The application of exergy analysis to the cooling of a deep UK colliery

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Synopsis

The extraction of minerals and coal at greater depth, employing higher-powered machinery to improve production levels, imposes an increased burden on the ability of a ventilation system to maintain an acceptable mine climate. Hence, mechanical mine cooling systems are often adopted, which can be expensive in terms of both their associated capital and operating costs. Consequently, in order to optimize the total mining costs, it is essential to provide the mine operator with a method with which to determine the most cost effective and efficient mine cooling system.

In a previous paper[1] a novel energy analysis employing the concept of *exergy* was proposed and applied to cooling systems applied to two conceptual model mines, representative of UK deep coal operations, and their resultant subsurface thermal environmental conditions predicted. This paper presents an analysis of the results obtained from the application of this novel technique to assess the performance of various cooling systems applied to a current UK colliery that is experiencing climatic problems due to its depth and highly mechanized production and development workings. To perform this analysis, ventilation and climatic data collected at the case study mine were used to construct balanced mine ventilation and climatic network models to replicate the subsurface environment. Where air conditions exceeded specified climatic limits within identified climatically control zones, mechanical mine cooling systems were employed. A number of cooling system configurations were applied to these model to investigate the potential to satisfactorily regulate the thermal environment. The heat energy transferred out of the air stream by the various cooling methods was absorbed using a variety of chilled water systems, which were designed to operate at various water flow rates and temperatures. Models of various cooling system were developed and applied to control the underground climate within this mine network to within pre-set climatic limits.

The results of a comparative analysis of the energy transfers that were produced by the application of the different cooling systems are presented in the form of exergy performance indices. The results produced by simulation models constructed to represent chilled water distribution networks to supply the various air coolers, are designed and balanced. The results of the exergy analyses applied to the operation of the various chilled water pipe networks are discussed and used to assess the exergetic performance of the application of each proposed cooling system to the mine ventilation network.

Introduction

As mineral extraction becomes deeper with increased levels of mechanization and higher production rates, the mechanical cooling systems used to maintain an acceptable underground climate become increasingly complex and expensive. To ensure 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.

The climatic conditions that exist within an underground mine ventilation 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 analyse the various cooling methods it was necessary to develop a representative model that could encompass the factors that influence the energy transfers between the ventilation air and a mine cooling system.

A commercial ventilation network solver Vnetpc™[2] was used to replicate the volumetric airflow rates and pressure distributions that were measured around the network. Using the data from the balanced network, the thermal climate existing within the mine was modelled using a commercial mine climate code Climsim™[3]. The simulations performed using this thermal model provided the data required to conduct the exergy analyses to assess the performance of the various mine cooling system configurations investigated.

Although the UK, currently, has no specific statutory regulations that quantify the level of an acceptable underground working climate, a

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mine manager is legally bound to provide a safe and adequate environment for employees within underground workings (1974 Health and Safety at Work Act). Therefore, UK underground coalmines have developed a range of local operational climatic limits based upon those enshrined in German mining law[4].

To date, the remediation of climatic problems in UK coalmines has seen the development of ventilation rather than mechanical cooling solutions. However, as minerals are extracted at increasing depth and employing higher levels of mechanization, the practicalities and economics of employing a ventilation-only solution becomes prohibitive. The cooling strategy adopted by this study was guided by the methodology, practice and experience of the German deep hard coalmines.

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 coalmines, highly productive and mechanized longwall coalfaces are the predominant mining method[5]. These operations are conducted at depths of up to 1,400 m, 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. These environmentally regulated areas are termed climate controlled zones (CCZ). Each CCZ is designed to encompass the production zones in which the major work activity takes place.

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

Exergy analysis

Thermal exergy analysis[6] examines the energy flows within a thermal system. Unlike traditional energy analyses, the concept of exergy analysis combines both the first and second law of thermodynamics. Thus, exergy recognizes that energy not only has quantity but also quality. Consequently, different forms of energy can be compared directly using their exergetic values. The key to exergy analysis though is that, unlike energy, exergy can not only be transferred but also destroyed. Therefore, the total exergy of a system changes when it undergoes a real process due to exergy transfer and destruction. The parameter that quantifies the destruction of exergy is *irreversibility*. Thus, through a combination of evaluated exergy transfers and irreversibilities, the performance of thermal systems may be assessed and optimized. This degradation of energy, represented by an increase in entropy, is equivalent to the irretrievable loss of exergy due to all real processes being irreversible. McGovern[7] defines exergy as the maximum useful work that could be produced by the interaction of a system with a specific reference environment

From this definition, exergy could be termed as the measured departure of the state of the system from its reference environment. Hence, exergy 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. Once the state of the system and the condition of its reference environment are known, a numerical value of exergy may be determined.

To perform an exergy analysis of a mine cooling system, the reference environment may reasonably be considered to be the conditions of the surface atmosphere of the mine and may be regarded as being in a perfect state of equilibrium as described above. The average ambient surface dry bulb air temperature T_0 and atmospheric pressure P_0 may reasonably be assumed to be the typical atmospheric conditions of the environment.

The mechanical cooling of the case study mine

A comparative analysis was performed on the predicted mine climate produced when the following cooling methods were applied to the model mine network: theoretical minimum cooling, standard spot air-cooling, combined machine and spot air-cooling, restricted temperature spot cooling (RT), and restricted temperature and volume cooling (RTV). Each cooling method was applied to the model mine to regulate the climate within the designated CCZs such that the ET limit of 28°C was not exceeded.

- *Theoretical minimum cooling*—the determination of a theoretical minimum cooling for a given mine establishes a benchmark with which the results produced by other cooling methods may be compared. The theoretical minimum cooling is that required to obtain a specified climatic condition by the most efficient thermodynamic means. This method involves the evaluation of the rate at which any excess heat load is to be removed from the air in order to maintain an ET of 28°C within each CCZ. The method of minimum cooling first employs standard spot air-cooling (see below) at the entrance to the CCZ, to lower its ET to 28°C. If required, an additional incremental linear cooling system may be 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 fully practicable, the system may be theoretically visualized as a series of infinitely large passive cooling panels operating with no temperature difference.
- *Standard spot air-cooling*—spot air-coolers are located at the entrances to the CCZs. Each cooler lowers the ET of the airflow below the required 28°C ET limit. The ET to which the air is cooled is set so as to ensure that only on exiting the CCZ will the airflow's ET be equal to the 28°C ET limit.
- *Combined machine and spot air-cooling*—where all or part of a machine's heat load may be defined as a spot heat source, the cooling method 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. If the ET within a CCZ remains above 28°C after machine heat has been removed, then standard spot air-cooling is applied to the inlet air of the CCZ. When air-cooling is required in the development, a spot air-cooler is

placed in the auxiliary forcing duct ventilating the development. It is assumed, with all three cooling methods employed, that the total volumetric airflow is cooled.

- *Restricted temperature spot cooling* (RT)—the RT cooling method employs the same techniques used in the Standard spot air cooling method, but restricts the cooler exit air temperature to a minimum of 20°C dry-bulb. This minimum exit air temperature is applied since at lower exit temperatures miners working in close proximity to the cooler may suffer from thermal stress.
- *Restricted temperature and volume cooling* (RTV)—the RTV cooling method represents the typical air cooling technique employed in the German deep coal mining industry. As in the case of the RT cooling method, coolers have a restricted exit temperature of 20°C dry-bulb. However, rather than bulk cooling the airflow entering a working, the quantity of ventilating air cooled by each cooler is also restricted.

Analysis of the results

In a previous study[1] it was demonstrated that the amount of cooling capacity required on each district increases from the lowest duty, on the application of the minimum cooling method, up to the highest duty on the application of the standard spot air-cooling method.

If it is assumed that the minimum predicted cooling requirement is achieved on the application of the minimum cooling method, this minimum value may be set as a datum against which the performance of alternative cooling methods can be compared. The parameter of *effective efficiency* has been devised and used to describe the performance of these various cooling methods:

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

Thus, an increase in cooling duty required by the different methods is identified as a decrease in the effective efficiency. The decrease in effective efficiency associated with the increasing cooling loads is the result of the positional effectiveness of the particular cooling method.

In applying the effective efficiency, the quantity of heat energy being removed by the cooling method is accounted for. However, no measure is made as to the quality of the heat energy being removed. To obtain a better understanding of the heat transfer that takes place under the individual cooling methods, the concepts of thermal exergy analysis are employed. Exergy analysis seeks to establish the potential work input and output of a cooling method and thus evaluate its true performance.

Initial exergy analysis of the employed cooling methods

In the following section the application of each cooling method is examined in terms of exergy transfers, and performance criteria are established. To assist in the exergy analyses, composite cooling curves were developed for each cooling method employed. These curves were initially employed to give a visual representation of the temperature range over which the heat load is removed by the cooling method. The curves were then used as the basis to derive the exergy diagrams used in an exergy analysis of the cooling methods.

Exergetic composite cooling curves

Each composite cooling curve was constructed from the predicted thermal data obtained on the application of each cooling method to the model mine network. The technique involved combining the cooling duties determined for each CCZ sequentially over their common temperature ranges.

