Novel Approach to the Energy Analysis of Mine Cooling Strategies

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ABSTRACT

The extraction of minerals and coal at increasing depth, employing higher-powered, mechanized machinery to increase production levels imposes an increased burden on the ability to maintain an acceptable mine climate. Any deterioration in the mine climate within working zones may adversely affect the health and safety of the workforce. The combination of the optimal design of the mine system layout, together with the selective application of suitable ventilation and cooling systems, may be used to control the climate within working zones.

The adoption of mechanical cooling within mines is an expensive process in terms of both capital and operating costs. Therefore, as mechanized mining takes place at increased depth, the need to maintain or improve the mine climate becomes more expensive. Consequently, to decrease overhead costs, reduce energy consumption and meet current and future environmental obligations, it is essential to provide the mine operator with a method with which to determine the most cost effective and efficient mine cooling system. To perform this analysis it is necessary to have a good understanding of the energy balances governing both the operation and utilization of a cooling system.

This paper introduces the application of a novel approach to energy analysis of mine cooling systems, with a combination of the concepts of exergy and composite curves. These methods are used extensively throughout chemical and process industries to increase energy efficiency and reduce capital and operating costs. An outline of the methods employed in the application of these techniques to the energy analysis of a mining cooling system is presented.

KEYWORDS

Mine Cooling, Exergy Analysis, Cooling Strategies, and Energy Efficiency.

INTRODUCTION

As mineral extraction becomes deeper with increased levels mechanisation and higher production rates, the mechanical cooling systems used to maintain an acceptable underground climate can become increasingly complex and expensive. So that mining operations may reduce their capital and operational costs it is essential that the industry is able to determine the most cost effective and energy efficient mine cooling system for each operation. It is the purpose of this paper to summarise the techniques currently being investigated to provide the engineer with an alternative means to identify the most practicable and cost effective cooling strategy with which to control the underground climate.

The application of the exergy concept to mine cooling is discussed. The development of a conceptual model mine used to examine the application of various cooling strategies is described. The results obtained from the application of these different cooling strategies to this model mine are examined using a combination of composite curves and exergy analysis.

EXERGY METHOD OF THERMAL ANALYSIS

Exergy analysis brings together the principles of the conservation of mass flow and energy and the second law of thermodynamics. It is particularly useful in the identification of thermodynamic inefficiencies enabling the location, type and magnitude of energy loss and destruction to be determined within a thermal system. The concept of exergy relies heavily on the 2nd law of thermodynamics and the use of the thermodynamic property of entropy. Exergy establishes the principle that energy has not only quantity, but also quality (measured as an ability to do work). This concept of energy quality may be illustrated by examining the effect of burning a finite source of fuel surrounded by excess air, in an isolated system, Figure 1.

As the fuel is burnt (Figure 1(b)) it warms the air, until finally a warm mixture of combustion products and air remains (Figure 1(c)). Although the isolated system still contains the same quantity of energy, the quality of this energy has been degraded. This is because, intrinsically, the fuel air combination would have been more useful than the final warm mixture. For example, the fuel could have been used in a

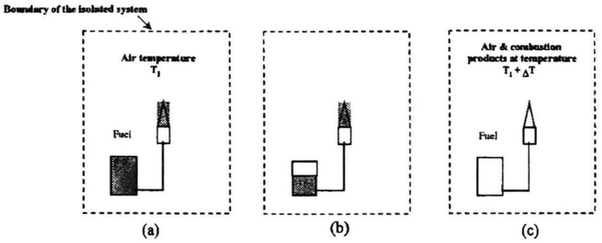

Figure 1. Illustration of the concept of quality of energy (Moran and Shapiro, 1995).

device to generate electricity, whereas the potential to recover the heat energy from the warm mixture to produce work is far less. The work potential in the above example was largely destroyed due to the 'irreversible' nature of the combustion process. It is this work potential or quality of energy that exergy quantifies. However, unlike energy, exergy can be destroyed and is generally not conserved; though, like many other extensive properties of a thermodynamic system it can be transferred.

In the following sections the main concepts of exergy theory are introduced and applied to the analysis of mine cooling systems.

