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Chapter 36

DETERMINATION OF THE IN SITU MINE SURFACE HEAT TRANSFER COEFFICIENT

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Abstract. The surface heat transfer coefficient is measure of the rate of heat transfer from exposed rock surfaces to the ventilating air. Knowledge of its value is of particular importance to accurately simulate the early stages of rock cooling after the opening of an excavation. A number of theoretical formulae for the calculation of the coefficient are available for use in mine climate simulation. However, direct determination by in situ measurement is preferred.

Instrumentation, which has been developed for in situ mine measurement, and experimental procedures involving measurement at varying air velocities, are described. In a major study covering four Australian underground mines, the system has been used to determine surface heat transfer coefficients.

A direct relationship was clearly established between the measured surface heat transfer coefficient and air velocity. Comparison is made between experimental results and those previously measured or calculated by others. The relationship established can be described by an equation and holds for air velocities above 0.4 m/s. The derived relationship was confirmed at all mines tested and is independent of geology and tunnel dimensions found in modern mines.

INTRODUCTION

The surface heat transfer coefficient, h, is a measure of the rate of heat transfer from rock to the ventilating air, and is of particular importance in the determination of the thermal flux into the ventilating air in underground openings in the early stages of rock cooling after excavation (Vost, 1973).

The rate of heat transfer, q_w, is proportional to the temperature difference across the boundary layer of air between the rock surface and the main air stream, and is given by the equation

$$q_w = h\ (T_w - T_\infty) \qquad (1)$$

where T_w is the rock surface temperature
T_∞ is the averaged dry bulb temperature of the main air stream
h is the surface heat transfer coefficient.

Various theoretical values of h have been calculated by authors such as Starfield (1966a,b). The practical approach of in situ measurement has gained increasing acceptance and a new method for taking indirect in situ measurement of h has been developed by Danko and Cifka (1984). This approach forms the basis of the method used to measure the rock surface heat transfer coefficient in a number of operating Australian mines described within this study.

Danko (1983) introduced the concept of a local heat transfer parameter, the local physical surface heat transfer coefficient (h_{ph}). This coefficient is independent of the mean temperature in the airway, and is defined by

$$h_{ph} = \frac{d_{qw}}{dT_w} \qquad (2)$$

where dq_w represents the change of surface heat flux, q_w and dT_w is the change in surface temperature.

The conventional heat transfer coefficient h (or h_t in Danko's papers) is not independent of the mean temperature in an airway, and is defined using Equation (1).

$$h = \frac{q_w}{(T_w - T_\infty)} \qquad (3)$$

where T_∞ is the temperature affected to a negligible extent by heat transport or the mean temperature in a pipe.

The relationship between h and h_{ph} was developed by Danko and is given by Mousset-Jones, Danko and McPherson (1987) as

$$\frac{h}{h_{ph}} = \frac{P_r}{P_r - \frac{C_{fo}}{C_f}\left(1 - \frac{1}{k\sqrt{\frac{C_{fo}}{2}}}\right)} \quad (4)$$

where

Pr = molecular Prandtl number (0.71 in air)
C_f = coefficient of skin friction for the underground airway

$$C_f = \frac{\Delta P \; D_h \; L\pi}{2V^2\rho} \quad (5)$$

where

ΔP = friction induced pressure loss (Pa/m)
D_h = hydraulic diameter of airway (m)
L = length of airway (m)
V = mean velocity of the ventilating air (m/s)
r = density of the air in the airway (kg/m³)
C_{fo} = coefficient of skin friction for a hydraulically smooth airway

$$= 0.046 \; X \; Re^{-0.2} \; when \; 30{,}000 < Re < 1{,}000{,}000 \quad (6)$$

$$Re = Reynolds' \; number = \frac{VD_h\rho}{\mu} \quad (7)$$

μ = coefficient of dynamic viscosity (Ns/m²) (8)

k = a constant within the range $11 < k < 14$

The imprecision in the value of k is a function of uncertainty of the heat penetration from a surface point into the boundary layer (Danko, 1983). Another relationship between h and h_{ph} was published by Danko, Mousset-Jones and McPherson (1988) taking into account the surface area increase due to the roughness. Assuming a ratio A_o/A between the smooth and the rough surface areas, it reads:

$$\frac{h}{h_{ph}} = \frac{4.17Pr + 2.62\,(C_f / C_{fo})}{4.17Pr\frac{A_0}{A} + 2.62\frac{C_f}{C_{fo}}\frac{A_o}{A} + 0.92\frac{1}{\sqrt{C_F/2} - 6.37}} \quad (9)$$

LITERATURE REVIEW

Over the last 50 years there has been a growth in the realisation of the importance of the surface heat transfer coefficient h. Early attempts at modelling convection over rough surfaces were made by several workers (see Dankó, Mousset-Jones and McPherson, 1988). These attempts were followed by theoretically calculated values for h whilst more recent efforts were directed at the actual measurement of this parameter.

