Rapid changes of air temperature in underground airways

by K. R. VOST*, B.Sc. (Glas.), M.Sc. (N.S.W.) (Visitor)

SYNOPSIS

Most theoretical methods for the prediction of air-temperature gradients in underground airways always assume that the temperature of the entering air either remains constant or has only a slow seasonal variation. Large changes of temperature, caused by variations in atmospheric conditions on the surface, were measured in a fourteen-day period in air entering a horizontal airway. The changes in wet-bulb temperature were damped along the airway less uniformly than the dry-bulb changes; significant variations occurred in the wet-bulb temperature of the air leaving the airway. The damping was associated with large variations in air-temperature gradients. Other causes of rapid changes in temperature are discussed. These changes must be taken into account in predictions of the frequency with which undesirable conditions can be exceeded at critical points in the ventilation circuit of a mine to allow proper planning of ventilation and refrigeration requirements.

SAMEVATTING

Die meeste teoretiese metodes vir die voorspelling van lugtemperatuurgradiënte in ondergrondse luggange neem aan dat die temperatuur van die ingaande lug òf konstant bly òf slegs 'n stadige seisoensvariasie het. Groot temperatuurveranderinge wat deur veranderinge in atmosferiese toestande op die oppervlak veroorsaak is, is oor 'n tydperk van veertien dae gemeet in die lug wat 'n horisontale luggang binnegaan. Die veranderinge in die natboltemperatuur is minder gelykmatig as die droëbolveranderinge in die luggang gedemp. Die demping het gepaard gegaan met groot variasies in die lugtemperatuurgradiënte. Ander oorsake van vinnige temperatuurveranderinge word bespreek. Hierdie veranderinge moet in gedagte gehou word by die voorspelling van die frekwensie waarmee ongewenste toestande by kritieke punte in die ventilasiekring van 'n myn oorskry kan word ten einde behoorlike beplanning van ventilasie- en verkoelingsvereistes moontlik te maak.

Introduction

The airways along which ventilating air travels from the surface to the working areas of a mine are an important source of heat and moisture. The prediction of air-temperature gradients has been attempted by theoretical[1–5] and empirical[6] methods. The heat flow in the rock depends on the full history of the air temperature (especially on the immediately preceding days), rather than only on the prevailing air temperatures. Theoretical methods can incorporate the air-temperature history by using Duhamel's theorem[1, 2], but this considerably increases the computation.

When changes in air temperature are rapid and the temperature history is ignored, only the prevailing input temperatures (i.e., the temperatures of the air entering a section of airways) being used, the calculated output temperatures can be significantly different from those based on the full air-temperature history. Starfield[1] calculated temperatures for a horizontal airway in which cooling plant at input was switched off every 12 hours. The changes in wet- and dry-bulb temperatures at input (6 °C and 11 °C) were damped at output to 30 per cent and 13 per cent with Duhamel's theorem and to 74 per cent and 45 per cent without it.

If temperatures change slowly, the differences between calculations with and without the full temperature history is small[1]. Sufficiently slow changes would occur if input air temperatures were constant; the heat flow would reduce with time, and air temperatures along the airway would fall, but only slowly. Such changes would also occur if input temperatures were influenced only by seasonal changes at the surface and followed a sinusoid of 12 months.

Most theoretical methods[3–5] assume that the input temperatures in underground airways are either constant or have a sinusoidal variation of 12 months; Duhamel's theorem is then not required. However, continuous measurements show rapid changes of temperature underground. Whillier[7] measured variations of 2 to 3 °C in wet-bulb temperature every day during 15 days at a depth of 2600 m and 760 m along an airway. These were caused partly by the wetting down of shaft and haulage stations on night shift. The maximum wet-bulb temperature fell 3 °C between two days owing to a change in surface weather conditions.

Changes of temperature in a shaft caused by variations in temperature at the surface from one day to the next were investigated by Vost[8]. Temperatures were measured three times daily at the surface, and continuously at a depth of 910 m. The changes in average temperature between successive days at the surface (Δt_{1d} and Δt_{1w}) and at depth (Δt_{2d} and Δt_{2w}) were calculated†. The linear correlation between Δt_{1d} and Δt_{2d} and between Δt_{1w} and Δt_{2w} was found to be small. The ratio $\Delta r_1/\Delta t_{1d}$ was introduced because enthalpy gain depends on both dry-bulb temperature and moisture content. Good positive linear correlations were found with $\Delta t_{2w}/\Delta t_{1w}$; i.e., large positive $\Delta r_1/\Delta t_{1d}$ gave the least damping of Δt_{1w} at depth, and significant changes occurred in t_{2w} from one day to the next. The largest Δt_{2w} was 2,4 °C, which was 60 per cent of the Δt_{1w}; r_1 on one of the two days was the largest measured (rain fell during the day), and the Δr_1 was also the largest measured.

