The analysis of ventilation and cooling requirements for mines

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SYNOPSIS

A systematic approach to the analysis of alternative methods of ventilating and cooling large hot mines is presented. The important factors that have a bearing on ventilation and cooling requirements and practices, such as air flow through the mine, geographical distribution of heat loads, and micro-ventilation considerations, are dealt with. The analysis of these factors leads to definitive ventilation and cooling strategies, air and water process design, specifications of details, and designs of the associated plant and equipment.

SAMEVATTING

'n Sistematiese benadering om alternatiewe metodes vir myn ventilasie en verkoeling te evalueer word beskryf. Belangrike faktore soos massa lug vloei, geografiese verspreiding van hitte bronne, mikro omgewings, ens., word behandel. Die evaluering van hierdie faktore lei tot finale en bepalende ventilasie en verkoelingsstrategieë, lug en water vloei proses ontwerp, detail spesifikasies en ontwerp van die sisteem en toerusting.

Introduction

The method presented here for the analysis of ventilation and cooling requirements in large, hot underground mines is that generally followed by the authors. The method has been developed over several years, and is based on experience gained on a number of mines in South Africa and overseas. This development would not have been possible without the research and development work conducted by the Chamber of Mines of South Africa [1-5]. The authors' exposure to mines in other parts of the world enabled them to modify the ventilation and cooling principles that had been established for the South African gold-mining industry to suit the totally different requirements of mines using a variety of mining methods under varying climatic conditions.

There are essentially three types of ventilation and cooling projects.

(1) In those associated with existing mines, the object is to audit the ventilation and cooling practices so that their inefficiencies can be determined and analysed, and ways can be found of improving the underground environment without having to increase the ventilation and cooling infrastructure significantly[6]. As the layout of the mine and the flowrates of air are essentially fixed, improvement of the underground environment depends primarily on the success with which the utilization of air and existing cooling plant and equipment can be improved. These are referred to here as type A projects.

(2) In those associated with existing mines where the object is to extend mining operations into new ground and often to greater depth, the aim is to make the best possible use of the existing facilities and to define the additional infrastructure required. An essential part of this type of project is to determine the influence of worked-out areas and extended airways on the underground environment for future mining operations, and to revise the mining practices and long-term production planning to best suit them [7]. These are referred to as type B projects.

(3) In those for new mines, the aim is to create the necessary infrastructure and to analyse the proposed mining methods and layouts to establish whether they are conducive to the creation of an acceptable environment[8]. These are referred to as type C projects.

The achievement of an acceptable underground environment often poses problems that are not only costly to rectify but can result in serious losses, particularly when these are associated with low productivity. The reasons for these problems are multiple and can be summarized as follows.

(a) Often historical management and organizational developments have not taken sufficient cognizance of environmental control. The need for a well-established ventilation or environmental department has not been recognized by many mines, particularly the older ones and those which started by mining the outcrops of an orebody. The long-term mine layout and production planning were conducted without the necessary expertise on ventilation and cooling, and consequently the associated infrastructure (shafts, airways, major exhaust fans, cooling plant, and associated facilities) became inadequate.

(b) Ventilation and cooling problems often escalate as mining operations extend into new ground. The effect of extending airways and keeping worked-out areas open usually results in
  - — an increase in the flow of pollutants such as heat and radon from the constantly increasing surface area of exposed rock, and
  - — an escalation of the problems associated with the distribution and control of air and cooling water to the working places[4].

(c) The thermodynamic and thermal behaviour of mines is complex and difficult to quantify. The significance of phenomena such as autocompression, the geothermal gradient of the earth's crust, thermal inertia of the side walls of excavations, etc. is often not