Goch and Paterson (1940) prepared tables to calculate radial heat flow into tunnels, based on values of conductivity, diffusivity, tunnel radius and time. It was assumed that the rock surrounding the tunnel was homogeneous, and that the tunnel surface was smooth. Starfield (1966a) noted that these tables apply to the case of an infinitely high coefficient of surface heat transfer, with the surface temperature of the rock equal to that of the circulating air. In practice there is a difference between the rock surface temperature and that of the underground mine air, and the rate of heat flow is proportional to that difference.

Scott (1956) was concerned with quantifying heat flow in hot and deep mines. He recognised the need for practical determination of heat transfer, and quoted two experimental attempts at in situ measurements, by De Braaf and Batzel. Using figures from these two authors he produced a graph of the total heat transfer coefficient against airway velocity. The relationship he proposed was of the form

h = m V + c

where h = total heat transfer coefficient

and V = air velocity

c = a constant

Scott (1956) stated that heat transfer by convection was most important in areas of very low air velocity, such as return air from "blind" headings. In areas of higher air velocity, as in normally ventilated tunnels, convection effects may be neglected.

Starfield (1966a) pointed out that the heat transfer coefficient h depends on both the diameter of the tunnel and the velocity of the air passing through it. A table for radial tunnel heat flow was prepared by him which allowed for the use of finite values of h which were obtained from analogy with heat flow in pipes. In addition, Starfield (1966b) stated that h is inversely proportional to the thickness of the boundary layer, which in turn depends on the velocity V of the main air stream. He assumed the power law

$$h = \text{constant} \times V^{0.8}$$

by analogy with that heat flow in pipes, and by the same analogy h will also depend on the diameter of a tunnel.

A mathematical approach to the determination of the heat transfer coefficient was developed by Starfield and Dickson (1967), but variables, such as a roughness factor f, made selection of suitable values still uncertain.

The increased recognition of the significance of the surface heat transfer coefficient in determination of the thermal flux into the ventilating air, particularly at the early stages of cooling rock, led Vost (1973) to investigate its in situ measurement. Vost measured the rate of temperature drop with thermistors in drill holes at various depths from the rock surface. The thermal conductivity value used in his study was obtained from a slide cut from a diamond drill core. The variation of h with air velocity was measured, but it was a method requiring a long period of stable ventilation (both in terms of velocity and temperature), probably more than 35 hours. Moreover, the whole exercise had to be repeated at different air velocities, and it implied that in terms of heat flow the rock was isotropic.

A new approach to the measurement of heat transfer was introduced by Danko in 1983. Danko was aware of the problem of accurate determination of airway temperature, and proposed the concept of a local physical heat transfer coefficient, h_{ph} defined by Equation (2).

A practical application of Danko's introduction of the parameter h_{ph} was undertaken by Danko and Cifka (1984) who sought to take in situ measurements of the coefficient, being critical of previously used methods, including Vost (1973). Their criticism refers to both the lack of precision and the inability to determine values on a rough surface with varying temperature. Comparison between the results obtained by this method and previously calculated figures showed a good agreement. However, at low air velocities the h_{ph} values measured were significantly higher than those expected by reference to published values. In addition, this method is still quite time-consuming.

Danko and Mousset-Jones (1985) established that the determination of both the physical heat transfer coefficient (h_{ph}) by Danko's Thermal System Identification device was unaffected by rock moisture content. Mousset-Jones, Dankó and McPherson (1986) undertook experiments using the equipment and techniques developed by Danko and Cifka at two mines in northern Idaho. Only the results obtained at higher air velocities (greater than 2.4 m/s) were used for further evaluation, due to uncertainties about figures obtained from lower velocities. It is at this stage considered that uncertainties may exist for air velocities less than 1.0 m/s.

Their results established that the technical heat transfer coefficient (h_t) as a function of air velocity appears to be 20 percent higher than comparable results in the literature and 100 percent higher than the value for a hydraulically smooth airway. However, the results obtained are 28 percent lower than the heat transfer coefficient value used in McPherson's program, CLIMSIM. A relatively high heat transfer coefficient was realized in the low velocity range in spite of a small surface/air temperature difference.

Mousset-Jones, Danko and McPherson (1987) emphasised that the method of Danko and Cifka is one which can measure the in situ value of the heat transfer coefficient while taking account of the natural roughness. Instead of using the coefficient h_t, the dimensionless Nusselt number (Nu) was used. In order to increase the accuracy of the determination of h_t, Danko, Mousset-Jones and McPherson (1988) attempted to introduce a surface correction to acknowledge the true perimeter of the airway. The conversion formula between h_t and h_{ph} in this case is given by Equation (9). This equation gave slightly different results from those obtained by Equation (4), and they concluded that the effect of the surface increment has not been clearly understood. In this paper the h_{ph} values were used in the determination of Reynold's and Nusselt's numbers, rather than h_t.