These experiments show that changes in atmospheric conditions at the surface can produce rapid variations in wet-bulb temperature at depth in a shaft, and provide one example of the penetration of these changes 3400 m from the surface. More information is required on the damping of rapid variations as air moves through underground workings. This was obtained for a

---

*School of Physics, W. S. & L. B. Robinson University College, University of New South Wales, Broken Hill, Australia.

†The symbols used are explained at the end of the paper.

horizontal airway from the measurements of air and rock temperatures described below.

Apparatus and Site

The drive was at a depth of 700 m, where the virgin rock temperature was 35 °C. Through-ventilation had first been established fourteen years before the measurements, and there was no splitting of the airflow or sharp bends in the portion used for the experiment. The drive was of a nominal 2,4 m by 2,4 m square cross-section. An open drain varying in width between 0,3 m and 0,5 m ran down one side, but there was very little flow of water. The water temperatures were less than the dry-bulb air temperatures. The surrounding rock was gneiss of thermal conductivity 3 W/m °C. There was no significant mineralization present, and little heat would therefore be produced by oxidation. There were no pipes carrying fluid, and no production on the level. A recorder of 100 W power was used for the measurement of rock and air temperatures. This was an insignificant source of heat at the airflows involved (minimum 3 m^3/s). The main source of heat was therefore the rock surrounding the drive. The portion of the drive used for the experiment was 196 m long, and the input cross-section was 37 m from the intake shaft. A description of the wetness of the floor between input and output is given in Table I.

TABLE I

WETNESS OF FLOOR

Distance from input cross-section	Description
m	
0,0	Drain contained a little water, but rest of floor dry
46,0	Drain filled, but rest of floor slightly damp
84,4	Whole floor covered with water
114,0	Drain filled, but rest of floor dry
139,6	Floor dry
196,3	

A Lambrecht Assmann psychrometer in which the thermometers were marked at intervals of 0,2 °C was used, and temperatures were recorded to 0,1 °C. The accuracy of the thermometers was checked against a calibrated thermometer using a temperature bath; no correction was found to be necessary.

At least 5 minutes was allowed for the psychrometer to attain equilibrium before the first measuremenes on each day. Since temperatures can vary in a given cross-section at a given time[9], measurements were made half-way across the floor and with the intake (i.e., the base) of the psychrometer 0,15 m and 1,2 m above the floor. Temperatures were recorded after 2 minutes, a constant reading usually being obtained within the first minute. The readings at each height were repeated and used only if agreement was obtained within 0,1 °C; the higher reading is quoted in this paper.

In the psychrometer surveys on 20/11, 24/11, 1/12, and 4/12, measurements were made at two intermediate cross-sections besides input and output. The variation of temperature with height at the four cross-sections is discussed in an earlier paper[9], where they formed the first series of observations. In the surveys on 17/11 and 27/11, measurements were made at input and output only. After the measurements at output, measurements were repeated at input in case there had been a general change in temperatures. The continuous records of dry-bulb air temperature kept at one cross-section were also checked. No change greater than 0,1 °C was found. The stability of the temperatures was partly because the measurements were made in a level not currently used for production and during an afternoon shift, when there was less movement of ventilation doors than on day shift.

For twenty months before the measurements, the air velocity, which was due to leakage through the ventilation doors, averaged 0,2 m/s. The doors were opened on 13/11, and air velocities were measured by anemometer on a continuous traverse in cross-section 60 m from input, whose area was 6,1 m^2. The velocities on surveys apart from that on 4/12 are given in Table II; the velocity on 4/12 was 0,97 m/s. The greatest change in velocity between successive surveys from 17/11 to 1/12 was 24 per cent, and this occurred in the surveys done on 20/11 and 24/11. A major adjustment was made to the airflow after the survey on 1/12, which gave an increase of 43 per cent in velocity by 4/12. The survey on 4/12 was excluded from the analysis of damping of changes in temperature between input and output since the change in velocity would have been a major cause of change in temperature at output.

The psychrometer readings at input and output are given in Table II. The error in the relative values of air temperature was assumed to be ± 0,1 °C. This gave errors of ± 0,15 g/kg in specific humidity, ± 0,15 kJ/kg in Ha and ± 0,4 kJ/kg in Hv.

Thermistors were used for the measurement of rock and dry-bulb air temperatures. To prevent the penetration of moisture, several layers of araldite were built round the thermistors and connections by repeated dipping and hardening. The thermistors, inserted in brass cylinders, then gave a temperature probe of approximately 8 mm in diameter and 23 mm in length. The thermistors were connected to an automatic resistance recorder with a period of 6 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 several times before and after the experiment by immersion in a constant-temperature bath, the temperature of which was found with a platinum resistance thermometer connected to a Mueller bridge. A least-squares fit to an exponential relation between the calibration temperatures and recorder readings was found by computer. The accuracy of the temperatures obtained from the recorder readings was estimated to be ± 0,01 °C.