To determine the exergetic values of the cooling methods, the composite cooling curves can be represented on an exergetic temperature cooling load diagram, Figure 1, where τ, represents dimensionless exergetic temperature defined as[6]:

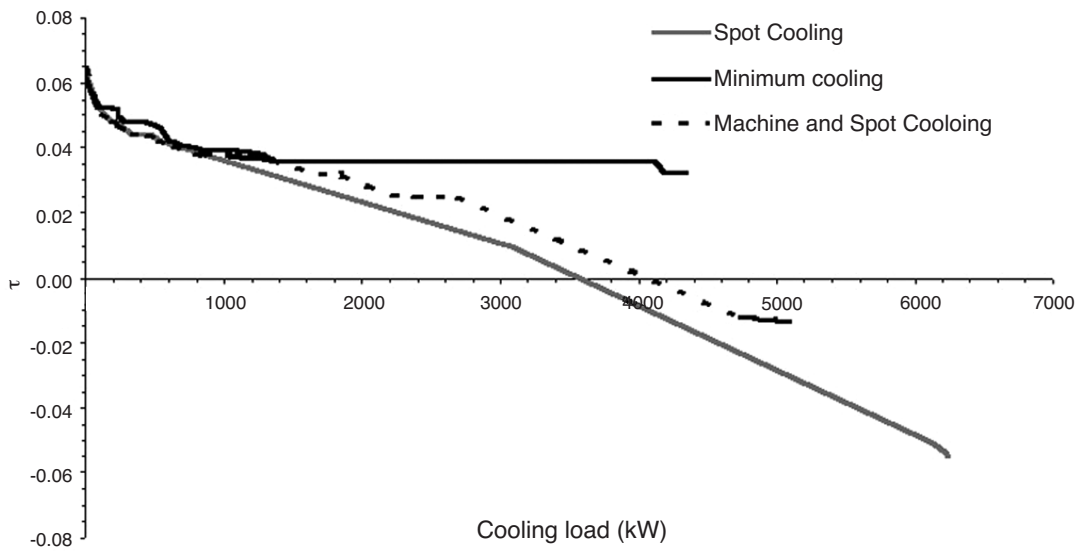


Figure 1—Exergetic temperature cooling load diagram

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

In the study, the conditions of the environmental state were set at the psychrometric conditions of the model mine's surface downcast air: 20°C dry bulb, 17°C wet bulb and a pressure of 101 kPa. Therefore, T_O is equal to 20°C.

The area bound between the x-axis and an exergetic composite curve, represents the exergy transfers associated with each cooling method. Thus, the exergy transfer values of the cooling methods can be determined by an integration of their respective curves. The analysis of the application of the three proposed methods to the cooling of a typical working district is illustrated in Figure 1.

To assist in the interpretation of Figure 1, the following scenario has been devised. If it is assumed that a cooling medium is available at an environmental temperature of 20°C, which is capable of providing cooling at temperatures and thermal capacities matching those of the exergetic curves, then the following results can be deduced. The exergy input (mechanical cooling) values, determined from an integration of the area under the curves in Figure 1, represent the amount of exergy/work required to conduct cooling at a temperature below that of the environment, 20°C dry-bulb. This is the result of heat being transferred into the cooling system below the environmental temperature ($\tau<0$). Although cooling at $\tau<0$ is represented here as an exergy input, in true exergy terms it would be an exergy output, provided a reversible heat engine could operate between the environmental temperature and the cooling stream at this lower temperature. However, in order to supply this cooling medium, work in the form of mechanical cooling would initially be supplied to lower a cooling medium to its initial start temperature of less than 20°C. Hence, cooling below $\tau<0$ can represent the exergy input of the mechanical cooling.

The derived exergy output of the cooling methods represents their potential work output, associated with heat being transferred to the cooling medium above the environmental temperature. Theoretically, work could be generated from this heat transfer using a reversible heat engine operating between the cooling stream temperature and the environmental temperature. However, in reality no heat engine is efficient enough to convert this exergy to useful work over the calculated temperature range. Instead the exergy output better represents the available free cooling of the cooling stream at the environmental state.

In order to compare the performance of the various cooling methods in exergy terms, the definition of an ideal cooling method is proposed. As in the definition of effective efficiency, the minimum cooling method is chosen. This represents the lowest cooling load at the highest average heat removal temperature.

Thus a measure of the degree to which an alternative cooling method tends to the ideal requires its exergy values to converge towards those of the minimum cooling method. Attempts were made to establish a suitable traditional measure of the exergetic efficiency to describe the performance of the cooling methods. However, it was not possible to define one. Instead the index of Potential Exergy Loss (PEL) was developed as a performance indicator for a cooling method applied to a mine.

Exergy transfers have been defined as being positive for exergy output and negative for exergy input. The PEL of alternative cooling methods compared to their ideal can then be determined using the following equation:

$$PEL = \sum \begin{matrix} \textit{ideal cooling method} \\ \textit{exergy transfer} \end{matrix} - \sum \begin{matrix} \textit{cooling method} \\ \textit{exergy transfer} \end{matrix}$$

In applying a thermal exergy analysis and formulating the PEL index, the true energy transfers in terms of both their quantity and quality may be assessed. Thus, it provides guidance to the performance of the alternative cooling methods as compared to an ideal.

Since the minimum cooling method represents the ideal case, it is considered to have zero PEL. Therefore, the smaller the PEL of an alternative cooling method the higher is its performance level. Thus, combined machine and spot air-cooling outperforms standard spot air-cooling. Ultimately, the value of the PEL could be assigned an economic value, which could be used to justify the use of a more expensive cooling method but with a much lower operating cost.

Having examined the exergy transfers of the cooling method, the study then investigates the irreversibility involved when heat energy, removed from the air stream, is transferred into a cooling system.

Application of exergy analysis to the case study mine cooling system

Although the combined machine and spot air-cooling method was shown to outperform the standard spot air-cooling method, the standard spot air-cooling method was chosen as the preferred heat removal regime on which to examine the exergy destruction. This was because the standard spot air-cooling method best represents current German cooling practice.

In order to absorb heat being removed by the standard spot air-cooling method, various cooling systems were investigated. Initially the concept of an *ideal thermodynamic cooling system* was developed and subsequently defined as: a coolant stream that follows the path of a mine's chosen cooling method's composite cooling curve exactly, matching both its temperature profile and thermal capacity. As with the previous analyses, the ideal thermodynamic cooling system determines a datum against which the relative performance of other cooling systems can be compared. It establishes the limits of a cooling system's exergy transfers when operated in an ideal manner.

An ideal thermodynamic cooling system can be visualized as an infinite number of coolers and pipes sequenced to absorb heat from the air stream in the most efficient thermodynamic manner.

Two specific 'ideal' systems were subsequently developed employing the concept of a minimum approach temperature (MAT), which defines the minimum temperature difference between the cooling stream and the air stream that must not be transgressed at any point through the cooling process.

- *Ideal series cooling system*—employs a single coolant stream, which flows at a constant mass flow rate and is capable of following a mine composite cooling curve, without contravening the imposed MAT, Figure 2.

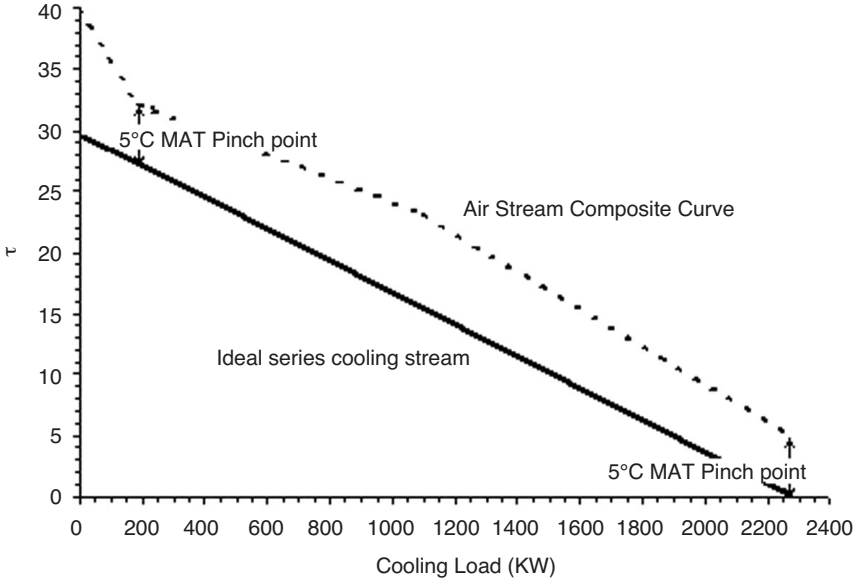


Figure 2—Ideal series cooling system

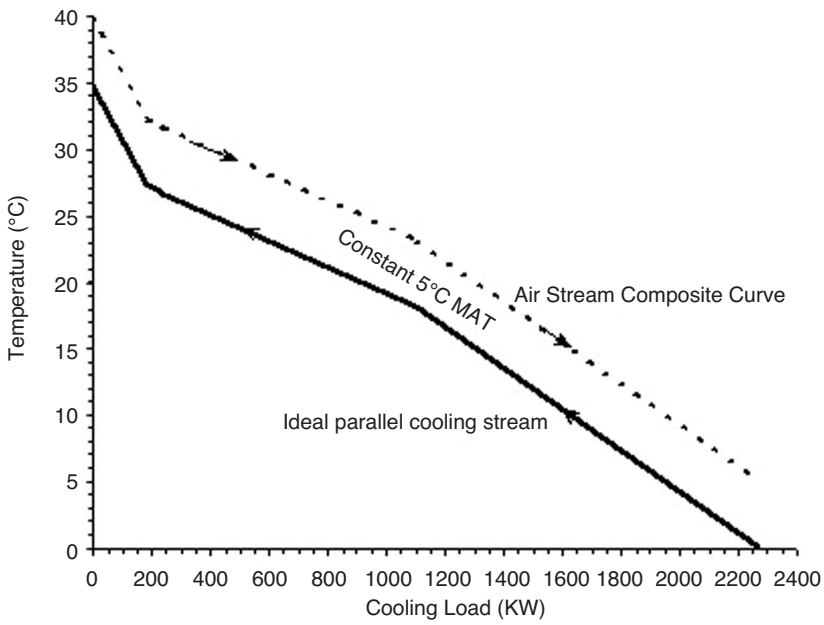


Figure 3—Ideal parallel cooling system

- *Ideal parallel cooling system*—employs numerous parallel coolant streams, which can possess variable thermal capacities in order to maintain a temperature difference, equal to the MAT, between themselves and the defined mine composite cooling curve, Figure 3.