Exergy Concepts

"Exergy is the maximum useful work that could be produced by the interaction of a system with a specific reference environment" (McGovern, 1990). From this definition, exergy can be termed as the measured departure of a system state from its reference environment. Hence, exergy it is an attribute of the system and its environment. Therefore, to precisely define the concept of exergy, we need to determine the condition of the environment.

Environment and Dead State. The environment for an exergy analysis is assumed an infinitely large system that is in a perfect state of thermodynamic equilibrium. This means that there are no gradients or differences involving pressure, temperature, chemical composition, kinetic or potential energy. The environment is also free from any form of irreversibility. Therefore, any system interacting with this environment varying in one or more of the above properties has the potential to produce work by coming into equilibrium with its environment. Therefore, it is essential to properly define the reference environment as to enable a quantitative exergy analysis of a thermal system to be performed.

To conduct an exergy analysis of a mine cooling system, the reference environment may for example be that of the atmospheric conditions existing at the mine surface. The reference conditions of temperature T_0 and pressure P_0 are assumed to be in a perfect state of equilibrium and to represent the typical surface environment.

If a system differs in anyway from its environment (see earlier) then it has the potential to do work. However, as the system changes state and moves towards that of the environment then its capability to produce work diminishes until it reaches a state of equilibrium with its environment. The system is now defined as being in a Dead State and has zero exergy (no potential for work). There is however, another form of dead state. This is when the system is in equilibrium with its environment in terms of its mechanical and thermal states only, known as a *restricted* dead state.

Components of Exergy. The total exergy of a system may be divided into four major components: physical exergy kinetic exergy, potential exergy and chemical exergy. Since exergy has been defined as the work potential of a system if brought into equilibrium with its environment, then both the kinetic and potential energies of the system can be considered to be fully convertible to work. For example, the kinetic exergy of a circulating chilled water stream is directly related to its velocity, whilst its potential exergy is principally determined by relative elevation, above or below the reference environment.

The physical exergy of a system quantifies the differences in thermodynamic state of the system (T_1,P_1) with respect to its reference environment (T_0,P_0). It is quantified by applying an energy and entropy balance between the closed system and its environment. Reversible heat transfer is the only interaction permitted between the environment and the system. Thus, physical exergy is equal to the maximum amount of work available from a system as it is brought from an initial state to the environmental state defined by P_0 and T_0 (Kotas, 1995).

In the application of exergy to the analysis of mine cooling systems, chemical exergy plays no role. This is because normally no chemical reactions, mixing or separation of any chemical components take place within a cooling circuit. This fact is normally accommodated in an exergetic analysis by assuming a restricted dead state.

The object of employing an exergy analysis, is that all energy transforms within a system may be represented and quantified in the forms of one common parameter, exergy. Thus, as a cooling system carries out its various heat transfer and flow functions, the associated energy transfers may be characterised and quantified in terms of gains or losses of exergy. Energy inefficiencies within the system are represented as a destruction of exergy.

The following section of this paper is devoted to the development of a climate prediction model of a representative conceptual mine. The paper concludes with a summary of results of a series of exergy and composite curve analyses applied to this model in order to compare the performance of three different cooling scenarios.

DEVELOPMENT OF A REPRESENTATIVE CONCEPTUAL MINE

The climate conditions that exist within a mine network are produced from a complex interaction of a range of contributing factors. These factors include: the surface air conditions, the depth of working, the method of working, the type of mineral mined, the local strata temperatures and the size and type of machinery used. In order to analyze the various available cooling strategies it is necessary to develop a representative model that can encompass the factors that influence the energy transfers between the ventilation air and a mine cooling system

Design of the Model Mine

A model mine network was constructed to represent the typical layout of an extensive, deep, longwall UK coal mining operation. The design is based upon the following assumptions and parameters:

- Average UK summer climate conditions are assumed to prevail at the surface.
- The rock mass possesses typical UK coal measure thermal values.
- The surface rock temperature is 10°C (50°F).
- The geothermal gradient is 30 m/°C (55ft/°F).
- All underground workings are level and developed in-seam.
- The mine employs conventional retreat longwall coal mining methods.
- The mine employs an antitropal ventilation and coal clearance system
- A surface exhaust fan provides the sole source of ventilation.