A sensitivity analysis on selected parameters for mine climate simulation programs (Danko, Mousset-Jones and McPherson, 1988) came to the conclusion that the sensitivity of the dry bulb temperature in an airway to the surface heat transfer coefficient is at its peak for a short time after the new face is exposed. This influence is greater in dry rock than in wet.

The literature reflects a steadily growing awareness of the importance of the surface heat transfer coefficient in the calculation of heat flow into mine airways. Early attempts were made to measure values of the coefficient in situ, but uncertainties on the accuracy of such attempts led to the derivation of theoretical models. Because of problems associated with previous in situ determinations of the coefficient, Danko adopted an oblique approach to its measurement. Danko's approach involved the initial measurement of the local physical heat transfer coefficient, followed by the derivation of the surface heat transfer coefficient. Both the measurement and the derivation depend on parameters which can be measured with a sufficient degree of accuracy.

EXPERIMENTAL PROCEDURE

Equipment

The equipment used in measurements of h_{ph} was developed by Danko and Cifka (1984). Their Thermal System Identification device consists of a temperature and heat flux measuring unit, a heat flux generating unit and a programmable measurement evaluating unit. The complete device is shown in Plate 1. A measuring sensor consists of a sensitive micro-foil heat flux sensor, a copper-constantan foil-type thermocouple and an electric heating resistor layer, all mounted in a sandwich arrangement. The sensor attached to the surface of a mine drift is shown in Plate 2. The sensor is attached to a tripod mounted extension arm which enables it to be held against airway perimeter rock surfaces.

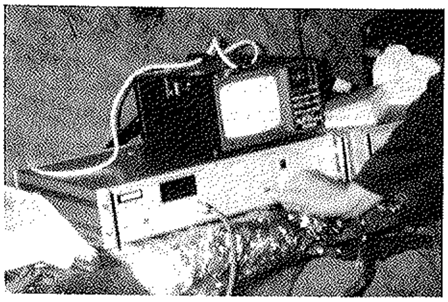

Plate 1. The Thermal Identification Device on location in a mine

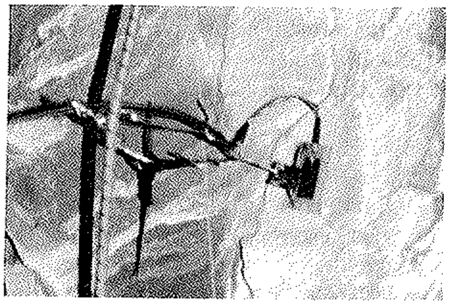

Plate 2. The Measuring Sensor held in place on a rock surface

A small TV monitor can be connected to the device to monitor measurements. The temperature and heat flux curves from the alternate heating and cooling cycles are displayed graphically on the screen, and the h_{ph} values are shown digitally both on the display of the device and the monitor. An example of the heating and cooling cycles is shown in Figure (1).

Approach

In order to take an h_{ph} reading the measuring sensor is held mechanically against the rock surface for a measuring period of about 5.5 minutes. Two heating and cooling cycles are undertaken. For each of these cycles, changes in heat flux and temperature are measured a number of times and a mean and standard deviation is calculated. In all tests, readings were not taken against the airway floor.

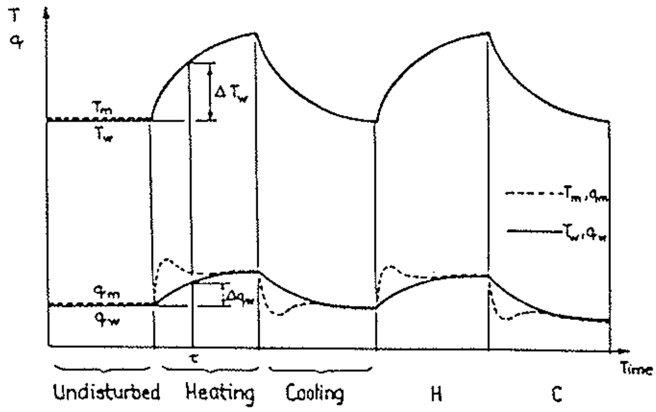

Figure 1. Illustration of Thermal System Identification device heating and cooling cycles

Since h_{ph} is directly related to air velocity, the latter has to be monitored throughout the measuring period. In practice the average velocity for the cross section is monitored through the test. To calculate h it is necessary to measure values for the parameters of hydraulic diameter, barometric pressure, wet and dry bulb temperatures and friction induced pressure drop.

Mine In-Situ Measurements

During a six-month period 1989-90 underground surface heat transfer measurements were undertaken at the four Australian underground operations of the Broken Hill-North Mine, the Gympie BHP gold mine, the Mount Isa Mine and The University of Queensland Experimental Mine.

<u>Broken Hill-North Mine Measurements</u>

Drives on the 36 and 24 levels were selected for measurements.

1. 36 level. The site was one of the few areas without any traffic. The total length of uniform airway was 37 m. The combination of short airway and low air velocity (about 0.4 m/s) made accurate measurement of friction induced pressure drop very difficult.

