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Passive Air-Conditioning: Flow Through Rock-Lined Tunnels Tempers Air*

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■ *The insulating properties of rock surrounding underground openings have been used to advantage in creating environments that have stable temperatures and are characterized by the mean annual climatic condition at a particular geographic location. However, significant flow rates of air at surface temperatures into subsurface space will cause much of the insulated advantage of the tempered environment to be lost unless the air is first passively conditioned by passage through a rock-lined tunnel.*

Changes in temperature and enthalpy as air passes along a length of rock-lined tunnel will be affected by many parameters, the more important of which include:

- *the airway length,*
- *the amount of free water present on airway surfaces,*
- *the thermal conductivity and thermal capacity of the rock,*
- *the temperature of the rock, and*
- *the air velocity through the airway.*

To achieve efficient tempering of outside air that exhibits extremes of climate, the influence of these conditions and the interrelationships of changes over time must be considered when designing an airway.

An in-situ study to examine these conditions over time was undertaken at the University of Missouri-Rolla Experimental Mine. Air was passed through a 185-m length of passageway in dolomite. Continuous measurement of air/rock for 2.5 days gave data that can be used to ascertain appropriate design conditions for a particular application. To examine seasonal effects, these tests were conducted during the summer, fall, and winter months.

Thermodynamic conditions at the air/rock interface are important in ventilation engineering of deep underground mines. Airflow heat transfer studies are of particular significance in hot mines in which air refrigeration is necessary. From various studies, theoretical relationships have been developed for predicting heat flow across the interface. Results of this study are compared with the theoretical relationships from which conclusions are drawn.

Introduction

The temperature of soil or rock at even a few meters depth demonstrates a profile markedly different from the diurnal and seasonal readings recorded on the surface. The earth tends to act as a thermal blanket because the low heat conductivity of soil and rock slows changes in temperature. At a depth of 10 m, an unfluctuating temperature is reached that characterizes the annual mean conditions at a particular location. Figure 1 illustrates the measured temperatures with depth and season at Rolla, Missouri. Note the rapid damping effect the soil has on the fluctuating air temperatures.

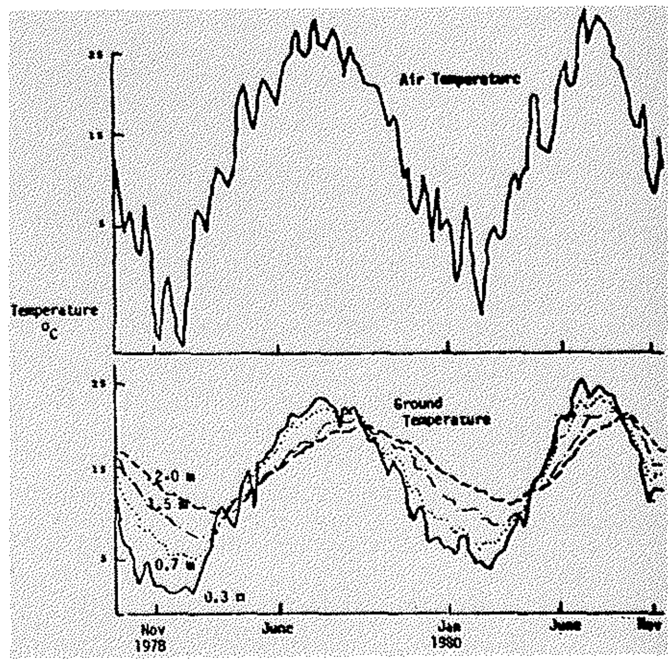

Fig. 1. Average daily temperatures, Rolla, Missouri. Air temperature and ground temperatures at depth.

The placement of structures partially or fully underground is a method of incorporating this natural insulation to achieve tempered or controlled environmental conditions throughout the year.

In the static environment in which little or no air enters or leaves an underground space, thermodynamic theory can predict the psychrometric conditions of the closed system. A number of studies have been undertaken to empirically verify these relationships. Stauffer (1978), Lorentzen (1978), Boileau and Latta (1978), and Warnock (1978) have used these relationships in examining the effects of heating and cooling underground rooms to maintain conditions above or below the virgin rock temperature. In the design of underground housing, however, some account must be taken of air movement from outside. Positive ventilation is necessary to satisfy respiration requirements and, in hot humid climates, to reduce moisture condensation on interior walls. Significant flow rates of air directly into the dwelling at surface temperatures will cause much of the insulated advantage of the tempered environment to be lost. To overcome this dynamic change in conditions as air movement occurs, conventional mechanically operated cooling or heating equipment can be used to condition surface air. Alternatively, passive systems can be incorporated in the design of underground openings.

One of these passive systems for tempering air flow involves passing the intake air through tunnels or buried pipes before it enters the subsurface dwelling. Contact with rock or earth-pipe surfaces transfers heat and moisture to or from the surrounding rock mass and adjusts the air temperature to subsurface conditions. As part of an in-situ investigation of roof stability in coal mines, Bruzewski and Aughenbaugh (1977) found that surface air used for ventilating a mine undergoes rapid tempering as it passes down the air shaft and along the passageways of a mine. Figures 2 and 3 illustrate some results from this study.

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In discussing passive ventilation, Wells (1977) states:

> . . . we think about earth pipes, about drawing fresh air into buildings through long, buried pipes that would warm the icy winds of winter and cool the hot air of summer, making air conditioning and heating far less expensive . . . we know that a straight buried pipe, even a hundred-feet-long pipe, will not do the job very well . . . but if a whole maze of such pipes was laid in a buried bed of stones?

