OPTIMISING THE OPERATION OF UNDERGROUND MINE REFRIGERATION PLANTS AND VENTILATION FANS FOR MINIMUM ELECTRICITY COST

Christopher Swart

Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the Potchefstroomse Universiteit vir Christelike Hoër Onderwys

Promoter: Prof. E. H. Mathews

2003

Pretoria

ABSTRACT

Title: Optimising the operation of underground mine refrigeration plants and ventilation fans for minimum electricity cost

Author: Christopher Swart

Promoter: Prof. E. H. Mathews

Keywords: Energy management, Load shifting, Mine thermal and energy systems, Ventilation and Cooling system simulation, Optimisation, Cost saving, Electricity tariffs.

This study describes the development and use of a mathematical model that will enable mine operators to minimise the costs of electricity consumed by the ventilation and refrigeration systems used for environmental control in deep mines.

This model was calibrated and tested by using actual data from a gold mine near Welkom in South Africa. In a first simulation, the mine's current practice of controlling conditions to a wet bulb temperature (T_{wb}) of 25.5°C, was optimised. The model demonstrated that this environmental condition could be sustained at lower electricity consumption. In so doing, the mine realised a saving of 30 000 kWh per day. The energy saving and load management led to a cost saving of R 1.5 million per year.

However, a better indicator of environmental conditions is the Air Cooling Power index, (ACP). Research has shown that for hard physical work in hot conditions workers need an ACP of 300 W/m^2. It was found that the case study mine actually supplied their workplace with a cooling capacity of 422 W/m^2. The new model optimised the refrigeration and ventilation systems in such a manner that the workers were supplied with exactly 300 W/m^2, no more and no less. It was found that by doing this, an electricity saving of 57 600 kWh per day could be realised when compared with the current mine practices. The energy saving and load management led to a potential cost saving of R 2.55 million per year. (Certain capital costs, such as for variable speed drives may have to be incurred to realise these savings.)

The new model could be further extended to take advantage of the new Real Time Price offerings from Eskom. It will be able to identify an operating point for the refrigeration and ventilation systems to supply 300 W/m^2 for the workers, in real time, at the lowest electricity cost.

SAMEVATTING

Titel: Optimeer die gebruik van ondergrondse myn verkoelings en vantilasie toerusting vir minimum elektrisiteitskoste.

Outeur: Christopher Swart

Promotor: Prof. E. H. Mathews

Sleutelwoorde: Energiebestuur, Lasverskuiwing, Termiese en energiestelsels van myne, Ventilasie en verkoelingstelsel simulasie, Optimering, Koste besparings, Elektrisiteitstariewe.

In hierdie studie word 'n nuwe wiskundige model beskryf wat in staat is om die gebruik van elektrisiteit in die verkoeling- en ventilasiestelsels van 'n myn te minimeer.

Data vanaf 'n operasionele myn naby Welkom, Suid-Afrika, was gebruik om die model the kalibreer en te toets. Nadat bewys is dat die model die myn akkuraat kan simuleer, is dit gebruik om nuwe simulasies en optimeringsberekeninge uit te voer.

Die myn beheer tans die ondergrondse klimaat op 'n T_{wb} van 25,5°C. Die model het bewys dat hierdie omgewingstoestande behou kan word, maar wel met 'n verminderde elektrisiteitsverbruik. Die gevallestudie-myn sou ongeveer 30 000 kWh per dag kon bespaar, sonder om enigsins die huidige omgewingstoestande hoef te verander. Dit sou 'n kostebesparing van R 1.5 miljoen per jaar beteken.

'n Beter indikator van ondergrondse toestande is egter die ACP (Air Cooling Power) indeks. Navorsing het getoon dat werkers wat onderworpe is aan harde fisiese werk in warm omstandighede, 'n verkoelingswaarde van 300W/m^2 benodig. In die gevallestudie myn was gevind dat die werkers met 422 W/m^2 voorsien word, wat onnodiglik hoog was.

Die nuwe model was toe gebruik om die ventilasie en verkoelingstelsel verder te optimeer sodat die werkers slegs met die nodige 300 W/m^2 voorsien word. Dit sou die myn 'n moontlike 57 600 kWh per dag kon bespaar, in vergelyking met huidige mynpraktyke. Die gepaardgaande kostebesparing sou R2.55 miljoen per jaar beloop. (Hierdie is egter nie 'n netto besparing nie, aangesien sekere kapitaalbeleggings gemaak sou moet word om die besparing te realiseer.)

Die nuwe model kan ook verder ontwikkel word om myne die moontlikheid te bied om voordeel te trek uit Eskom se nuwe RTP (Real Time Pricing), die uurlikse verandering in elektrisiteitspryse.

ACKNOWLEDGEMENTS

The following people and institutions have to be thanked for their contributions to this report:

Institutions

- AVGOLD Ltd. for allowing us to do this study, for the help and information they supplied.

People

- Prof. E.H Mathews for guidance and support throughout the whole process;
- Deon Arndt for his help and guidance in developing the new simulation models;
- Martin den Boef for his help and guidance in developing the new simulation models;
- Ronny Webber for his assistance and guidance during this study
- Faan Muller for the mine information he supplied
- Chris van der Watt for the mine information he supplied
- Dieter Kruger for his help in preparing this thesis
- My family and friends, for their full support during this study;

Most importantly, I want to thank the Lord for His guidance, strength and love throughout my life, and especially throughout this study.

TABLE OF CONTENTS

Abbreviations

ACP	Air Cooling Power
DSM	Demand Side Management
EDI	Electricity Distribution Industry
EM	Energy Management
EMS	Energy Management System
GW	Giga Watt
HVAC	Heating, Ventilation and Air-Conditioning
MD	Maximum Demand
NER	National Electricity Regulator
RED	Regional Electricity Distributors
REM	Real time Energy Management
RTP	Real Time Pricing
SCADA	Supervisory Control and Data Acquisition
SADC	Southern African Development Community
SAPP	South African Power Pool
TOU	Time-of-Use
WEP	Wholesale Electricity Pricing

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

1.1. Background to the problem

The mining industry plays a substantial role in the South African economy. It creates jobs for over 417 000 people [1] and purchases 18 % of the country's electricity [2]. In the South African mining industry, the gold industry is the largest. Gold production in South Africa peaked in 1970 with some 1266 tons being produced. Since then production has decreased with 517 tons of gold being produced in 1994, 420 tons in 1995 [3] and 394 tons of gold in 2001 [4].

The South African gold mining industry is facing severe problems. During the late 1980's, the cost of ton per ore milled has doubled. When compared with other main gold producing countries, South Africa had the lowest working costs in 1984. In 1990 South Africa's working costs were on average the highest in the world. [5].

It is clear that the output of the gold mining industry, and its contribution to the wealth of South Africa, is decreasing. However, there are still massive gold resources in the South African Witwatersrand basin and it is estimated that only 40% of the available gold has been mined so far. But, to recover these resources, mining depths need to be increased [3].

In 1995, only approximately 10% of South African gold production came from mining depths greater than 2500m [3]. It is projected that by the year 2010 close to 60% of production will be at depths greater than 2000m [6] and an estimated 50% at a depth greater than 2500m in 2015 [3]. As the mining depths increases, so do the technical challenges, operating and input costs.

The deeper the mine, the more difficult it is to maintain acceptable environmental conditions for the underground workers. A good underground environment enhances productivity and production. As mining depths increase, so will the cost of maintaining an acceptable underground environment.

Down to a depth of approximately 1600m ventilation alone is adequate to provide suitable underground environmental conditions [7]. Beyond that depth, the amount of air and water cooling required to maintain safe air temperatures, rapidly increases. Cooling, then, becomes a dominant operating cost factor.

The History of the cooling of mines, using mechanical refrigeration, dates back to the 1920's in Brazil and 1930's in India [8]. From 1940 to 1960 several cooling plants were installed on deep level gold mines on the Witwatersrand in South Africa. Currently more than 1400 MW of refrigeration capacity is installed at South African mines. The capital value of these installations is approximately R800-million. Electrical running costs alone exceed R100-million per year [9].

On a large and deep mine, environmental control accounts for some 20% of the total operating costs [7]. The major element of this is the cost of electrical power. For some deep mines environmental control can account for as much as 40% of the electricity bill [10]. Refrigeration is the major consumer in this instance. For a mine to reduce its operating costs, the management will have to optimise the operational efficiency of the ventilation and refrigeration systems.

Although the South African mining industry is the world leader in virtually all aspects of environmental control [11] more work has to be done to optimise these underground systems to operate at the optimal working point. Electrical energy will be saved if this can be done. This will contribute to South Africa's target to be more energy efficient. South African mines are large consumers of electricity and consume about one fifth of the electrical energy supplied by Eskom [12].

It has been projected that, in 2007, Eskom will not have enough supply capacity during certain high demand (peak) periods [13]. New power stations will then be needed at very high capital costs. This will lead to higher electricity costs for the client. For this reason, Eskom has decided to enrol new DSM initiatives to shift load from peak periods to off-peak periods. In the long term, DSM will not be sufficient and new power stations will have to be constructed.

A substantial rise in electricity cost will have a highly negative impact on the South African mining industry. With working costs, as described above, and electricity costs rising some gold mines may have to close down. It is therefore important for both Eskom and the mining industry that underground environmental systems be optimised to use less electricity at peak times and, more importantly, use as little electricity as possible.

In order to be more energy efficient, new ways have to be developed to simulate and optimise ventilation and refrigeration systems. A lot of work has already been done on the optimisation of air-conditioning systems in buildings [14][15][16][17][18]. Here operating strategies, efficient control, optimisation of controller parameters, cold storage and intelligent control were investigated. It was found that in some cases up to 25% of operating costs could be saved [19].

Various studies have been done on the optimisation of mine cooling and operating systems[20][21]. These include the optimum use of the refrigeration plant, cooling towers etc. Other studies investigated electricity cost management in deep mines. One specific case study mine showed a potential electricity cost saving of 7 % per year [22]. Specific and comprehensive software programs have been developed to assist in the design of mine cooling and ventilation systems [23][24][25].

With all these studies and design tools available, the mining industry still struggles to use its cooling and ventilation systems optimally. This leads to the continuous wastage of valuable electrical energy.

There is a need for a real time, integrated, simulation and optimisation model to control underground environmental conditions. This model needs to combine air velocity with air temperature to maintain the generally acceptable cooling power of 300 W/m^2 [26] at the workplace. The model must also control fan rotation speeds and the compressor power of the refrigeration plant to maintain 300W/ m^2 cooling continuously throughout the day.

1.2. Mine safety and environmental conditions

A good underground environment enhances worker productivity. Therefore there is a need to improve and maintain acceptable underground conditions in the workplace.

Excess humidity, high temperatures and the need for adequate oxygen have always been the issues of concern. With increasing mining depths, modern mines struggle to maintain acceptable environmental conditions. With virgin rock temperatures rising up to 64°C and other heat sources, like electrically and diesel powered equipment, explosives, metabolic heat and other energies released by mining, the cooling of new mines is becoming an increasing challenge [27].

Poisonous underground gasses, exhaust gasses from diesel powered equipment and dust, also put the health of the underground worker at risk. Comprehensive ventilation systems for deep mines are needed to supply the workers with enough oxygen as well as to remove polluted air from the underground workings.