The mine contains three longwall districts each with an associated development working. A schematic of the mine's ventilation network is shown in Figure 2.

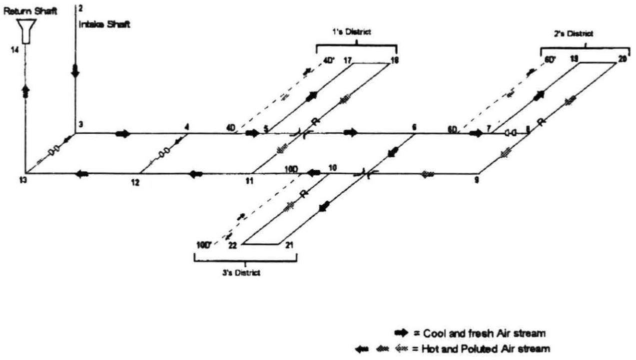

Figure 2. Ventilation network of the model mine.

Climate Prediction Procedure

A commercial ventilation network solver (VnetPC^{TM}) is used to determine the volumetric airflow rates and pressure distributions around the network. The network was balanced so that each longwall district receives a fixed airflow quantity of 20m^3/s (42,378cfm). In the following thermodynamic analysis the above airflow distribution is assumed to define the optimum ventilation solution, prior to the application of a mine cooling system.

The climate prediction exercises for this extensive network were executed using the commercial code (Climsim^{TM} for Windows).

The climatic conditions within the mine network are sequentially determined from the surface, follow the divisions of the intake flow through the mine workings and into the return flow circuit back to surface. The climatic conditions across the longwall coalfaces are calculated using the simulation program FACE ^{TM}.

Climate Prediction Analysis

A series of thermodynamic studies were performed, to determine the range of the climatic conditions, which are produced within the model network, on the application of three specific cooling strategies. The application of any cooling strategy requires the identification of the areas within the mine which present the highest potential heat load to the ventilating air. These areas often coincide with the location of the major production zones within the mine. Where the climatic conditions of the ventilating air within a particular working zone exceed the legislative or local climatic limits, the installation of a suitable cooling system may be considered. *The modelling of each cooling strategy assumes that the volumetric airflow distribution within the network is optimal.*

The Definition of the Cooling Criteria. The UK 1956 Mines and Quarries and 1974 Health and Safety at Work Acts require a mine manager to provide a safe and adequate environment for workers within underground workings. However, although under review at this time, there are currently no specific statutory regulations that quantify the level of an acceptable climate within the underground workings. The UK underground coalmines have developed a range of local operational climatic limits based upon those enshrined in German mining law. The current concentration of heat problems to a number of specific deep UK coal mines, has seen the development of ventilation rather than mechanical cooling solutions. Therefore, the cooling criteria adopted in this study are guided by the methodology, practice and experience of the German deep hard coal mines.

Climate Control Zones (CCZs). The overall cooling strategy adopted by a mine depends upon the mining methods used and the geothermal conditions under which mining takes place. In European coal mines, highly productive and mechanised longwall coal faces are the predominant mining method. These operations are conducted at depths of up to 1400m (4593ft), often in areas of high geothermal gradient. Consequently, the general cooling strategy employed is to control the climate in the near vicinity of the production and development workings. In the case of the model mine, these areas are identified as; the headend of the development workings; the maingate and tailgate access roads and the total length of the longwall coal face.

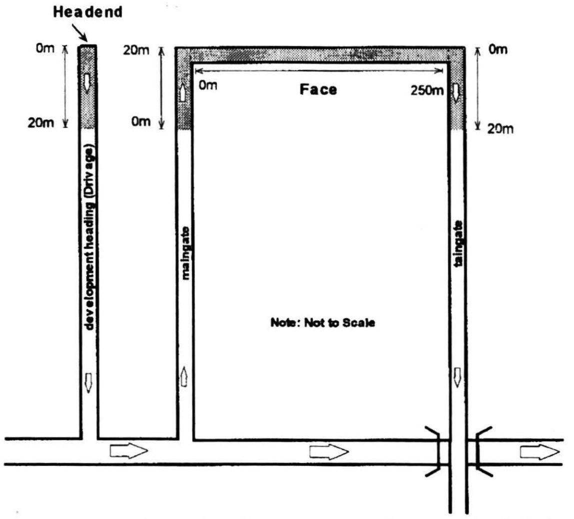

Figure 3. Details of the climate control zones (CCZ) for a longwall district and development drivage.