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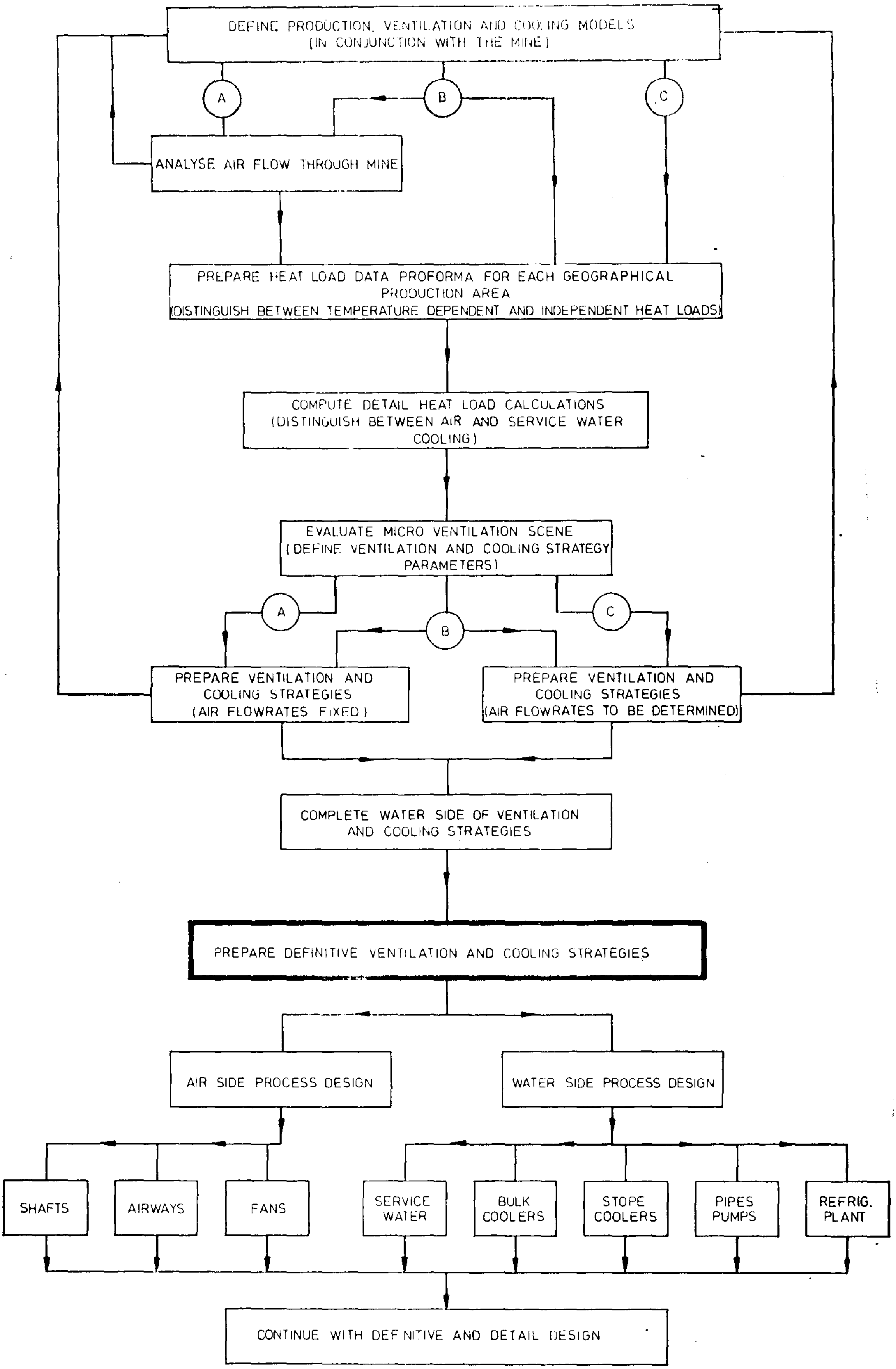


Fig. 1—Project sequence in the analysis of ventilation and cooling requirements for mines

fully understood, resulting in the provision of facilities that are inadequate.

(d) The thermodynamic and process design requirements associated with ventilation and cooling are often in conflict with practical operational constraints.

(e) Ventilation and cooling engineering on mines is multi-disciplinary and involves the co-ordinating and planning of mining, process, mechanical, electrical, and instrumentation engineering. In other words, it is project-engineering orientated, which is often not recognized.

Analysis of Requirements

The most important aspect in the auditing and engineering of ventilation and cooling systems for underground mines is the preparation of *definitive* ventilation and cooling strategies. These strategies are similar to those for the dilution of other pollutants such as radon, methane, and diesel exhaust fumes, except that they are more complex and involve considerably more calculation. These strategies have the following objectives.

(i) They serve to define the policy to be followed by the mine, as well as the operational responsibilities associated with ventilation and cooling that are to be borne by the various departments on the mine, viz mining and production engineering, engineering services, environmental (ventilation) engineering, etc. It is therefore essential that the senior personnel of each department, who have extensive experience of the mine, should provide the input for the preparation of the strategies. Furthermore, it is essential that the strategies devised should be acceptable and clearly understood by all who will be concerned with their implementation. To ensure that the measures and decisions finally agreed upon are carried out, it is preferable that a senior manager, or even the Mine Manager, should assume the responsibility for co-ordinating their preparation.

(ii) The associated major capital and operating expenses (such as those for shafts, airways, major fans, refrigeration machines, cooling towers, bulk spray coolers, stope air coolers, pumping, and piping) are all determined.

(iii) The strategies serve as the basis for the process design of the ventilation-air and cooling-water systems, and the refrigeration installation, as well as for the process analysis of the entire ventilation and cooling system. Here *process analysis* means the evaluation of the performance and utilization of equipment under the various conditions that exist on the mine.

A diagram showing the sequence of activities in the preparation of definitive strategies is given in Fig. 1 for the three types of projects referred to previously. The diagram depicts the various steps and the iterative nature of the preparation.

Production, Ventilation, and Cooling Models

Mines are usually too complex, and the future production planning too undefined, to permit the preparation of detailed strategies. Care must therefore be taken not to create too much work in their preparation for one soon reaches a point of diminishing returns.