The air cooling power (ACP) index and the wet bulb temperatures are the two most important parameters that determine the quality and acceptability of underground mine environmental conditions. A wet-bulb temperature of 27.5°C and a cooling power of 300 W/m^2 are suitable for humans to do hard physical work and these figures can be used for environmental design purposes [28].

1.3. Minimising electricity costs in deep underground mines

Demand versus supply strategy

Good electricity management has become increasingly important in deep underground mines. The ventilation system, fridge plant and underground pumping system constitute up to 40% of a mine's electricity bill [29]. The optimum use of electricity in these systems will contribute to the lowering of the electricity cost of a mine substantially.

Energy in the form of cold air is also continually being wasted through excessive cooling. Fan speeds are often too high, creating an unnecessarily high air volume flow through the haulages. The challenge is to limit the supply of energy to only what the mine actually needs. This means that the supply of energy must equal only the real energy demand of the mine.

For hard physical work, an air cooling power of 300 W/m^2 is acceptable at the underground working environment [26]. The cooling power in a haulage (airway) is mainly dependant on the air velocity and the air temperature. The optimum will be reached when the air speed and air temperature are combined to supply 300 W/m^2 at the working place using the minimum amount of electrical energy.

Exploring energy storage in mines

The cost of electricity is higher during peak periods. Therefore many mines currently explore ways to use less energy during these high cost periods. In some deep mines, various methods to store energy already exist. Mines make use of ice storage systems to store refrigeration energy during low demand periods. The energy stored in the ice can then be used to cool the mine during peak periods at a lower cost.

Refrigeration energy can also be stored in the refrigeration water systems, as well as in the air and side walls (rock) of the underground haulages. Although a lot of research has already been done on the storage of refrigeration energy in buildings, there is still a need for research to apply this to the mining industry.

Underground dams are also successfully used to store energy. Huge dams are filled with cold water during off-peak periods. This cold water can then be used for cooling during periods of peak electricity costs, and the energy intensive refrigeration plants can be switched off during this time.

Pumping energy can also be stored in huge underground clear water systems. During off-peak periods, the clear water dams are emptied, using pump energy. There will then be enough volume capacity left, to absorb the water flow during peak periods, from the mine, into the dams. In this way the clear water pumps do not need to be active during the peak periods.

Preparing for Real Time Pricing (RTP)

Real Time Pricing has been specifically designed to align customers' daily demand side decisions with Eskom's short-term system costs in order to help drive down the cost of electricity [29]. The consumer basically pays directly for the cost of generation. The RTP cost profile is provided daily for the next day and the consumer can adjust the use of electricity to best suit the next day's profile.

Specific systems have already been developed to control certain mining equipment to respond to the RTP price signal. An example of this is REMS (Real time Energy Management System) that automatically controls mine equipment to respond, within mining constraints, to the RTP signal. By doing this, the mine can save electricity costs and assist Eskom in obtaining peak load reduction. The introduction of RTP in South Africa is still in the test phase and various opportunities exist in the mining industry to utilise this tariff system [29].

1.4. The need for simulation and optimisation

The computer simulation of underground systems enables designers in the mining industry to improve the design and operation of their systems. Simulation packages can predict quickly and accurately how the underground conditions will react when a proposed change is made to such a system. No expensive and time consuming tests have to be done in the mine anymore.

Since the layout of a mine changes continually, the ventilation and refrigeration systems need to be adjusted accordingly. Simulation models of these systems will assist in the design of the correct adjustments, quickly and effectively. Various simulation packages, like ENVIRON, for mine cooling and ventilation design, do exist. In spite of this, it is still difficult to find the optimum combined working point for the ventilation and refrigeration systems in order to minimise electricity costs.

1.5. Problem statement and objectives

It is widely known that especially gold mines are under extensive financial pressure because of increasing costs and fluctuating gold prices as determined by global markets. Mining companies have responded with restructuring and the closure of uneconomical shafts. This has caused extensive retrenchments and subsequent labour and social turmoil. Much is being done to reduce input costs but very little in the field of electricity cost saving.

The environmental control systems can account for up to 40 % of the electricity costs of a deep gold mine [10]. If the use of electricity in environmental control systems is optimised, and large savings and/or 'surplus electricity' obtained, the following benefits will be realised:

- Increased tax payments and shareholder value because of reduced expenses and increased profits;
- Long term savings in costs, and the delay in capital investment in new power stations, transmission and distribution systems;
- Reduced pollution and an attendant decrease of the non-quantifiable external costs of electricity generation.

The problem statement of this study is:

Can the environmental control system of a mine be simulated and optimised to reduce electricity cost and still maintain acceptable environmental conditions ?

From the above problem statement the following objective was established:

To develop a simulation and optimisation model that has the capacity to calculate the combined optimum working point for the environmental control systems of an underground mine. At this optimum working point the electricity consumption of the ventilation and refrigeration systems will be the minimum while the underground environment will be supplied with the correct amount of cooling power.

This primary objective can be subdivided into the following secondary objectives:

- Gather information pertaining to mining electricity consumption and the electricity situation in South Africa;
- Gather information on simulation techniques and other simulation software;
- Gather information on underground mine environmental conditions and design;
- Develop a new integrated simulation and optimisation model;
- Calibrate and verify this new model;
- Apply this new model to a case study mine;
- Determine the potential to save electricity cost at the case study mine;
- Explore the potential to extend the new model to simulate and optimise energy storage in deep mines.

1.6. Contribution of this study

Mines are not always capable of optimising the operation of complicated underground environmental control systems. *A new easy-to-use model, for the simulation and optimisation of the underground mine environmental conditions, was developed in this study. This model can not only simulate, but also* ***optimise*** *the operation of the ventilation and refrigeration systems, in an underground mine, to supply the acceptable environmental conditions, at the* ***minimum*** *electricity cost.*

The new model was used to do an optimisation study on the environmental control system of an actual South African gold mine. In this study, the electrical energy and monetary savings were calculated. The findings of the study were laid before the mine's management.

A conference paper based on the findings and results of this study was presented at the symposium *Computer Application in the Mining Industry (CAIM), in Calgary Canada, during September 2003* [30].

1.7. Brief overview of this thesis

Each chapter in this thesis has been written so that it may be read independently. Each has its own introduction, conclusion and list of references. This is to enhance readability. However, some repetition of important concepts was necessary. A brief overview of each chapter is given below:

- Chapter 2 discusses, in detail, the current and future electricity situation in South Africa and the impact thereof on the mining industry.

- Underground mine environmental conditions and equipment are discussed in Chapter 3. This gives the environmental boundaries and constraints that will influence the simulation and optimisation model;

- Chapter 4 describes the method of simulation and explains the various mathematical models used in the simulation process of mine environmental control systems;

- In Chapter 5 the developed simulation model is applied to a real mine as a case study. The calibration and verification of this mine's simulation model is discussed;

- Chapter 6 discusses the development of the new optimisation model. This new optimisation model is applied to the case study mine. The results of this application are given in this chapter;

- Future work is discussed on Chapter 7.

- Chapter 8 concludes this study, where the work done in this thesis, is briefly summarised;

- Lastly, a list of the references used in this study is given per chapter;

1.8. Conclusion

The electricity situation in South Africa is changing rapidly. It is already accepted that electricity prices will increase significantly in the near future. The gold mining industry is a large consumer of electricity and is also struggling to show sensible profits. Gold mines are now challenged to lower their operating costs. One way to do this is to use electricity more efficiently.

One significant proportion of electricity cost is to power the ventilation and refrigeration systems of mines. These systems are responsible for the important underground environmental conditions.

Various methods are already in place at mines to improve the management of electricity. For example, the storage of cheap off-peak electricity in water systems is a widely used method. Mines are also now using new simulation software to plan and design these storage systems better.

Nevertheless, there is still a need in the mining industry for a software program that can simulate and optimise the ventilation and refrigeration systems in order to maintain correct environmental conditions and simultaneously minimise the use of electricity. In this study such a model is developed.

1.9. References

[1] The Economics Advisory Unit of the Chamber of mines, ***The South African mining industry fact sheet***, Tel. +27 11 498 7100, www.bullion.org.za, 2002.

[2] Lynch, R., ***An energy overview of the Republic of South Africa,*** US Department of Energy, Office of Fossil Energy, FE-27/ Germantown Building, 1000 Independence Avenue SW, Washington, D.C. 20585-1290, USA, October 2003.

[3] Pickering, R.G.B, ***Deep level mining and the role of R&D***, SAIMM, Vol. 96 no. 5, September/October 1996.

[4] Mbendi, Information for Africa, South Africa: Gold mining overview, http://www.mbendi.co.za/indy/ming/gold/af/sa/p005.htm, 23 September 2003.

[5] Ramsden, R., **Mine cooling towards the 21st century**, Journal of the Mine Ventilation Society of South Africa, September 1990.

[6] Chadwick, J., ***Deep Mining***, Mining Magazine, January 1997

[7] Haase, H., ***The potential for cost reductions by reducing heat loads in deep level mines***, Journal of the Mine Ventilation Society of South Africa, March 1994.

[8] van der Walt, J., Pye, R., Pieterse, H., Dionne, L., ***Ventilating and cooling of Barricks Meikle underground gold mine***, Mining Engineering, April 1996.

[9] Bailey-Mcewan, M., ***Use of the "chiller" computer program with conventional water chilling installations on South African gold mines***, Journal of the mine Ventilation Society of South Africa, Vol 44 nr.1, January 1991

[10] Stroh, R.M, ***Energy conservation with mine refrigeration systems***, Electricity tariffs and metering (ETAM) and Management and Auditing of Electrical Energy (MAFE), Johannesburg, 13 March 1992.

[11] Marais, D., ***Mine ventilation society alive to the challenges of a new era***, S.A Mining World, Vol. 13, no. 8, September 1994.

[12] Statistics SA, ***Gross Domestic Product, Third quarter 2001, P0441***, Private bag X44, Pretoria, 0001, Tel. +27 12 310 8304, www.statssa.gov.za, 2001.

[13] Eskom NEWS, page 2, May 2003.

[14] Edward J, O' Neal, P.E., ***Thermal storage system***, Achieves operating and first-cost savings, ASHRAE Journal, April 1996.

[15] Kintner-Meyer, M., Emery, A.F., ***Optimal control of an HVAC system using cold storage and building thermal capacitance***, Energy and Buildings, December 1994.

[16] Huang, W., Lam, H.N., ***Using genetic algorithms to optimise controller parameters for HVAC systems***, Energy and Buildings, January 1997.

[17] Ben-Nakhi, A.E., Mahmoud, M.A., ***Energy conservation in buildings through efficient A/C control using neural networks***, Department of Mechanical Engineering, College of Technological Studies, Kuwait, May 2002.

[18] Zaheer-uddin, M., Zheng, G.R., ***Optimal control of time-scheduled heating, ventilating and air-conditioning process in buildings***, Energy conversion and Management, 41 (2000).

[19] Yang, K.H., Su, C.H., Hwang, R.L, ***The analysis on intelligent control strategies of a thermal energy storage air-conditioning system.***

[20] Usta, N., Ileri, A, ***Computerised economic optimisation of refrigeration system design***, Energy Conversion and Management, Volume 40, page 1089-1109,1999.

[21] Matthews, E.H., et al., ***New software for dynamic simulation of mine cooling and ventilation,*** Temm International, Contact no. (+27 12 991 5110)

[22] Delport, G.J., Lane, I.E., ***Electricity cost management in mining***, Power engineering Journal, August 1996.