2. 24 level. This site was selected for the following reasons.

i) No mining or stope filling was in progress.
ii) There was good control over air velocity.
iii) There was a relatively straight test section of reasonably uniform surface texture.

The total length of uniform airway was 51 m. This was shorter than desirable for two main reasons. Firstly, a longer airway would allow the establishment of streamlined air flow, and secondly, it was difficult to measure accurately the pressure drop due to friction over this short distance.

Measurements were taken on 24 level at four different velocities, three complete sets of readings were taken, plus a single cross section set at a lower velocity. This latter reading was taken to enable a comparison to be made with the values on 36 level.

The general experimental procedure was as follows.

1. An 8 m long test section was marked in 2 m increments, and five cross sections marked with nine measuring points each on the walls and back.
2. Cross section dimensions were measured by radial measurements with a survey staff.
3. An anemometer traverse was taken at each section at the beginning and end of the set of readings. A measurement of centre line velocity was taken immediately before and after the traverses to allow calculation of a centre line correction factor.
4. During each h_{ph} measurement, a continuous centre line velocity reading was taken and used to determine the average velocity.
5. Wet and dry bulb temperatures and barometric pressure were taken at least once for each cross section. The values obtained were used to determine air density with Barenbrug Psychometric Charts.
6. A manometer and trailing hose were used to measure friction induced pressure drop over the 51 m long section of airway. The combination of short airway length and low air velocity in some tests resulted in low values which were difficult to measure accurately.
7. Physical surface heat transfer coefficient (h_{ph}) measurements were taken by carefully positioning the sensor on the rock surface at each of the nine section circumferential points. A tripod with extension boom was used to hold the sensor against the rock.
8. The same procedure was used for the five cross sections. Once a complete data set for the five cross sections had been obtained, airway velocity was changed and the procedure repeated.

Gympie BHP Gold Mine Measurements

The test site selected was on 18 Level in the O 55N crosscut. Because of limited air velocity range (the maximum average velocity achieved was 1.1 m/s) and difficult working conditions, only three sets of readings were taken. Ventilation was by means of flexible ducting, and air requirements elsewhere in the mine precluded the supply of more air to obtain an increased velocity in the test section. The length of the test section for the first set of readings was 51 m, but for the third set this was reduced to 35 m in order to avoid disturbance of hot stagnant air in drives beyond the crosscut. These short lengths of test section made accurate measurements of the pressure drop difficult.

A 6m long test section was marked in 1m increments, and seven cross sections marked with nine measuring points each on the walls and back. An additional measuring point was selected on the floor at about the centre line. A single cross section was selected as typical of all seven, and was measured by radial measurements with a survey staff. Measurements of air velocity, density, friction induced pressure drop and physical surface heat transfer coefficient (h_{ph}) were taken as on 24 Level at Broken Hill.

Mount Isa Mine Measurements

Readings were taken in the O 62N drive on 18 Level. This drive was selected for the following reasons.

1. It was a return airway, and carried no traffic.
2. A wide range of air velocities could be achieved.
3. It was relatively straight with reasonably uniform surface texture.

The total length of uniform airway was 60.2 m. This was reduced to 47.1 m in an attempt to stabilise pressure readings on the inclined manometer. Again, these lengths were shorter than desirable, however, longer sections elsewhere in the mine with air velocity control were not available.

A 6 m long test section was marked in 1 m increments and seven cross sections marked with nine measuring points each on the walls and back. An additional measuring point was selected on the floor at about the centre line. Air velocity measurements were taken as on 24 Level at Broken Hill. Barometric pressures for air density calculations were obtained from the mine weather station and reduced for 18 Level. Air density was calculated as at Broken Hill.

A manometer and trailing hose were used to measure pressure drop over the 60.2 m and 47.1 m long sections of airway. The fluid level in the manometer fluctuated continuously, indicating varying pressure at the upwind end, making it impossible to achieve reliable measurements of pressure drop. The close proximity of the return air raise was the probable cause of unstable air flow at the upwind end of the measuring section. Due to these problems, frictional impedance determined at Gympie was used in place of the actual measured values from Mount Isa as there were similar airway surface conditions at both mines.

Physical surface heat transfer coefficient readings were undertaken using the procedure adopted at Broken Hill.

The University of Queensland Experimental Mine

Readings were taken at this mine as high air velocities could be achieved and results could be obtained from different rock types and surfaces with different degrees of weathering.

All readings were taken in the Ventilation Drive on the 140 Level. This drive was selected for the following reasons:

1. A 24.7 m long section of tunnel without timber sets was available, whereas much of the mine has artificial support.

2. Good velocity control was available.

A 6 m long test section was marked in 1 m increments, and seven cross sections marked with nine measuring points each on the walls and back. An additional point was selected on the floor at about the centre line.

Measurement of cross sections, air velocity, density, friction induced pressure loss and physical surface heat transfer coefficient (h_{ph}) were taken as on 24 Level at Broken Hill.