In the development heading the climate control zone is set, such that it extends from the face to a distance 20m (62.6ft) back down the drivage, see Figure 3. A 20m CCZ is also applied to the working areas at the head of the maingate and tailgate roadways adjacent to the coalface. The CCZ for the longwall coal face is set to extend along its full length. Figure 4. shows the location of these CCZ's around a the working districts of the model mine.

Each CCZ is designed to encompass the production zones in which the major work activity takes place. The current analyses does not include workings outside the main production and development zones.

The definition of the climatic limit. The Effective Temperature (ET) heat stress index was selected as the parameter to determine the thermal condition of the ventilating air, with regard to its effect on the performance and health of the workforce (Tuck, *et al.*, 1997).

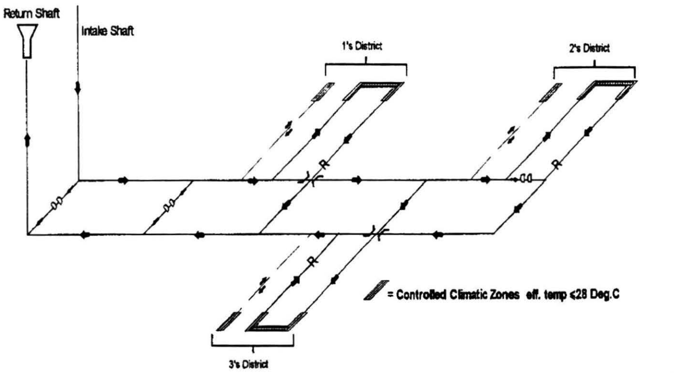

Figure 4. Schematic of the Climate Controlled Zones specified in the conceptual model mine.

An ET of 28°C (82.4°F) was set as the upper climatic design limit within the CCZs. Where the climatic conditions of the air exceed this limit, a range of mechanical cooling methods may be employed to regulate the climate.

The Mechanical Cooling of the Climatic Control Zones

A comparative analysis was performed on the mine climate predicted within the model mine on the application of each of the following cooling strategies: minimum theoretical cooling requirement, combined machine and spot air cooling, and spot air cooling exclusively. Each cooling strategy is applied to the model mine to regulate the climate within the designated CCZ's.

The climatic prediction of the mine network. To choose the correct cooling strategy it is necessary to perform a series of climate prediction exercises to ascertain the CCZs in which the ET may exceed 28°C (82.4°F). The model mine has been designed to simulate a hot mine; each longwall retreat face produces a maximum ex-raction capacity of 10,000 t/day (9842 imperial t/day) and operates an antitropal ventilation system.

The theoretical minimum cooling requirement. The determination of a minimum theoretical cooling requirement for a given mine, establishes a benchmark with which the results produced by other cooling strategies may be compared. The theoretical minimum cooling requirement is the minimum duty necessary to cool the ventilating air to a specified climatic condition by the use of the most efficient thermodynamic means.

Should the condition of the incoming air to a CCZ be above an ET of 28°C (82.4°F), the minimum cooling strategy will first employ spot cooling at the entrance to the CCZ to reduce the ET to this value. Following this, an incremental linear cooling system is installed within the CCZ to maintain the air at a constant 28°C ET. Although the installation of a true linear cooling circuit is not feasible, the system may be theoretically visualised as a series of large continuous passive cooling panels. The surface area of these panels varies to absorb any changes in the heat load experienced as the air flows through the CCZ.

