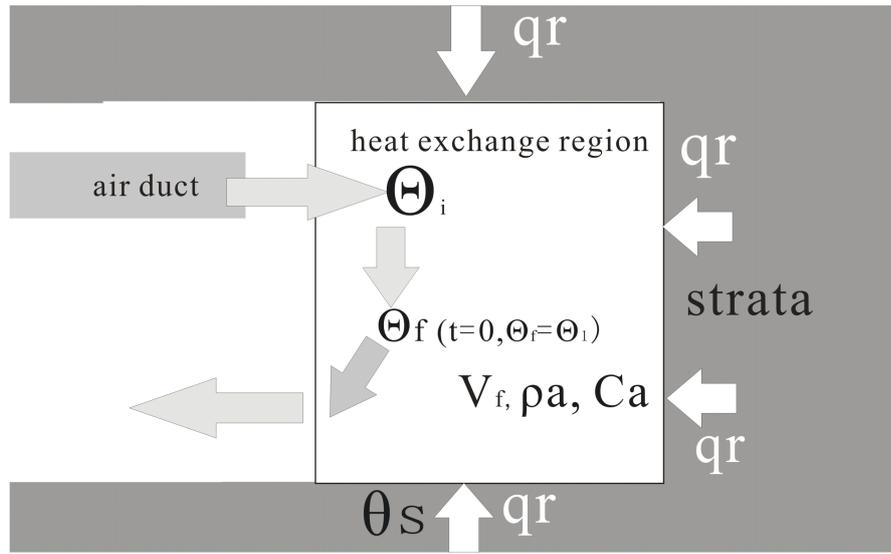
### 5. Feature of the Heat Exchange

The heat that is produced by the explosives causes a peak heat load on the ventilation system. Air temperature increased to a peak point  $\Theta_1$ . Afterward, the hot air was cooled by the airflow from the air duct. The heat exchange process would take place and hot and cooled air would mix in a short period. Hence, the air temperature would decrease from  $\Theta_1$  to  $\Theta_f$ . Meanwhile, strata heat which plays the role of the heat source also warmed the air from the air duct as shown in **Fig.10**.

Ignoring the small change in kinetic energy, the steady flow energy balance in this case gives:

$$C_f \cdot \Theta_i \cdot dt - C_f \cdot \Theta_f \cdot dt + q_r \cdot dt = V_f \cdot \rho_a \cdot C_a \cdot d\Theta_f \dots \dots \dots (22)$$

where  $q_r$  = strata heat (W),  $V_f$  = volume of heat exchange region ( $\text{m}^3$ ),



**Fig.10** Side view of the airway that illustrates the process of heat exchange.

Strata heat gives

$$q_r = A \cdot (\theta_s - \Theta_f) \dots\dots\dots(23)$$

It should noted the strata heat will change with the variation of air temperature.

Substituting for equation (23) in equation (22) gives

$$C_f \cdot \Theta_i \cdot dt - C_f \cdot \Theta_f \cdot dt + A \cdot (\theta_s - \Theta_f) \cdot dt = V_f \cdot \rho_a \cdot C_a \cdot d\Theta_f \dots\dots\dots(24)$$

or

$$\frac{dt}{V_f \cdot \rho_a \cdot C_a} = \frac{d\Theta_f}{((C_f \cdot \Theta_i + A \cdot \theta_s) - (A + C_f) \cdot \Theta_f)} \dots\dots\dots(25)$$