These ideal model systems provide a benchmark against which the performance of practical systems may be compared, with the introduction of a temperature differential, allowing heat transfer to take place without the conceptual use of infinitely large heat exchangers. Thus, the evaluated thermal irreversibility (exergy destroyed) resulting from heat transfer between the ideal thermodynamic system and the ideal series and parallel systems, represents the intrinsic irreversibility (unavoidable irreversibility) of a cooling system when it operates in an ideal manner under optimum thermodynamic design conditions.

Using the concept of thermal irreversibility, where the ideal thermodynamic system represents zero irreversibility, it can be demonstrated that the application of the ideal parallel system has a lower thermal irreversibility than the ideal series system. This occurs because the temperature difference between streams is always equal to MAT in parallel circuits, whereas it is always ≥ MAT in a series circuit, with decreasing irreversibility associated with diminishing temperature differences between streams.

The exergy transfers were then determined for a number of practical cooling systems that employ series and parallel cooling distribution networks. A practical cooling system differs from the ideal system by using a finite number of coolers, each fed by a single coolant stream.

Background: Maltby colliery

Maltby colliery is situated in South Yorkshire, 12 km east of Rotherham (Figure 4) and is owned and operated by UK Coal Ltd (Figure 4).

The mine was opened in 1911, since when it has worked a number of seams. The mine infrastructure was reconfigured in the 1980s to exploit the Parkgate seam Figure 5. Access to the workings is via shafts, two downcast air shafts No. 1 and 2 and a single upcast airshaft No. 3. The first longwall coalface that operated in the Parkgate seam, was an advancing unit, which was worked from April 1992 to May 1993. Since then development for retreat longwall faces has been undertaken. Currently Maltby operates a single retreating longwall production face, which has a average projected working life of approximately 12 months. Concurrent access road development is taking place to provide successive longwall face capacity as required. Coal at present is being extracted from T05 retreat longwall panel at an average rate of 5000 tons/day. The coalface is 300 m long with a seam height of 1.4 m. Development is principally in T16 maingate, where an advance of approximately 15 m/day is maintained.

In a recent UK government Department of Trade and Industry report[8], conducted by International Mining Consultants Ltd., Maltby colliery was identified as being able to play a role in the future of deep mining in the UK. However, it was concluded that some future action would be required to remedy its current climate problems with a view to increasing its production rate. Hence, Maltby mine has been chosen for the following mine cooling investigation.

To perform this feasibility study, the ventilation and engineering staff from Maltby Colliery supplied recent ventilation and climatic survey data and mining systems operational data.

The climatic prediction of the underground environment at Maltby colliery

The airflow rates within the main roadways (gateroads, the longwall face and developments) were determined from a series of ventilation and climatic surveys conducted at the colliery. This survey data was subsequently used to produce balanced ventilation and climatic network models representative of the environmental conditions currently experienced within the colliery. A simplified ventilation network for Maltby colliery is shown in Figure 6. The main working TO5's longwall face is supplied with 39.1 m^3/s of air, whilst 7.2 m^3/s of air is supplied to the T16 development heading.

The nominal and actual drawn electrical power for the electrical machinery installed within the working district, development and main conveyor roadways were determined from an analysis of actual electrical power draw records held by the colliery engineering staff. Details of the location and nominal power ratings of the electrical equipment are given in Figure 7 and Figure 8.

