“In situ” measurements of the surface heat transfer coefficient in underground airways

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SYNOPSIS

Few “in situ” measurements have been made of the surface heat transfer coefficient in mine airways despite the importance of this coefficient in determining the heat flow into the ventilating air. In this paper, the values obtained at various air velocities and the comparisons of these values with theoretical values are given. Examples are also given of the errors which would result if rock surface temperatures were obtained by extrapolation from temperatures further into the rock without taking into account the time delay which occurs before a given change in air temperature reaches the points from which extrapolation is carried out.

SINOPSIS

Min in plaas opmetings was tot dusver gemaak teneinde die oppervlakte hittetransmissie- koëffisiënt in myn lugbane te bepaal ten spyte van die belangrikheid van hierdie koëffisiënt vir die bepaling van hittevloei in geventileerde lug. Die waardes wat verkry was op verskillende lugsnelhede en die vergelyking van hierdie waardes met die teoretiese waardes word in hierdie verhandeling weergegee. Voorbeelde word ook gegee van die foute wat begaan kan word wanneer rotsoppervlakte temperature verkry word deur ekstrapolasie vanaf temperature dieper in die rots sonder om die tydsvertraging in ag te neem wat voorkom voordat ’n gegewe lugstemperatuursverandering die merk bereik waar die ekstrapolasie uitgeoefen is.

INTRODUCTION

The surface heat transfer coefficient is a major factor in determining the thermal flux into the ventilating air in underground workings in the early stages of cooling rock. With modern mining and tunneling methods giving rapid rates of exposure of uncooled rock, knowledge of the magnitude and distribution of the surface heat transfer coefficient is necessary to allow prediction of changes in temperature of the ventilating air. Few values have been published of the surface heat transfer coefficient measured “in situ” and one objective of the work described here was to obtain values for different air velocities.

NOMENCLATURE

H_{con} = convective component of surface heat transfer coefficient (W/m$^2\cdot$°C)
H_{rad} = radiative component of surface heat transfer coefficient (W/m$^2\cdot$°C)
H = surface heat transfer coefficient and is the sum of H_{con} and H_{rad}. (W/m$^2\cdot$°C)
k = thermal conductivity of rock (W/m$\cdot$°C)
r = distance from centre of drive (m)
a = radius of drive (m)
$R = \frac{r}{a}$
$\beta = \frac{aH}{k}$ (Biot number)
θ = rock temperature (°C)
$\left(\frac{\partial\theta}{\partial r}\right)_s$ = rock temperature gradient near the surface (°C/m)
θ_s = rock surface temperature (°C)
θ_1 = ventilating air temperature (°C) dry bulb.

POSSIBLE METHODS FOR MEASURING H

Hitchcock and Jones[1] equated heat flow plate measurements made on the dry walls of a driveway to $H(\theta_s-\theta_1)$. θ_s was obtained by thermocouples. At each cross-section, variations of about 25 per cent were obtained in the values of H which, according to the authors, was due mainly to the uncertainty in determining θ_s. The drive had a wet floor and therefore some radiation from the rock surface to the floor would have occurred. The values of H obtained are given in Table IV.

Jones[2] measured air temperatures along a dry driveway just after a reversal of ventilation and then applied the theory for air temperatures along an instantaneously created roadway. The values of H thus obtained were used to make a prediction from theory of the rise in air temperature in the drive at longer times of cooling but the prediction was not found to be satisfactory and the values were discarded. They were replaced by values which gave a better prediction from theory of the rise in air temperature in the drive. However the values obtained in 2 sections of the drive differed by a factor of three even though the boundary conditions and air velocities in the sections were only slightly different. The author concluded that H could not be well determined by this method since small errors in the air temperatures would have a great effect on the values of H.

Values of H could also be obtained if heat flow into a length of dry drive were obtained by measuring the enthalpy increase in the airstream. However again it is difficult in practice to measure the air temperatures to the required accuracy since the temperature increases encountered are generally not very large.

Another possible method of measuring H is to obtain first the ratio H/k using either:

$$k\left(\frac{\partial\theta}{\partial r}\right)_s = H(\theta_s-\theta_1) \quad \ldots\ldots\ldots\ldots \quad (1)$$

or

$$\frac{\partial\theta}{\partial \ln\cdot R} = \beta(\theta_s-\theta_1) \quad \ldots\ldots\ldots\ldots \quad (2)$$

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where the θ_s value could be obtained either by extrapolation from the θ values or by direct measurement. Then k could be obtained by laboratory methods using drill core samples. This method was used by Jones[2] to obtain a value of β. No value of k was given, so comparison cannot be made to H values measured by the author.