In the ventilation of deep mines, consideration has to be given to the transfer of heat from hot country rock as air passes through tunnels. Practical engineering criteria used in the design of mine ventilation systems or underground refrigeration units has application to the tempering of intake air to subsurface dwellings.

To study the tempering effect of passing surface air along rock-lined passages before it enters occupied subsurface space, a series of tests were undertaken using ventilation facilities at a small mine in dolomite rock at the University of Missouri-Rolla. Experimental results have been collated and compared with thermodynamic relationships and heat transfer equations used successfully in South African goldmines, in an effort to determine their application to the design of inhabitable subsurface space at shallow depths.

Experimental Procedure

The tempering effect of passing air along rock tunnels was investigated by the following in-situ test procedure at the mine:

(1) A continuous airway 185 m in length from the surface intake to the flow outlet in part of the mine was prepared. This air-flow pathway was composed of a 10-m long vertical shaft connected to a surface blowing fan and associated ductwork, and a horizontal section through the dolomite mine with average dimensions of 2 m by 2 m. The airflow was forced to pass around a number of bends; the depth of the rock and soil cover was approximately 10 m throughout the airway length.

(2) A variable speed vane-axial fan powered by a 15 kW motor forced air through the test airway. During the tests, an air velocity of approximately 1.0 m/s through the system was measured, giving a quantity flow rate of a little over 4 m^3/s.

(3) To evaluate changes in air psychrometric conditions while considering the effects of diurnal and seasonal climatic influences, tests were run in the summer, fall, and winter. Continuous measurements were recorded over a 49- to 54-hour period on each occasion.

(4) During each test, air-temperature readings were taken at regular intervals (30 minutes initially, less frequently as differential changes became less) on the surface and at points along the underground airflow path. Further, airflow rate was checked regularly, and rock temperatures were taken at a number of test stations. At these stations, rock temperatures were recorded at depths of 25 mm, 100 mm and 300 mm from the air/rock interface by use of previously installed thermister temperature probes. All tests were undertaken at an approximately uniform flow rate. Further details as to experimental test procedures are recorded in Smith, Orlandi, and Gillies (1981).

Experimental Results

Because the University of Missouri Experimental Mine is not an operating mine, ventilation fans are inoperative for most of the year, and natural airflow passing through the workings is slight. Throughout the year, air temperatures in the underground passageways and rock mass temperatures (virgin rock temperature) are almost constant, varying from 10 to 15° C. The minimum value demonstrates a seasonal lag, occurring in early spring, while the maximum takes place in early fall.

The test sequences were undertaken at different times during the year: summer — July 16, 17, and 18, 1980; fall — September 5, 6, 7, 1980; and winter — January 30,31, February 1, 1981. Outside surface readings recorded during the first 24 hours of each test reflected diurnal and seasonal changes. Weather conditions were relatively stable during each 2.5-day test period; daily temperature patterns repeated themselves.

As the surface air passes along rock-lined passageways (in which the rock surface temperatures are colder in summer and warmer in winter than the intake air), the air is tempered. The rate of change can be seen on a plot comparing air temperature against flow distance along the tunnel where the measurements were made. The relationship plotted is for readings taken at mid-afternoon after air