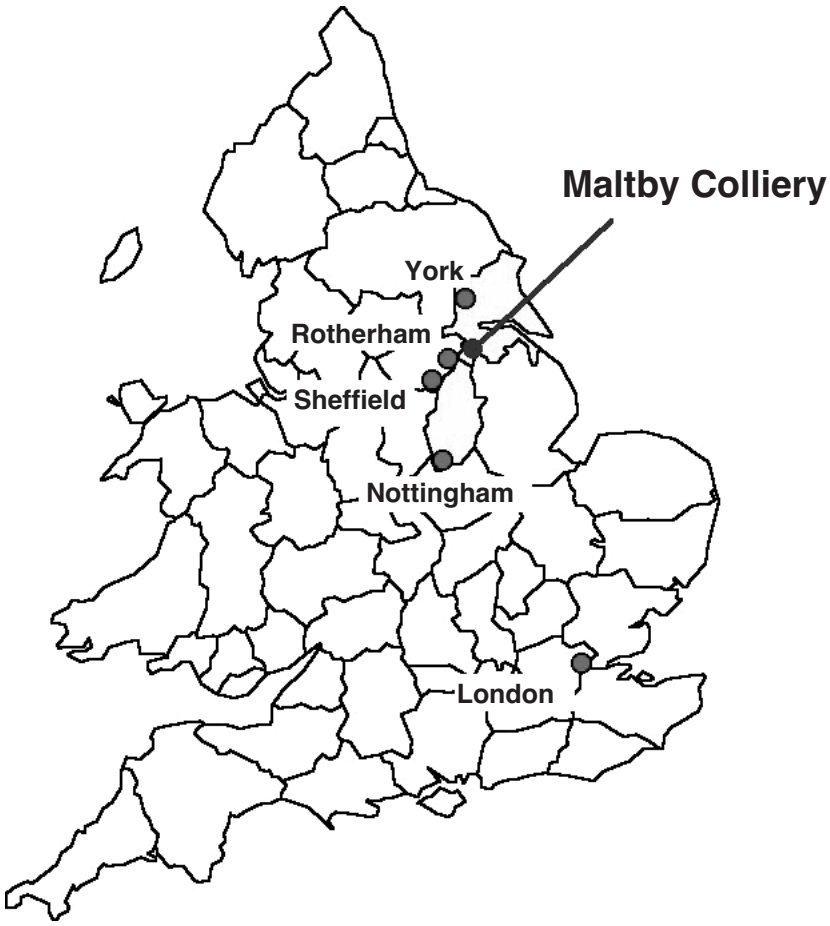


Figure 4—Location of Maltby colliery

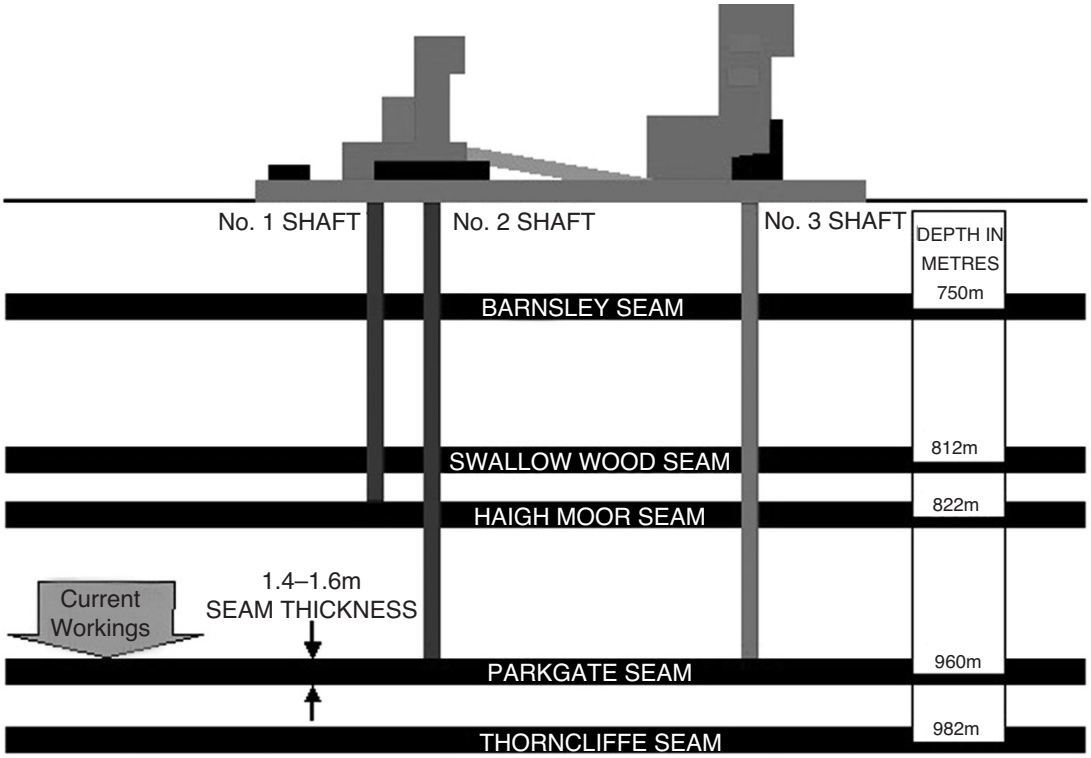


Figure 5—Maltby colliery Pargate seam

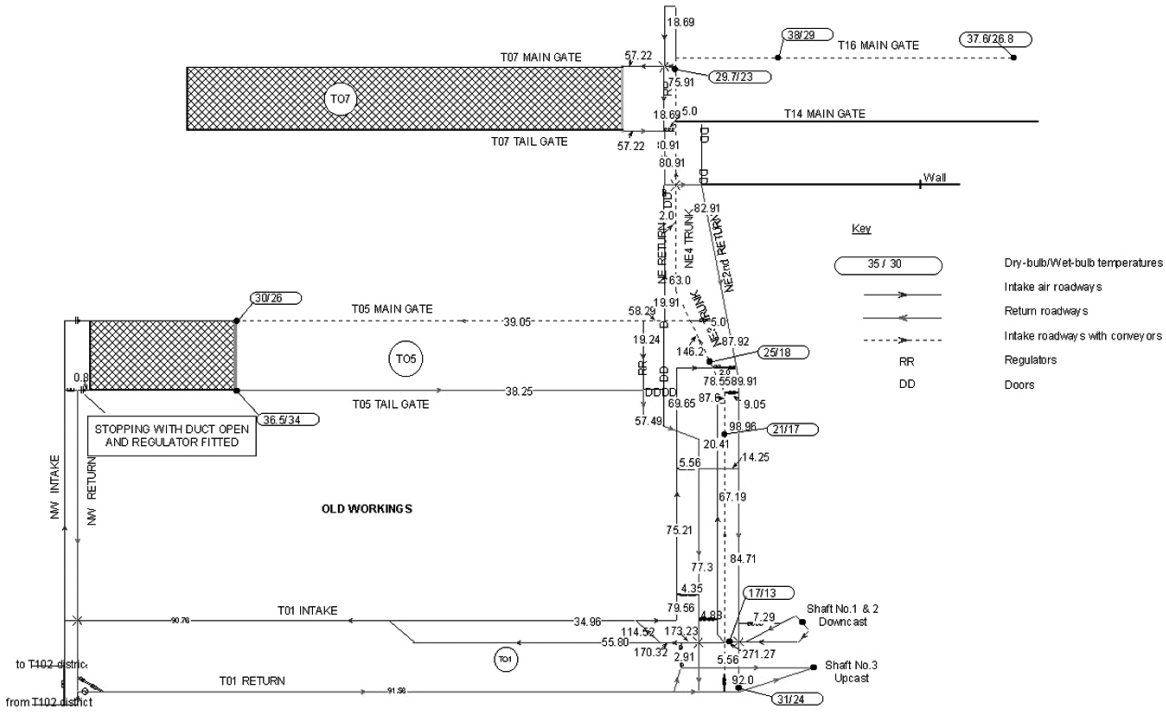
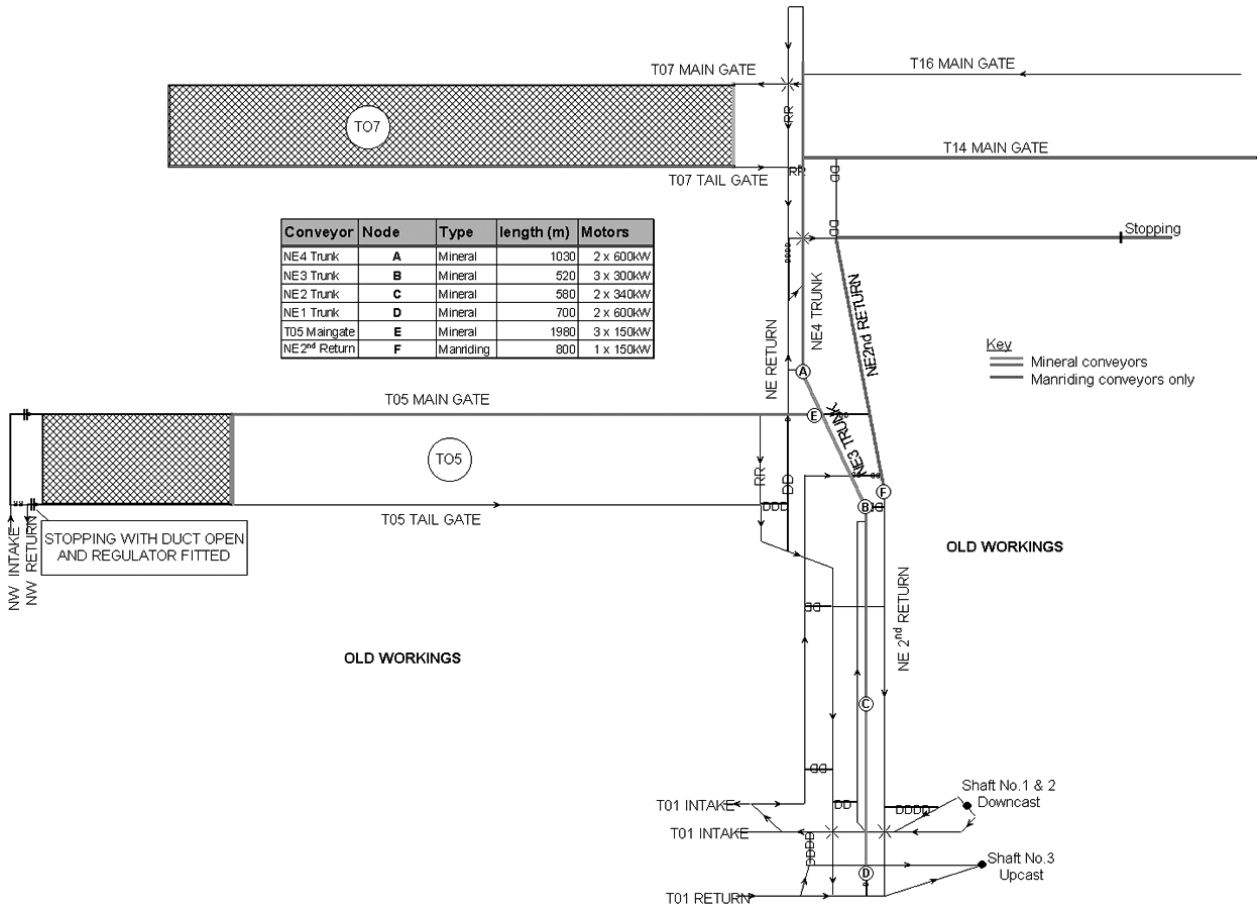


Figure 6—Simplified ventilation network for Maltby colliery

The thermal environment of the Maltby mine was modelled using the mine climate simulation package, Climsim™3; the model predictions were validated against the measured climatic conditions. Following an analysis of the underground climatic survey data and the recorded power draw and utilization rates of the electrical equipment, it was concluded that the heat load contributed by the various electrical machines lay between 30–60% of the nominal installed power. The climatic simulations produced by the various climatic models were validated against those measured underground. The presence of service and surface water can severely affect the climatic conditions within mine



Conveyor	Node	Type	length (m)	Motors
NE4 Trunk	A	Mineral	1030	2 x 600kW
NE3 Trunk	B	Mineral	520	3 x 300kW
NE2 Trunk	C	Mineral	580	2 x 340kW
NE1 Trunk	D	Mineral	700	2 x 600kW
T05 Maingate	E	Mineral	1980	3 x 150kW
NE2nd Return	F	Manriding	800	1 x 150kW