DETAILS OF THE METHODS OF MEASUREMENT ACTUALLY USED

The method of measuring H described in the last paragraph was the one used.

The drive chosen for the experiment was in a mine in Broken Hill, Australia, owned by North Broken Hill Ltd. It appeared from visual inspection to be completely dry; (it was not long enough to prove that it was dry from measurements of moisture pick-up by the airstream). The drive was not used for production. Any desired value of air velocity could be obtained by adjusting a brattice; the only ventilation for some years had been leakage in this brattice. There were no supports in the drive. The surrounding rock was mainly gneiss. The rock appeared to be solid; (the surface condition was assessed both by visual inspection and by sounding). The radius of the circle of the same area as the cross-section of the drive containing the collar of the diamond drill hole was 1,67 m.

Thermistors were used to measure rock and dry bulb air temperatures. To prevent penetration of moisture, several layers of araldite were built round the thermistors and connections by repeated dipping and hardening. The thermistors were then inserted in brass cylinders giving a temperature probe of approximately 0,008 m diameter and 0,032 m length. The thermistors were connected to an automatic resistance recorder which had a period of six minutes. A precision resistor was inserted in one channel of the recorder to allow correction to be made for chart slipping. The probes were calibrated three times in an eight month period and again after the experiment. Calibrations agreed within ±0,015 °C.

Some of the probes were inserted in a horizontal diamond drill in one side of the drive. The probes had been placed on brass shims in slits in polythene pipe and a tin cylinder rivetted on the outside of the pipe to hold the probes in position and also give good contact with the rock. No air movement was possible from the drive up the inside or outside of the polythene pipe. The two probes nearest the drive were 0,49 m and 0,94 m from the rock surface.

A probe was also placed at the end of a 0,076 m hole which had been hammer tapped near the collar of the diamond drill hole mentioned in the previous paragraph. The hole was of slightly greater diameter than the probe. A layer of rock chips was built up between the probe and the air. The probe was first put in this position during the 2nd period of ventilation at the end of this section.

Two probes were used to measure dry bulb air temperatures in the cross-section of the drive which included the collar of the diamond drill hole. The probes were set as near as possible to the maximum and minimum temperatures in the cross-section.

Air velocities were measured approximately every 2 days by anemometer using a continuous traverse. Adjustments were made to the brattice to produce 4 distinct periods of ventilation with different ranges of air velocity.

EXPERIMENTAL OBSERVATIONS

The probe in the 0,076 m tapped hole followed not only the major changes in air temperature but also minor fluctuations such as the diurnal change which averaged about 0,8 °C. The diurnal change was damped to about a third of the value in air. Falls in air temperature of approximately a degree and lasting about half an hour (due to drilling further up the drive) were damped to about 10-15 per cent of their value in air.

The probe in the diamond drill hole at 0,49 m from the rock surface did not reproduce minor fluctuations in air temperature, such as the daily variations, but did reproduce the main variations. This was true also of the probe at 0,94 m from the rock surface, although the changes in air temperature in this case were damped more heavily. Later experiments by the author with probes inserted in diamond drill holes by the same method, and also in gneiss, have shown that daily air temperature variations of similar magnitude could still be just discerned at 0,18 m from the drive.

The results described in the last two paragraphs must be borne in mind when planning experiments to test the theory of heat flow in horizontal driveways using drives which have an appreciable daily air temperature fluctuation. Comparison could be made to theory by measuring θ_s or $(\partial\theta/\partial r)_s$ or the gain in enthalpy by the airstream or the air temperatures at points along the drive. For any real chance of agreement between theory and experiment to be achieved in such cases, a continuous record of temperatures would have to be kept, rather than only temperatures every few days.

The difference between the two probes used to measure dry bulb air temperatures during the lowest air velocities used (see Table III below) averaged 0,2 °C and as the air velocity was increased, the difference became less until it was a few hundredths of a degree at the highest velocities. The temperatures of the two probes were averaged to give θ_1. Later experiments were carried out by the author in a drive in which the floor was wet and the air velocities were between 0,3 and 0,8 m/s. These showed that drops of over half a degree in dry bulb temperature and rises of up to one degree in wet bulb temperature could occur with these velocities near the floor of the drive if the floor was wet.