The exercise should start with simplified ventilation and cooling models that accurately represent the current and expected future production scenes on the mine. These models define the production areas geographically, as well as the principal routes for ventilating the various areas. A model should be prepared for each future production phase, starting with a situation, say, 3 to 5 years in the future and further models for, say, 7 to 9, 12 to 15, 18 to 22, and 25 to 30 years in the future. In defining the models, it is essential that all concerned, and particularly the production engineering staff, should be involved. Mistakes or erroneous interpretation of production requirements at this early stage will inevitably result in a considerable amount of abortive work, and will lead to incorrect assumptions and decisions.

Each geographical production area is defined by

- the production for both ore and waste,
- the centre (depth) of production, as well as the geographical boundaries, i.e. the shallowest and deepest production levels,
- the virgin-rock temperature at the centre of production,
- the total length of haulages, airways, and accesses, as well as their average cross-sectional dimensions, and
- the number of stoping areas and the average dimensions of stopes and working excavations, each stoping (mining) method being treated separately.

A geographical production area is defined in such a manner that a ventilation and cooling strategy can be devised on the assumption that all production is on one level, i.e. at the centre of production, and the extremities of the area do not have to be treated differently from the averages. Fig. 2 depicts the principle of a simplified model, and Fig. 3 indicates the model for a typical mine.

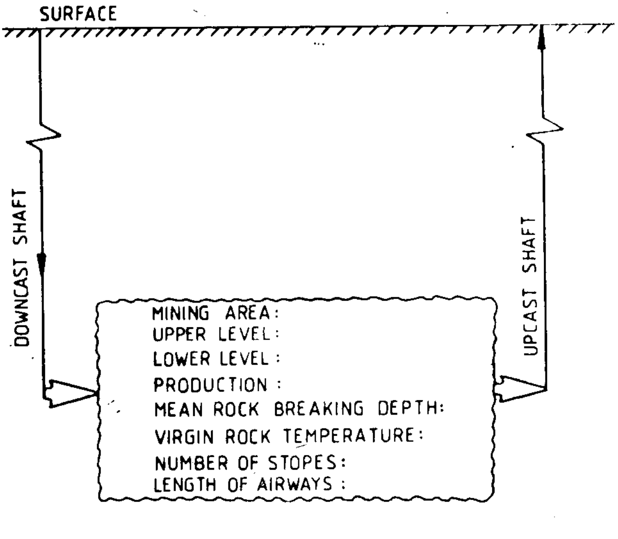
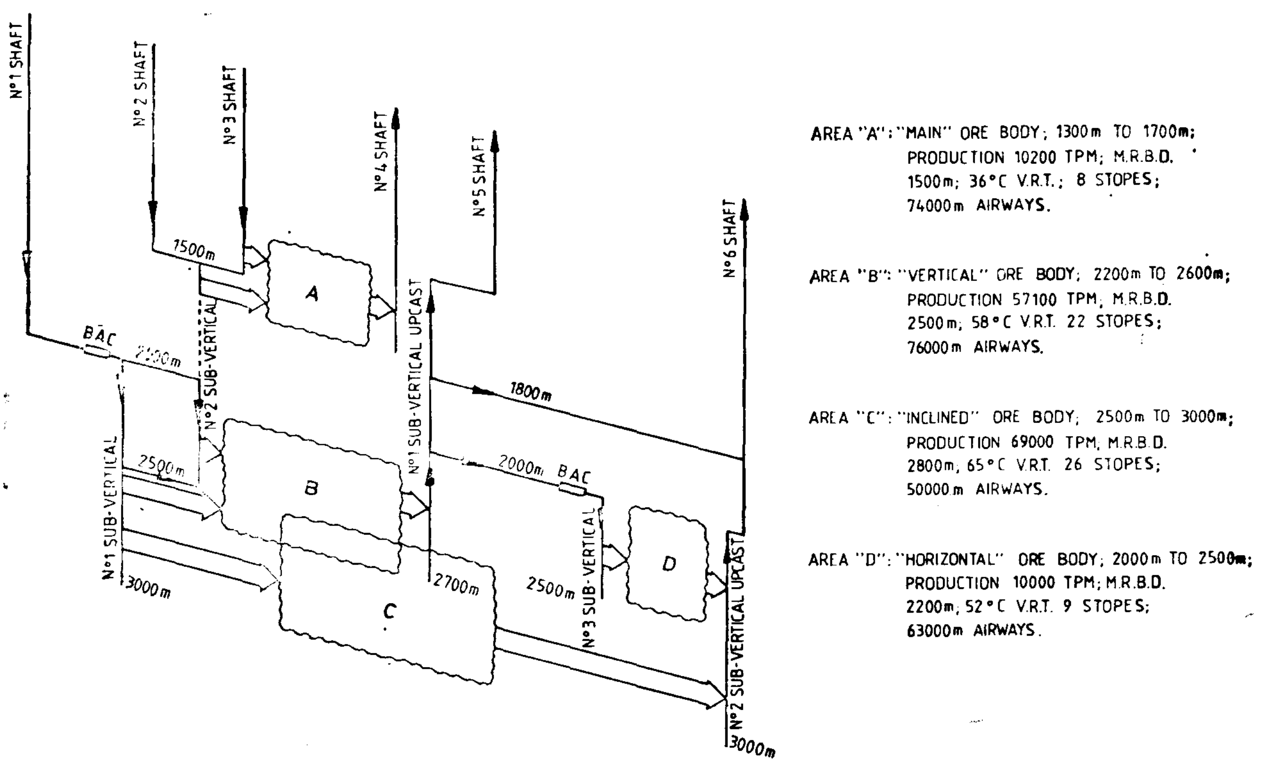