Figure 7—Location and nominal power ratings of electrical equipment

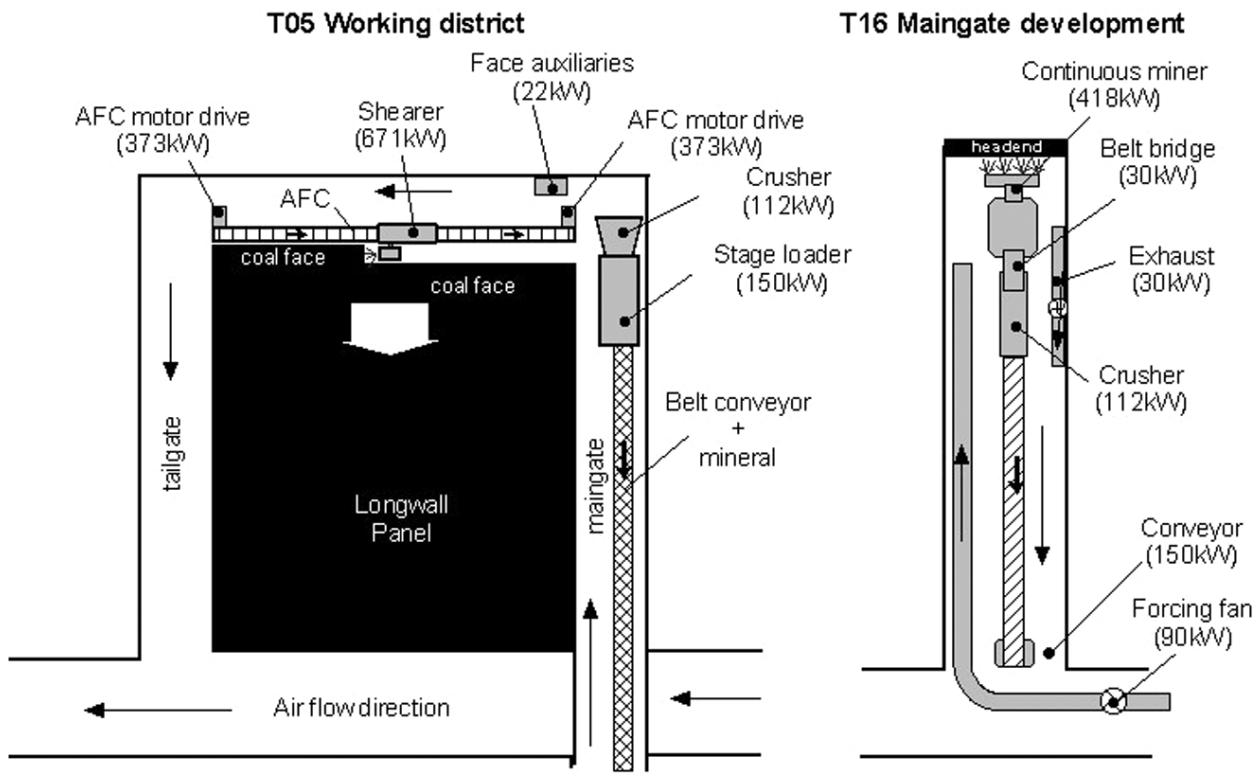


Figure 8

workings. By employing known water spray consumption levels, a series of sensitivity analyses were performed to identify the values of the wetness factors to simulate the psychometric conditions measured underground.

Table I gives a comparison between the measured and the predicted climate data. The slight variations between the measured and predicted values occur due to the complexities of the environment and the modelling assumptions made. The largest deviation occurs inbye (upstream) of the T05 tailgate, where the ventilation air exits the longwall face. However, the predicted temperatures were all within 5% of the measured data.

Imposed climatic regulation

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 coalmines, highly productive and mechanized longwall coalfaces are the predominant mining method. These operations are conducted at depths of up to 1,400 m, 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. These environmentally regulated areas are termed climate controlled zones (CCZ). Each CCZ is designed to encompass the production zones in which the major work activity takes place.

The Effective Temperature (ET) heat stress index[4] was initially 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. An ET of 28°C was set as the upper climatic design limit within the CCZs. Where the climatic conditions of the air exceed this limit within the CCZ, a range of mechanical cooling methods are employed to regulate the climate.

For the case of the Maltby colliery ventilation network, the CCZs were specified within the T16's development and the T05's maingate, longwall face and tailgate, Figure 9. Table II below details the predicted entrance and exit air conditions of the imposed CCZ.

Table I

Measured and predicted climatic data

Location	Details	Measured temperature		Predicted temperature	
		DB °C	WB °C	DB °C	WB °C
T1	Inbye windy city	17.0	12.5	17.0	12.5
T2	NE3 trunk road	25.0	18.0	25.3	17.9
T3	NE4 trunk road	29.7	23.0	29.6	23.2
T4	T16 inbye, behind continuous miner	37.6	26.8	37.4	26.6
T5	Outbye T16	37.7	29.6	37.5	29.6
T6	Inbye TO5 maingate	30.0	26.0	30.0	26.0
T7	Inbye TO5 tailgate	37.0	35.0	38.5	34.8

Table II

Climate control zone predicted environments without thermal regulation

CCZ	Entrance conditions			Exit conditions		
	DB °C	WB °C	ET °C	DB °C	WB °C	ET °C
T16 development	29.60	23.15	23.34	37.42	26.59	29.80
TO5 maingate	27.25	24.79	18.80	30.02	26.02	22.18
TO5 face	30.02	26.02	21.89	38.49	34.79	34.62
TO5 tailgate	38.49	34.79	34.76	38.45	34.79	34.74

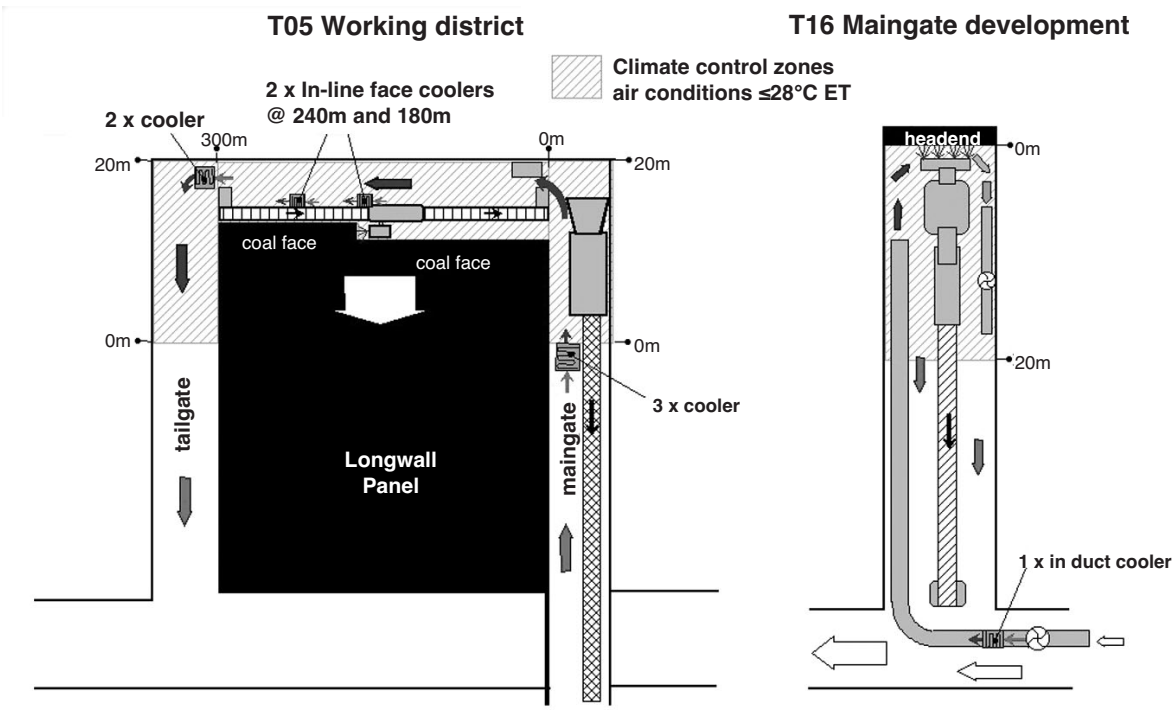


Figure 9—Climate control zone of Maltby collieiry ventilation network

From an examination of the data it can be seen that for the modelled operational conditions, the 28°C ET limit is exceeded in the T16's development and the T05's longwall face and tailgate. Therefore, to maintain acceptable climatic conditions, some form of climate control strategy is required. In this study, it is assumed that the ventilation quantities of the network are optimal and that all applicable heat source control measures are utilized. Therefore, to control the thermal climate requires the application of mechanical mine cooling systems.

The cooling of Maltby Colliery

The modelled Maltby mine network was first cooled by the application of the minimum cooling method. The results obtained from this simulation established the minimum cooling duty required to satisfy the airstreams flowing through the CCZs. This data also establishes a datum by which the performance of alternative cooling methods may be compared. The CCZs of the mine were then regulated using the RTV cooling method. This method was identified as the most representative cooling technique currently used by the German deep coalmining industry. Rather than bulk cooling the total airflow in an airway, these coolers cool a fraction of the airflow (typically 8 m^3/s) with the conditioned air then being introduced back into the main airstream before it can undergo further cooling. The coolers have a restricted exit temperature of 20°C dry-bulb. This method allows for the incremental cooling of the air by a series of inline cooling machines.

Although from the climatic analysis the maingate CCZ does not require cooling, due to the limited available clearance space at the face end of the maingate, spot coolers were placed at its entrance in order to cool the air that will subsequently flow through the CCZ defined across the longwall face. The range of cooler types employed to cool the Maltby colliery network using the RTV configuration are given in Table III. The numbers of gateroad coolers were restricted to three, due to the limited amount of available space within these roadways.

Cooling results and analysis

On the application of the RTV cooling method, three coolers were located at the entrance to the maingates CCZ. The coolers lowered the air temperature to the minimum allowable cooler exit temperature that was specified as 20°C dry-bulb. A modified form of the RTV version was subsequently used to cool the mine. This method does not attempt to cool the final 10 m section within the face using in-face installed coolers. To maintain the climate within the longwall CCZ to below 28°C it was determined that two inline face cooler units were required within the face line, followed by two gateroad coolers installed inbye of T05's tailgate, to cool the tailgate CCZ. The general layout of the RTV cooling methods for the Maltby working districts is illustrated in Figure 9.

A summary of the cooling duties required under both the minimum and RTV cooling methods are given in Table IV.

Composite cooling curves were constructed for the two cooling methods and are illustrated in Figure 10. On examination of the curves, it is noted that the RTV cooling method removes some heat at a higher temperature than the minimum cooling. This occurs because on the application of the RTV cooling method, the air in the last 10 m section of the face is uncontrolled. Hence, the temperature of the air increases rapidly due to the heat produced by the shearer and the leakage of hot, moist air from the goaf. Consequently the coolers located in the tailgate have to cool the air at a higher temperature. This situation does not occur on the application of the minimum cooling method as the condition of the air is controlled along the entire length of the longwall face CCZ.

As with the analysis of previous cooling methods, exergetic composite cooling curves were constructed and the exergy transfers of the two cooling methods evaluated (Table V).