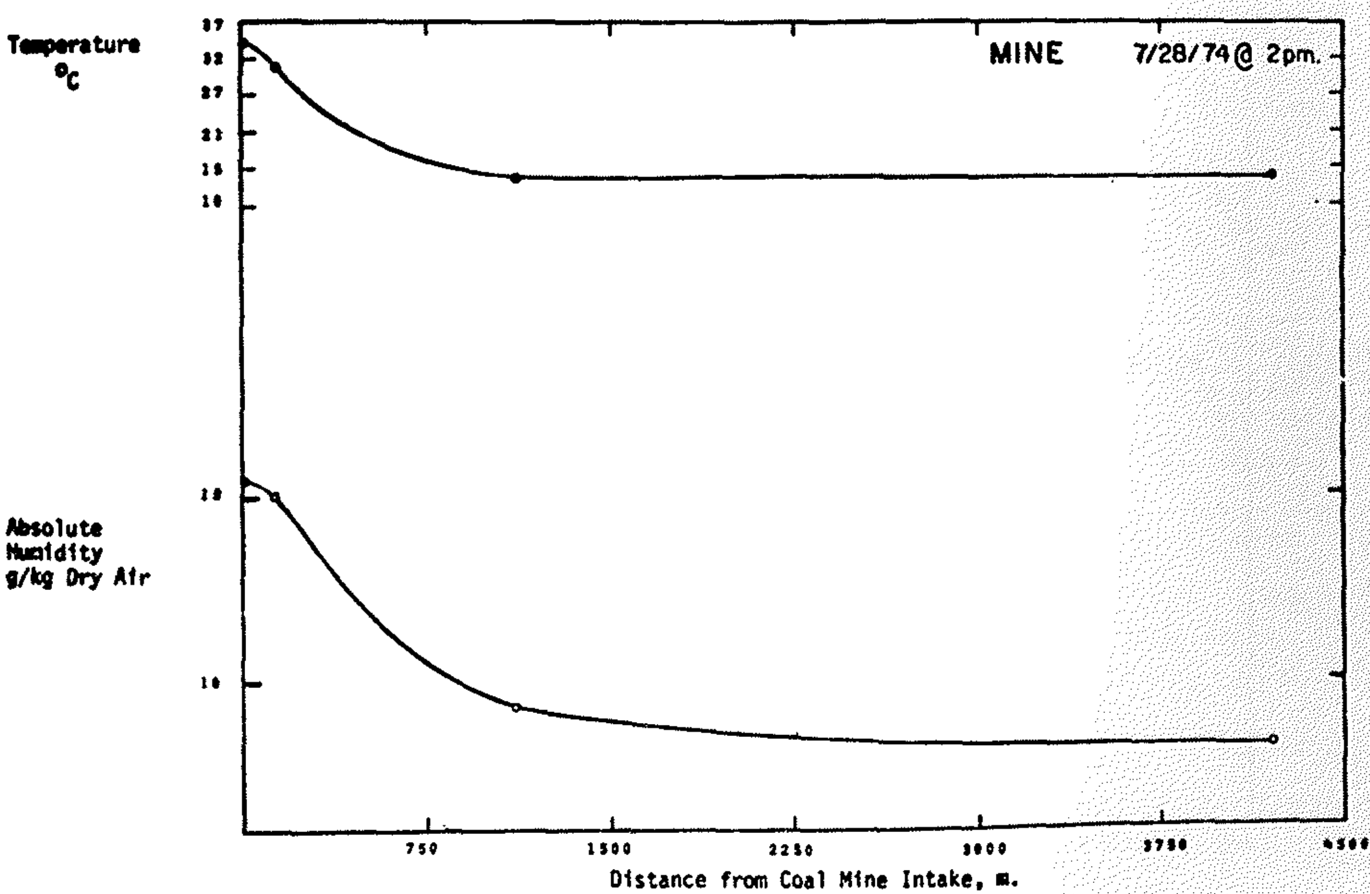

Fig. 2. Tempering of air with distance from mine surface intake portal (after Bruzewski and Augbenbaugh).

had been flowing continuously for 49 to 54 hours. Statistical curve fitting demonstrates that the relationships follow an exponential function, with a rapid rate of change in the first tens of meters of the air course and a slower rate of change towards the ends of the airway. For each season the flow air temperature at the end of the passageway closely approximates the virgin rock temperature (Fig. 4).

Using statistical curve fitting, the relationships can be described as:

(a) $t = 25.02e^{-0.014x}$, for summer conditions,

(b) $t = 33.19e^{-0.0034x}$, for fall conditions, and

(c) $t = 2.21 + 0.05x$ for winter conditions, x in meters being the distance from the air intake point.

The impact of the changing rate of airflow tempering at different points along the passageway can be determined by plotting the change in air temperature that has occurred at any point as a percentage of the total change that occurs between intake and outlet of the passageway. Using data for the same time intervals as in Figure 5, it can be seen that 50% of flow temperature drop occurs within the first 53 m in summer and fall, and in the first 69 m in winter. These results emphasize the decreasing economic return that would be achieved by lengthening an air-tempering tunnel or tube.

As the airflow is tempered in moving along a rock-lined passageway, two important energy transfer processes occur: exchange of heat energy between the rock mass and the airflow, and the latent heat change as water vapor condenses in contact with cooler rock surfaces or free moisture on the rock is evaporated by the warmed, unsaturated air.

(1) Energy conduction to or from the rock mass. The temperature-sensing probes set into the rock at points along the air passageway recorded temperature changes in the rock mass during the tests. Using data recorded at the same times as in Figures 5 and 6, a temperature profile was plotted at incremental distances into the rock mass. The readings were recorded in the rock mass at a point 56 m along the air passageway from the intake air shaft.

These relationships demonstrate an exponential function with the outer rock surface layers adjusting at a much faster rate than the inner layers. Although measurements taken to construct the plot in Figure 7 were recorded after the air had been continuously flowing for 49 to 54 hours, little change occurred in the rock mass temperature at a short depth in from the air/rock interface.

(2) Latent heat energy changes. Passageways in the underground mine in which measurements were taken had free water present; groundwater inflow had formed puddles, and condensation had formed on the tunnel roof and walls. The water vapor content or absolute humidity level in the air at any point in the passageway was a function of the intake air level and the gain or loss that occurred from evaporation or condensation along the airway. Humidity levels at all points in the system were determined by the use of wet and dry bulb thermometer readings and psychrometric constants. The amount of water vapor that air can hold is a function of its temperature (with an assumption of constant atmospheric pressure); unsaturated air can hold an increased mass of moisture, while saturated air can hold more only if the air temperature is increased. Humidity levels can be calculated at points along the airflow passageway, and from these data energy transfer from or to the airflow system as latent heat of evaporation or condensation can be determined. Humidity levels in the air along the passageway are plotted from measurements recorded at mid-afternoon on the last

Table 1. Energy changes in airflow through rock-lined passageways.

	Summer	Fall	Winter
Mid-afternoon readings			
1. Enthalpy Change in Air	108.6	60.6	137.3
2. Air Energy — Sensible	111.7	69.7	60.0
— Latent	-12.3	-14.8	39.4
— Total	99.4	54.9	99.4
3. Rock Energy	57.9	50.3	57.4
Early morning readings			
1. Enthalpy Change in Air	36.1	9.4	50.2
2. Air Energy — Sensible	41.6	16.6	23.7
— Latent	-2.5	-7.4	22.1
— Total	39.1	9.2	45.8
3. Rock Energy	54.0	49.6	79.6
All calculated energy flow values are expressed in units of kJ/s.			