The four thermistor probes used to measure rock temperatures were inserted in a horizontal diamond-drill hole of diameter 35 mm. The probes had been placed on brass shims in slits in polythene pipe with a tin cylinder riveted on the outside of the pipe to hold the probes in position, and also to give good contact with the rock. No air movement was possible from the drive inside or outside the polythene pipe. The collar of the drill-hole was 62 m from input and 1,1 m above the floor in the centre of a 2,4 m high section of one wall of the drive, which was plane apart from surface roughness. The centres of the probes were 0,19 m, 0,37 m, 0,56 m, and 0,74 m from the rock surface (the distance up the drill-hole was corrected for the angle of 66° between the drill-hole and the rock surface).

The dry-bulb air temperature was measured continuously by a thermistor probe in the cross-section containing the collar of the drill-hole and 1,3 m horizontally from the collar. The variation in air temperature with height in this cross-section was found to be small, and measurement was necessary at only one point.

Experimental Results

The average wet- and dry-bulb temperatures at input (t_{1w} and t_{1d}) and output (t_{2w} and t_{2d}) for each survey are shown in Figs. 1 and 2. The total ranges of t_{1w} and t_{1d} were 4,2 °C and 3,9 °C. Although the changes in temperature between surveys at input were damped along the airway, the range in t_{2w} of 2,5 °C was appreciable. The dry-bulb changes were more heavily damped, and the range in t_{2d} was 1,1 °C. The rises in temperature along the drive between input and output — given in Table III— showed considerable variation (0,8 to 2,5 °C for wet-bulb rises and −0,9 to 2,1 °C for dry-bulb rises).

The daily maxima and minima of the dry-bulb temperatures, measured continuously near the rock probes, are shown in Fig. 3. The survey times are marked on the horizontal axis; all the surveys were started at 1700 hours. The diurnal changes are superimposed on a larger period variation with maxima on 17/11, 24/11, and 1/12. The main ventilation fan was cut off for a few hours on 16/11, giving a sharp rise in air temperatures whose effect on the rock temperatures can still be seen on 17/11.