As can be seen from Table V, all the heat transfer takes place at exergetic temperatures above the environmental reference temperature, $\tau > 0$. However, unlike any of the previous cooling methods applied to the representative model mines, the RTV cooling method operating under the simulated Maltby colliery conditions results in an exergy output higher than that produced by the minimum cooling method. Consequently, this creates a problem in the assessment of its performance. As the minimum cooling method is considered as the ideal case, the evaluated *Potential Exergy Loss* (PEL) value is negative on the application of the RTV cooling method to the Maltby mine network. However, the definition of the PEL index specifies that a zero value be considered as a measure of the ideal case, with increasing positive values indicating the degree by which an applied cooling method deviated from the ideal. However, it was assumed that the minimum cooling method,

Table III

Indirect cooler operational data used to cool Maltby colliery network

Indirect cooler type	Air volume flow rate range (m^3/s)	Cooling water flow rate range (ℓ/s)	Cooling capacity range (kW)
Gateroad cooler	6–8 per cooler	4.67–8.33	150–350
In-line face cooler	2.60	2.78	15–50

Table IV

Summary of Maltby cooling method results

Cooling method	T16 development cooling (kW)	T05 maingate cooling (kW)	T05 longwall face cooling (kW)	T05 tailgate cooling (kW)	Total mine cooling (kW)
Minimum	20.5	0.0	735.0	0.0	757.5
RTV	30.0	486.0	80.0	420.0	1016.0

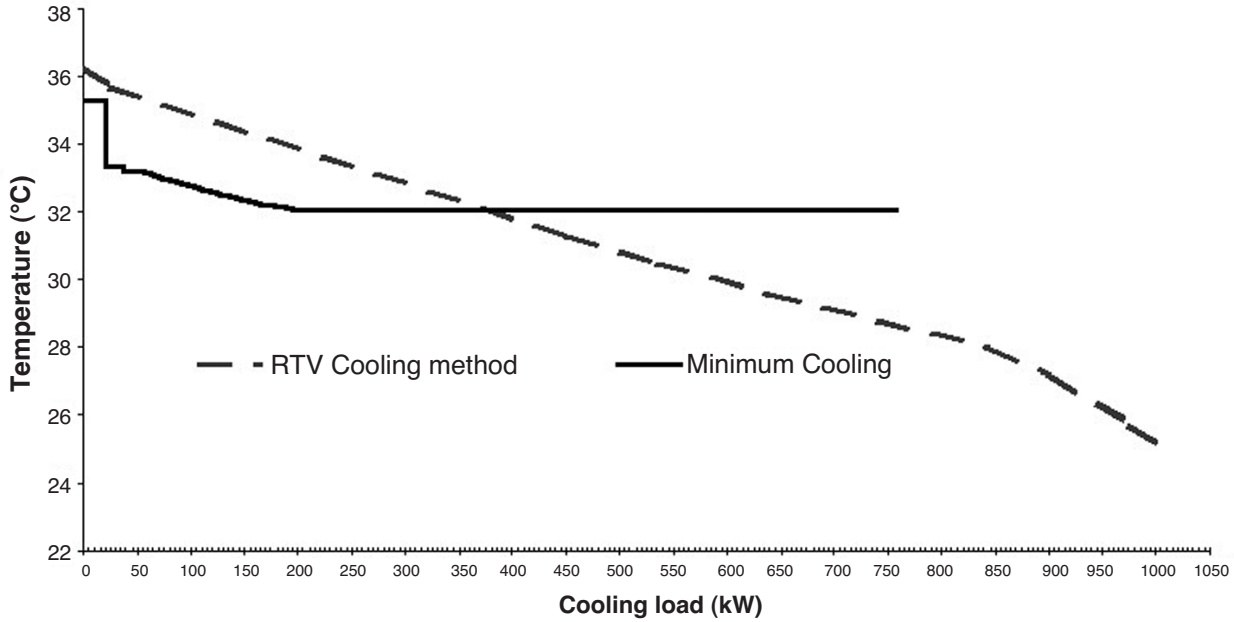


Figure 10—Composite cooling curves for minimum and RTV cooling methods

Table V

Cooling method exergy transfers and performance indicators

Cooling method	Exergy input τ<0 (kW)	Exergy output τ>0 (kW)	PEL (kW)	Exergetic cooling ratio
Minimum	0.0	30.4	ZERO	0.0402
RTV	0.0	35.0	-4.62	0.0345

the ideal, would always have the largest exergy output. This is not the case in the current investigation.

Although the application of the PEL performance indicator is invalid, the RTV cooling method performance can still be assessed using the *exergetic cooling ratio*,

$$Exergetic\ cooling\ ratio = \frac{\left(\begin{matrix} Exergy\ Output - \\ Exergy\ Input \end{matrix}\right)}{Cooling\ duty}$$

The use of the exergetic cooling ratio ensures that the effect of the cooling load size is taken into account. Consequently, the performance of a cooling method can now be compared to the ideal cooling ratio value. In the current investigation the minimum cooling method transferred 0.0402 kW of exergy to every kilowatt of cooling, whereas the RTV cooling method only transfers 0.0345 kW exergy to every kilowatt of cooling. Hence, the minimum cooling strategy, the ideal, is transferring a higher quality of heat energy.

Parallel distribution cooling systems

Having applied the RTV cooling method as a practical solution to control the Maltby mine thermal environment, models of chilled water distribution systems to absorb the heat energy being removed from the air were then developed. As was concluded from the previous studies, parallel-distributed cooling systems generally provide the most practical and thermally efficient distribution networks. However, in order to assess the effectiveness of a parallel cooling system, the concept of ideal parallel cooling was developed. This provides a datum by which the performance of practical parallel systems may be compared.

The development of the Maltby mine RTV ideal parallel cooling system

It is assumed that within any parallel cooling system an unavoidable amount of irreversibility occurs, often referred to as *intrinsic irreversibility*. The definition of an ideal system helps to quantify this irreversibility, which is a consequence of the temperature difference between the air and water required to drive the heat transfer. In the current study a 13°C MAT was applied.

Using Figure 11, the following results were determined from an application of an ideal parallel cooling system to the RTV exergetic cooling curve.

The bracketed figure in Table VI represents the irreversibility ratio for the ideal parallel cooling system, which is defined as the kilowatts of irreversibility per kilowatt of cooling.

Once the intrinsic irreversibility of the ideal parallel cooling system for the RTV cooling method is determined, a practical parallel cooling system may be developed and its irreversibilities compared to the ideal system.

Applied practical parallel cooling systems

Four parallel cooling system configurations were applied to absorb the heat from the RTV cooling method.

Three of these methods used a cooler supply water temperature of 3°C. This inlet temperature represents the

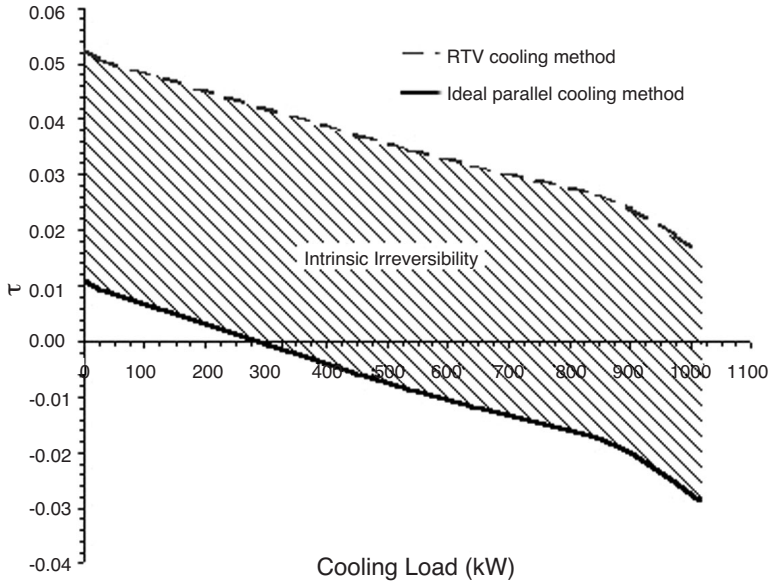


Figure 11—Intrinsic irreversibility

Table VI

Exergy transfer of the ideal parallel chilled water stream

	Exergy input τ<0 (kW)	Exergy output τ>0 (kW)	Unavoidable irreversibility (kW)
Ideal parallel cooling	1.5	8.7	37.6 (0.370)

typical temperature of chilled water supplied underground for cooling purposes. However, a further water supply temperature of 15°C has also been investigated. This represents a possible cooling water supply temperature that may be used directly from a surface reservoir, or pre-cooling tower. This has been included in the study in order to present an alternative cooling source.

Systems using two different flow rates have also been considered. Fixed flow rate systems employ coolers with known flow rates. The details of their operational performances may be found in Table VII. Calculated flow rates systems are those in which a cooler's flow rate is determined such that the temperature difference between its exiting chilled water and inlet air is at precisely at the MAT.

Water reuse is only possible for the case of a fixed flow at an inlet temperature of 3°C because water reuse in the other systems would result in the MAT being contravened.

Since each of the systems has an intrinsic amount of irreversibility, determined from the ideal parallel system, their performances may be judged by how closely their irreversibility value approximates the intrinsic value. Figure 12 illustrates the determined irreversibilities of the various parallel cooling systems, with their intrinsic irreversibility overlain.