[23] Lilic, N., et al., ***An expert system for mine ventilation system analysis, Department of Mining Engineering, Faculty of Mining and Geology***, University of Belgrade, Yugoslavia, February 1997.

[24] ENVIRON- ***A comro computer program for the full thermodynamic analysis of a mine environment***, Information leaflet-43, Chamber of mines of South Africa, Research organisation library. For further information: The Director Environmental Engineering, COMRO P.O Box 91230, Auckland Park, Tel. (011) 726-3020.

[25] VUMA, http://www.vuma.co.za, CSIR, PO Box 395 Pretoria 0001 South Africa, Tel. + 27 12 841 2911.

[26] Webber, RCW., ***Determining the Physical and Economic impact of Environmental Design Criteria for Ultra-deep Mines***, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, University of Pretoria, page 28, 2000

[27] Really cool ventilation system saves Rustenburg's Turffontein, Mining Mirror. August 1998.

[28] MacPherson, M.J., ***Mine ventilation planning in the 1980's.*** International Journal of Mine Engineering, Volume 2, page 191-202, 1984.

[29] Els, R, ***Potential for load shifting in ventilation and cooling systems***, Thesis is presented in partial fulfilment of the reguirements for the degree of Master of Engineering, University of Pretoria, page 70, 2000.

[30] Swart,C., Webber, RCW. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003.

2. ELECTRICITY IN SOUTH AFRICA AND THE MINING SECTOR

2.1. Introduction

The mining industry consumes about one fifth of the electricity generated by Eskom. Clearly, electrical energy is a huge expense for this industry. Mines continually try to be more efficient in their use of electrical energy. This chapter describes the effect on the South African mining industry of current and foreseen changes to the electricity supply industry.

2.2. Current electricity situation in South Africa

Electricity generation and consumption

The current electricity industry is not open to any form of competition as is the case in many other countries. It is strongly regulated by government policies through the National Electricity Regulator (NER), a Government watchdog. The main players in the generation of electricity are Eskom (95.7 %), the municipalities (1.5 %) and private generators (2.7 %)[1]. Electricity is fed into the South African grid from where it is distributed via transmission systems to the distributors who supply the end-user [2].

The importance of mining to the South African Electricity Supply industry is shown by the fact that it is responsible for 18.4 % of all sales (Other sectors' usage is as follows: Manufacturing 43.8 %, Domestic 18 %, Commercial 9.4 %, General 4.6 %, Agriculture 3.3% and Transport 2.6 %)[2].

There are typically two peaks in the demand for electricity per day. This changes with the seasons due to the heating load that is added during the winter. **Figure 2-1** shows the average and maximum peak demands for the year 2000. On 20 July 2000 and 24 July 2001 the maximum demand was 29 188 MW and 30 599 MW respectively [3][4].

These figures can also be interpreted as an indication of the cost of generation. During the peak demands the more expensive power plants have to be activated, which drives up the total cost of generation for the day. The high cost of electricity generation during peak periods is reflected in the electricity tariffs offered by Eskom [2].

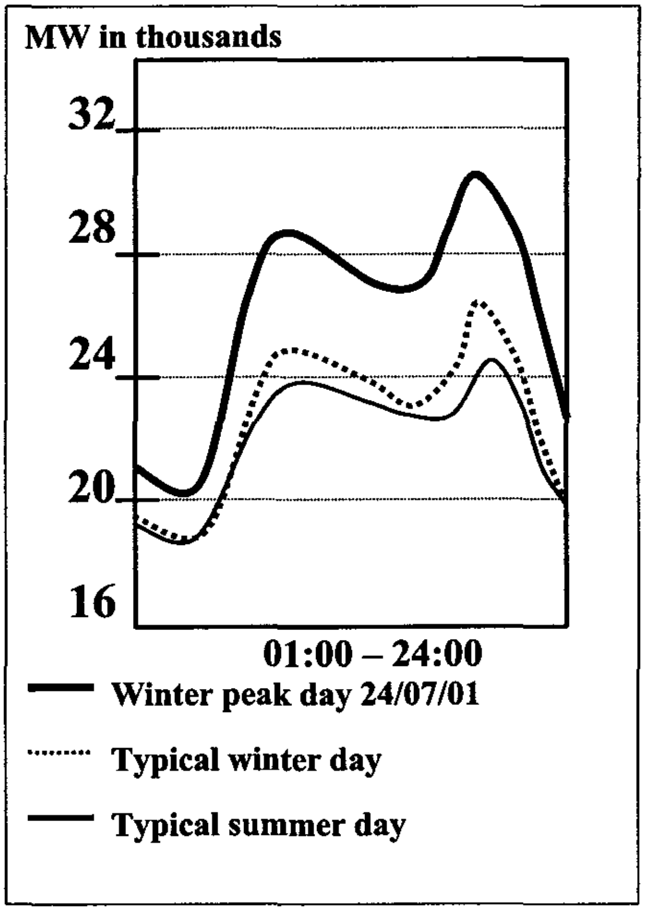


Figure 2-1: Electricity demand profile

Electricity tariffs for the mining industry[2]

Eskom provides alternative pricing structures for large consumers of electricity, such as mines. The six main tariffs available to them are NightSave, MegaFlex, MiniFlex, RuraFlex, Real Time Pricing (RTP) and Wholesale Electricity Pricing (WEP). RTP and WEP are still in the testing phase with various pilot sites being used.

Many mines are not fully aware of these alternatives and the possible benefits to them with regard to Demand Side Management (DSM) opportunities. The more advanced tariffs are advantageous for mines that are capable of shifting load for a certain period of time[5].

NightSave is a tariff that rewards consumers able to shift load to the time, between 22:00 and 6:00 during the week [6]. This is known as the off-peak period. The Time-of-use (TOU) component for NightSave can be seen in **Figure 2- 2a**. This tariff is not very cost reflective since it doesn't really specifically take the peak demands (**Figure 2-1**) during the day into account.

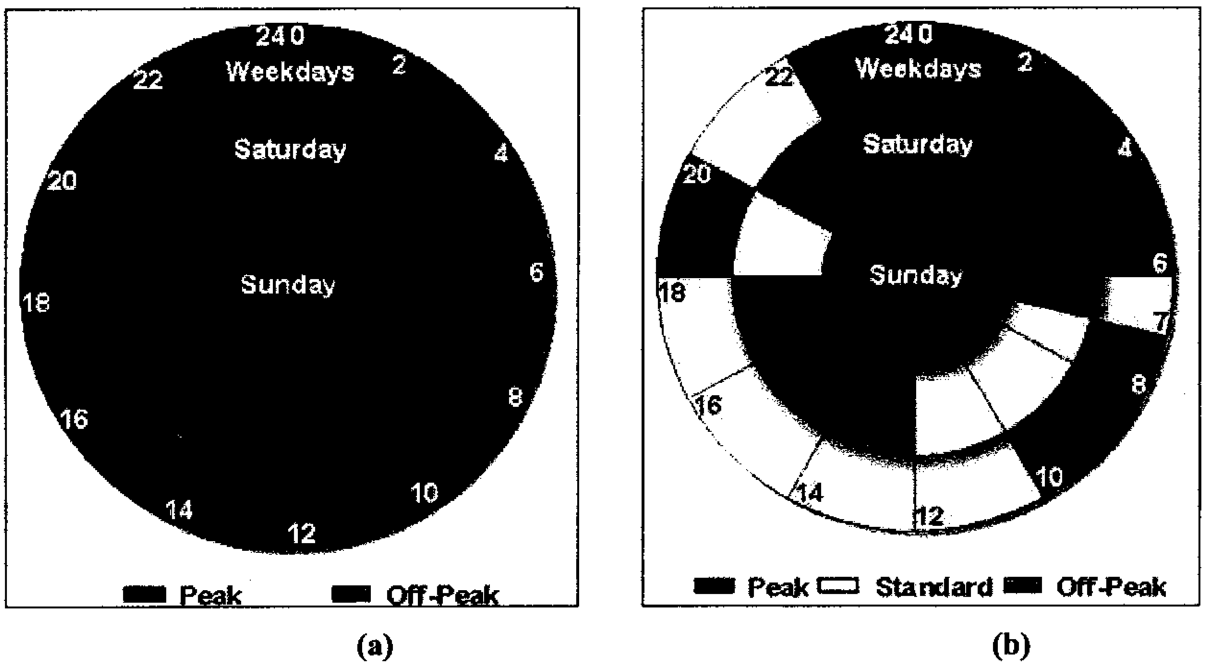


Figure 2- 2: Time-of-use for a) NightSave, b) MiniFlex, RuraFlex and MegaFlex

MiniFlex is for medium sized consumers with different charges for the different TOU periods for different seasons [7]. **Figure 2- 2b** shows the TOU periods for MiniFlex. MiniFlex is more cost reflective, but very static. The consumer must be able to shift load for a substantial period of time to be able to profit from this tariff. The consumer pays for peak demands (kW) and energy used (kWh).

RuraFlex is much the same as MiniFlex but is more specifically aimed at consumers with three phase supplies from a rural reticulation network [8]. The TOU is exactly the same as MiniFlex as seen in **Figure 2- 2b**.

MegaFlex is more suitable for large consumers that need a supply of 1 MVA and above[9]. The TOU period is exactly the same as MiniFlex as seen in **Figure 2- 2b**. This is ideal for large consumers capable of shifting load for long periods (4 to 5 hours per day). The only negative is that this tariff is very rigid with little room for innovative scheduling. Most of the mines in South Africa make use of this tariff.

Wholesale Electricity Pricing (WEP) basically works on the principle of MegaFlex. It has a time-of-use tariff component, closely corresponding to the levels of MegaFlex. WEP is mainly for clients that have an annual consumption of electrical energy of more than 100 GWh at a single site over the last three years[10][11].

Real Time Pricing (RTP) was specifically designed to align customers' daily demand-side decisions with Eskom's short-term system costs to help drive down the cost of electricity. The consumer will basically pay directly for the cost of generation. The RTP cost profile is provided daily for the next day and the consumer can adjust the use of electricity to best suit the next day's profile.

As the name of the tariff suggests, the planning and consumption of electricity is done in real time. The cost profile includes both the charge for using electricity above the consumer's determined base load and the credit available for using less than the base load. This is also referred to as the Two-Part RTP price. Currently the tariff is still under development with changes still being implemented. Some pilot mines do use RTP but it is not yet commonly used, though it is available for large consumers [2].

Future predictions and the possible effect on the mining industry[2]

The economic situation of some of South Africa's major commercial entities, currently owned and controlled by government is set to change rapidly in the near future. These entities (electricity, telecommunications, transport and defence) are set for an open market where private companies will compete with traditionally state run public enterprises. Minister Radebe, Minister of Public Enterprises, recently made the following statement [12]:

" ... This will enable major public corporations in the energy, telecommunications, transport and defence sectors to play a critical role in the socio-economic development of the South African people. It will focus on the restructuring of Transnet, Telkom, Eskom and Denel. The main elements of the process are expected to be complete by the end of 2004 ... "

The government has certain ideas and ideals for the electricity industry in South Africa and Southern Africa. From Minister Radebe it is obvious that Eskom is to be deregulated and restructured. This means that there will be some drastic changes in the whole electricity industry of South Africa and the role that Eskom plays will change greatly. Minister Radebe also said the following regarding Eskom [12]:

" ... Eskom is to be corporatised, with Transmission, Distribution and Generation becoming separate corporate entities. The Department of Public Enterprises envisages the formation of different generating companies and subsequently some form of private sector participation ... "

This means that Eskom will have to become a competitive company and will have to compete with other companies and utilities for customers and income. Certain change processes are currently running even though there is no real outside competition for Eskom. Eskom is putting structures into place for the changes that will take place in the near future. Parts of Eskom's generation capacity will be sold off by 2003. Some 10% will be sold initially with a further 20% later on [13]. Eskom is running a simulated competitive generation market to test the structures and various possibilities.