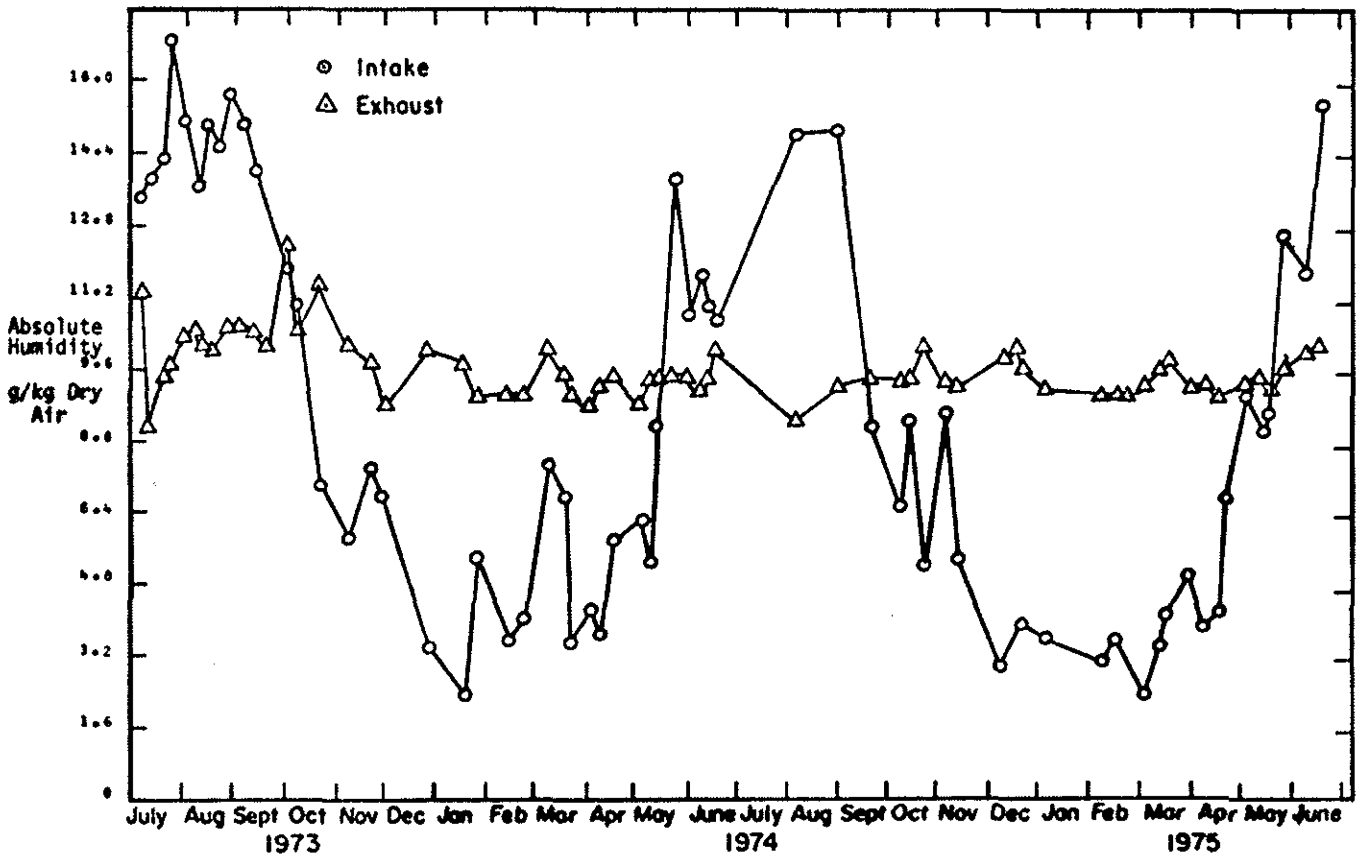

Fig. 3. Seasonal plots comparing absolute humidity at mine intake and exhaust stations (after Bruzewski and Aughenbaugh).

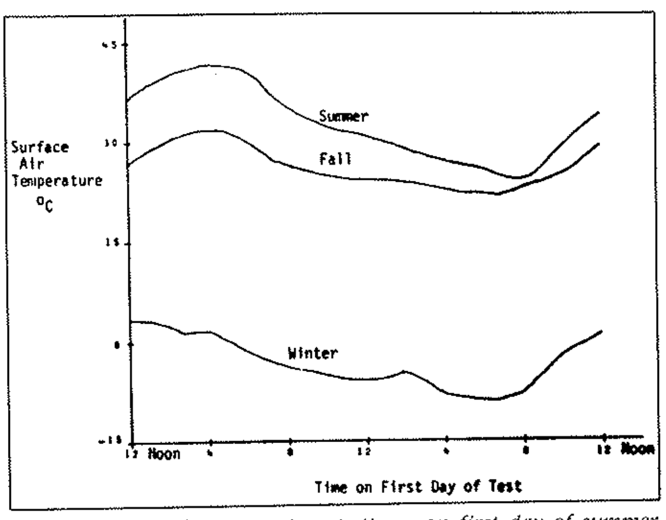

Fig. 4. Surface air temperature patterns on first day of summer, fall, and winter tests.

day of the test sequence for each season.

During the night, while surface air temperature is cooler and drops to a minimum recording (normally measured in the early hours of the morning), the air humidity level remains relatively constant. Humidity levels in the air flowing along the passageway are plotted from measurements recorded at 3 a.m. on the last day of each test sequence.

Thermodynamic balance

An examination of the energy changes occurring as air moves along the passageway demonstrates the existence of a number of heat-transfer processes. In an endeavour to quantify the magnitude of these changes, energy exchange pathways will be examined.

Enthalpy of air

Enthalpy is a measure of total heat or energy in a system. The enthalpy of air is readily calculated by measurement of wet bulb and dry bulb temperatures and reference to psychrometric charts or tables. Energy change as air goes through the passageway system is found by calculating the difference in enthalpy between intake surface air and outlet system air. Calculations have been made to examine these changes. The data used are from mid-afternoon and early morning readings on the last day of the summer, fall, and winter tests. These observed readings demonstrate day and night airflow characteristics after 30 hours of continuous passageway flow. System enthalpy changes are given in Table 1.