EXPERIMENTAL RESULTS

For each mine site and selected air velocity, physical surface heat transfer coefficient (h_{ph}) values measured at points around drive perimeters were graphically examined on drive cross sections. The values of h were calculated using equations 5-8, and a value of 12.5 was used for the constant k in equation 9. Calculated h values are shown in Tables 1 to 4.

DISCUSSION OF RESULTS

Figure 2 has been plotted with experimentally derived results from the four Australian mines plus three surface heat transfer values obtained by Vost (1973); values from the Recsk Mine obtained by Danko (1984); one value from the Sunshine Mine obtained by Mousset-Jones, Danko and McPherson (1986); four values derived from the Broken Hill data using the CLIMSIM program equation (Mousset-Jones, Danko and McPherson, 1986); and five values from Scott (1956).

A regression analysis was carried out on the calculated values in this study and the one available value from the Sunshine Mine. The resultant line has the values

$$h = 4.87V + 2.43 \qquad (10)$$

which is shown graphically on Figure 3. In preparation of the relationship, the h values at zero velocity have been omitted. The value of h calculated from the 36 Level readings at Broken Hill has not been included because of questions of experimental error. A correlation of 0.98 was obtained for the straight line shown on the figure.

In theory the measured physical surface heat transfer coefficient (h_{ph}) should be zero at no air velocity. However, as pointed out by Danko and Cifka (1984), natural convection gives positive h_{ph} values at zero or very low velocities. The transition from a total to a minimal convection effect has not been quantified, but from observation it has been assumed to be about from zero to 0.3 m/s, and an approximation has been drawn on Figure 3.

The geology of the four mines varies significantly. The areas tested covered rocks of igneous, metamorphic and metasedimentary nature. The three deep mines presented fresh rock surfaces. The quartz phyllite at The University of Queensland Experimental Mine was mostly moderately weathered, and certainly oxidised. Broadly the tests could be stated to have covered a reasonable range of rock types and conditions. All measured values fit closely to a straight line. Confidence limits for measured physical surface heat transfer coefficient (h_{ph}) values (Figure 4), and uncertainty in the value of the constant k in equation 8 are apparently much greater than the influence of rock type.

In a practical sense, the conclusion that can be reached from the field measurements is that h is independent of rock type in the mines visited.

In the introduction a constant, k, within the range $11 < k < 14$, and which relates to the penetration depth of the local heat transfer, is described. A figure of 12.5, which is midway between those limits has been used for k in all calculations.

Scott (1956) prepared a graph of velocity against surface heat transfer coefficient, based on experimental determinations by De Braaf and Batzel. By taking the values on his graph where the velocity is above about 1.0 m/s, a linear regression has been applied with a resultant line of equation

$$h = 5.57V + 6.56 \qquad (11)$$

As shown in Figure 3 this line is virtually parallel to the one determined in this study (equation 10), but offset towards higher values of h. At this stage it has not been possible to gain access to the original figures used by Scott, so no comment is possible on his determination.

Vost (1973) measured h at three different velocities at Broken Hill. Those values are also shown on Figures 2 to 4. The straight line through those three points is parallel but below the one calculated in this study, with h values about 20 percent lower. Factors which may have affected the reliability of Vost's figures include a laboratory determined value of k (thermal conductivity of rock), rather than an in situ determination. His values also depended on very accurate measurements of small changes in temperature. Diurnal changes in temperature were observed by him, as were falls in air temperature of approximately a degree lasting about half an hour due to drilling further up the drive. It would seem inevitable that there will be some uncertainty in the value of h as determined as a function of thermal conductivity, rock temperature gradient near the surface, rock surface temperature and ventilating air temperature.

Starfield (1966b) postulated that the relationship between h and the velocity v of the main air stream would be of the form

$$h = \text{constant} \times V^{0.8}$$

by analogy with heat flow in pipes. By plotting h against $V^{0.8}$, the slope of the best fit line is 6.76, with an intercept of 0.74. A graph has been prepared (Figure 3) to compare the curve

$$h = 6.76V^{0.8} + 0.74 \qquad (12)$$

TABLE 1

Measured h values at Broken Hill

Average air velocity (m/s)	Standard deviation	Mean value of h (W/m².°C)	Standard deviation
0.4 approx	-	7.3	1.2
0.62	0.02	5.9	1.9
0.9	0.05	7.1	2.1
1.44	0.08	9.6	3.3
1.62	0.1	10.5	3.4

TABLE 2

Measured h values at Gympie

Average air velocity (m/s)	Standard deviation	Mean value of h (W/m².°C)	Standard deviation
0	-	2.8	0.9
0.43	0.03	3.3	2.0
1.13	0.08	11.5	6.4

TABLE 3

Measured h values at Mount Isa

Average air velocity (m/s)	Standard deviation	Mean value of h (W/m².°C)	Standard deviation
0.59	0.08	5.1	2.0
1.32	0.11	8.3	3.4
2.38	0.18	13.8	4.6
4.48	0.35	22.8	7.8