Combined machine and spot air cooling. Where all or part of a machine's heat load, may be defined as a spot source, e.g. a shearer, the cooling strategy assumes that the cooling system directly absorbs this heat. It is further assumed that the heat load is absorbed at a temperature equal to the dry-bulb temperature of the air flowing over the machine. Any linear sensible machine heat source e.g. a mineral conveyor is modeled such that its heat energy transfers directly to the ventilation air.

The quantity of machine cooling required within the CCZs is first determined. The maximum amount of machine cooling possible is equal to the sensible heat load attributed to the particular machine. If the ET within a CCZ remains above 28°C (82.4°F) once the machine(s) have been cooled, then spot cooling may be applied to the inlet air. Air coolers are positioned at the beginning of the cooling zone. Each cooler has a theoretical duty capable to cool the air well below 28°C ET. This ensures that the ET of the air is maintained at or below the maximum permitted level as it flows through the CCZ. The layout of a typical district, which employs a combined machine and spot air cooling system, is illustrated in figure 5.

In a development, if air-cooling is required in addition to machine cooling, a spot cooler is placed in the auxiliary forcing duct after the fan. This will remove any excess heat pollution from the air drawn from the trunk roadway and also any heat picked up across the forcing fan.

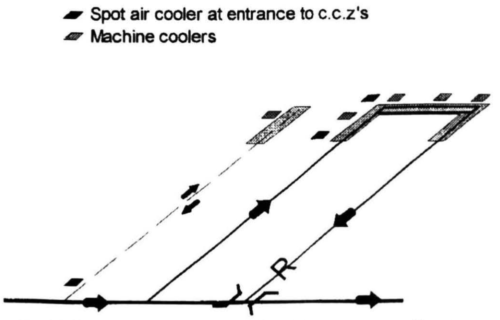

Figure 5. Schematic layout of a district employing a combination of a machine and spot air cooling systems.

The application of spot air-cooling. The most representative of the cooling strategies employed in German collieries is spot cooling. Spot air coolers are typically located at the entrances to the CCZs (figure 5.). Each cooler removes any excess heat load to ensure that the ET of the airflow may only reach its 28° C (82.4°F) limit as the flow exits the CCZ. In this model, the air acts as a sink for all heat transfers, any excess heat load being removed by the action of the air coolers. The air cooling model employed assumes that the total volumetric airflow is cooled, rather than as is often the practice a fraction of the air is cooled before being mixed with the remaining fraction of the main airflow.

Results of Climatic Predictions of Cooled CCZ's

The airflow and pressure distribution was determined for the model mine by the application of the ventilation the network solver. The main surface exhaust fan delivers an airflow of 81 m^3/s (171,631 cfm) at a pressure of 1.95 kPa (7.8in wg) pressure to maintain the fixed-quantity longwall face volumes at the required 20 m^3/s (42,378 cfm). The branch volume flows are converted to equivalent mass flow rates. The volume airflow rates entering each roadway are sequentially corrected as the climate within each of the network branches is evaluated. This procedure is followed in the modelling of both the non-cooled and cooled mine climate control strategies discussed previously.

From the climate data predicted for the non-cooled control mine network, it is observed with the exception of the first development heading, that the airflow entering each of the specified CCZs exceeds the prescribed 28°C (82.4°F) ET limit. Consequently, any cooling strategy adopted will be required to cool the air at entry to the CCZ to a level at or below the ET limit of 28°C (82.4°F). Further cooling may be applied within the zone to remove any excess heat load and hence maintain the airflow within at exit to the CCZ at or below the ET limit of 28°C.

Each of the three cooling strategies, described above were applied to the model mine network, to ensure that the climatic condition of the air flowing through the CCZs is less than or equal to the ET of 28°C. It was noted that on application of these strategies, no mechanical cooling was required within the CCZs at the head of the district tailgates. This is due to the use of an antitropal ventilation system, which removes any further major heat sources such as machinery or conveyed material from the path of the airflow leaving the face. Therefore, at the face end of the tailgate CCZs the ET of the air is maintained at 28°C. Furthermore, as retreat longwall access roads are pre-developed, the strata is able to act as a heat sink rather than heat source, thus potentially assisting the removal of any excess heat energy from the air.