From the point of view that there will be some form of competition in the electricity market in the future of South Africa, Eskom will need to look at the potential to shift load in certain markets to enable it to sell it in other markets and to other customers.

The main driving force behind all these changes is found in the White Paper on Energy Policy, compiled by the Department of Minerals and Energy, where the guidelines are set forward for this whole shift to happen [14]. To ensure the success of the electricity supply industry, various developments have to be considered by government, namely:

- Giving customers the right to choose their electricity supplier;
- Introducing competition into the industry, especially the generation sector;
- Permitting open, non-discriminatory access to the transmission system, and;
- Encouraging private sector participation in the industry;
- Looking at the future electricity supply. This includes supply and demand side management programs.

The NER has compiled a summary report on the various electricity market scenarios that might be followed in the new electricity environment [15]. The study covered the following basic objectives:

- Understanding the implications and mechanisms of competition;
- Identifying the key choices facing policy makers and industry participants;
- Preparing for a transition to a competitive market structure.

The traditional generation, transmission and distribution systems, run mainly by Eskom, are set to change and be unbundled. Cabinet has approved the consolidation of the current Electricity Distribution Industry (EDI) into new Regional Electricity Distributors (RED's) [16]. Transmission will be owned by a single entity or company and the generation can be done by Independent Power Producers (IPP) and by traditional Eskom power stations divided into competing blocks [17].

The Energy White Paper carefully considers future supply and demand situations and forms the guiding criteria by which decisions on electricity should be made. On the supply side there is a strong movement towards more environmental friendly power generation and the possibility of environmental tax being levied on electricity consumers. The reduction in supply through Demand Side Management (DSM) is also discussed in this paper.

Furthermore, if one looks at international trends, electricity might also become a tradable commodity. Electricity dealers will buy and sell electricity from suppliers and sell it to consumers for a profit. Consumers can then actually make money selling unused pre-paid electricity.

The purpose of presenting this future analysis here, is to underline the importance for mines (and other large electricity consumers) to anticipate the change and to prepare for it. One obvious approach would be for mines to analyse their electricity consumption patterns, and optimise these where possible, even using these changes to their own advantage. Demand Side Management is one of the areas where mines could benefit and this should definitely be looked into.

Environmental impact [2]

Very little attention is currently being given to the environmental impact that electricity supply and demand has on the country. Some studies have been conducted but so far very little has been done about it in South Africa. Internationally, the first world countries are more environmentally sensitive with penalties and taxes being raised against electricity consumers to ensure that they do so responsibly.

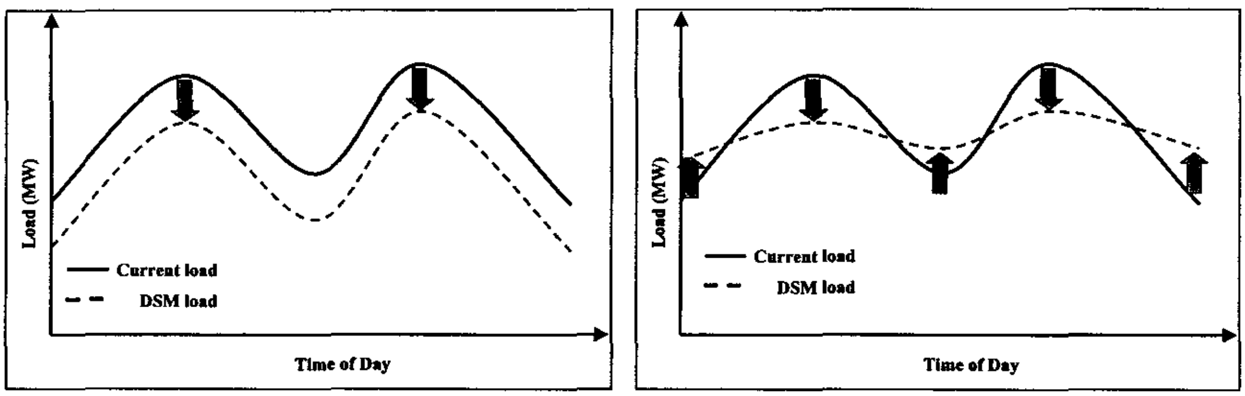
At the World Summit on Sustainable Development, which was held in August 2002, the attention of the world was focused on South Africa and what it does to ensure the longevity of the country's resources and natural environment. In the White Paper on Energy Policy [13] the government supports the idea of sustainable renewable energy and gives it high priority.

The paper also hints at including environmental costs in electricity tariffs to ensure that electricity is used in a responsible and sustainable manner. These costs will be above and beyond the current electricity costs and will force everyone, including the mining industry to look closely at their electricity bills.

It is clear that the electricity supply in general, and the mining industry in particular, can no longer ignore the environmental effects that the consumption of electricity will have on their business. One method of reducing these effects is by Demand Side Management. This study outlines one way in which this can be achieved.

2.3. The mining industry and Demand Side Management [2]

The term Demand Side Management (DSM) is used to describe the planning (scheduling) and implementation of activities to influence the time, pattern and amount of electricity usage in such a way that it produces a change on the load profile of the industry, while still maintaining customer satisfaction [18]. This will assist the utility, like Eskom, to reduce or shift electricity peaks (See **Figure 2-3**).



(a) (b)

Figure 2-3: DSM through (a) Energy Efficiency and (b) Load Management

Figure 2-3 shows the typical methods of DSM. **Figure 2-3a** shows DSM through increasing energy efficiency. This implies that less energy will be consumed and therefore the area under the load curve will decrease. **Figure 2-3b** depicts DSM through load shifting. This implies that moving some of the usage to lower demand periods will decrease the peak demands, but the area under the profile will remain the same. An ideal DSM project will satisfy both of these types of DSM. The type of applicable DSM is dependent on the industry and its ability to shift load and save energy.

The current peaks can be attributed to three main sectors, namely: Residential, Commercial buildings and Industrial (including mines). At present there is a surplus in the electricity peak demand capacity of South Africa, but the peak demand is expected to increase in the next five years (see **Figure 2-3** where the demand profiles till 2015 are forecast) [19]. This means that the peak demand will become higher than the present delivery capacity of the system. At the current growth rate the electricity demand will exceed the generating capacity in 2007 [20].

In accordance with Eskom's latest planning, building a new conventional power station takes about four years with a further two years of environmental impact studies before the start of construction. Three years are needed for the return of mothballed and gas-fired plants, but they offer limited additional capacity.

It is therefore clear that there will be a potential peak demand shortage within the next five to seven years if no decisions are made soon. At the very least the mining industry will soon pay more for electricity, especially during the peak periods. This is, due to both higher marginal costs resulting from the recomissioning of older plants with higher operating costs, as well as making provision for capital costs for new generating capacity.

By contrast, the advantages provided by DSM are that a DSM programme can be rolled out in less than twelve months and at significantly lower costs than conventional generating capacity. Furthermore it requires no environmental impact study, which would require two years for power plants.

Eskom has set specific goals and targets for DSM to be realised by. To achieve these objectives it is imperative that the initiative is sustainable over the next 25 years and acceptable for all parties and stakeholders involved. The goal is set at a deferral of 3.67 GW over the period. For the industrial and commercial sector, that includes the mining sector, it is envisaged to defer some 535 MW by 2020 by means of load management [19].

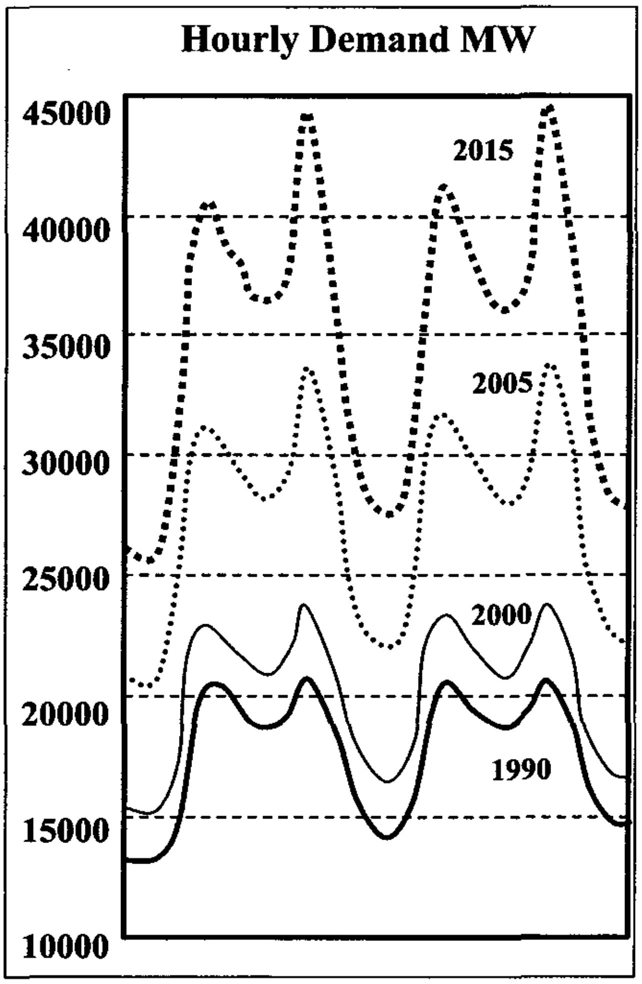


Figure 2-4: Typical average winter load profile forecast till 2015 for two days

The capital costs associated with these deferrals are R 1.6-million per MW for Energy Efficiency programmes and R 1.45-million per MW for Load Management programmes. These values are estimated costs [18]. Compared with the cost of building a new power station (in the order of R 10-million per MW), DSM certainly offers some attractive possibilities.

2.4. Mine systems and a new model

Production and environmental control systems are the mining industry's main electrical energy consumers. Production includes drilling, winding, conveyor and clear water pumping systems.

A substantial amount of work has been done on the scheduling of these systems to shift load from peak periods to off-peak periods [21]. Large underground clear water dams create the opportunity to shift the clear water pumping load easily, but other systems like the winders, drilling and conveyors are so directly linked to production, that the scheduling of these systems is sometimes impossible. However, the efficiency of the operation of environmental control systems can be increased without affecting either production or safety.

As a general rule, a mine's underground working areas are cooled to the maximum operational capacity of the mine's ventilation and refrigeration equipment. In this way, electrical energy is wasted by supplying a "too good" underground environment. The challenge is to supply only the minimum acceptable underground environment, thus using the minimum electrical energy.

Environmental control systems are complicated. An easy-to-use simulation and optimisation model needs to be developed to assist mines to increase the energy efficiency of their environmental control systems.

2.5. Conclusion

It is clear that the future of electricity as we know it may change quite drastically in both systems and prices in the future. The mining industry may not be fully aware of these changes and even if they were, they may not be capable of taking advantage of these changes.