TABLE 4

Measured h values at the University of Queensland Experimental Mine

Average air Velocity (m/s)	Standard deviation	Mean value of h (W/m².°C)	Standard deviation
0	-	3.6	1.3
0.54	0.11	4.5	2.0
1.61	0.26	9.9	4.9
2.31	0.21	13.6	5.27

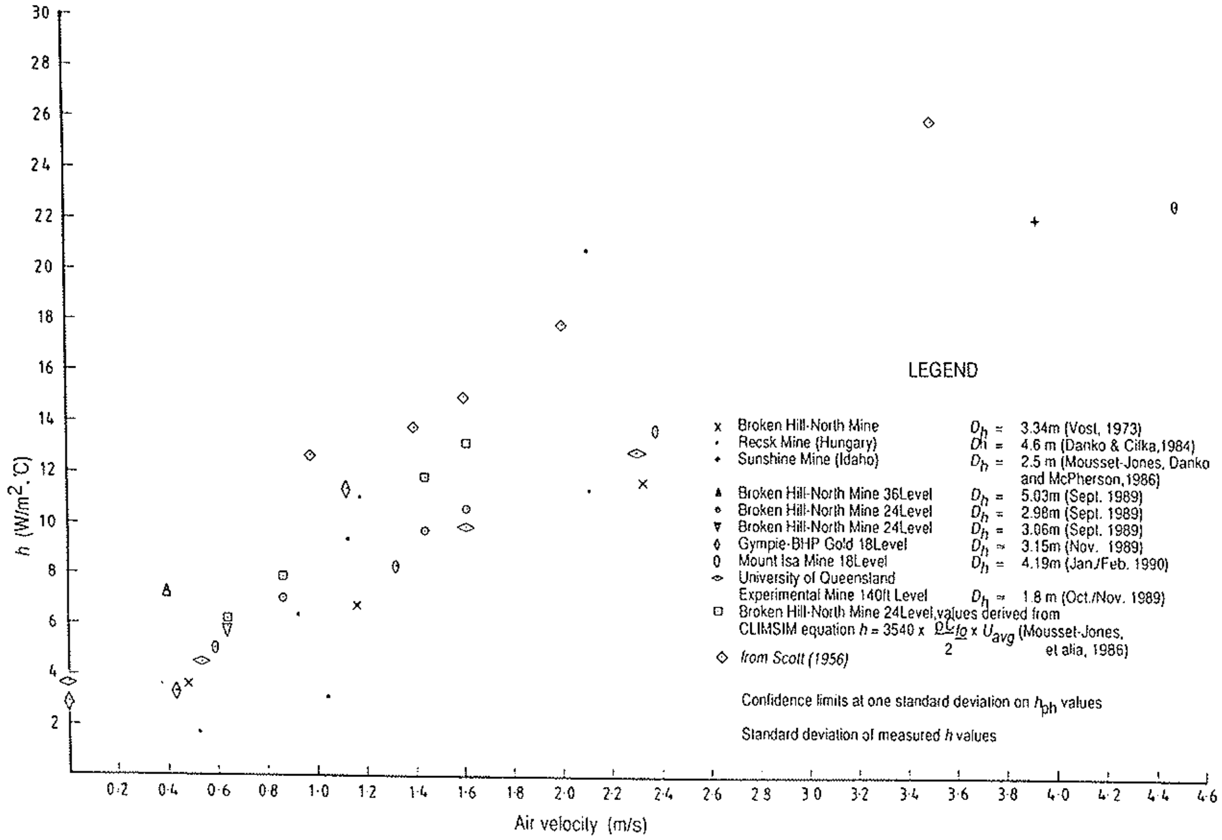

Figure 2. Surface Heat Transfer Coefficient vs Air Velocity - All sites

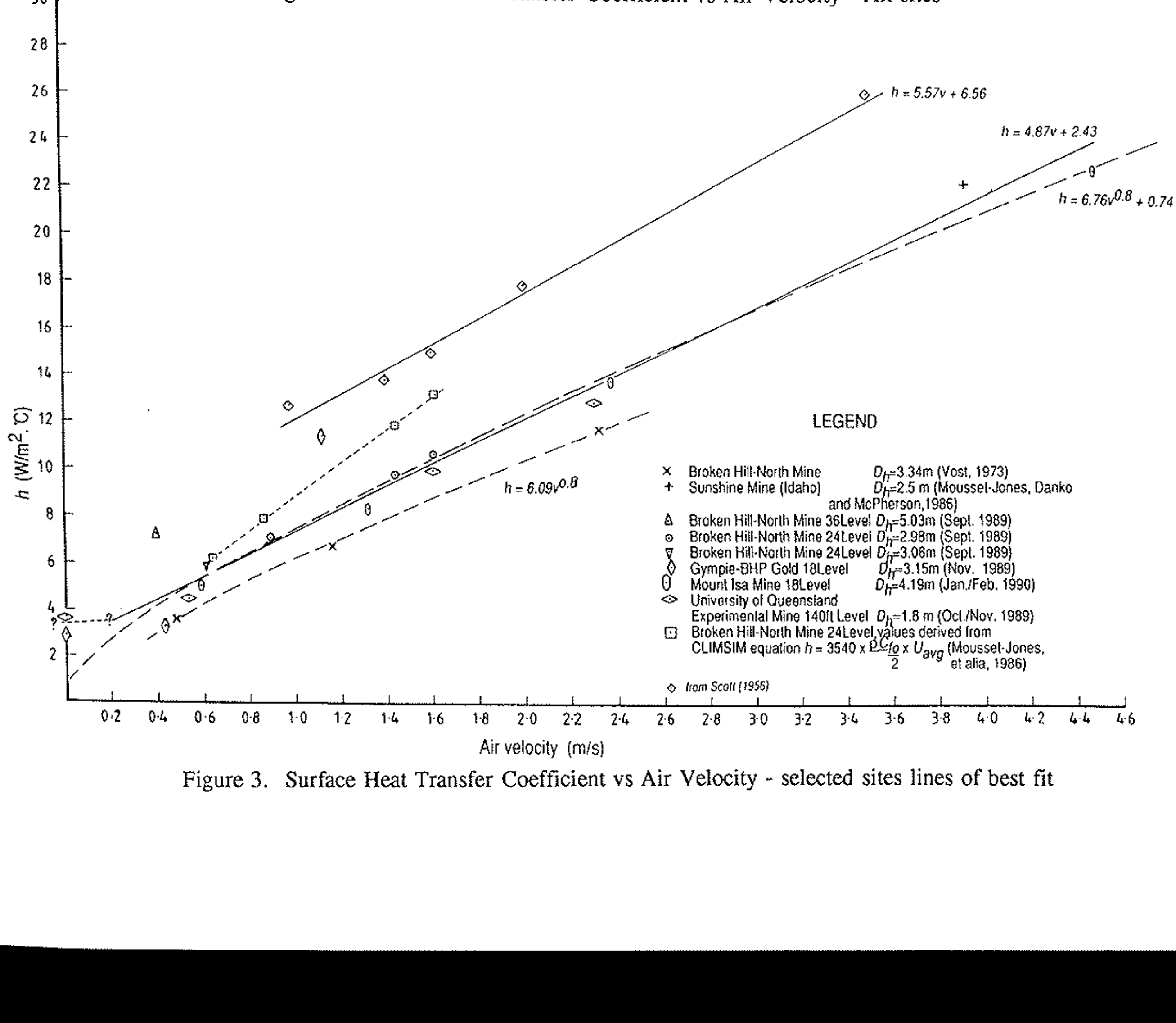

Figure 3. Surface Heat Transfer Coefficient vs Air Velocity - selected sites lines of best fit