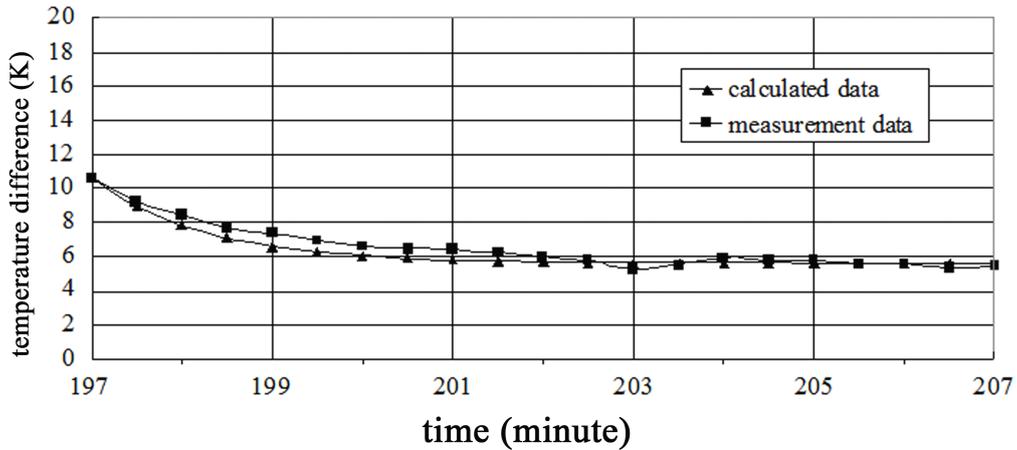
Integrate equation (25) and apply an initial condition as  $\Theta_f = \Theta_i$  when  $t = 0$ . The equation can be converted to the equation as shown below.

$$\Theta_f = \frac{C_f \cdot \Theta_i + A \cdot \theta_s}{A + C_f} + \frac{(C_f + A) \cdot \Theta_i - C_f \cdot \Theta_i - A \cdot \theta_s}{A + C_f} \cdot \exp \frac{-t \cdot (C_f + A)}{V_f \cdot \rho_a \cdot C_a} \dots\dots\dots(26)$$

Equation(26) shows air temperature increased to a peak point  $\Theta_1$  due to a blasting. At the same time, cooled air is passed from the air duct into this region. When there is a temperature difference between the rock surface and airstream, heat transfer will take place. This equation also shows the air temperature variation should be subject to exponential decay during the heat exchange process. In this case, when the heat exchange region was  $V_f = 669.6 \text{ m}^3$  and there was  $58.4 \times 10^3 \text{ kg}$  blast, equation (26) can be simplified as

$$\Theta_f - \Theta_i = 5.6 + 5 \cdot \exp(-0.0134 \cdot t) \dots\dots\dots(27)$$

The air temperature can be calculated as shown in **Fig 11**. A good match is achieved between the calculated data and measured data. This equation is an important discovery in this paper. It also can be widely used in other heat exchange systems.



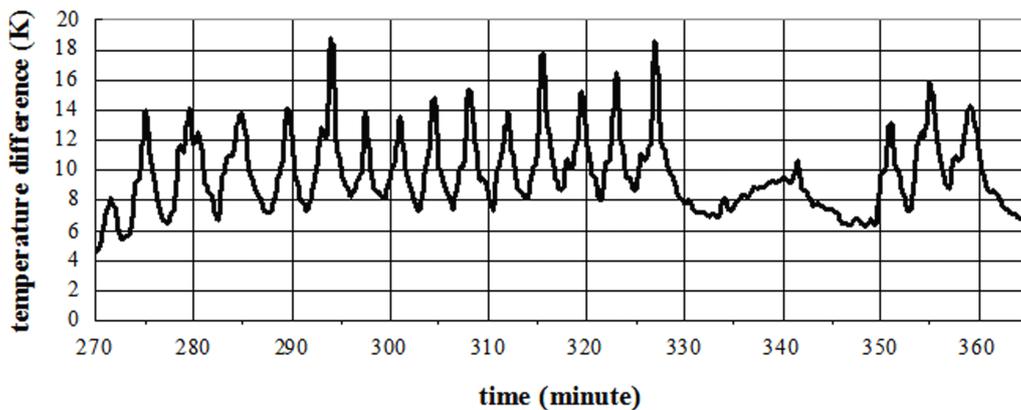
**Fig.11** Comparison of the calculated data and measured data from 197 minutes to 207 minutes.

**6. Heat from Diesel Equipment**

It can be seen that diesel equipment which was working in the blind heading could affect the thermal environments much more than the blasting from **Fig. 6** and **Fig. 7**.

**6.1 In situ measurement**

**Figure 12** shows the area *e* of **Fig. 6** 294 minutes, 315 minutes and 328 minutes are the peak points. LHD can be thought to have been doing the heaviest work at that time. The temperature difference increased to more than 18 K which means the heat produced by LHD increased the air temperature.