Energy changes in the air mixture

Energy changes in the air mixture can be described in terms of the heat changes in its components:

(1) Heat change in dry air or sensible heat change. This is quantified by multiplying air mass flow rate by air dry bulb temperature change through the system and by the specific heat constant for air.

(2) Heat change in water vapor. This is the energy to super heat water vapor from the wet bulb to the dry bulb temperature at a point. Quantified, this energy level is negligible and has been ignored in the study.

(3) Heat to evaporate or condense water. Latent heat changes in an air mixture can be considerable and are quantified by multiplying moisture mass change in air passing through the system by the constant for water latent heat of condensation or evaporation.

Energy changes in the air mixture are quantified by summation of these components and are listed in Table 1.

During the winter test, the cold dry air that entered the air passageway was warmed as it passed over relatively hot rock surfaces. The resulting warm air could hold more of the moisture evaporated from free water on the rock surfaces. Figures 8 and 9 demonstrate that air moisture levels increase steadily along the passageway during winter. In the summer and fall tests, the warm outside air loses its ability to hold moisture as it passes over relatively colder rocks. The relative humidity of the ventilation air increases until the dew point is reached; then condensation of moisture onto the cold surfaces begins.

While this trend of decreasing moisture content can be seen in Figures 8 and 9 in the later half of the passageway flow, another influence significantly affects air moisture level in the initial sections. The warm intake air to these sections is exposed to free water on the

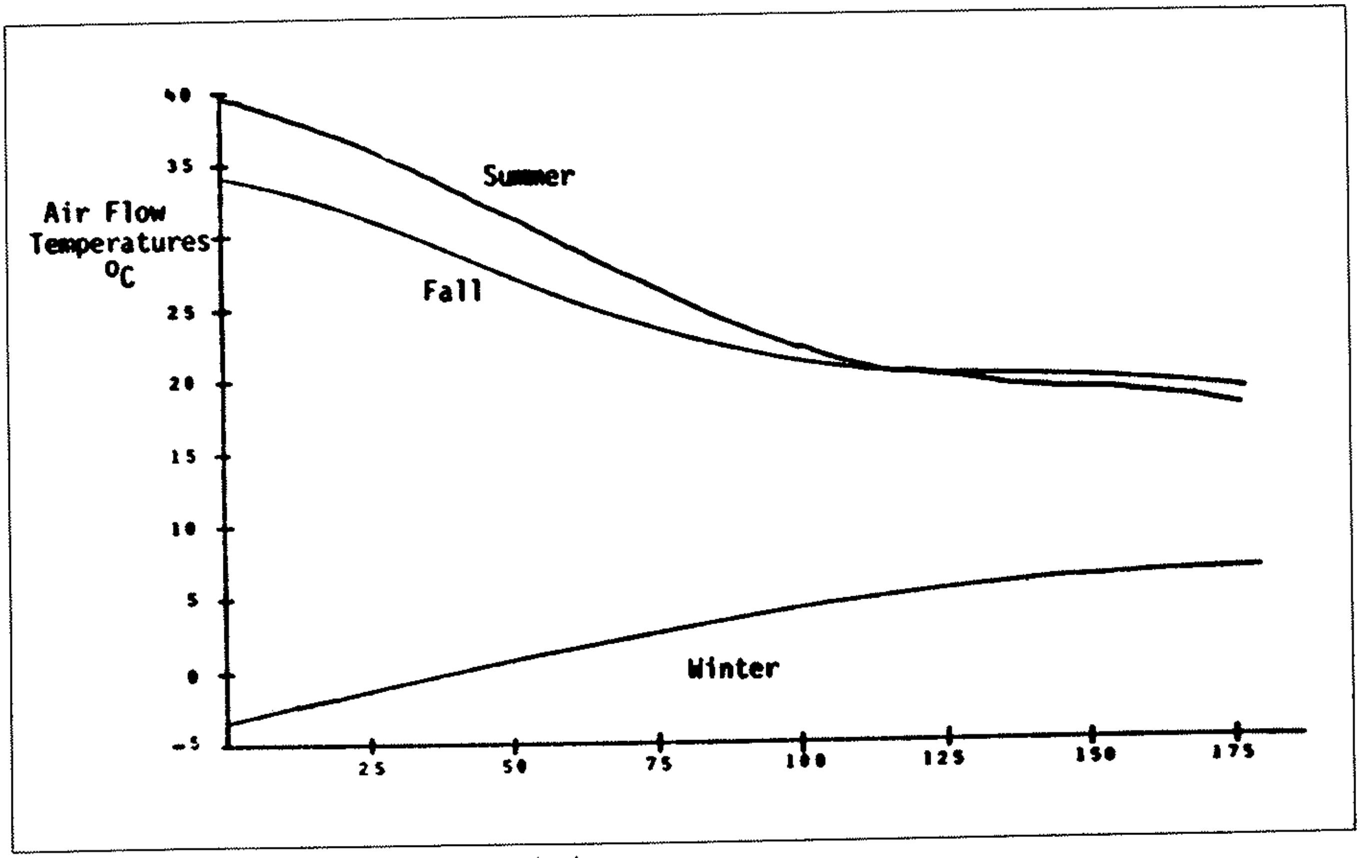

Fig. 5. Airflow temperature at distance from passage intake.

Table 2. Data on rock mass temperature profiles.