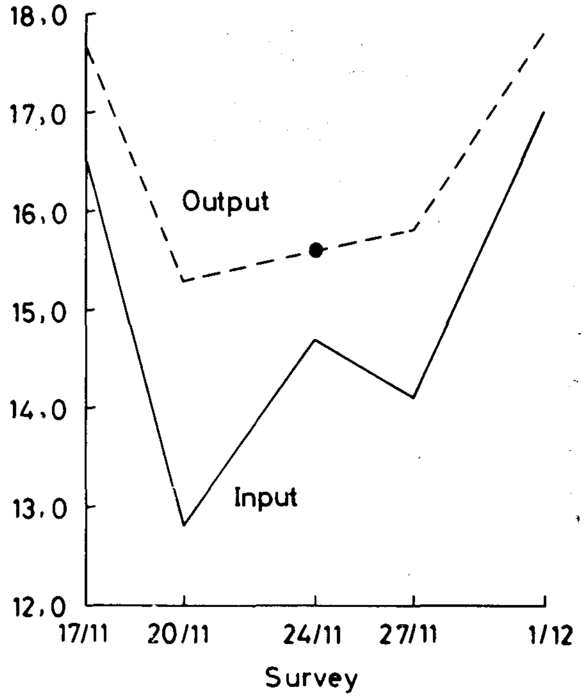

Fig. 1—Wet-bulb air temperatures for each survey

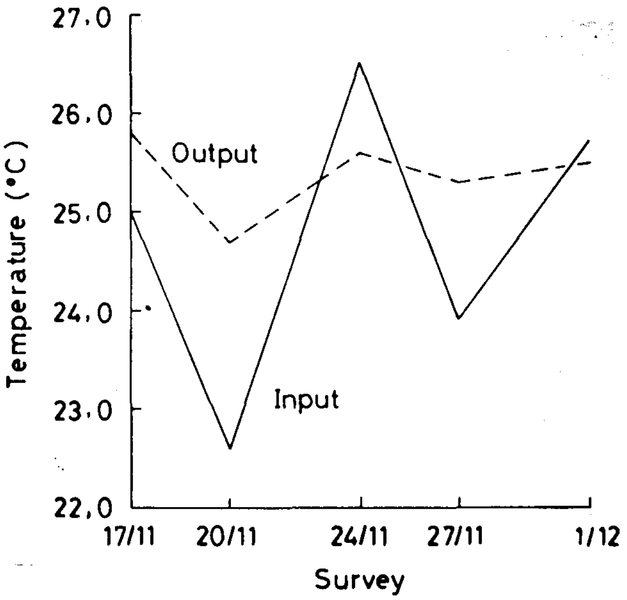

Fig. 2—Dry-bulb air temperatures for each survey

TABLE II

MEASUREMENTS DURING SURVEYS

Date, barometric pressure, and air velocity	Cross-section (input-I or output-O)	Height above floor* m	Air temp.		Moisture content (r) g/kg	Enthalpies		
			Wet bulb °C	Dry bulb °C		Ha kJ/kg	Hv kJ/kg	H kJ/kg
17/11	I		16,5	25,0	7,7	25,1	19,6	44,8
105,9 kPa	O	1,2	17,6	25,8	8,7	25,9	22,1	48,0
0,48 m/s	O	0,15	17,8	25,7	8,9	25,8	22,8	48,6
20/11	I		12,8	22,6	4,7	22,7	12,0	34,7
106,7 kPa	O		15,3	24,7	6,4	24,8	16,4	41,2
0,45 m/s								
24/11	I		14,7	26,5	5,1	26,6	13,0	39,6
106,3 kPa	O	1,2	15,3	25,7	6,1	25,8	15,5	41,3
0,56 m/s	O	0,15	15,8	25,5	6,7	25,6	17,0	42,7
27/11	I		14,1	23,9	5,6	24,0	14,1	38,2
106,1 kPa	O		15,8	25,3	6,8	25,4	17,3	42,7
0,63 m/s								
1/12	I		17,0	25,7	8,1	25,8	20,5	46,4
105,3 kPa	O	1,2	17,7	25,6	8,9	25,7	22,7	48,5
0,68 m/s	O	0,15	17,9	25,4	9,2	25,5	23,6	49,1

*Where the height is not given, the measurements at both heights agreed.

The two minima of the larger period variation span several days whose daily minima were within 0,2 °C of each other. These minimum regions were 19/11 to 21/11 and 28/11 to 29/11. The larger period variation appeared to be caused by changes in average daily temperature on the surface; dry-bulb temperatures measured by North Broken Hill Limited showed a similar larger period variation with maxima on 16/11 to 17/11, 24/11, and 30/11, and minima on 18/11 to 19/11, and 27/11.

The surveys, which started at 1700 hours, were all within 12 hours of the maxima or of the minimum regions of the larger period variation in the air temperatures (Fig. 3). The changes in temperature between the surveys should therefore provide information on the damping along a horizontal airway of changes in temperature caused by variations in atmospheric conditions at the surface. The changes between surveys in the average temperatures at input and output (Δt_{1w}, etc.) are given in Table IV. Changes in dry-bulb temperatures at input were damped heavily at output in three out of four cases ($\Delta t_{2d}/\Delta t_{1d}$ was less than 25 per cent). The damping of wet-bulb changes showed a greater variation: $\Delta t_{2w}/\Delta t_{1w}$ was much higher on 17/11 to 20/11 and 27/11 to 1/12 than the other two cases, i.e., the damping of Δt_{1w} at output was much smaller; $\Delta r_1/\Delta t_{1d}$ was also much higher. On 24/11 to 27/11, a fall in t_{1w} and a rise in t_{2w} occurred (negative $\Delta t_{2w}/\Delta t_{1w}$ also occurred in the shaft analysis[8] discussed earlier).

TABLE III

INCREASES IN TEMPERATURE AND ENTHALPY BETWEEN INPUT AND OUTPUT

Survey	Increases between input and output				H kJ/kg	W/m
	Wet-bulb °C	Dry-bulb °C	*Ha* kJ/kg	*Hv* kJ/kg		
17/11	1,2	0,8	0,8	2,8	3,5	64,3
20/11	2,5	2,1	2,1	4,4	6,5	112,2
24/11	0,9	—0,9	—0,9	3,2	2,3	49,4
27/11	1,7	1,4	1,4	3,2	4,6	111,0
1/12	0,8	—0,2	—0,2	2,6	2,4	62,4
						heat pickup W per m of tunnel length