Mines need to be prepared for the new challenges and must start to use electrical energy more efficiently. In the area of production equipment, there is limited scope for DSM. Since production is the mine's reason for existence, mine management is reluctant to "experiment" with cost savings measures in this area. However, the area of environmental control, which is *also* a large consumer of electricity has significant scope for both load management as well as energy efficiency.

To assist mines in managing electricity costs in the area of environmental control, a new model is required to assist mine management in achieving energy savings and so reduce the cost of electricity. The development of such a model is the subject of this study.

2.6. References

[1] National Electricity Regulator, ***Electricity supply statistics for South Africa 1999***, page 4, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 1999.

[2] Els, R., ***Energy evaluations and load shift feasibility in South African mines,*** Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the University for Christian Higher education, 2003.

[3] Gcabashe. T.S., ***Eskom Annual Report 2001: Eskom Chief Executive section***, Eskom, P.O. Box 1091 Johannesburg, 2001.

[4] Gcabashe. T.S., ***Eskom Annual Report 2000: Eskom Chief Executive section***, Eskom, P O Box 1091 Johannesburg, 2000.

[5] Conradie, D., Eskom, ***Eskom's retail pricing plan: 2002***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[6] Conradie, D., Eskom, ***Eskom Tariffs 2002: NightSave***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[7] Conradie, D., Eskom, ***Eskom Tariffs 2002: MiniFlex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[8] Conradie, D., Eskom, ***Eskom Tariffs 2002: Ruraflex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[9] Conradie, D., Eskom, ***Eskom Tariffs 2002: MegaFlex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[10] Mkhwanazi, X.H., ***Annual Report 1999/2000: National Electricity Regulator***, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, **www.ner.org.za**, p. 12, 2000.

[11] Mkhwanazi, X.H., Speech on "***The changing regulatory environment during electricity supply industry reform***", to the South African Institute of Electrical Engineers, 8 February 2001.

[12] Radebe, J., MP, ***Policy Framework: An Accelerated Agenda Towards the Restructuring of State Owned Enterprises***, Pretoria, 10 August 2000.

[13] Chalmers, R., ***Eskom's reshaping plans are on track***, Business Day, 28 February 2002.

[14] Department of Minerals and Energy, ***White Paper on Energy Policy for Republic of South Africa***, pp. 28 – 46, DME, Private Bag X59, Pretoria, 0001, Tel: +27 12 317 9000, December 1998.

[15] Mkhwanazi, X.H., ***Electricity market scenarios study***, Report no. NER 01-2001, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2001.

[16] Department of Minerals and Energy, ***EDI Restructuring update***, Electricity Regulatory Journal August 2001, p.1, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2001.

[17] National Electricity Regulator, ***NER licenses South Africa's second IPP***, Electricity Regulatory Journal September 2001, page1, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2001.

[18] Eskom, ***Demand Side Management's Information Guide for Energy Services Companies***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[19] NER, ***An Integrated Electricity Outlook for South Africa***, National Electricity Regulator, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2002. *(Document was only available for a few months till April 2002 for public discussion and planning)*

[20] Africa, A., ***Eskom: Demand Side Management, Short to medium term demand side strategy***, National Energy Efficiency Conference, 17 July 2001, VW Marketing Conference Centre, Midrand, South Africa, http://www.dme.gov.za/, 2001.

[21] Claassen, D.T, ***New procedures to reduce cost in HVAC systems,*** Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the Potchefstroom University for Christian Higher education, 2003.

3. UNDERGROUND MINE ENVIRONMENTAL CONTROL AND ELECTRICITY

3.1. Introduction

The previous sections described the need to develop models that will assist mines to prepare for future electricity price increases. Environmental control systems are some of the biggest contributors to the electricity bill of an underground mine. The efficient operation of these environmental control systems will therefore save the mines money.

Mines provide their underground workplaces with specified air temperatures and airflows, determined in accordance with criteria that relate to worker health, safety, productivity, comfort and legal and regulatory requirements. The Air Cooling Power (ACP) index and the wet bulb temperatures two important parameters that determine the quality and acceptability of underground mine environmental conditions.

During simulation and optimisation calculations, the ACP index and the wet bulb temperatures must be kept within an acceptable range. This chapter deals with the underground wet bulb temperature and ACP in more detail. These are the important parameters that have to be included in the modelling and optimisation process.

3.2. Wet bulb temperature in mines

Creating a suitable environment for removing metabolic heat from workers' bodies (and thus limiting the negative impact on their health, safety and productivity) depends primarily on the underground wet-bulb temperature and air velocity. The wet-bulb temperature has been proven to be the most useful single-measurement indicator of environmental heat stress.

Research, as well as experience, have indicated that formal controls, in the form of a structured heat stress management (HSM) programme, are required where the wet-bulb temperature (T_{wb}) reaches 27,5°C [1]. It has also been recommended that routine work should not be permitted where T_{wb} exceeds 32,5°C or the dry-bulb temperature (T_{db}) exceeds 37°C [2].

These are important constraints to remember for the simulation and optimisation calculations later on in this study. The disadvantage of these constraints is that it does not take the particular air velocity in the workplace into account. A specific wet bulb temperature in the workplace can be obtained under conditions of different air velocities. Therefore, a new index, Air Cooling Power, was developed to include workplace air velocities.

3.3. Air Cooling Power

Air Cooling Power (ACP) is calculated using both air velocity and the wet bulb temperature in the mine. For the design of underground environmental conditions it is recommended that ACP should not be less than 300 W/m^2 [3]. Lower design and control limits for ACP are in use, most notably in Australia, but those are in the context of high levels of mechanisation and air-conditioned operator cabins.

From **Figure 3- 1** [4] it can be seen that air velocities of approximately 0,5 and 1,5 m/s are required to achieve an ACP of 300 W/m^2 at wet-bulb temperatures of 27 and 29°C, respectively. This is a 300 % increase in airflow against a 2°C increase in allowable air temperature. Looking at it from another point of view, one can see that increasing air velocity from 0,5 to 1,5 m/s at a constant wet-bulb temperature will increase ACP by only 20%. On the other hand, decreasing the wet-bulb temperature from 31 to 25°C for a constant air velocity of 0,5 m/s will have the effect of increasing ACP by nearly 60%. At 1,5 m/s this increase is even higher.

Air velocity and wet bulb temperature influence each other significantly in terms of costs. It is therefore important that in the context of ventilation and cooling planning the effect of an increase in pressure drop and an increase or reduction in design temperatures, be considered continuously and simultaneously. Only in this way can the ACP be optimised.

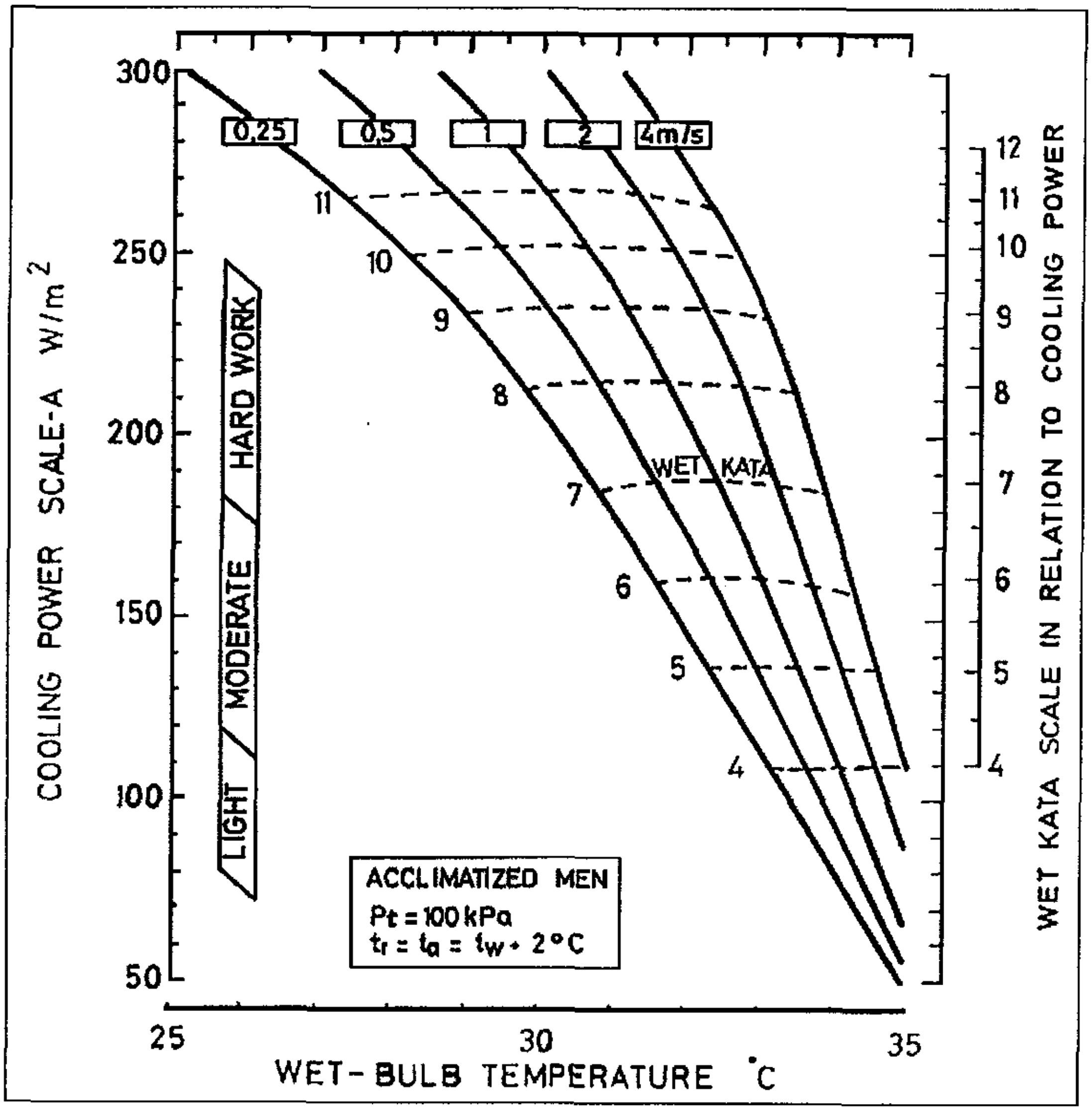


Figure 3- 1: Environmental design parameters in relation to Air Cooling Power (ACP)

3.4. Electricity consumers in Mine Environmental Engineering

In order to optimise the energy consumption of mine environmental control equipment, the primary electricity consumers in these systems have to be identified. These are the air supply units (ventilation fans) and the cooling of the air (which includes the refrigeration units).

The ventilation system of a mine normally consists of one or two main extraction fans situated on surface. However, in order to overcome the resistances of the ducting, these main fans are normally supported from underground by an additional amount of smaller booster fans.

The cooling system consists mainly of the refrigeration plant, bulk air coolers and spot coolers. The refrigeration plant cools the system water down. This cold water is then transferred to the bulk air coolers and the spot coolers for the cooling of the mine ventilation air.

In order to optimise the environmental control systems, simulation models for each component of the system need to be developed. These simulation models must predict the characteristics, performance and energy consumption of the individual mine systems accurately. Furthermore, the simulation models for these systems must also be designed in such a way that it will be possible to apply optimisation calculations.