The range of values found for the air velocities in any given period (given in Table III) was small. (The experiment was conducted during the summer shut down period of the mine when there was little opening of ventilation doors.)

The time taken for the initial air temperature drop at the start of the experiment to penetrate 0,49 m from the rock surface was approximately six hours and the time taken to penetrate 0,94 m was approximately 20 hours. A linear θ against lnR relation between the surface and

0,94 m from the surface could not therefore be expected until a few hours more than 20 hours after a change in air temperature even if the air temperature remained constant at its new value. Calculation of $\partial\theta/\partial lnR$ from the temperatures at 0,49 m and 0,94 m from the rock surface (and hence θ_s by extrapolation and hence β from equation (2)) was carried out only when the air temperatures had settled down for at least 30 hours within a range of a few tenths of a degree.

CALCULATION OF β AND H FROM EXPERIMENTAL MEASUREMENTS

Before the start of ventilation, the average θ_1 in the drive was 29,7 °C. 2½ hours later, the initial fast fall in temperature was over and the air temperature averaged 27,75 °C for approximately 44 hours. Calculation of β was made at two times within this period and the results are given in Table I.

TABLE I
MEASURED β VALUES IN THE FIRST 47 HOURS OF VENTILATION

No. of hours of ventilation	Temperature at 0,94 m from the rock surface (°C)	Temperature at 0,49 m from the rock surface (°C)	$\frac{\partial\theta}{\partial lnR}$ (°C)	θ_s (°C)	β
35	30,90	30,40	2,63	29,73	1,33
47	30,85	30,32	2,79	29,60	1,50

($\theta_1 = 27,75$ °C)

If account had not been taken of the time delay which occurs before a linear θ against lnR relationship can be established, and if β had been calculated at earlier times than those in Table I, the β values listed in Table II would have been found.

Thus large errors in β would have occurred if account had not been taken of the time delay mentioned in the previous paragraph. The β values obtained during the experiment (including the 2 values in Table I) when account was taken of the above time delay are given in Table III below.

TABLE II
MEASURED β VALUES IN THE FIRST 47 HOURS OF VENTILATION USING INCORRECT BASIS FOR CALCULATION

No. of hours of ventilation	Temperature at 0,94 m from the rock surface	Temperature at 0,49 m from the rock surface	$\frac{\partial\theta}{\partial lnR}$ (°C)	θ_s (°C)	β
5½	30,97	30,71	1,37	30,36	0,52
11	30,97	30,65	1,68	30,22	0,68
15	30,97	30,62	1,84	30,15	0,77
23	30,95	30,54	2,16	29,99	0,96
26	30,93	30,50	2,26	29,92	1,04

($\theta_1 = 27,75$ °C)

The extrapolated θ_s values and the average value of the temperatures in the tapped hole over the period of settled temperatures concerned were within 0,1 °C of each other in 6 out of 7 cases.

Values of H were calculated from the mean β for each period of ventilation. The thermal conductivity value used was obtained from a slide cut from a core sample near the collar of the diamond drill hole. The value of k was 3,2 W/m°·C which gave good agreement with the value of 3,1 W/m·°C quoted by Le Marne[3] for the average k for gneiss in the Broken Hill area. The resulting values of H are given in Table IV.

TABLE IV
MEASURED H VALUES

Period of ventilation	Mean value of H (W/m^2.°C)	Standard deviation in H
1st	3,5	0,6
2nd	6,7	0,75
3rd	11,7	—

The values of H obtained by Hitchcock and Jones[1] for air velocities which were between the 1st and 2nd period velocities above were 1,9 to 2,6 W/m^2·°C for sandstone and 3,9 to 6,1 W/m^2·°C for shale. The driveway was larger than in the author's experiment (arched section of 4,8 m by 3,6 m). The floor was wet and therefore some radiation from the rock surface to the floor would have occurred.