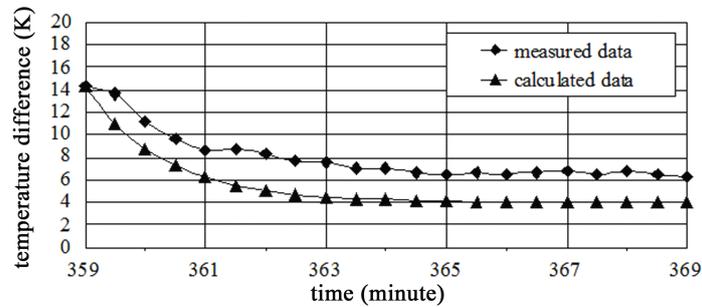


**Fig. 12** Variation of air temperature with time from 270 minutes to 370 minutes.

LHD finished the mining operation and left the blind heading at the time of 359 minutes. The heat that was produced by LHD caused a peak heat load on the ventilation system. For simplicity’s sake, the heat exchange process from 359 minutes to 369 minutes is discussed as shown in **Fig 13**. At 359 minutes, there were two kinds of heat source: heat produced by LHD and strata heat. Hence the temperature difference increased to 14.3 K. Afterward, the hot and cooled air mixed over a short period. The air temperature variation should be subject to exponential decay which can be calculated as equation (28) originated from equation(26).

$$\Theta_f - \Theta_i = 4 + 10.3 \exp(-0.0129 \cdot t) \dots\dots\dots(28)$$

The calculated data are also shown in **Fig 13**. It is clear that after the exit of LHD, the airstream took much longer time returning to the stable states than the calculated data. Hence it could be concluded that the much longer period of time the LHD worked could affect the thermal environments much more than the relatively quick blasting.



**Fig. 13** Comparison of the calculated data and measured data from 359 minutes to 369 minutes.

The total heat that was produced by LHD and strata is

$$q_{total} = C_f \cdot \Delta\Theta = 9370\text{W/K} \times 14.3\text{K} = 134000\text{W} \dots\dots\dots(29)$$

The strata heat can be calculated by equation (15)

$$q_{r2} = A_0 \cdot (\theta_s - \Theta_{f2}) = 1178.4\text{W/K} \times 21.5\text{K} = 25300\text{W} \dots\dots\dots(30)$$

Hence the heat produced by LHD is:

$$q_{d1} = q_{total} - q_{r2} = 134000\text{W} - 25300\text{W} = 108700\text{W} = 109\text{kW} \dots\dots\dots(31)$$

**6.2 Theoretical calculation**

The average fuel consumption of the LHD employed in the mine is 16.1 liters per hour. The calorific value of diesel fuel is 34000kJ/l.<sup>7)</sup> *in situ* tests have shown that each liter of diesel fuel consumed produces approximately 3 to 10 liters of water <sup>7,13)</sup>. Hence diesel equipment produces part of its heat output in the form of latent heat.

The total amount of heat produced from burning 16.1 liters of fuel (assuming a combustion efficiency of 95%):

$$16.1/3600 \times 34000\text{kJ/l} \times 95\% = 144\text{kW (total heat)}$$

If water vapour is produced at a rate of 4liters per liter of fuel

$$16.1 \times 0.95 \times 4 = 61.18 \text{ l(liquid equivalent)}$$

$$\text{Latent heat emitted in one hour: } 61.18 \times 2450 = 149891\text{kJ/h}$$

Where 2450kJ/kg is an average value for the latent heat of evaporation of water,

$$149891/3600 = 42\text{kW (latent heat)}$$

$$\text{Then, sensible heat produced} = \text{total heat} - \text{latent heat} = 144 - 42 = 102\text{kW}$$

In summary, the calculation result meets good agreement with the *in situ* measurements. The LHD produces heat at an average of

- 102kW sensible heat
- 42kW latent heat
- 144kW total heat

### 7. Heat from Explosives

44.4kg of water gel explosives were used in the blasting. The amount of heat released by water gel explosive is 3066kJ/kg<sup>7</sup>. The theoretical heat produced by water gel explosive is,

$$Q_e = 3066 \times 44.4 \text{ kJ/kg} = 136.1 \times 10^3 \text{ kJ}$$

The heat from explosives caused the air temperature to increase rapidly at 197.5 minutes as shown in Fig.14. There were two kinds of heat source: the explosives and strata heat, when the blasting was carried out.