3.5. Optimisation of mine environmental control systems

If optimisation of the mine environmental control system is attempted, it is important to remember that the two main controllable parameters, i.e. the quantity of air and the air temperature, are interrelated. For example, increasing the air velocity (which entails an increase in the fan input power costs) is unnecessary if the same effect can be achieved by reducing the air temperature through additional cooling.

In this whole simulation and optimisation process it is therefore important to establish what the required amount of air velocity and air temperature must be. Through this process an optimised amount (physical and financial) can be determined based on an optimised demand strategy versus a supply (available) strategy for ventilation and cooling in mines.

3.6. Conclusion

The ideal working environment of an underground mine has been defined as needing an ACP index of 300 W/m2. This index takes account of both air temperature as well as air velocity. In order to achieve a specific level of ACP, either air velocity or air temperature, or both, have to be adjusted. However, the costs of increasing airflow can be significantly different from that of decreasing air temperature. For this reason, a simulation and control model must be built which can be optimised.

3.7. References

[1] Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003

[2] COMRO, 1991. ***Heat stress management: A comprehensive guideline***. Chamber of Mines Research Organisation, User guide No. 22, Johannesburg.

[3] MacPherson, M.J., 1984. ***Mine ventilation planning in the 1980's***. International Journal of Mine Engineering, Volume 2, page 191-202.

[4] Stewart, J., 1989. ***Practical aspects of human heat stress.*** In: J. Burrows, R. Hemp, W. Holding and R.M. Stroh (Eds.), Environmental Engineering in South African Mines, page 535-567. Johannesburg, The Mine Ventilation Society of South Africa.

4. INTRODUCTION TO SIMULATION OF UNDERGROUND MINE AIRFLOW AND COOLING

4.1. Introduction

The future electricity situation can have a negative impact on the South African mining industry, as described in Chapter 2. New simulation model need to be developed to assist the mining industry to do better electrical energy management. This chapter discuss the current simulation packages available, how they work and what are the advantages of using them in the engineering industry.

This chapter shows that a new easy to use simulation model is needed for the simulation and optimisation of underground environmental control systems. Then the basic elements for the simulation of underground ventilation and refrigeration systems are developed.

4.2. Background to simulation

With the coming of the computer age and its ability to solve continuous and discrete time systems, the numerical simulation of systems, fluid flows, aerodynamics, etc. has developed rapidly [1]. Today various powerful solution algorithms are available that can be used to simulate just about any conceivable system or problem over any time frame [2].

A whole range of system simulation software exists in the market place and includes: ACSL, APROS, ARTIFEX, Arena, AutoMod, C++SIM, CSIM, FluidFlow, Gepasi, GPSS, JavaSim, JavSim, MJX, MedModel, Multiverse, Network, OPNET Modeler, POSES++, PowerSim, QUEST, REAL, SHIFT, SIMAN, SimBank, SIMPLE++, SimPlusPlus, Simulat8, SMPL, SPICE, TIERRA and Witness [3].

System simulation implies that various physical components (Equipment, thermal flow, fluid flow, etc.) are simulated, taking into account their interaction with each other, e.g. the airflow or ambient air temperature may have an influence on the thermal performance of a chiller. This performance then has a direct impact on the electricity usage of the chiller and the cold water it produces that is sent to the next component, like air-cooling coils or heat exchangers.

In the field of thermal and energy systems, the simulation is a steady state calculation of operating variables (like pressure, temperature, flow rate, electricity used, heat transferred, etc.) at specific points [4].

Simulation software can also be used for a variety of purposes. Some software can be used as a design tool. Given the boundaries (cost, cooling capacity, water flow, space available, etc.) the simulation software can make suggestions, show problem areas and write out specifications. A user can test his/her design with simulation software to ensure the proper functioning of it.

The software can also be used for problem solving and enhancements on already installed systems. Using the software, simulated tests can be run on the system to test its response to different settings, new equipment or the effect of breakages on the system. This is a non-intrusive testing method that, if software is properly verified, can avoid costly, and sometimes dangerous, physical testing.

Whatever the purpose of the software, simulation traditionally means the solving of a set of equations that model the various components (equipment or working substance) of the system. Most often the equations are solved for a steady state at certain points in the system. A growing number of simulation packages include unsteady state solving and emphasize the changing variables with time.

The building blocks of a system simulation software package are the individual components representing the equipment or a certain process in a system. Most components have characteristics according to which they react on specified or calculated inputs. These characteristics can be modelled using derived mathematical equations. It can be derived through either elemental mathematical and physic laws or through empirical methods using measured data.

The derived mathematical equations will have three categories:

- **Input:** User defined inputs or calculated inputs from a previous component;
- **Equation/Calculation:** The inputs are converted into usable answers;

- **Output/Results:** The converted answers can be sent on to the next component or be exported to a data sheet for further use.

Accurate mathematical equations are not always obtainable. Many ideal equations exist for a variety of thermal components, but they often lack accuracy. Accurate models are often very complex in nature and need many inputs from the user to enable it to calculate usable outputs. A combination between the two types (physical laws or empirical methods) of equations usually provides the most satisfactory results in the engineering industry.

Simulation of mine environmental control systems

Mine ventilation simulators are in general adequate in terms of airflow simulation, but not adequate when it comes to integrated cooling system simulation [8]. Current simulation software is powerful but it will be difficult to apply them to simulate and optimise underground mine environmental conditions. A new-easy-to use and accurate simulation and optimisation model are required for underground environmental control systems.

The rest of the chapter will describe the necessary components and mathematical models needed for a new underground ventilation and cooling simulation model. This simulation model will be developed specially for optimisation purposes.

4.3. Simulation of ventilation systems

Background

A certain amount of airflow is needed in the mine to maintain the correct supply of fresh air for a suitable underground working environment. Ventilation fans are responsible for airflow through the mine. To be able to calculate the potential energy saving of fan power, a simulation model has to be developed to predict the underground airflows at different fan performances.

The airflow mathematical model

The airflow model consist of three components. One component represents the amount of airflow (Q), one the airflow resistance (a), and the other the pressure source (P) in the airway or haulage. To explain the models the inlet and outlet of an airway are represented by two nodes and are named, node 1 and node 2.

Airflow component

The airflow between node 1 and node 2 are represented by Q, as shown in **Figure 4- 1.**

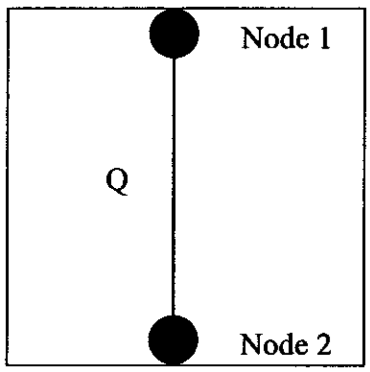


Figure 4- 1: Schematic of the airflow between two nodes

Air resistance component

The air resistance between node 1 and node 2 is represented by a, as shown in **Figure 4- 2**

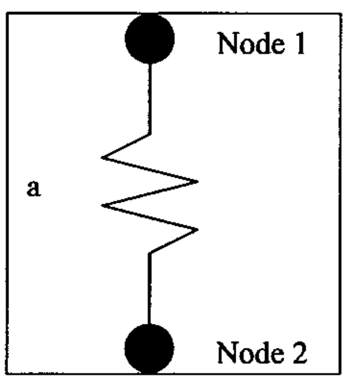


Figure 4- 2: Schematic of the air resistance between two nodes

Pressure source component

The pressure source between node 1 and node 2 is represented by P, as shown in **Figure 4- 3**

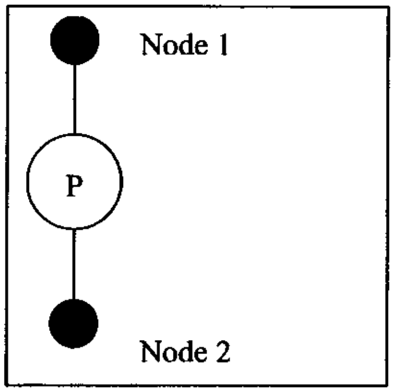


Figure 4- 3: Schematic of the pressure source between two nodes

Integrate components into a flow diagram

The above components are integrated to form part of an airflow network. An airflow network is represented by a flow diagram. This flow diagram works on the same principle as an electrical circuit. The electrical resistances are replaced by the air flow resistances through the airways. The electrical power sources are replaced by the pressure sources which are the fans. The electrical current is replaced by the amount of airflow through the airway. See the layout of a simple airflow circuit in **Figure 4- 4**.

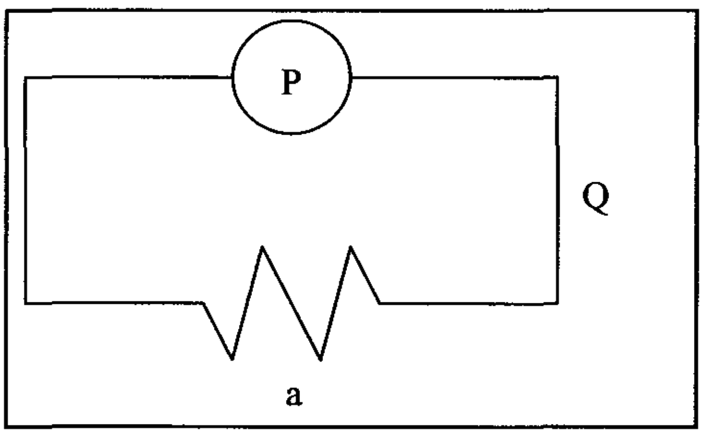


Figure 4- 4: Schematic layout of an airflow network

Like in electrical circuit calculation it is possible to generate a series of equations which can be solved simultaneously. The same can be done for airflow, to calculate all the unknown airflows and fan pressures in the circuit. This is done by revising Kirchoff's current laws to solve airflow and air pressures.

Kirchoff's laws applied to airflow:
Airflow: The algebraic sum of all the airflows at any node in a circuit equals zero.
Air pressure: The algebraic sum of all the pressure differences around any closed path in a circuit equals zero.

Using the airflow circuit in **Figure 4- 4**:

The pressure drop between two nodes (airway) is a function of the airflow resistance and the amount of air flowing between the two nodes.

Pressure drop through airway:

$$\Delta P = aQ^2$$

with :

a = Resistance of the airway

Q = Amount of airflow through the airway (kg/s)

There will always be a pressure drop through an airway. The ventilation fans must overcome these pressure drops. The pressure difference created by the ventilation fans are calculated using a known fan mathematical model.

The fan mathematical model:

The pressure P that is set up by a fan is a function of various fan and air characteristics. The calculation procedure to calculate P, also P_{total}, will now be described:

The model is based on the following two non-dimensional variables which can be derived by employing the Buckingham-Pi theorem:

The flow coefficient defined as:

$$K_f = \frac{m_a}{\rho_a n D^3}$$

with:

ρ_a the air density

n the rotational speed of the fan

D the rotor diameter

m_a is the mass flow rate of dry air at the inlet in kg/s.

The pressure head coefficient defined as:

$$K_h = \frac{P_{total}}{\rho_a n^2 D^2}$$

P_{total} is the total pressure set up by the fan and is made up of the static pressure (dP_a) and the dynamic pressure ($\frac{1}{2}\rho\ velocity^2$).

Any specific fan is characterised by the relation between these two coefficients. To continue a simple polynomial regression will be used namely:

$$K_h = a_0 + a_1 K_f + a_2 K_f^2 + \ldots + a_k K_f^k$$

With a_0 to a_k the $k+1$ correlation coefficients derived from fan performance data sheets. The order of the polynomial equation may vary from model to model and will be determined by the shape of the K_h versus K_f relation.