Fig. 2—The principles of a simplified production, ventilation, and cooling model defining a geographical production area



AREA "A": "MAIN" ORE BODY; 1300m TO 1700m;
PRODUCTION 10200 TPM; M.R.B.D.
1500m; 36°C V.R.T.; 8 STOPES;
74000m AIRWAYS.

AREA "B": "VERTICAL" ORE BODY; 2200m TO 2600m;
PRODUCTION 57100 TPM; M.R.B.D.
2500m; 58°C V.R.T. 22 STOPES;
76000m AIRWAYS.

AREA "C": "INCLINED" ORE BODY; 2500m TO 3000m;
PRODUCTION 69000 TPM; M.R.B.D.
2800m; 65°C V.R.T. 26 STOPES;
50000m AIRWAYS.

AREA "D": "HORIZONTAL" ORE BODY; 2000m TO 2500m;
PRODUCTION 10000 TPM; M.R.B.D.
2200m; 52°C V.R.T. 9 STOPES;
63000m AIRWAYS.

Fig. 3—A typical production, ventilation, and cooling model

Analysis of Air Flow through a Mine

Before the preparation and collection of data for the determination of the heat loads of the various production areas of a model, it is necessary for the airflows, particularly the associated air velocities and pressure losses, to be analysed briefly to ensure that the model represents a practical proposition. The following are guidelines for use in the assessment of the practicality of models.

(1) Flowrates should typically be between 3 and 5 m^3/s per kiloton per month at standard density. However, values outside this range are not necessarily incorrect or unacceptable.

(2) Pressure losses should typically be between 1000 and 1500 Pa for each of the downcast and upcast shafts, and between 2000 and 4000 Pa through the workings. The total pressure losses at this stage of the investigation should not exceed 7000 Pa. These values may be too high for shallow mines.

(3) Velocities should preferably be less than 7 m/s in intake airways that are in constant use. In the return airways, where there is little activity, they should preferably be less than 10 m/s. Experience has shown that mine layouts that have been based on higher air velocities often result in unacceptable pressure losses.

When existing mines (type A projects) are audited, it is usually possible for the relationship between air flowrates and pressure losses to be determined fairly accurately. This also applies to type B projects provided the extensions depend largely on the existing shafts and airways. On type C projects (new mines), the sizes of airways and shafts are usually dictated by the air flow requirements and the above guidelines.

Heat Load Data and Data Proforma

Once the models have been prepared, i.e. the mine has been divided into geographical production areas for each of the future production phases, data sheets can be prepared for the collation of the necessary information. The data sheets have to comply with the requirements of the model, and must present the results of the heat-load calculations in such a way that they can be transferred onto the flow diagrams depicting the ventilation and cooling strategy. For this reason, the heat-load data sheet consists of two parts.

TABLE I

HEAT-LOAD DATA FOR THE SIDE WALLS OF SHAFTS

Exposed surface area	m^2
Thermal diameter	m
Thermal age	mth
Heat from side walls	kW

In the first part, the tables distinguish firstly between heat loads that depend on air temperature and those that are independent of temperature, and secondly between heat generated in downcast shafts, main interconnecting airways, airways in the geographical production area, and stopes (Tables I to IV.)

In the second part, the values are re-arranged and distinguish between the geographical distribution of heat loads for each of the various areas, i.e. shafts and/or interconnecting airways, airways in the production area, and stopes. For each of these, the tables then distinguish between temperature-dependent and temperature-independent heat loads with the added complication of defining what portion of each of these should be countered by the ventilation air and/or by the use of chilled service water (Tables V to VII.)

TABLE II

HEAT-LOAD DATA FOR THE WALLS AND BROKEN ROCK IN AIRWAYS

Development production (rock breaking)	t/mth
Heat from broken rock	kW
Airways and drifts:	
Total length	m
Average width	m
Average height	m
Age of production area	mth
Heat from side, hangingwall, and footwall	kW
Number of development headings	—
Face advance for all headings	m/mth
Face advance per heading	m/mth
Development cycle	mth
Heat from side, hangingwall, and footwall	kW

TABLE III

HEAT-LOAD DATA FOR THE WALLS AND BROKEN ROCK IN STOPES

Stope production (rock breaking)	mth
Heat from broken rock	kW
Number of stopes	—
Average length of stopes	m
Average width of stopes	m
Average height of stopes	m
Average time between blasts	mth
Exposed rock surface area	m^2
Heat from side, hangingwall, and footwall	kW