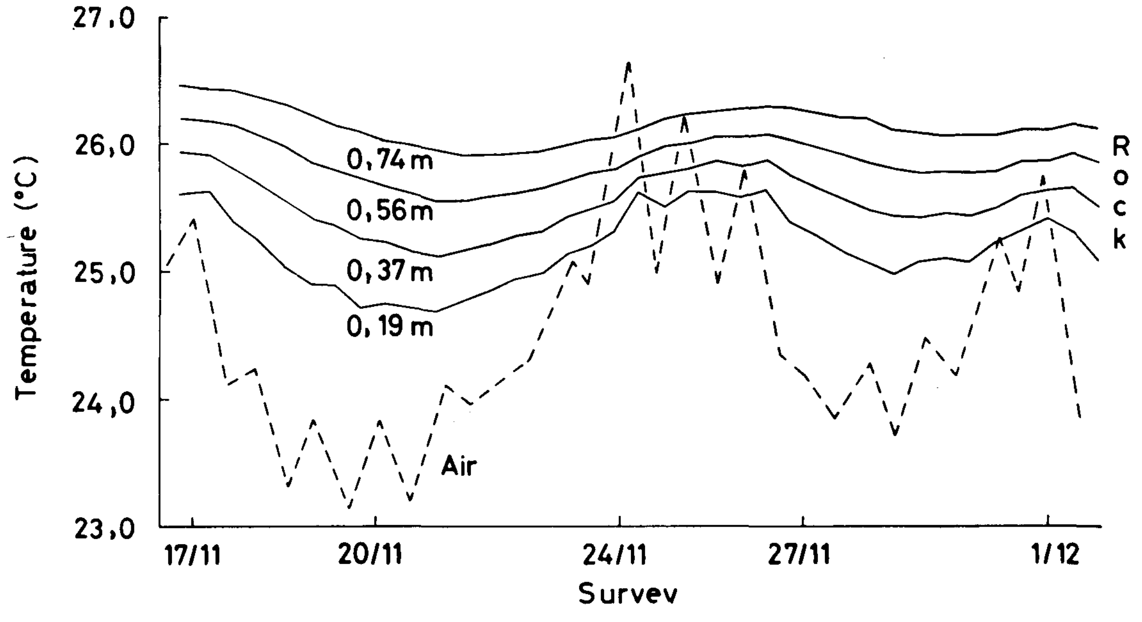

Fig. 3—Continuously measured rock and dry-bulb air temperatures

TABLE IV

CHANGES IN TEMPERATURE AND SPECIFIC HUMIDITY BETWEEN SURVEYS

Surveys	Changes between surveys					$\frac{\Delta t_{2w}}{\Delta t_{1w}}$	$\frac{\Delta t_{2d}}{\Delta t_{1d}}$	$\frac{\Delta r_1}{\Delta t_{1d}}$ g/kg. °C
	INPUT			OUTPUT				
	Δt_{1w} °C	Δt_{1d} °C	Δr_1 g/kg	Δt_{2w} °C	Δt_{2d} °C			
17/11 to 20/11	—3,7	—2,4	—3,0	—2,4	—1,1	0,65	0,46	1,3
20/11 to 24/11	1,9	3,9	0,4	0,3	0,9	0,16	0,23	0,1
24/11 to 27/11	—0,6	—2,6	0,5	0,2	—0,3	—0,33	0,12	0,2
27/11 to 1/12	2,9	1,8	2,5	2,0	0,2	0,69	0,11	1,4

Because of the variation in temperature with height, the changes of temperature at output between 24/11 and adjacent surveys were different at each height. The calculation was repeated to find the effect of this variation, and the results are given in Table V. The differences between $\Delta t_{2d}/\Delta t_{1d}$ at the two heights was small. The differences for $\Delta t_{2w}/\Delta t_{1w}$ were larger, but the conclusions drawn from Table IV for these pairs of days still hold, namely that Δt_{1d} was heavily damped and that $\Delta t_{2w}/\Delta t_{1w}$ was much smaller than on the other two pairs of days.

Part of the variation in output temperatures was due to the changes in air velocity between the surveys. Theoretically, an increase in the air velocity has a two-fold effect: on the one hand, a decrease in the air-temperature gradients results from the increased air quantity, giving a $1/V$ relationship between gradients and velocity; on the other hand, there are increases in the heat and mass transfer coefficients, giving a $V^{0,8}$ dependence. The increases in transfer coefficients lose significance as the velocity increases, and the air-temperature gradients have a $1/V^{\alpha}$ relationship, where α is less than 1 and only approximates 1 at velocities much higher than in this experiment.

To see whether the patterns of damping of Δt_{1d} and Δt_{1w} shown in Table IV were caused by the differences in air velocities between surveys, the measured rises in air temperature along the drive (Table III) for each survey velocity were adjusted to the rise at 0,56 m/s, which was the average of all the survey velocities. The air-temperature gradient was assumed proportional to $1/V$, which over-compensated for the effect of velocity; the results are shown in Table VI. The Δt_{2w} and Δt_{2d} were then recalculated as shown in Table VII. Damping of Δt_{1d} at output was still heavy in three out of four cases; $\Delta t_{2d}/\Delta t_{1d}$ was 33 per cent or less. The variation of $\Delta t_{2w}/\Delta t_{1w}$ was still large, with light damping in the first and last pairs of days and a rise in Δt_{2w} on 24/11 to 27/11 despite a fall in Δt_{1w}.