The highest irreversibilities are observed for the 3°C fixed flow systems, 1M and 2M. The irreversibility determined for the 2M network is slightly lower as a consequence of the water from the face coolers being mixed with 3°C water and reused in the tailgate coolers. This reduces the average temperature difference over which heat transfer occurs in the tailgate coolers. With the variable flow systems, 3M and 4M, water flows rates are evaluated such that the water-air temperature difference matches the MAT on the exit of the water from the cooler. This reduces the average temperature difference between the two streams, thus lowering the irreversibility. This is more pronounced in the case of the 4M configuration, as a result of the higher water temperature supplied to the air coolers. A further effect seen for both the 3M and 4M configurations is that the cooling water in the tailgate coolers rises above T_0, 20°C. This results in the water, which initially loses exergy, gaining exergy when above $\tau > 0$.

As in the previous studies only the thermal irreversibility associated with the cooler heat transfer have been determined so far. Further exergy transfers and destruction within parallel cooling systems, related to the delivery of the chilled water around the pipe network, are now evaluated.

Chilled water distribution networks for Maltby colliery

Four chilled water distribution networks were developed to supply the modelled parallel cooling systems. The networks were designed and balanced using the commercial hydraulic network solver, Hydroflow™[9], and by a thermal energy balance. The pipe size ranges were restricted to those commonly used within the mining industry. For the networks 1M, 3M and 2M, pipe sizes were chosen from those available such that water velocities through the pipes are as close as possible to the optimum 2 m/s identified by Van Vuuren 10. For network 2M, its pipe sizes remain the same as those used for the 1M layout; this enables a comparison to be made should a system switch to water reuse without a resizing of the pipes.

Figure 13 shows the layout of the chilled water network(s) used to cool Maltby mine. Intake chilled water

Table VII

The practical cooling distribution systems investigated

Parallel system	Flow rates	Cooler inlet chilled water temp.	Chilled water reuse
1M	Fixed	3°c	×
2M	Fixed	3°C	✓
3M	Calculated	3°C/	×
4M	Calculated	15°c	×

pipes are located within the main intake airways, while the return warm water pipes are predominately positioned in the return airways. Both intake and return pipes are insulated.

Using the hydraulic network solver, each cooling network was balanced, with the relevant hydraulic parameters for each network element determined. Table VIII summarizes the data determined for the individual network data.

As expected, 2M with the lower water flow rate, but with the same pipe sizes used in 1M, had a reduced head loss and consequently a 35% reduction in pumping power compared to its predecessor. 3M has the lowest head loss and pumping

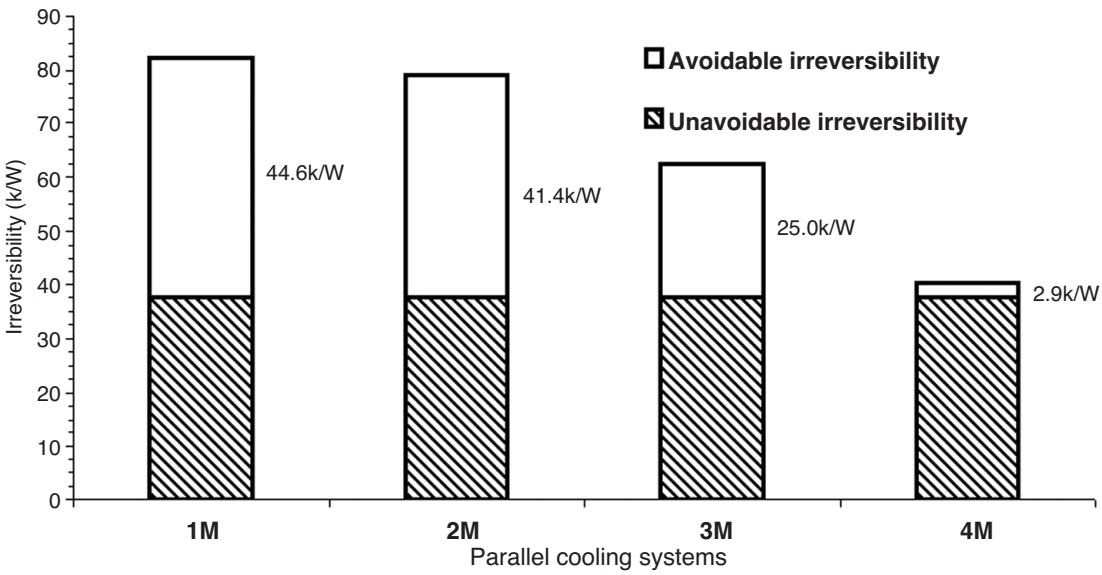


Figure 12—Determined irreversibility of various parallel cooling systems

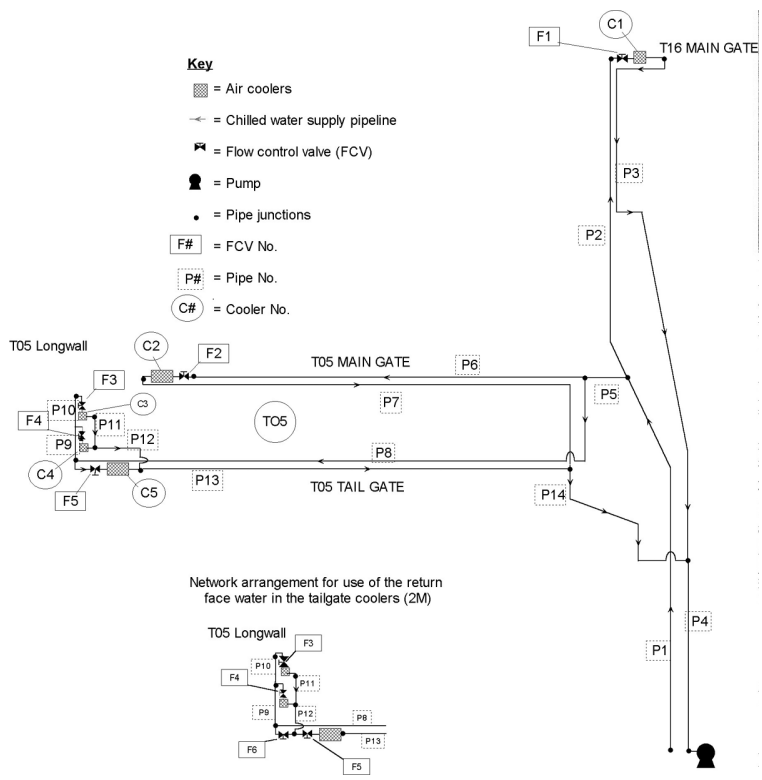


Figure 13—Layout of chilled water network

Table VIII

Summary of the results obtained for the hydraulic models of the various chilled water networks

Cooling network	Total flow rate (ℓ/s)	Total head loss (kPa)	Required pump power (kW)
1M	31.68	2019	64.0
2M	26.13	1810	47.3
3M	12.65	1062	13.4
4M	38.27	2029	77.6

power as a result of cooler flow rates being reduced to a minimum without the MAT being breached. Layout 4M requires the greatest pumping power input as a result of its high volumetric flows and head loss.

Once the hydraulically balanced data for the various chilled water networks and the data determined from Hydroflo™ are combined with the predicted climate data from Climsim™ for the Maltby mine network, an exergy analysis may be conducted on each of the modelled water networks.

Exergy analyses of Maltby model chilled water networks

An exergy analysis was conducted on all four parallel cooling networks developed for Maltby mine network under the application of the RTV cooling method. As account is now taken of the water temperature change as a result of head loss and heat transfer through the pipes, the water temperature reaching the coolers will be slightly higher. However, this is assumed not to significantly affect their performance. An exergy analysis of the networks was carried out using data from Hydroflo™ and Climsim™, with the heat transfers and exergy changes associated with pipe flow determined using a pipe exergy model. Table IX gives a summary of the thermo fluid results obtained.

From an examination of the results presented in Table IX it can be seen that the evaluated head loss for each network is slightly lower than that predicted using Hydroflo™.

The differences in head loss between those calculated by Hydroflo™ and those by the pipe exergy model are relatively small, less than 10 kPa. However, in the case of the 4M network, a much larger difference is seen. This is the result of the use of the higher water supply temperature of 15°C. However, the difference between the calculated head loss values is still less than 2% of their totals

For each of the networks modelled, a Grassmann diagram was constructed to represent the relative magnitude of the exergy transfer and the irreversibility that takes place as the chilled water flows around the cooling system. These diagrams, as before, give a visual representation of the exergy flows around the network, allowing comparisons to be made easily between the different systems. An example Grassmann diagram for the cooling network 4M is given in Figure 14.

Table X summarizes the evaluated exergy transfers and irreversibilities for individual element types and the total exergy change of the system. The bracketed figures represent the specific flow exergy of the various water streams. Since networks 1M to 3M all start at the 3°C and 35 bar, their initial specific exergies are the same. 4M has a lower specific exergy to start with because of its 15°C water supply temperature.

Network 1M exhibits the largest change in the exergy content of the water streams. This is due to both the large exergy transfer from the water when it passes through the coolers, and the high irreversibility associated with the water flow through the network. In network 2M the exergy change is reduced by approximately 15% as compared to the 1M network.