TABLE IV

HEAT-LOAD DATA FOR ALL ELECTRICALLY- AND DIESEL-POWERED EQUIPMENT

	Rating kW	Utilization %	Heat %	kW
Shaft and shaft stations:				
Fans				
Pumps				
Hoists				
Other				
Total				—
Airways:				
Locomotives				
Pumps				
Transformers (kVA*)	*			
Other				—
Total				
Stopes:				
Fans				
Scrapers				
LHD vehicles				
Other				
Total				—

TABLE V

HEAT-LOAD DATA FOR HEAT GENERATED IN THE DOWNCAST SHAFT

	Cold air kW	Cold service water, kW
Temperature dependent:		
Exposed rock		
Ground water		
Total		
Temperature independent:		
Fans		
Pumps		
Hoists		
Other		
Total		

TABLE VI

HEAT-LOAD DATA FOR HEAT GENERATED IN THE AIRWAYS

	Cold air kW	Cold service water, kW
Temperature-dependent:		
Exposed rock		
Broken rock		
Ground water		
Total		
Temperature-independent:		
Locomotives		
Pumps		
Transformers		
Other		
Total		

TABLE VII

HEAT-LOAD DATA FOR HEAT GENERATED IN THE STOPES

	Cold air kW	Cold service water, kW
Temperature-dependent:		
Exposed rock		
Broken rock		
Ground water		
Total		
Temperature-independent:		
Fans		
Scrapers		
LHD vehicles		
Other		
Total		

Although it is possible to standardize on the format for the calculation and presentation of heat-load data, care must be taken to ensure that a systematic and logical set of data sheets is prepared for each model, and that a clear definition of the geographical boundaries and equipment for each of these is given.

Calculations of Heat Load

The various sources of heat in the mine can be placed in one of two categories: temperature-dependent or temperature-independent loads. Temperature-dependent heat loads are those of which the magnitude depends on the temperature of the ventilation air. There are essentially three sources of heat in this category: from the side walls of excavations and the broken rock, from water on the footwall, and from fluids in pipes, e.g. ground water that is pumped out of the mine in an uninsulated pipe. Temperature-independent heat loads are those of which the magnitude is independent of the temperature of the air, e.g. all heat generated by electrically driven equipment such as pumps, hoists, scrapers, and fans, as well as heat from diesel-driven equipment such as loco's and LHD vehicles.

Experience on a number of mines has shown that typically 70 to 80 per cent of all the heat generated comes from two or three sources. On the gold mines in South Africa, heat from the exposed rock surfaces dominates the scene to such an extent that other sources of heat are often ignored. On many coal or base-mineral mines, heat from mechanical equipment, particularly from diesel-driven LHD vehicles, is the major source of heat. On other mines, it may be the ground water or, where blind-hole mining takes place, it could be the fans for ventilating the blind-hole working ends, etc.

Much has been written on the subject of sources of heat in mines[2,3,9–12]. Reference is therefore made only to the sources of heat that often dominate the heat-load scene.

Heat from the Rock

Heat from the exposed rock surface, i.e. from the side walls, hanging walls, and footwalls of airways and stopes is often the major source of heat. Although the Starfield method[9] is the theoretically correct one for the calculation of the heat load in airways, it is often difficult to apply because it depends on air velocities. These are not always known with an accuracy that justifies the use of this method over others such as the Goch–Patterson method[10], which assumes that the temperature of the rock face is the same as that of the air. Also, the accuracy with which lengths and average cross-sectional dimensions of airways can be obtained or anticipated is usually far less than the improved accuracy obtainable with the Starfield method. When the Goch–Patterson method is used, the heat load for airways is likely to be overestimated by about 10 to 20 per cent, and for this reason it is advisable not to allow for a contingency in the heat load. Furthermore, care should be taken in the use of the Goch–Patterson tables that the correct value is chosen since two values are given for each time interval. The first relates to the instantaneous heat load after a period of time has elapsed and should be used only for shafts and connecting airways that are old, i.e. 5 or more years after the excavations have been completed. The other value is the time-average heat load, being a measure of the amount of energy stored in the rock walls, and should be used in all cases where excavation and development work is a continuous activity.

The calculation of heat from the side walls in stopes is usually difficult, and requires a fair amount of investigation before a reliable and satisfactory method can be developed. This is because of the great variety of mining methods, and the odd shapes and sizes of stopes associated with them. For narrow-reef mining as found in the gold mines of South Africa, and for some room-and-pillar mining, the method proposed by Van der Walt and Whillier[2] gives satisfactory results. For other mining methods, it is best to relate stopes to cylindrical equivalent shapes and to apply the Goch–Patterson method[10].

The heat from broken rock is usually small compared with that from the side walls of excavations. The other temperature-dependent heat loads, i.e. heat from ground water and water on the footwall, can be neglected and often are. As these can be detrimental to the environment, they should be countered by containing the water in a pipe that is preferably insulated. Seldom can the cost associated with an increase in air flowrate and refrigeration requirements be justified to counter the effect of heat from this source, although instances do exist[8].