The changes of temperature with height (Table II) caused the enthalpy gains between input and output to have ranges of values that were too large to allow quantitative comparison between different days. For example, on 24/11 the gains in *Hv* and *H* between input and output ranged from 2,5 to 4,0 kJ/kg and from 1,7 to 3,1 kJ/kg. The errors in the average gains would exceed 20 and 30 per cent.

Variations in the rate of convective flow between rock and air on different surveys are one cause of the large differences between air-temperature gradients on different surveys, and also of the damping of the changes in temperature between surveys. For example, Tables II

TABLE V

CHANGES BETWEEN SURVEYS AT DIFFERENT HEIGHTS ABOVE FLOOR

		Changes between surveys					
		INPUT		OUTPUT			
Surveys	Height above floor m	Δt_{1w} °C	Δt_{1d} °C	Δt_{2w} °C	Δt_{2d} °C	$\frac{\Delta t_{2w}}{\Delta t_{1w}}$	$\frac{\Delta t_{2d}}{\Delta t_{1d}}$
20/11 to 24/11	1,2	1,9	3,9	0,0	1,0	0,0	0,26
	0,15	1,9	3,9	0,5	0,8	0,26	0,21
24/11 to 27/11	1,2	—0,6	—2,6	0,5	—0,4	—0,83	0,15
	0,15	—0,6	—2,6	0,0	—0,2	0,0	0,08

TABLE VI

TEMPERATURE RISES BETWEEN INPUT AND OUTPUT FOR A VELOCITY OF 0,56 m/s

	Measured quantities			Calculated quantities			
		Temp. rises		Temp. rises		Output temp.	
Date	Air velocity m/s	Wet-bulb °C	Dry-bulb °C	Wet-bulb °C	Dry-bulb °C	Wet-bulb °C	Dry-bulb °C
17/11	0,48	1,2	0,8	1,0	0,7	17,5	25,7
20/11	0,45	2,5	2,1	2,0	1,7	14,8	24,3
24/11	0,56	0,9	—0,9	0,9	—0,9	15,6	25,6
27/11	0,63	1,7	1,4	1,9	1,6	16,0	25,5
1/12	0,68	0,8	—0,2	1,0	—0,2	18,0	25,5

TABLE VII

CHANGES IN TEMPERATURE BETWEEN SURVEYS FOR A VELOCITY OF 0,56 m/s

	Changes between surveys					
	Measured at input		Calculated at output			
Surveys	Δt_{1w} °C	Δt_{1d} °C	Δt_{2w} °C	Δt_{2d} °C	$\frac{\Delta t_{2w}}{\Delta t_{1w}}$	$\frac{\Delta t_{2d}}{\Delta t_{1d}}$
17/11 to 20/11	—3,7	—2,4	—2,7	—1,4	0,73	0,58
20/11 to 24/11	1,9	3,9	0,8	1,3	0,42	0,33
24/11 to 27/11	—0,6	—2,6	0,4	—0,1	—0,67	0,04
27/11 to 1/12	2,9	1,8	2,0	0,0	0,69	0,0

and III show that, when the dry-bulb temperatures at input rose 3,9 °C from 20/11 to 24/11 (to the highest value of all surveys), the increase in *Ha* between input and output of 2,1 kJ/kg on 20/11 became a decrease of 0,9 kJ/kg on 24/11. This decrease on 24/11 would have been mainly due to convective flow out of the air. In Fig. 1, which shows the rock temperatures at 10-hour intervals and the daily maxima and minima of the dry-bulb temperatures, the air temperature during the 24/11 survey was much higher than the rock probe nearest the drive (0,7 °C by the recorder charts), verifying that the flow was from air to rock in the region of the rock probes. The rise in dry-bulb temperature along the drive on 20/11 was 2,1 °C, whereas on 24/11 it was −0,9 °C. Consequently, the Δt_{1d} of 3,9 °C was damped at output to 0,9 °C.

The convective flow, and hence the air-temperature gradients, for given air temperatures depend on the temperatures on the preceding days. For example, if the air temperatures had fallen between 20/11 and 24/11, the convective flow to the rock on 24/11 would have been lower or would have reversed direction.

Table VI shows that, when the measured rises in air temperature between input and output were adjusted to those at a common velocity to eliminate the effect of the differences in velocities between surveys, the range of the rises in temperature was still large (0,9 to 2,0 °C for wet-bulb rises and −0,9 to 1,7 °C for dry-bulb rises).