	Summer	Fall	Winter
Mid-afternoon readings			
Line of Best Fit	t = 22.02-1.11 ln x	t = 29.94-1.58 ln x	t = 1.80 + 1.17 ln x
Rock Surface Temperature °C	26.3	26.0	2.0
Virgin Rock Temperature °C	13.5	15.0	10.6
Average Rock Temperature °C Change	2.4	2.0	2.15
Early morning readings			
Line of Best Fit	t = 21.41-1.10 ln x	t = 20.04-0.61 ln x	t = 3.58 + 0.9 ln x
Rock Surface Temperature °C	22.0	21.0	5.5
Virgin Rock Temperature °C	13.5	15.0	10.6
Average Rock Temperature °C Change	1.66	1.44	2.19
t denotes rock temperature, °C x denotes distance into rock from rock: air interface, mm			

tunnel roof, walls, and floor. Moisture evaporation in these early sections causes an initial increase in moisture level; further, considerable energy in the air is required for this latent heat of evaporation. For the summer and fall test data examined, moisture evaporation in the early sections of the passageway is more significant than the condensation stages later in the airway. Energy flow leading to this net increase in moisture level is given a negative sign in the data in Table 1, as it is not in the direction of the assumed flow path from high temperature air to cold rock mass.

Energy changes in rock mass

As air flows along the passageway, heat is conducted to the surrounding rock in summer and fall, and from the rock mass in winter. Figure 7 shows the effect of this flow on the temperature of the rock. The total heat energy change within the rock mass can be calculated by multiplying the average observed temperature change by the mass of rock affected and by the specific heat constant for the rock. Results for each test are shown in Table 1.

The temperature change in an incremental unit of rock is a function of the distance from the beginning of the passageway and the distance into the rock from the air/rock interface. Figure 5 shows that the maximum temperature change and the rate of heat energy flow occurs at the air intake point. For all test results, the 50% air temperature change point along the passageway occurred between 50 m and 70 m. The closest rock temperature probe location, at 56 m, has been taken as representative of average passageway air temperatures. The average temperature change experienced by the rock can be found from examination of the temperature profiles at distance from the air/rock interface. For the test data recorded, profiles of these data were constructed and mathematical functions representative of "lines of best fit" were calculated (Table 2).

The average rock mass temperature was found by integrating the equation for the "line of best fit" with respect to "t." Examination of the profile data from the tests shows that at a distance into the rock of 1.0 m, the temperature change was negligible. Rock mass energy calculations were based on the assumption that heat flows in all

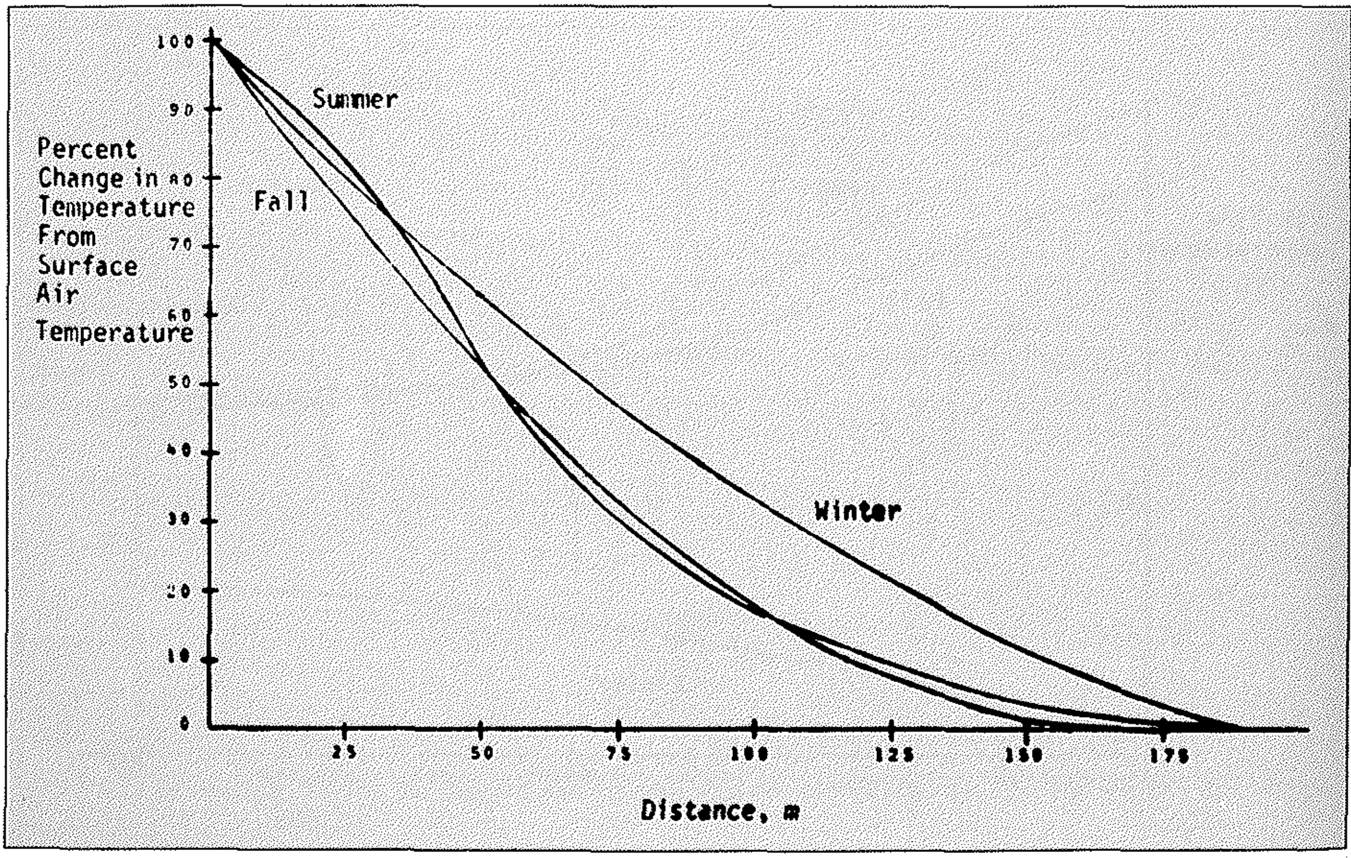

Fig. 6. Percentage change in air temperature between intake and outlet airway points against distance along passageway.