Analysis of the Results

The amount of cooling capacity required on each district increases from the lowest duty, on the application of the minimum cooling strategy, up to the highest duty on the application of the spot air cooling strategy, Figure 6. The cooling methods applied within each CCZ across a district follow a similar trend. However, within the CCZ located at the head of 2's district maingate a higher cooling duty is required on the application of the machine and spot air cooling strategy as compared to that required by the spot air cooling strategy. This lower cooling duty is due to the previous incremental spot cooling of the ventilation air in the development headings of districts 1and 2. The air in these headings was cooled to below its dew point temperature, effectively dehumidifying it. Therefore, although the dry-bulb temperature of the air, at the entrances to 2's maingate CCZ, had increased to a level comparable with that predicted for the combined machine and spot air cooling strategy, its wet-bulb temperature had not. Consequently, in this case the lower predicted ET for the airflow results in the calculation of the reduced cooling requirement within this CCZ.

Since the theoretical minimum cooling requirement is achieved by the application of the minimum cooling strategy, then this value may be chosen as the datum against which the performance of alternative practical cooling strategies may be compared. The *effective efficiency* is defined to measure the relative performance of these various cooling strategies, where:

$$Effective\ Efficiency = \frac{Minimum\,Cooling\ Load}{Applied\,Cooling\ Load} \times 100\%$$

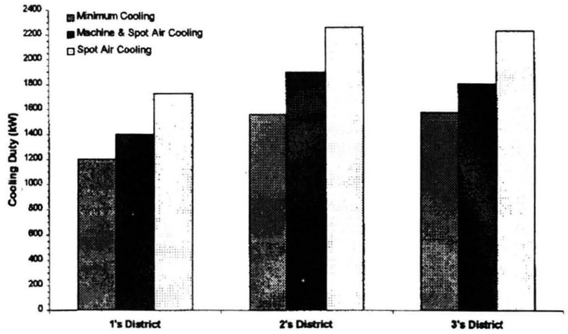

Figure 6. The predicted district cooling duties on the application of each cooling strategy. (1kW = 1.341hp).

The *effective efficiency* is defined in terms of the 1st Law of Thermodynamics, which quantifies only the total amount of energy required to operate the cooling strategy examined. The effective efficiency for each of the modelled cooling strategies is given in Table 3, below.

The increase in cooling duty required by the different methods is clearly identified from an analysis of the results presented in Table 3. The difference between the predicted thermal efficiency of the two methods is directly related to the positional efficiency of the applied cooling systems.

However, in order to improve the performance analysis of the individual cooling strategies, then an examination is required that also takes into account the effects related to the temperature at which this heat transfers occurs. This requires an analysis consistent with the 2nd law of thermodynamics.

Table 3. Effective efficiencies of machine & spot, and spot air cooling strategies.

	Machine & Spot Air Cooling	**Spot Air Cooling**
Effective Efficiency %	**82**	**78**

Composite Cooling Curves. Composite curves, adapted from the technique of Process Integration, have been used to develop a better understanding of the true efficiency of a cooling system. This analysis allows the performance of system to be expressed in terms of both quantity and quality of the energy transfers involved, namely exergy.

Composite cooling curves may be constructed using the thermal prediction data obtained from an application of each of the cooling strategies to the model mine. This technique involves the systematic combination of the determined cooling duties within the individual CCZs, for each of the cooling strategies examined. The cooling duties for each zone are sequentially combined over their common temperature ranges. This results in the definition of a curve that represents both the total cooling load required and the temperature ranges over which it is to be delivered. Each composite curve represents the most thermodynamically efficient manner in which the cooling process may be delivered. However, in practice it is not normally possible to apply the theoretical cooling network. For example, consider the construction of the composite curve shown in Figure 7. To remove the excess heat from the air in the most efficient manner, the cooling stream would have to follow the composite curve as closely as possible. An examination of the curves on Figure 7 reveals that the cooling stream is first delivered to 3's development heading (3D), the coolest sector in the network. The chilled water stream partly cools the air in this CCZ to the design ET, from where it is piped to 1's face (1F) where it partly cools this CCZ, before being piped to 3's longwall coalface (3F) etc. This process continues until the cooling water is transferred to the CCZ at the end of 2's maingate (2M). Where the composite curve represents more than one district, e.g., 2M+3F+3D+1F, the cooling water splits into parallel streams to provide cooling to these areas before recombining to continue flowing along the cooling path. Although the derived cooling path is theoretical, it does identify an optimum thermodynamic solution against which different cooling layouts and strategies may be compared. Thus, a unique composite cooling curve may be constructed for each individual cooling strategy applied to a mine network.