Therefore, when temperatures change rapidly underground, large variations in temperature gradient can be expected. Most theoretical methods of predicting gradients, as already discussed, use a slowly varying input, e.g., a sinusoid of 12 months. Very little change of gradient would have been predicted for the fortnight in which the measurements were made since the rate of change of temperature on the sinusoid would be small during the summer.

Discussion

Variations in atmospheric conditions on the surface were shown in an earlier paper[8] to produce large changes in wet-bulb temperature in a shaft; the largest was 2,4 °C between the two days with the largest change in specific humidity at the surface. The experiment described here shows that changes in input temperature 37 m from a shaft, which were caused by variations in atmospheric conditions at the surface, were damped non-uniformly at output 196 m along the drive; the damping of wet-bulb changes covered a greater range than that of dry-bulb changes. The least damping of Δt_{1w} and the largest Δt_{2w} were associated with the largest Δr_1; the maximum Δt_{2w} was 2,4 °C in three days, whereas the maximum Δt_{2d} was 1,1 °C. The air-temperature gradients had a considerable range of values. The variations in the damping of temperature changes along the drive and in the temperature gradients were only partially caused by the differences in air velocities between the surveys. Whillier[7] found that a change in atmospheric conditions at the surface penetrated 3400 m and caused the maximum wet-bulb temperature to fall 3 °C between two days. Variations in atmospheric conditions on the surface therefore seem an unavoidable cause of changes in temperature and temperature gradient underground.

Some other possible causes of temperature fluctuations underground are modifications of the sources of evaporation resulting from wetting down to reduce dust or from overflow into the airways during back-filling operations in stopes. Others are alterations in air-flow quantities and in heat transfer from pumps and compressed-air columns;[10] many others could be listed.

Rapid changes in air temperature appear inevitable throughout the ventilation circuit and are accompanied by large ranges in air-temperature gradients. It is not sufficient therefore to predict the average gradients and the average temperatures at output; the entire variation is required to provide, for example, the frequency with which undesirable temperatures could be exceeded. In a theoretical solution, the full air-temperature history at input must be used with a method incorporating Duhamel's theorem.

Theoretical methods incorporating Duhamel's theorem have not been adequately validated. This requires continuous measurements (preferably of rock as well as air temperatures) at several cross-sections, and comparison with temperatures predicted from the measured input temperatures. Jones[11] compared air-temperature gradients measured in a horizontal airway with those predicted according to Jordan's[2] theory, which incorporates Duhamel's theorem. However, a full history of the input temperature was not available, and a sinusoidal input was assumed; the theory was not therefore adequately tested. (The validation of Starfield's rapid method[4], which does not incorporate Duhamel's theorem, has been discussed by the author[9].)

Some of the basic assumptions in the theoretical methods require further investigation. Air temperatures are assumed to be uniform in a given cross-section at a given time[1-5], but measurements by the author[9] contradict this. Radial flow is assumed[1-5] in the rock, which is valid for distances from the centre of the drive of more than a few diameters; linear flow, however, occurs near the drive in the central portion of the plane surfaces to which parts of the roof, floor, and side-walls often approximate[12].

If a validated theoretical method incorporating Duhamel's theorem were available, then, as already discussed, the full air-temperature history at input would be required to provide the full variation at output. Input temperatures must be measured continuously if daily prediction at critical points is required. In the prediction of temperatures to assist in advance estimation of ventilation and refrigeration requirements, it is not sufficient to use an input that is the average of likely temperatures, e.g., a sinusoid to represent the variation during the year. The frequency of rapid changes in surface temperature, obtained from records over several years, must be included in the calculation. Alterations in heat and moisture sources in the ventilation circuit must be included when these are predictable. Examples are wetting down for dust, and reduction in refrigeration and air flow in non-production periods. There are other less predictable changes, e.g., air flow, heat from machinery, overflow from back-filling operations, etc. It may be necessary to measure output temperatures in existing mines and subtract the variation due to predictable changes to obtain statistical data on the effect of the unpredictable change. Proper planning of ventilation and refrigeration requirements can be made only when the frequency with which undesirable conditions are likely to be exceeded at critical points in the ventilation circuit is known; and this requires prediction of the full temperature variation.

Lambrechts[6], using an empirical method, has predicted wet-bulb temperature gradients for horizontal airways. From an analysis of a large number of measurements, he deduced a linear relationship between the wet-bulb gradient and the difference between virgin rock temperature (*v.r.t.*) and the wet-bulb temperature at input (t_{1w}). Considerable scatter occurred, which Lambrechts stated was partly due to the unstable heat flux caused by atmospheric weather changes. According to Starfield[3], part of the scatter was due to the separate influence of *v.r.t.*, t_{1w} and t_{1d} not being taken into account and part due to seasonal effects. Even if the number of graphs in the empirical analysis were increased to reduce the scatter due to these factors, there would still be considerable scatter since the temperature gradients for given *v.r.t.*, t_{1w} and t_{1d} are strongly affected by the air temperatures on the preceding days. Elimination of this scatter would require an even larger number of graphs, and the amount of data required to allow valid statistical deductions to be made would be correspondingly larger.