The total pressure across the fan are written in terms of the mass flow rate as:

$$P_{total} = dP_a + \frac{m_a^2}{2\rho_a A_e^2}$$

with the assumption that the dynamic pressure difference across the fan is negligible.

With A_e equal to the outlet area of the fan discharge we use the explicit equation for P_{total}:

$$P_{total} = K_h \rho_a n^2 D^2$$

For the fan motor power (*Pwr*) the following equation are used:

$$Pwr = \frac{m_a P_{total}}{\rho_a \eta_{fan} \eta_{motor}}$$

with the fan efficiency, η_{fan}, calculated with:

$$\eta_{fan} = b_0 + b_1 K_f + b_2 K_f^{\,2}$$

and η_{motor} the drive motor efficiency. In this study we assume $\eta_{motor} = 1$. For b_0 to b_k the k+1 correlation coefficients are derived from fan performance characteristic data.

4.4. The simulation of mine underground heat transfer

Background

Underground mine ventilation air are heated mainly by the hot virgin rock and hot underground mining equipment. Heat from underground mining equipment includes mainly diesel powered engines, electrical powered motors, lights etc.

The underground air temperatures depend mainly on the cooling capacity of the refrigeration plant, the amount of airflow supplied by the ventilation fans and the heat sources described above. For simulation purposes the accurate prediction of underground temperatures, especially the wet-bulb temperatures, at all the critical areas in the mine is essential.

The heat transfer mathematical model needs to predict the air dry-bulb and wet-bulb temperatures at the end of each airway. The inlet air temperatures to each airway will be the input values to the model for that specific airway. The following methodology will explain clearly:

Methodology

Figure 4- 5 shows a schematic layout of a thermal model of a shaft (airway).

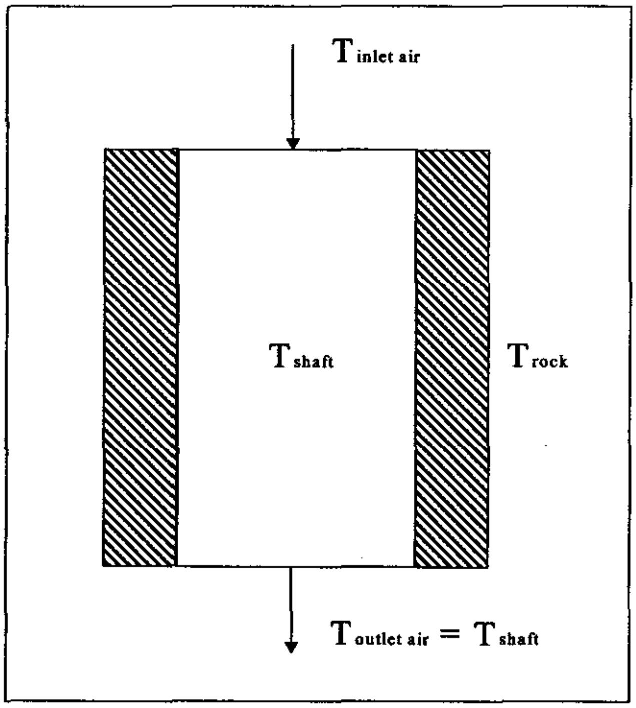


Figure 4- 5: Schematic layout of the thermal model of a shaft or airway.

The heat transfer network of this shaft or airway model looks as follows:

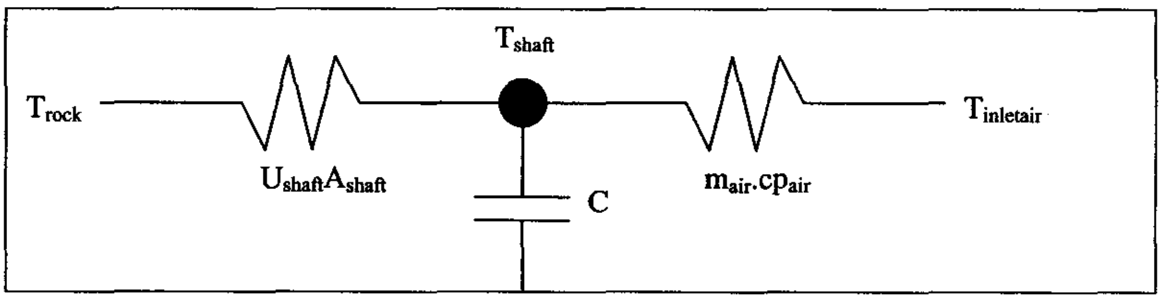


Figure 4- 6: Schematic of the heat transfer network of a shaft or airway.

With:

T_{rock}	=	temperature of the rock at the side of the airways
T_{shaft}	=	temperature of the air inside the airway
$T_{inletair}$	=	temperature of the air that enters the airway
C	=	thermal capacity of the air inside the airway
UA	=	Heat transfer coefficient ($W/m^2.K$)
m	=	mass flow of the air through the airway (kg/s)
cp	=	Heat capacity of the air (KJ/kg.K)

T_{rock} and T_{inlet} air are the heat sources of the model. T_{shaft} is the temperature of the air currently in the shaft or airway. $U_{shaft}.A_{shaft}$ and $m_{air}cp_{air}$ are the heat transfer resistances. C is the thermal capacity (heat storage ability) of the combination of the air and rock in the shaft or airway.

The energy balance of the system in **Figure 4- 6** are written as:

$$C\frac{dT_{shaft}}{dt} = U_{shaft}A_{shaft}\left(T_{rock} - T_{shaft}\right) + m_{air}cp_{air}\left(T_{inletair} - T_{shaft}\right)$$

Separating the variables and using the initial values $T_{shaft} = T_{shaft}^0$ at $t = 0$ the shaft temperature is solved using the following equation.

$$T_{shaft} = \frac{1}{a}\left[\left(aT_{shaft}^0 - b\right)\exp\left(\frac{-a\delta t}{C}\right) + b\right]$$

where $$a = U_{shaft}A_{shaft} + m_{air}cp_{air}$$

and $$b = U_{shaft}A_{shaft}T_{rock} + m_{air}cp_{air}T_{inletair}$$

The airway between each node set is divided into three separate segments (or models) as seen in **Figure 4- 7** (detail inspection and iterative calculations showed that only three separate segments are needed to simulate air conditions in an airway accurately). The models are interconnected through the air temperature that is passed from one model to the other, starting with the inlet air temperature at the first segment right through to the leaving air temperature of the third segment. This leaving temperature is then the inlet temperature to the next set of nodes.

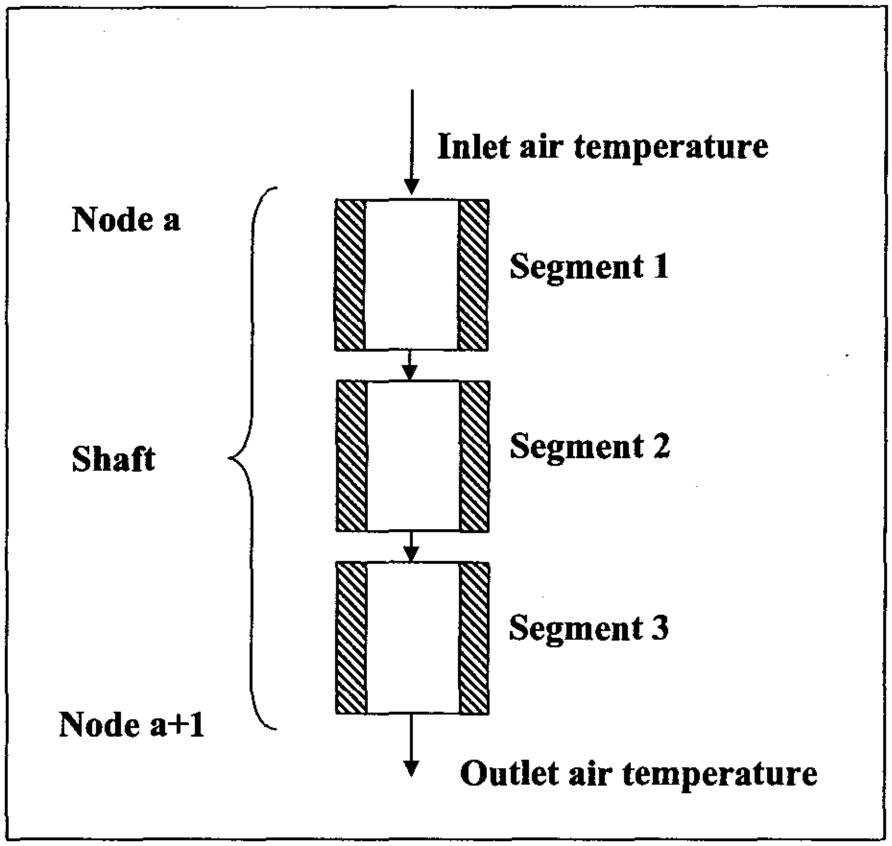


Figure 4- 7: Schematic layout of the underground cooling model for each of the shafts/airways.

Unique mathematical model for the workings area

The mathematical model of the area where most of the mining takes place (workings) are set up as follows:

Q represents the heat that is generated by mining activities as well as the heat transferred from the surrounding rock to the air in the workings. Q will change throughout the day, depending on mining activities. Normally a standard constant daily profile exists.

Q consists of two parts, q_s and q_l with q_s the sensible and q_l the latent heat transfer.

$$Q = q_s + q_l$$

with:

$$q_s = mc_p(t_o - t_i)$$

and

$$q_l = m(W_o - W_i)i_{fg}$$

with

m = Mass flow of the air through the workings (kg/s)
c_p = Heat capacity of the air (KJ/kg.K)
t_o = Temperature of the air at the outlet of the workings (°C)
t_i = Temperature of the air at the inlet of the workings (°C)
W_o= Humidity ratio of the air at the outlet of the workings (kg/kg)
W_i = Humidity ratio of the air at the inlet of the workings (kg/kg)
i_{fg} = Enthalpy of the air (KJ/kg)

See the schematic layout of the workings area in **Figure 4- 8.**

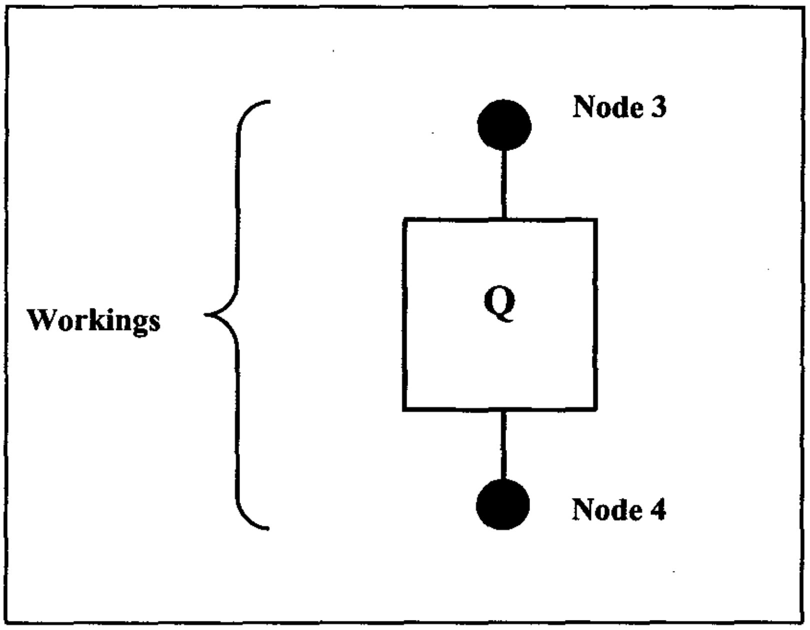


Figure 4- 8: Schematic layout of the workings area

By calculating a suitable daily average trend q_s and q_l from real mine measured data it is possible to predict the average outlet dry-bulb and wet-bulb temperatures for the workings area. The inlet temperatures and humidity ratio are calculated by the shaft model that exits into the workings area. With the average q_s and q_l known it is possible to calculate t_o and W_o for the workings area. By means of the psychometric formulas the wet-bulb temperature at the outlet are calculated. It is assumed that no mass transfer takes place.