Although the exergy transfer in the 2M network coolers is decreased, due to the reuse of the face cooler exit water in the tailgate coolers, the majority of the reduction seen in the total exergy change is a result of lower pipe irreversibility. The reduced pipe irreversibility is a direct result of the lower water velocities, with the pipe network having not been resized from that of the previous 1M network. As expected, the 3M network sees a much reduced exergy change as compared to that determined for the 1M and 2M layouts. This occurs because the use of calculated variable flow rates are significantly lower than the previously considered fixed flows. Hence, water within the coolers reaches a higher temperature, and thus reduces the coolers exergy transfer parameter. The use of the lower flow rates in conjunction with the pipe sizes available also results in a much lower frictional irreversibility. Network 4M, with the 15°C chilled water supply temperature, shows a very small exergy transfer at the coolers. This is due to the heat transfer into the water occurring at temperatures close to that of the environment. In fact, exergy is not only transferred out of the water, but as its temperature rises above 20°C, exergy begins to transfer back into the water. The value shown in Table X represents the overall exergy transfer out of the water. Exergy transfer into the water also occurs along return pipes of the 4M layout, and to a smaller degree in some of the return pipes and coolers of the 3M network, but again the overall exergy transfer for these components is out of the network, and hence it is not possible to apply an exergetic efficiency performance parameter, which was valid for all situations.

Table IX

Summary of Maltby networks thermal fluid results

Network	Total heat transfer through pipes (kW)	Final water temperature (°C)	Total head loss (kPa)	Final pressure (kPa)
1M	80.9	11.7	2015.5	1484.5
2M	75.7	13.4	1807.6	1692.4
3M	51.3	23.4	1051.3	2448.7
4M	43.6	22.1	1987.5	1512.5

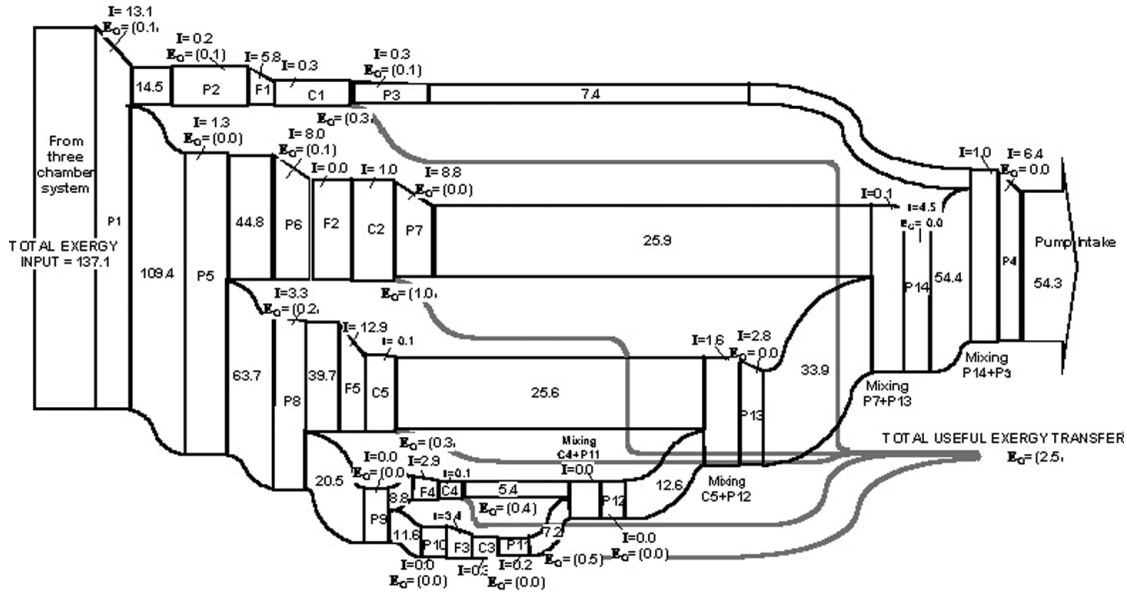


Figure 14—Grassman diagram for 4M cooling network

Table X

Summary data from Maltby colliery networks exergy analyses

		Network			
		1M	**2M**	**3M**	**4M**
	E_{in} (kW)	175.2 (5.5)	144.5 (5.5)	70.0 (5.5)	137.1 (3.6)
	E_{out} (kW)	59.7 (1.9)	49.2 (1.9)	30.5 (2.4)	54.3 (1.4)
	ΔE (kW)	**115.5**	**95.3**	**39.5**	**82.8**
Exergy transfer E^Q (kW)	Cooler	43.6	39.8	22.8	2.5
	Pipe	3.5	4.5	2.5	0.6
	Total	**47.1**	**44.3**	**25.3**	**3.1**
Irreversibility I (kW)	Cooler	2.0	2.0	0.9	2.7
	Pipe	60.9	37.5	12.0	48.9
	FCV	3.1	8.5	0.6	24.9
	Mixing	1.8	2.9	0.8	3.6
	Total	**67.8**	**50.9**	**14.3**	**80.1**

Note: Specific flow exergy; (# .#)

On the basis of the results of the exergy analysis presented in Table X, the best operational network is 3M. However, with the MAT fixed at 13°C for all networks, the various temperature ranges over which the heat is transferred into the system would in reality affect the required heat transfer areas of the coolers. Hence, although the 3M network carries out its function 'consuming' the least amount of exergy, at a reduced power cost, it could at the same time greatly increase the capital cost of the network.

Summary

In this paper the model of a mechanical mine cooling system was applied to a climatic simulation of an operational UK mine, Maltby colliery. The climate model of the Maltby mine was developed using the Climsim™ climate prediction program and measured climatic and ventilation survey data. This allowed the climate of the model mine network to be effectively modelled to best represent the conditions currently being observed underground. Although the measured climate data was obtained for several positions throughout the mine, it was not possible to model the climate exactly. This is as a consequence of the complex and numerous thermal interactions and heat sources that occur within a dynamic subsurface environment. However, in all cases it was possible to model air conditions within 5% of the measured values.

The 28°C ET climate limit was then imposed on the colliery network. It was observed that this climate limit was exceeded within the CCZs of the longwall face, tailgate and development heading. Hence, the minimum cooling method and the RTV cooling method, previously identified as the best and most practical cooling method, were applied to regulate the air conditions within the CCZs.

Exergetic composite cooling curves were constructed for each cooling method and their respective exergy transfers determined. It was found that under model conditions, the RTV cooling method had a greater exergy output than the minimum cooling method, while also having no exergy input. This resulted in the potential exergy loss (PEL) index of the RTV method having a negative value. However, with the minimum cooling method chosen to represent the ideal case, the lowest valid value for a PEL for alternative methods is zero. Hence, the PEL index in not valid for all conditions. However, the exergetic cooling ratio parameter does remain valid. Therefore, it is possible to observe the thermal exergy transfer difference between the ideal cooling method, minimum cooling, and the RTV cooling method, with the former transferring 16% less exergy out of the air per kilowatt of cooling, than the ideal.

Parallel cooling streams were then used to absorb the heat being removed from the air using the RTV cooling method. Initially the ideal parallel cooling system was evaluated, to give a practical ideal datum with which to compare the performance of other parallel cooling system.

Four further parallel cooling systems were then developed. The irreversibility of each system was determined and their avoidable irreversibilities compared. As expected, the systems with calculated flow rates had significantly lower irreversibilities, with the 15°C chilled water supply system operating very close to its ideal.

For each parallel system, a chilled water reticulation network was constructed and balanced using Hydroflo™. It was demonstrated that if a network was converted for water reuse, e.g. from the 1M to the 2M network, there was a resultant reduction in pumping power. The analysis also highlighted the reduction in system pumping power if low water supply temperatures are used in conjunction with calculated cooler water flow rates, such that the MAT is matched as the water exits a cooler, as in the case of network 3M.

Each network was then subjected to an exergy analysis using a pipe exergy model. An examination of the results of this analysis highlighted the dramatic effect that the different water flow rates and supply temperatures have on the exergy transfers and irreversibilities as the water flows through the network. These results were shown both in tabular form and illustrated as Grassmann diagrams. It was observed that the thermal exergy transfer is dominated by the coolers, over 90%, whereas the irreversibility is dominated by pipe friction loss, 70% or more. The exception to these values was seen in the 4M network. This differed significantly from the others due to the use of a 15°C chilled water supply temperature. This resulted in only 2.5 kW exergy being transferred out of the network at the coolers. The low thermal exergy transfer observed was the result of exergy transfer into the system as well as out. The irreversibilities determined within the 4M network mostly split between the pipe and FCV components, which also dominated the overall exergy change parameter. This relatively high irreversibility is the result of the high volume flow rates required so that the MAT set for the coolers was not contravened. However, of the four networks compared it was 3M layout that exhibited the lowest exergy 'consumption' and thus in exergy terms represents the best operational network.

In order to assess the overall performance of a cooling system, consideration must be given to four areas: the performance of the cooling method, the exergetic-cooling ratio, the thermal irreversibility generated across the coolers, and the results of the exergy analysis on the cooling network. The application of exergy analysis in the proceeding investigations has revealed the relative magnitudes and nature of the exergy transfers and irreversibilities within subsurface mine cooling systems. Thus, in general terms, system performance may be judged against these evaluated exergy parameters. However, in order that the results of the previous exergy analyses may be practically used, it is necessary to change from an analysis to an optimal synthesis to determine the optimum system. Consequently, this would require the application of thermo-economic optimization procedures. It is concluded that the analytical methods investigated in this preliminary academic study may be further developed to produce a tool to assist engineers in the optimal design and operation of practical mine cooling systems.

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