Acknowledgements

The author thanks North Broken Hill Limited for permitting the measurements to be made and for providing air temperatures at the surface, R. Mew, Ventilation Engineer, North Broken Hill Limited, for willing co-operation, and L. Wheatley, University of New South Wales, for draughting assistance.

References

1. Starfield, A. M. The computation of temperature increases in wet and dry airways. *J. Mine Vent. Soc. S. Afr.*, vol. 19. 1966. pp. 157-165.
2. Jordan, D. W. The numerical solution of underground heat transfer problems, Part I. *Int. J. Rock Mech. Min. Sci.*, vol. 2. 1965. pp. 247-270.
3. 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.*, vol. 68. 1967. pp. 211-234.
4. Starfield, A. M. A rapid method of calculating temperature increases along mine airways. *J. S. Afr. Inst. Min. Metall.*, vol. 70. 1969. pp. 77-83.
5. Hiramatsu, Y., and Amano, K. Calculation of the rate of flow, temperature and humidity of air currents in a mine. *Int. J. Rock Mech. Min. Sci.*, vol. 9. 1972. pp. 713-727.
6. Lambrechts, J. de V. Prediction of wet-bulb temperature gradients in mine airways. *J. S. Afr. Inst. Min. Metall.*, vol. 67. 1967. pp. 595-610.
7. Whillier, A. Prediction of wet-bulb temperature gradients in mine airways (contribution to ref. 6). *J. S. Afr. Inst. Min. Metall.*, vol. 68. 1967. pp. 200-204.
8. Vost, K. R. Prediction of wet-bulb temperatures at depth in a mine shaft. *J. Mine Vent. Soc. S. Afr.*, vol. 28. 1975. pp. 17-27.
9. Vost, K. R. Variation in air temperature in a cross-section of an underground airway. *J. S. Afr. Inst. Min. Metall.*, vol. 76. 1976. pp. 455-460.
10. Hemp, R. A rapid method of calculating temperature increases along mine airways (contribution to ref. 4). *J. S. Afr. Inst. Min. Metall.*, vol. 70. 1970. pp. 338-339.
11. Jones, C. Air temperatures along a main intake roadway. *Colliery Guard*, vol. 208. 1964. pp. 844-850.
12. Vost, K. R. 'In situ' measurements of the thermal diffusivity of rock around underground airways. *Trans. Instn Min. Metall.* (Sect. A: Min. Industry), vol. 85. 1976. pp. A57-A62.

Symbols

r = moisture content (g of moisture per kg of dry air)
t_d = dry-bulb temperature of ventilating air (°C)
t_w = wet-bulb temperature of ventilating air (°C)
H = enthalpy of ventilating air (kJ/kg of dry air)
Ha = sensible heat component of H (kJ/kg of dry air)
Hv = latent heat component of H (kJ/kg of dry air)
V = velocity
Subscript 1 indicates measurements made at input, i.e. in the air entering the airway
Subscript 2 indicates measurements made at output, i.e. in the air leaving the airway
Prefix Δ indicates a change in a quantity between successive surveys, e.g. Δt_{1d} indicates the change in dry-bulb temperatures at input between surveys.

Student prizegiving

The first annual student prizegiving function of the South African Institute of Mining and Metallurgy was held in the Dorothy Susskind Auditorium, University of the Witwatersrand, on Thursday, 26th May, 1977. The address (see opposite page) was given by Dr M. G. Atmore, a director of Anglo American Corporation and Vice-President of the Institute.

The Institute has introduced student prizes to encourage recruitment into the departments of mining and Metallurgy at South African universities. The number of graduates in mining and metallurgy is well below the requirements of local industry, and a continued shortage of qualified mining engineers and metallurgists could lead to severe problems in the industry in the next few years.

The prizes fall into two categories: one is of great prestige value and is awarded to a student in his third or fourth year of study whose academic performance, contribution to student affairs, and interaction with the department of mining or metallurgy and the Institute is of high order. The second is a book prize, which is awarded to the best fourth-year student in a specialized field of mining or metallurgy.

The prize winners for 1976 are as follows:

Prestige prize

J. S. van Zyl, University of Pretoria, Department of Metallurgy.

Book prizes

M. R. O'Brien, University of the Witwatersrand, Department of Mining Engineering.

A. Burrow, University of the Witwatersrand, Department of Metallurgy

P. Gericke, University of Pretoria, Department of Mining Engineering.

J. D. Krige, University of Pretoria, Department of Metallurgy.