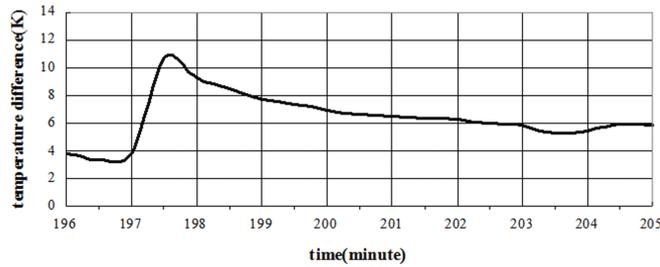


Fig. 14 Variation of air temperature with time from 196 minutes to 205 minutes.

Hence equation which is originated from equation(26) can be rewritten as

$$C_f \cdot (\Theta_i - \Theta_f) \cdot dt + q_r \cdot dt + q_{el} \cdot dt = V_f \cdot \rho_a \cdot C_a \cdot d\Theta_f \dots\dots\dots(32)$$

where  $q_{el}$  is the actual heat load from explosives (W).

At the point of blasting, It can be considered  $q_{el} \cdot dt$  was much larger than

$C_f \cdot (\Theta_i - \Theta_f) \cdot dt$  and  $q_r \cdot dt$ . Equation (32) can be simplified to

$$q_{el} \cdot dt = V_f \cdot \rho_a \cdot C_a \cdot d\Theta_f \dots\dots\dots(33)$$

Integrating equation (33) and applying an initial condition as  $\Theta_f = \Theta_0$  when  $t=0$ . Equation (33) can be converted to

$$\int_0^t q_{el} \cdot dt = \int_{\Theta_0}^{\Theta_1} V_f \cdot \rho_a \cdot C_a \dots\dots\dots(34)$$

where  $\Theta_1$  = the peak point of air temperature (K). Hence,

$$Q_{el} = V_f \cdot \rho_a \cdot C_a \cdot (\Theta_1 - \Theta_0) \dots\dots\dots(35)$$

$$= 669.6 \text{ m}^3 \times 1.2 \text{ kg/m}^3 \times 1005 \text{ J/(kg.K)} \times 7.2 \text{ K}$$

$$= 5.8 \times 10^3 \text{ kJ}$$

where  $Q_{el}$  = calculated heat produced by water gel explosive, here  $\Theta_1 - \Theta_0 = 7.2 \text{ K}$ .

Hence,  $Q_{el}/Q_e$  is 4%. Macpherson<sup>7</sup> also pointed out that the heat from explosives is dispersed in two ways. A fraction of it will appear in the blasting fumes whilst the remainder will be stored in the broken rock.

In this case it can be concluded 4% of the blast heat was removed with the blasting fumes. The remain 96% of the heat was stored in the fragmented rock.

### 8. Conclusion

In the present research, *in situ* measurements were carried out in a blind heading of an underground mine. It was found that the initial strata heat is 34kW around the measuring area.

Although, care should be taken to note strata heat changes in the event of the air temperature changing. The characteristics of heat load from fragmented rock were discussed. The heat load from fragmented rock was nearly a constant. In the case of a  $58.4 \times 10^3$  kg blast, the fragmented rock produced approximately 17kW of heat. The authors also showed the relationship between variation of air temperature and mass of fragmented rock which can be meaningful to guide the mining production.

Then, an important equation for describing the process of heat exchange has been presented in the paper. With the help of this equation, features of air temperature variation can be predicted. In this model, air temperature is subject to exponential decay. This equation can be also widely used in other heat exchange systems.

Heat produced by diesel equipment has been also discussed in this paper. Both the *in situ* measurements and theoretical calculation showed about 105kW of heat could be produced by the 144kW LHD.

The heat that was produced by explosives caused a peak heat load on the ventilation system. According to the *in situ* measurements, 4% of heat appeared in the blasting fumes approximately  $5.8 \times 10^3$ kJ while 96% of the heat was retained in the rock.

The research provides reliable parameters for the simulation of thermal environments.

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