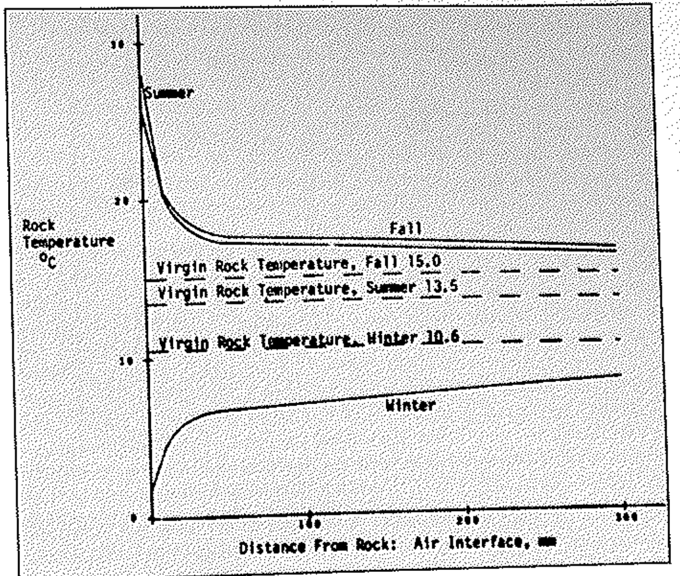

Fig. 7. Rock temperature at depth from rock/air interface.

directions from the passageway to that depth. Along a 185 m passageway, 2,061 m^3, or 5,709,000 kg of rock (with a density for dolomite of 2,770 kg/m^3, Clark 1967) were affected. For the calculations, a specific heat constant of 0.825 kJ/kg-°C was used (Touloukian and Ho, 1981).

Comparison of thermodynamic balance results

The results in Table 1 indicate that while the correlation between air enthalpy and air energy is good, rock energy values do not show the same agreement.

(1) Since enthalpy values are a function of the air wet bulb temperature, inaccuracies in taking this reading, or in calculating values from psychrometric chart or table data, can lead to significant error.

(2) Accuracy in determination of air energy sensible heat readings is dependent on the reliability of dry bulb temperature readings in the air flow. The calculated latent heat readings rely on the accuracy in the measurement of both wet and dry bulb readings and the calculation of air moisture levels. Complex heat exchange processes, in which moisture evaporation and condensation occur simultaneously in the system, were observed in the passageway airflow. The calculated results are average readings for the system. Additional detailed studies and data for sections of the passageway would be of considerable value in evaluating the energy and heat-transfer process. Despite the limitations in experimentally determined readings for interpretation of the tempering phenomenon, the correlation between total air energies and enthalpy results is good. For all tests, except one, results indicate agreement to within 10% accuracy.

(3) Rock energy values are based upon accuracy of experimentally determined rock temperature data and assumptions with respect to rock properties of density and specific heat. A special effort was made to cement the temperature probes within rock boreholes by a procedure that would return experimental temperatures representative of the rock mass at depth. Interpretation of data is based on averaging techniques to obtain system values representative of a complex heat exchange process. In interpreting the results, it is assumed that the heat flow rate of conduction through the rock mass is uniform and constant throughout the test time period. While the intention of this study has been to calculate average system results, this assumption opens up a chance for potential error by not accounting for shunting and diurnal changes in rate of heat conduction. Refinement of interpretation techniques to account for varying rates of heat flow conduction in the mine rock at different times day and night, and at different points along the air passageway, would considerably improve the model description of the heat exchange process.

Heat flow in underground mine airways

In the ventilation of deep underground mining operations, an understanding of the effects of heat flow from hot surrounding rock into airways carrying cool air to the working faces is important. As a result of conditions in South African gold mines, a number of studies have been undertaken to optimize the design of mine refrigeration plants used to cool the air before it enters the mine stoping areas.

Whillier and Ramsden (1976) have proposed a formula for calculating heat pickup along mine airways. The formula has been used wih success by Hemp and Deglon (1980) and Steyn (1980) in determating heat load on mine refrigeration units. The relationship proposed is:

$$Q = 5.57\,(WF + 0.255)(VRT - DB)CF$$

Q = Heat pick-up, kW/100m length of airway
WF = Wetness Factor, 0 for dry airway, 1.0 for very wet airway
VRT = Virgin Rock Temperature, °C
DB = Dry Bulb Temperature, °C
CF = Correction Factor for Airway Size, Airway Age, and Type of Rock

In application, the formula requires that a number of assumptions be made. A subjectively determined airway wetness factor is needed in the equation and a correct estimation of that factor is necessary in order for heat flow values to be accurately calculated. A correction factor can be applied to account for:

(a) airway sizes varying from the normal South African dimensions of approximately 3 m by 3 m,

(b) airway age, where airway surrounding rock is cooler than normal due to heat liberation over time, and

(c) rock type, if thermal characteristics vary from those of quartzite. The equation takes no account of air quantity or air velocity rate through the passageway.