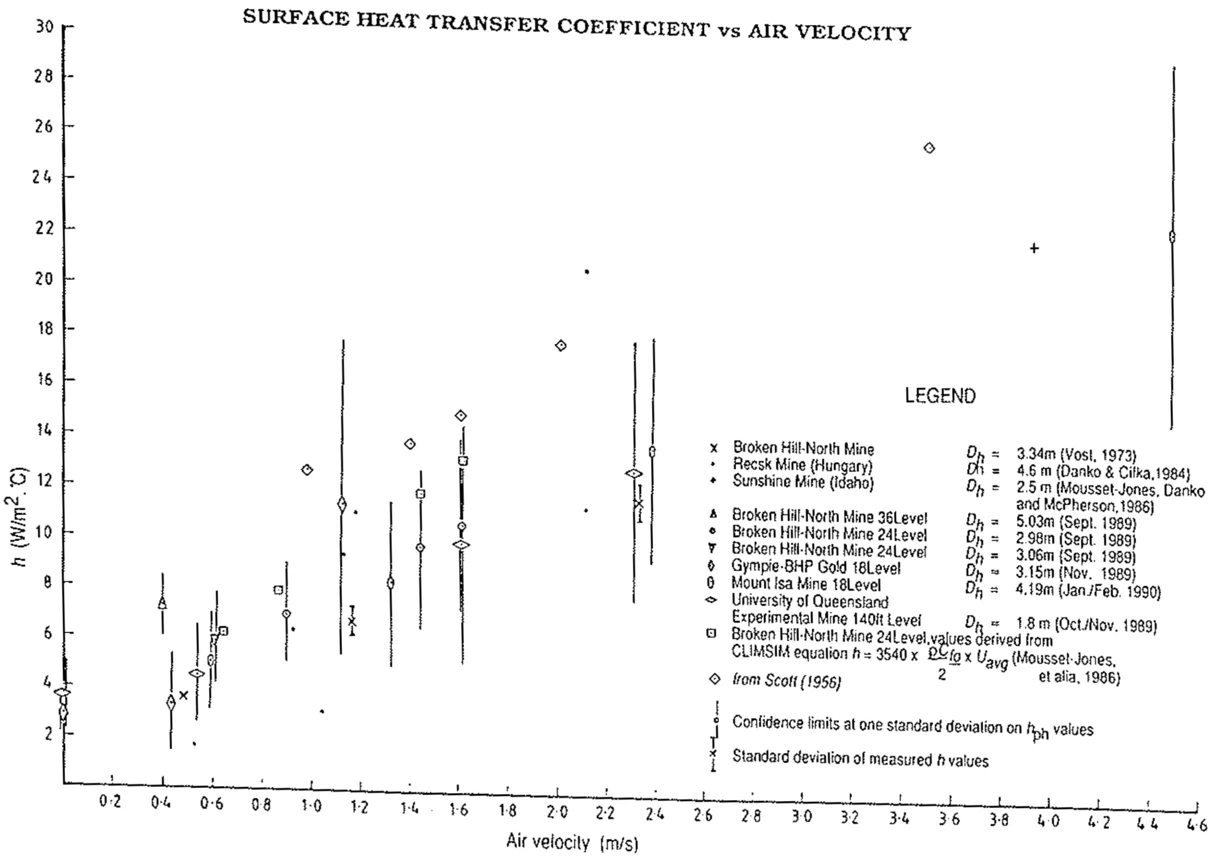

Figure 4. Surface Heat Transfer Coefficient vs Air Velocity - All sites with confidence limits

with the straight line

$$h = 4.87V + 2.43 \qquad (13)$$

At velocities between about 0.4 and 1.5 m/s the Starfield equation curve appears to better fit the field measurement data than the straight line. At higher values where there is a relative scarcity of data there is little to choose between the two lines. At velocities below 0.4 m/s neither line fits the observed values. This is no doubt due to the effects of convection.

Fitting Vost's three measurements to equation 12, the value

$$h = 6.09\,V^{0.8} \qquad (14)$$

is reached, which apparently fits well (Figure 3). This, however, is based on too few values for a confidence test.

Danko and Cifka (1984) derived the relationship

$$h_{ph} = c_1 V^{0.85} \qquad (15)$$

between the physical heat transfer coefficient and air velocity. Their average value for the constant c_1 was 6.07.

In a later study, Mousset-Jones, Danko and McPherson (1986) derived a value for the same constant of 8.18 following field measurements at the Sunshine Mine, Idaho.

The ratio of h/h_{ph} in this study averaged about 0.93. For a given value of V, a comparison was made between the h and h_{ph} values. For example

when $V = 2$, $h = 6.76 \times 2^{0.8} + 0.74 = 12.5$

(from equation 12) and

when $v = 2$, $h_{ph} = 8.18 \times 2^{0.85} = 14.74$

(from Mousset-Jones, Danko and McPherson, 1986)

then $h/h_{ph} = 0.85$

compared to the average in this study of 0.93, so these are broadly comparable results.

In plotting the values of h, no allowance has been made for the effects of variations in airway diameter. Whillier (1982) states that in smooth pipes h should be inversely proportional to pipe diameter. However, the values of h calculated from the University of Queensland Experimental Mine were only slightly below those at other mines with larger airway diameter.

It was observed that values of h calculated in this study are about 140 percent higher than those for smooth pipes of equivalent diameter.

Mousset-Jones, Danko and McPherson (1986) refer to their results being 100 percent higher than the value for a hydraulically smooth airway, and 20 percent higher than comparable results in the literature. In addition, they refer to their results being 28 percent lower than the heat transfer coefficient values used in CLIMSIM.

The Broken Hill measurements were fitted to the CLIMSIM equation (Mousset-Jones, Danko and McPherson, 1986), and the resultant values plotted on Figure 3. The CLIMSIM values are both higher than and non-parallel to those determined by equation 4 used in this study (Danko and Cifka, 1984).

CONCLUSION

Using the formula and equipment developed by Danko and Cifka at four underground mines a relationship has been established between the surface heat transfer coefficient h and air velocity.

At air velocities above about 0.3 m/s the relationship may be taken as a straight line where

$$h = 4.87V + 2.43 \qquad (16)$$

this line having a correlation coefficient of 0.98. However, based on an analogy with flow in smooth pipes a curve where

$$h = 6.76V^{0.8} + 0.74 \qquad (17)$$

can be used, and appears a better fit between air velocities of 0.4 and 1.6 m/s. Both lines fit within the confidence limits of the method used in this study. The value in equation (12) is the preferred one, as best fitting the available data.

In practice, at air velocities of 0.4 m/s or above, the value of h may be derived from Equation (13) or read directly from the graph on Figure 3.

Below an air velocity of about 0.4 m/s convective forces alter the relationship between V and h. Difficulties in the accurate measurement of air velocities below 0.3 m/s mean that the relationship is poorly defined in the velocity range 0 - 0.3 m/s.

In normal mine airways up to at least 4.5 m diameter, the effects of both geology and airway diameter can be ignored as variables.

In the application of this investigation technique to operating mines some compromises have been inevitable, as ideal conditions were generally unavailable. Despite these compromises, the results achieved have a good degree of consistency.

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