TABLE III
MEASURED β VALUES AND AIR VELOCITIES

Period of ventilation	Average air velocity (m/s)	Standard deviation in average air velocity (m/s)	No. of hours of ventilation	β values	Mean β	Standard deviation in β
1st	0,48	0,023	35 47 116 276 530	1,3 1,5 1,9 2,0 2,1	1,8	0,3
2nd	1,15	0,097	585 644 884 1 060	3,3 2,9 3,9 3,7	3,5	0,4
3rd	2,32	0,070	1 500	6,1	—	—
4th	0,46	0,007	1 755	1,7	—	—

(The mean value of both air velocity and of β in the 4th period of ventilation lay within the range of air velocities and β in the 1st period of ventilation)

CALCULATION OF H FROM THEORY AND COMPARISON WITH EXPERIMENTALLY DETERMINED VALUES

H_{con} values were calculated in terms of a roughness factor F from:

$Nu = F\ 0{,}023\ (\mathrm{Re})^{0{,}8}\ (\mathrm{Pr})^{0{,}4}$ (Starfield and Dickson[4])

where Nu is the Nusselt number
F is the roughness factor
Re is Reynold's number
Pr is the Prandtl number

The values obtained in terms of F are given in Table V below.

H_{rad} was calculated from:

$H_{rad} = H_{rad\ \mathrm{equiv},}\ E$

where $H_{rad\ \mathrm{equiv},} = 6{,}3\ \mathrm{W/m^2 \cdot {}^\circ C}$ (Wiles[5])
and E is the emissivity of the air in the tunnel which was estimated from figure 13.22 of Rohsenhow and Choi[6] to be 0,16.
Therefore $H_{rad} = 1{,}01\ \mathrm{W/m^2 \cdot {}^\circ C}$.

The roughness factor (F) can be determined by subtracting H_{rad} from the measured H values and dividing by the theoretical H_{con}. Values of F are given in Table V below.

TABLE V
THEORETICAL VALUES OF H_{con} AND VALUES OF F

Period of ventilation	Average air velocity m/s	Measured H values W/m².°C	Theoretical H_{con} W/m².°C	Roughness factor F
1st	0,475	3,5	1,65F	1,5
2nd	1,153	6,7	3,36F	1,7
3rd	2,317	11,7	5,85F	1,8

Roughness factors for mine airways can be estimated using the method outlined in Starfield and Dickson[4]. Values of F in the range 1,65 to 1,7 would be predicted. Therefore agreement between the values in Table V and the predicted values is good.

SUMMARY

Small fluctuations in air temperature (e.g. diurnal changes) were damped out in the first 0,18 m of the rock. Larger changes in air temperature were still discernible at 0,94 m from the rock surface. Air temperature changes took approximately six hours to penetrate 0,49 m from the rock surface and approximately 20 hours to penetrate 0,94 m.

θ_s could only be determined by extrapolation from temperatures in the rock further back if the air temperatures had settled down within a range of a few tenths of a degree for long enough for the previous air temperature changes to have penetrated into the rock beyond the points from which extrapolation was carried out. If extrapolation was carried out at shorter times than this and if the θ_s thus obtained was used to calculate H, then large errors in H could occur.

The values of H obtained for a given air velocity range gave good agreement with each other. Values of F calculated using the measured values of H and theoretical values of H_{con} and H_{rad} were in good agreement with independently estimated values of F.

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REFERENCES

1. Hitchcock, J. A. and Jones, C. "Heat flow into a new main roadway". *Colliery Engineering*, 35, 1958, 73-76 and 117-122.
2. Jones, C. "Air temperature along a main intake roadway". *Colliery Guardian*, 209, 1964, 844-850.
3. LeMarne, A. E. "A geothermal investigation in Broken Hill and Cobar, N.S.W.". M.Sc. thesis submitted to the University of N.S.W.
4. Starfield, A. M. and Dickson, A. J. "A study of heat transfer and moisture pick up in mine airways". *J.S. Afr. Inst. Min. Metall.*, 68, 1967, 211-233.
5. Wiles, G. G. "Wet bulb temperature gradients in horizontal airways". *J.S. Afr. Inst. Min. Metall.*, 59, 1959, 339-359.
6. Rohsenhow, W. M. and Choi, H. Y. Heat, mass and momentum transfer. Prentice-Hall Inc., U.S.A., 1963.

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REPORT ● VERSLAG

No. 1484

COST ESTIMATES FOR THE PRODUCTION OF COPPER WIREBARS FROM SULPHIDIC ORES

7th November, 1972

Investigator: B. M. Wilson

SYNOPSIS

Capital and operating costs are estimated for the annual production of 15 000, 50 000, and 100 000 tonnes of copper wirebars from sulphidic ores having copper contents of 0,5, 1,0, and 1,5 per cent. The process considered for the treatment of the ores include flotation of the copper minerals, smelting of the flotation concentrates, and electrolytic refining. The costs are intended to serve as a basis for comparison with the costs incurred in the processina of sulphidicy ores b other methods.