An essential part of the calculations associated with the preparation of a flow diagram depicting ventilation and cooling strategy is the calculation of marginal heat loads. These are the portion of the temperature-dependent heat loads because the actual temperature of the air is above or below the 'reference' temperature (often taken as 30 °C).

Heat from Underground Ventilation Fans

Underground fans can be major contributors to temperature-independent heat loads since all the energy required for the fans is converted to heat. A phenomenon that could easily be overlooked in respect of fans and the associated rise in the wet-bulb temperature of the air as it passes through a fan is the amount of cooling that is required to re-cool the air to its original wet-bulb temperature. Large underground booster fans may require up to twice as much cooling energy as the energy absorbed by the fan to offset its effect on the wet-bulb temperature. Auxiliary fans require somewhat less, depending on the type of installation and the length of discharge ducts. In a number of instances where auxiliary fans were used to force air through coolers and into stopes, the effect of the fan on the wet-bulb temperature was greater than the cooling effect of the cooler, resulting in a net increase in the temperature of the air passing through the system. In such cases, preference should be given to other methods of ventilation and mine layout that would eliminate as many of the underground fans as possible.

Heat from Mechanical Mining Equipment

All the energy that is required to power mining equipment is converted to heat, and results in an increase in the wet-bulb temperature of the ventilation air. The heat generated from the equipment depends on

- the rated capacity,
- the percentage of time it is utilized, which can vary from as little as 5 per cent for poorly utilized scrapers to as much as 80 per cent for continuous mining equipment, and
- the extent to which the rated capacity is employed, which once again can be low for tramming equipment and high for continuous mining equipment
- whether it is driven by internal combustion engines or electrically.

It should be noted that the heat load associated with internal combustion engines can be much higher than the rated capacity of the equivalent electrical piece of equipment. In a number of instances where serious problems with the thermal environment were experienced, a change from equipment driven by internal combustion engines to electrically driven equipment alleviated the problem to such an extent that no further action was necessary.

Pumps and hoists located underground are also contributors to temperature-independent heat, even though they are not necessarily major contributors. In this regard, it should be borne in mind that most of the energy required to raise matter such as sludge, water, and rock goes into increasing its potential energy. When matter is lowered or transported horizontally, all the potential energy or the energy required to move it horizontally is converted to heat. It should be noted that these heat loads are not based on the rated capacity of the equipment but on the actual mass and height that is raised or lowered during a given period of time.

Micro-ventilation and Cooling Strategy Parameters

Before strategies are prepared, the micro-ventilation scene, i.e. in stopes, drawpoints, etc., should be evaluated, which involves

- the analysis and definition of layouts and design principles in regard to the ventilating and cooling of the underground environment, cognizance being taken of all related matters;
- the definition of airflow requirements; and
- the definition of the desired wet-bulb temperatures of the air entering and leaving in view of the expected temperature distribution in these areas.

When the heat dissipated by the exposed rock surfaces in working places is analysed, it should be borne in mind that this heat is time-dependent and that it is often not possible for cooling to be provided to offset the heat dissipated during the first few days after a blast. The reason for this is that a large surface area at a temperature close to the virgin-rock temperature is exposed, and it usually requires several hours or days for the skin of the rock to cool to the 'reference' temperature.

For the determination of air flowrates in working places, and of the required wet-bulb temperatures for the air entering and leaving them, the calculation of heat load is based on the average heat dissipated in the first 15 to 20 per cent of the period between consecutive blasts. This implies that the temperatures will generally exceed the desired wet-bulb temperature for that period. In the case of continuous mining, or when blasting of the working face takes place once a day or once every two days, this problem does not exist and the calculation of heat load is fairly straight-forward.

One of the most important aspects in the evaluation of working-place layouts and design practices is the preference for through-flow ventilation, which is the passing of the majority of the air on a particular level through each of the working places with a minimum of air bypassing them and without auxiliary fans. This generally has the following advantages over the alternative of forcing air to the working places with fans.

(a) The temperature distribution is generally between the temperature of the air entering and the temperature of the air leaving. In the case of blind-hole mining where it is not possible to employ through-flow ventilation, the temperature distribution in the stopes is largely unpredictable.

(b) The need for underground auxiliary fans is significantly reduced.

(c) The wet-bulb temperature of the air entering the working place can often be significantly higher without jeopardizing the thermal environment.

(d) Less air is required to pass through the mine.

(e) Less refrigerated cooling is required.

The main disadvantage of through-flow ventilation is the requirement for ventilation doors and additional airways and for their control, which could be costly.

Preparation of Ventilation and Cooling Strategies

The model, together with the results of the associated heat-load calculations and strategy parameters, can be presented in flow diagrams like those given in Figs. 4 and 5. Fig. 4 demonstrates the principles employed in the strategies, while Fig. 5 is a typical strategy flow diagram. In Fig. 4, the basic flow path for the ventilation air is shown along with the various cooling elements and the heat loads in the shaft, airways, and stopes. The effect of adiabatic compression (autocompression) on the temperature of the descending air is taken into account in the leg depicting the downcast shaft. The flow diagram refers to the macro-ventilation and cooling scene, which is applicable to the entire mine, as opposed to the micro-scene, which is applicable only to the various working places.