The Ramsden equation has been applied to the study of test data from which calculated energy change values are obtained, as shown in Table 3. In the application of the Ramsden equation, no allowance has been made for variation from the assumed airway size, airway age, and type of rock, and a correction factor of 1.0 has been applied. The wetness factor used for each determination is based on personal observation of airway surface characteristics as tests were in progress.

From the results, it can be seen that, while there is reasonable correlation between energy flow levels determined by the Ramsden

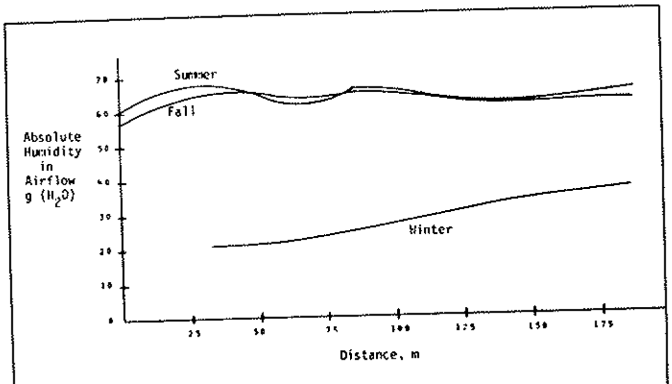

Fig. 8. Humidity levels in air flowing along passageway, mid-afternoon readings.

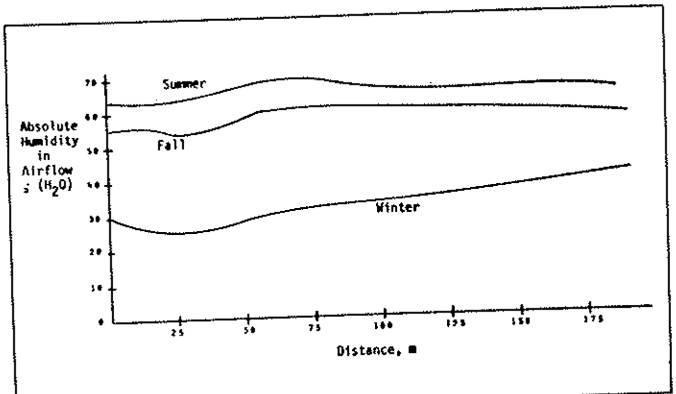

Fig. 9. Humidity level in air flowing along passageway, 3 a.m. readings.

Table 3. Energy changes in airflow applying Ramsden equation.

	Summer	Fall	Winter
Mid-afternoon readings			
Energy Change — Section 1*	62.2 (0.25)**	45.4 (0.25)	32.5
— Section 2	50.1 (0.75)	41.8 (0.75)	53.1 (1.0)
— Total	112.3	87.2	85.6
Air Enthalpy Change***	108.6	60.6	137.3
Early morning readings			
Energy Change — Section 1	27.5 (0.25)	16.7 (0.25)	15.7 (0.25)
— Section 2	36.2 (0.75)	25.1 (0.75)	32.2 (1.0)
— Total	63.7	41.8	47.9
Air Enthalpy Change	36.1	9.4	50.2

*Airway Section 1: Length 0m to 85 m
Airway Section 2: Length 85 m to 185 m
**Assumed Wetness Factor in Calculation: All Surface Dry-0
All Surfaces Wet-1.0
***Enthalpy readings from Table 1

equation and air enthalpy calculation for winter test readings, discrepancies are apparent for results from other seasons.

For the summer and winter data, energy change by application of the Ramsden equation exceeds that calculated from enthalpy considerations. It is appropriate in this case to look at how the Ramsden equation was originally intended to be applied.

(1) The equation is put forward for use in determining heat flow from rock at high temperature to cooler air.

(2) The equation is designed to be applied to situations of airflow through long passageways where air is at a high relative humidity and airway surface moisture is from groundwater inflow.

The summer and fall studies examine a heat exchange situation in which the flow is from warmer air to colder rock mass. Further, the passing air has not reached a high and stable relative humidity level. Considerable energy transfer is involved in latent heat of evaporation and condensation, and these changes require complex explanation. Further detailed interpretation of test results by examining the response of airflow in different sections of the passageway may allow most discrepancies to be explained, thereby improving the correlation.

Conclusions

As air moves through a rock-lined passageway, temperature changes take place as heat energy transfer occurs within the air and rock mass system. To obtain a better understanding of this process, an in-situ study was undertaken to monitor and record the changing conditions at various locations along a 185-m passageway in dolomite rock with regulated airflow. The investigation consisted of three test periods of 2.5 days each, conducted in July 1980, September 1980 and January 1981.

Based on recorded data, relationships have been determined that (1) describe the rate of change in air temperature and air moisture level as outside air was circulated through the passageway and (2) identify temperature changes occurring in the surrounding rock due to the interfacing of exposed mine rock with the air. An attempt was also made to calculate the thermodynamic balance of the system. The results of the study were compared with empirical and theoretical approaches used in deep mine air cooling investigations in South Africa.

Changes in air moisture level along the passageway, the latent heat of evaporation, and the condensation energy flow considerations are important to a full understanding of the physical principles involved in the energy balance of a ventilation system. Such an understanding involves a detailed examination of changes in air behavior along the passageway on a section-by-section basis. Experimental determination of conditions must be undertaken with care and accuracy, and interpretation made on a basis that examines unit changes within the system. Good correlation has been obtained between experimentally determined and theoretically based results. Areas where further efforts in interpretation are needed have been identified.

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