Composite curves have been constructed for each of the three cooling strategies modeled within the conceptual mine network and are shown in Figure 8. An initial analysis concludes that there are significant differences between the predicted cooling capacity required by each strategy, which are reflected as an increase in the length of the composite curves. However, the curves also graphically illustrate the range of temperatures across which the individual cooling strategies are applied. It is this variation in the coolth delivery temperature that further reduces the efficiency of a cooling system.

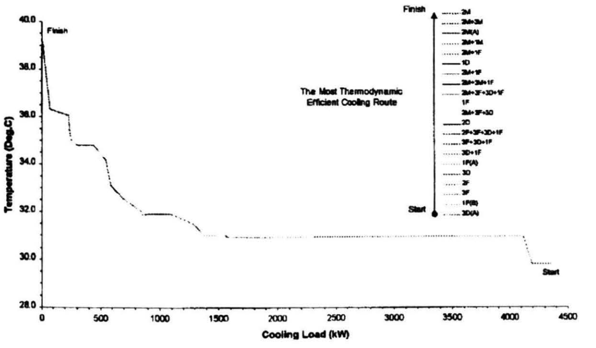

Figure 7. Minimum cooling strategy's composite cooling curve illustrating cooling network path. (1kW =1.341hp)

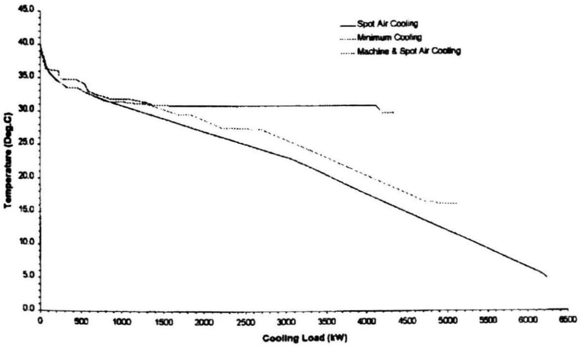

Figure 8. Composite cooling curves for the model mine.

Comparison of the exergy transfers within the modelled cooling strategies. The concept of exergy may be used to quantify the variations in the quantity and quality of energy involved in the delivery of the cooling within the mine. The area between the minimum cooling curve and the other composite curves is representative of, but does not quantify, the exergy loss (inefficiency), which exists between the different cooling strategies. The exergy loss may be determined by plotting the composite curves on a τ - *cooling load* diagram, Figure 9., where τ is the dimensionless *exergetic temperature*, defined as:

$$\tau = 1 - \frac{T_o}{T_a}$$

Where: T_o = dry-bulb of environment state (°K)
T_a = temperature of cooling stream (°K)

The area bound by the axis represents the exergy transfers associated with the cooling systems. Therefore, the total exergy of each system is determined by the integration of their respective composite cooling curves.

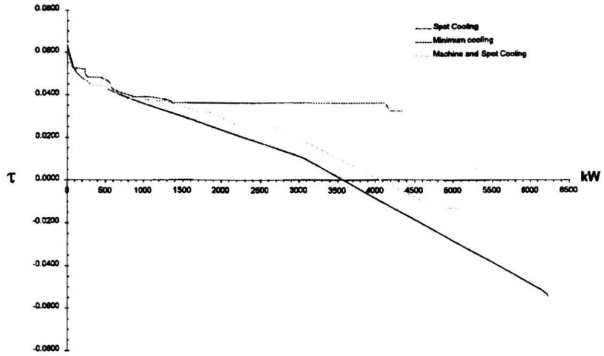

Figure 9. Exergetic composite cooling curves.