Although there are several types of strategies with varying degrees of complexity and sophistication, they can generally be placed into one of two categories.

(1) Those where the air flowrates are determined by factors that are not related to the thermal environment such as
    - — the availability and sizes of existing shafts and airways, and the ventilation and cooling infrastructure,
    - — the dilution of pollutants other than heat, i.e. dust, radon, noxious vapours, gases, etc.

    This category is largely limited to type A projects and to type B projects where the extension of mining operations depends heavily on the utilization of the existing infrastructure. Experience has shown that too little air is likely to be available from the point of view of the thermal environment.

(2) Those where the air flowrates are to be determined with the aid of the strategies, i.e. where heat is the major pollutant. The amount of air passing through the mine in this instance is determined by factors such as
    - — the micro-ventilation requirements in respect of the wet-bulb temperature of the air entering and leaving stopes and working places,
    - — the preference for bulk cooling of the ventilation air, rather than cooling of the air at entrances to stopes and in stopes for practical considerations.

    This category of strategies is applicable to type C projects (new mines), as well as to type B projects where the extension of mining operations requires a major new surface and underground infrastructure.

Cooling of Service Water

Service water is an integral part of the mine operation, and provides effective cooling in remote working places where men are using the water and where the wet-bulb temperatures are often high as a result of problems with ventilation. Cooling with service water is essentially a direct form of cooling, i.e. the water is not used to cool the ventilation air but to remove heat directly from certain sources, thus preventing them from raising the temperature of the air. Because this form of cooling is so effective in practice, it is essential that consideration is given to artificially increasing the quantity of water used.

Bulk Cooling of Air on Surface

This type of cooling should be considered in all cases where the average daily wet-bulb temperature for the hottest month in the year is above about 16 °C. The factors that should be evaluated are the magnitude of the temperature-dependent heat loads in the shaft and intake airways, air leakages, and the year-round utilization of equipment associated with the cooling of the air on surface. In the evaluation of a strategy employing this form of cooling, the marginal heat load is calculated and shown on the flow diagram in the same block that gives the details of the temperature-dependent and temperature-independent heat loads. The amount of cooling that has to be wasted when the air is cooled on surface can thus be assessed. Experience has shown that, when the air flowrates are low, or when shafts are wet owing to a continuous inflow of ground water, it is most unlikely that cooling of the ventilation air on surface can be justified.

The main advantage of cooling the air on surface is that it reduces the amount of cooling to be done underground, and hence the flowrate of the cooling water, which is often a major problem on large installations. The operating and capital cost per unit of cooling is low when compared with other alternatives. The success with which surface bulk air coolers can be operated and maintained generally offsets many of the inefficiencies associated with them.

Bulk Cooling of Air Underground

Where underground cooling of the air is required, it is essential that consideration should be given to cooling the air in bulk near to the shaft. This is particularly the case where the effect of autocompression and shaft heat loads on the temperature of the air is appreciable. The factors that should be evaluated are the effect of the cold air leaving the bulk coolers on the temperature-dependent heat loads in the airways to the stopes, and the amount of air that leaks through worked-out areas and is therefore not used beneficially.

When air flow through a mine is limited to what can pass through the shaft and airways, the thermal capacity of the air after it leaves the bulk coolers is often inadequate, resulting in a rapid rise in the temperature of the air due to the increase in temperature-dependent heat loads. In such cases, there is little merit in cooling the air in bulk as it leaves the shaft unless the air flowrate can be increased. In type B or C projects where the extension to mining operations requires additional infrastructure and shafts, the flowrate through the mine is usually determined by the requirement to cool the air in bulk without any subsequent cooling.

The relative ease, reliability, and success with which bulk coolers can be operated generally justifies the inefficiencies associated with air leakages and the increase in the temperature-dependent heat loads in airways. They remain an essentially fixed installation over the life of the mine, and hence are more accessible and require less manpower for maintenance, reduce the amount of water to be handled in stopes and airways, and have a lower capital and operating cost per unit of cooling over the life of the mine than those of the remaining alternatives[4].

Cooling of Air at Entrances to Stopes and Working Places

Although this is not desirable for many practical reasons[4], it is often unavoidable for type A projects and certain type B projects, viz when the air flow through the mine is inadequate and recirculation of the air is necessary to introduce the required cooling. For practical and economic reasons, cooling of air *at the entrances* is preferred to cooling *in* the working places. Most strategies involving coolers at the entrances to stopes require less refrigeration capacity than a bulk air-cooling installation for the same end result. The reason for this is the loss of cooling associated with air leakages and the increase in temperature-dependent heat loads in the airways when bulk air coolers are employed. However, care should be taken that this does not become a decisive factor in the choice of strategy since there are many practical considerations that are much more important than this apparent saving.

The disadvantage of this method is that it is a moveable form of cooling installation that, if not fully integrated with the mining operation and properly maintained, can be very ineffective. Experience has shown that these installations are expensive, and difficult to maintain and advance timeously as new stopes are being developed and brought into production. In very few cases in practice can it be stated that their use has achieved the design objective. In successful applications, it was noted that very little cooling was required to achieve acceptable thermal environmental conditions and that the refrigeration requirement was of the order of 50 kW (R) per kiloton per month. Furthermore, the life of all these stopes was several years and the installations were in fixed positions during this period.

Cooling of Air in Stopes

If possible, this should be avoided since it usually creates serious problems in stopes and is seldom worth the trouble and expenditure[13]. It can often be overcome only by an increase in the air flowrate or by recirculation of some of the air that passes into the stopes. Both this and the previous method can seldom be afforded if the wet-bulb temperature of the inlet air during the summer months at stopes and working places is below about 24 °C since air at this temperature is often acceptable.

The regulation of water to the various cooling installations is usually the main problem. This is because the pressure losses through the cooling-water pipes are usually much higher than those across the cooling units (particularly cooling coils) and, with a multiple of parallel paths and continuous changes to the system, it becomes totally impossible to balance[4].

Water Side in Ventilation and Cooling Strategies

Once the air side of the strategy has been defined, the water side can be completed and a first estimate of the refrigeration plant requirements and pipe sizes made.

Fig. 4 depicts cooling water being supplied to the various users from a common source with the return through a common pipe system. The latter is not necessarily correct: the strategy serves only as a basis for the process design of the air and cooling-water distribution system. What is important, however, is that the water requirements and temperatures of the water entering and leaving the various cooling elements (users) should be defined.

An important rule with regard to the temperature at which water is supplied to the various elements is that it must at all times be as low as is practically possible. The reason for this is that water flowrates should be kept to an absolute minimum, thus permitting the maximum amount of cooling to be distributed for a given quantity of water.

The principle of the supply of chilled water to bulk air coolers on surface is different from that of the supply of cold water to other users because there are no restrictions to water flowrates. In the former, the temperature of the supply water depends on the wet-bulb temperature of the ambient air, and it is therefore desirable for the refrigeration plant to be separate from the other plants supplying water to the underground users. The engineering of refrigeration plant forms the subject of other publications[14,15].

Ventilation and Cooling-water Distribution Systems

After definitive strategies have been prepared, the process design and analysis of the ventilation and cooling-water distribution system, as well as the process analysis of the various cooling elements and the refrigeration plant, can be undertaken.

Process Design for Air Side

This involves the preparation of flowsheets and the analysis of the shaft and airways with respect to
- air flowrates (mass and volume) for each leg,
- pressure losses through each leg,
- air velocities in each airway,
- dimensions of each airway,
- air control facilities.

During the process design, consideration should be given to the elimination of areas where the pressure losses are relatively high by the provision of additional airways. The natural distribution of the air through the mine should be carefully evaluated, and may require the use of computer programs as these calculations are often of an iterative nature that cannot be done manually. The air distribution underground should be controlled, preferably by the use of air-control doors and regulators rather than fans, unless the latter are close to the exhaust facilities. Fans introduce heat into the mine, are less flexible, and can fail, resulting in a maldistribution of air.

Once flowsheets have been prepared for each of the strategies over the life of the mine, the exhaust fans and associated equipment can be specified to meet the long-term requirements of the mine.

Process Design for Water Side

This involves the preparation of quantitative and engineering flowsheets for
- the overall water distribution and reticulation system,
- the bulk air coolers including the air side,
- the stope air coolers including the air side,
- the refrigeration plant[14,15],
- the water-settling and treatment plant.

Quantitative flowsheets essentially depict the design energy and mass balances, i.e. mass flowrates of air and water, pressure losses, temperatures, and heat-transfer rates across heat exchangers such as air coolers, evaporators, condensers, and cooling towers. Engineering flowsheets depict pipe and valve sizes, control gear and instrumentation, electrical equipment, etc. For the air side, only quantitative flowsheets incorporating the engineering flowsheets are required. Once the process design for each cooling strategy over the life of a mine has been completed, the specifications for the various pieces of equipment can be prepared.

Process Analysis of the Ventilation and Cooling System

With the aid of the various flowsheets, the process characteristic of each of the cooling elements and major pieces of equipment can be determined with respect to daily fluctuations, seasonal variations, and lifetime changes to water and air flowrates and temperatures, as well as the utilization of equipment.

It should be borne in mind that shafts, airways, and pipes serve a mine throughout its life, and failure to meet this requirement can be costly and may force the mine to interrupt production. Major capital equipment such as fans, refrigeration plant, and bulk air coolers should be selected accordingly, and their installation should be scheduled to cope with the various production phases throughout the life of the mine and yet offer a neatly engineered installation that at all times fulfils the requirements of simplicity and ease of operation and maintenance.

Conclusion

The method described in this paper offers a systematic approach to the analysis and definition of the ventilation and cooling requirements for hot underground mines. The importance of definitive ventilation and cooling strategies prepared in conjunction with senior personnel on a mine prior to any process or detail design work is stressed.

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