Table 4 shows the exergy transfers calculated for each of the different cooling strategies.

Table 4. Exergy transfers associated with each of the cooling strategies studied. (1kW =1.341hp).

	Exergy Output *(Free Cooling)* **(kW)**	**Exergy Input** *(Mechanical Cooling)* **(kW)**	**Irreversibility (kW)**
Minimum Cooling	160	0	Ideal case Irreversibility = zero
Machine & Spot Air Cooling	120	9	49
Spot Air Cooling	103	70	127

If it is assumed that a cooling medium is available at an environmental temperature of 20°C (68°F), and capable of providing cooling at temperatures and thermal capacities matching exactly those of the composite curves, then the following results can be deduced.

The calculated exergetic input (mechanical cooling) values indicted in Table 4., represents the amount of exergy/work required to perform cooling at a temperature below that of the environment. This is the result of heat being transferred into the cooling system below the zeroth exergetic temperature ($\tau \leq 0$). The derived exergy output of the cooling systems represents their potential work output, associated with heat being transfer to the cooling medium above the environmental temperature. Theoretically, this work could be generated using a reversible heat recovery engine operating between the cooling stream temperature and the environmental temperature. However, in practice no heat engine is efficient enough to convert this exergy to useful work over the calculated temperature range. Consequently, this exergy output better represents the available free cooling of the cooling stream at the environment state.

To compare the different cooling strategies in terms of the exergy, then the concept of irreversibility is used, where irreversibility represents the destruction and loss of exergy within a defined system. In the current analysis the minimum cooling strategy has been denoted as the ideal system, with the mine's maximum exergetic output from a cooling system calculated to be 160kW (214.5hp), and its minimum exergy input of 0kW. Therefore, the irreversibility of a cooling strategy may be represented as the sum of the increase in exergy input (mechanical cooling), and decrease in exergy output (free cooling) as compared to the ideal case, see table 4.

Although an exergetic efficiency has not been defined for the various cooling strategies, differences in their performances may be deduced from a comparison of their determined irrevesibilities. However, unlike the effective efficiency derived earlier, the irreversibility represents both the differences in the quantity of the energy transfers taking place and also the temperature at which they occur, i.e. the quality of the energy transfer. Thus, a combined exergy and composite τ - *cooling load* curves analysis provides a more realistic measure of the efficiency of a mine cooling system.

DISCUSSION

An examination of the results provided by an application of composite curves and exergy analysis has established a method by which a measure of the true efficiency of a cooling system may be determined. The predicted efficiencies of the cooling strategies tested represent the departure of their performance from that determined for the minimum cooling strategy. The calculated performances principally highlight the effect of an increasing cooling load with a decrease in cooling temperature, as the application of the cooling methods become more remote from the heat sources. Thus, this analytical method enables any changes in a cooling strategies efficiency to be quantified, using a 2nd law analysis.

The difference predicted between the thermal efficiencies of the combined machine and spot air cooling, and spot air cooling strategies is determined to be 4%. This small difference obtained by a 1st law analysis infers that there is little practical advantage in the provision of machine cooling. However, when the exergetic irreversibility of the two systems are compared, there is a marked difference in the their predicted performance. This is due to the inclusion of the applied cooling temperature parameters within the exergetic calculations. Therefore, this approach has highlighted the improved thermodynamic performance that may be obtained from an application of a combined machine and spot air cooling as compared to a sole spot air cooling system.

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REFERENCES

Moran, M., and Shapiro, H.N. (1995), "*Fundamentals of Engineering Thermodynamics*," John Wiley & Sons, United States.

McGovern, J.A., (1990), "*Exergy analysis - a different perspective on energy Part 1: the concept of exergy*," J. of Power and Energy, 204, pp. 253-262.

Kotas, T.J., (1995), "*The Exergy Method of Thermal Plant Analysis*," Krieger, London.

Tuck, M.A., Stokes, M.R., and Lowndes, I.S., (1997), "*Mine Climate Control Options in Underground Working Zones.*" Final Report on ECSC Research Project No. 7220 -AC / 006.