4.5. The simulation of refrigeration performance

Background

The simulation model must predict the inlet and outlet water temperatures to and from the refrigeration plant. To ensure accurate predictions it is necessary to develop an integrated simulation model. This model will include different smaller models that each characterise one of the components in the refrigeration system.

These components are the refrigeration machines (chillers), and the condenser and evaporator spray ponds. The compressors, which are part of the refrigeration machines, are the only simulation component that uses electrical energy.

The prediction of the compressor power (electrical energy) consumption of the refrigeration plant is essential for electrical energy consumption calculations. To predict a realistic operating point for the refrigeration plant the following have to be simulated:

- Thermal performance of the evaporator spray ponds
- Thermal performance of the condenser spray ponds.

The way each of these where handled in the simulation will now be described in the methodology.

Methodology

Chiller compressor power simulation

The schematic layout of the refrigeration, evaporator and condenser spray ponds are shown in **Figure 4- 9.**

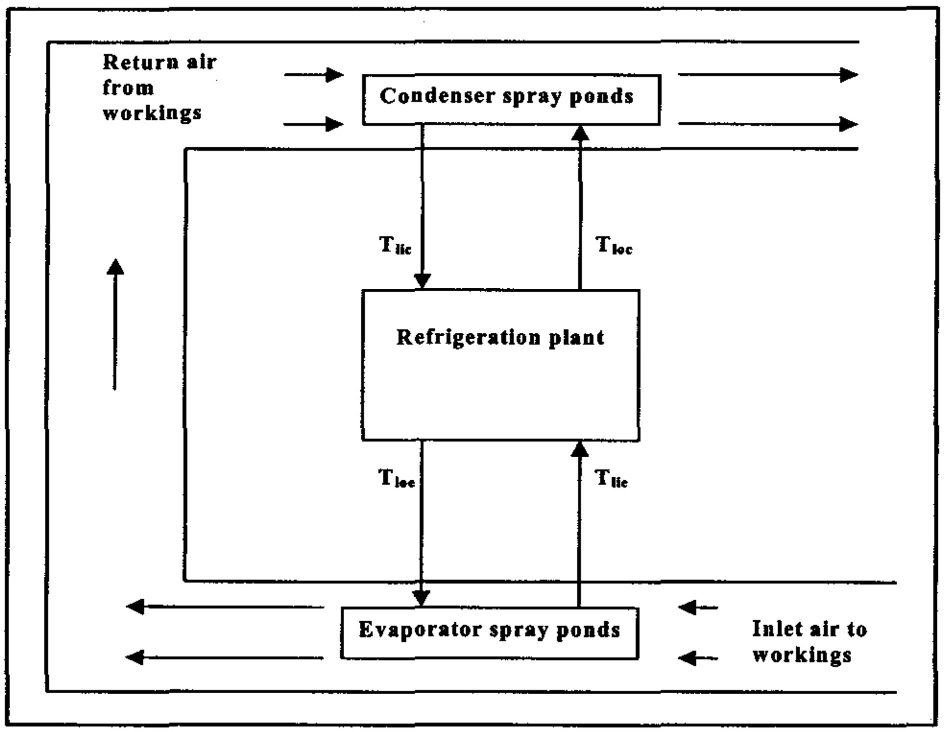


Figure 4- 9: Schematic layout of the refrigeration plant, evaporator and condenser spray ponds.

First the cooling capacity of the evaporator spray ponds is predicted with the following function:

$$Q_e = \left(\left(b_1 T_{loe} + b_2\right) T_{wb} + b_3 T_{loe} + b_4\right) m_{\max}{}^{0.37} \left(\frac{m_{sp}}{m_{\max}}\right) \quad [5]$$

With:

Q_e = Cooling capacity of the evaporator spray ponds (kW)

m_{max} = Maximum water flow through the spray ponds (kg/s)

m_{sp} = Water flow through the spray ponds (kg/s)

T_{loe} = Temperature of the water leaving the evaporator (°C)

T_{wb} = Wet-bulb temperature of the air through the spray ponds (°C)

b = Correlation coefficients derived for cooling capacity

The compressor power is calculated with the following function:

$$P_{wr} = \frac{m_{lie} m_{lic} c_p \left(a_0 + a_1 T_{lic} + a_2 T_{lie}\right) - Q_e \left(m_{lic} c_p m_{lie} - m_{lie} a_1 - a_2 m_{lic}\right)}{m_{lie} a_1} \quad [6]$$

With:

P_{wr} = Compressor power (kW)

m_{lie} = Mass flow of the water that enters the evaporator (kg/s)

m_{lic} = Mass flow of the water that enters the condenser (kg/s)

T_{lie} = Temperature of the water that enters the evaporator (°C)

T_{lic} = Temperature of the water that enters the condenser (°C)

a = Correlation coefficients derived for compressor power

c_p = Specific heat capacity of the water (J/kgK)

To complete the cycle the cooling capacity of the condenser spray ponds is calculated as follows:

$$Q_c = \left(\left(c_1 T_{loc} + c_2\right) T_{wb} + c_3 T_{loc} + c_4\right) m_{\max}{}^{0.525} \left(\frac{m_{sp}}{m_{\max}}\right) \quad [5]$$

Q_c = Cooling capacity of the condenser spray ponds (kW)

m_{max} = Maximum water flow through the spray ponds (kg/s)

m_{sp} = Water flow through the spray ponds (kg/s)

T_{loc} = Temperature of the water leaving the condenser (°C)

T_{wb} = Wet-bulb temperature of the air through the spray ponds (°C)

c = Correlation coefficients derived for cooling capacity

(Note: The equations used to calculate Q_e, Pwr and Q_c was developed through the use of multi-dimensional curve fitting and not from fundamental principles. This explains why the coefficients a, b and c are dimensionless.)

With the outlet water temperature from the condenser:

$$T_{lec} = T_{lic} - \frac{Q_e + Pwr}{m_{lic} c_p}$$

and the outlet water temperature from the evaporator:

$$T_{lee} = T_{lie} - \frac{Q_e}{m_{lie} c_p}$$

4.6. Integrate the mathematical models and the simulation process

The challenge is to link and combine all the mathematical models to form an integrated simulation model. In this model each smaller mathematical model will receive input from other mathematical model/models and will supply another model/models with input data. This leads to a closed loop calculation cycle. See **Figure 4- 10.**

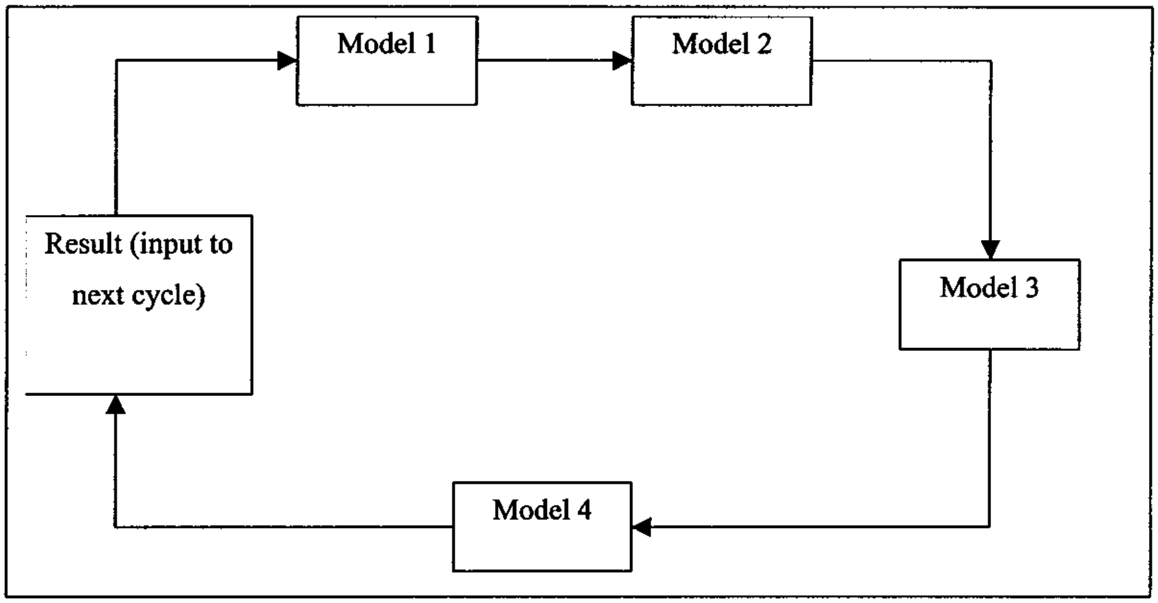


Figure 4- 10: Simple schematic of the simulation calculation cycle

Each calculation cycle receives its input data from the previous calculation cycle and will supply the next cycle with input data. Each calculation cycle are completed within a specific time step. Doing this the simulation of a specific system can be done over a chosen time period consisting of any number of time steps.

4.7. Disadvantages of the simulation models

The simulation model was developed specifically for mine environmental control equipment. Each individual mathematical model was developed to provide accurate results within a specific operational range. Outside these ranges the models may provide inaccurate results. Each mathematical model has to be calibrated before it can be used for calculations. This is complicated and time consuming.

4.8. Conclusion

The basic elements for a simulation model to simulate underground environmental conditions were described. The models are designed for the inclusion of optimisation in order to minimise the use of electrical energy.

The simulation model consists of various mathematical models. These models are linked to supply each other with the correct input data for the calculation of the desired result. One result is calculated for each time step. The simulation done for a number of time steps will complete the specified simulation time period and give the final desired end result.

4.9. References

[1] Bouwer, W, ***Dynamic integrated simulation of mine thermal and energy systems***, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001.

[2] Law, A.M., Kelton, W.D., ***Simulation modelling and analysis***, McGraw-Hill, 1991

[3] Vladimirescu, S., Zhang, K., Newton, A.R., Pederson, D.O., ***SPICE Version 2.5 User's guide***, Berkeley, CA, 94720.

[4] Stoecker, W.F., ***Design of Thermal Systems***, McGraw Hill, 3rd Edition, page 349-352, 1989.

[5] Taljaard, J.L.F, ***Simplified mathematical models of specific system components for thermal simulation software***. Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001.

[6] Swart, C., ***Integrated simulation of heat transfer networks***. Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001

[7] Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003

[8] von Glehn, F., ***Simulation and control of mine ventilation and cooling systems,*** Journal of the mine Ventilation society of South Africa, July/September, page 91, 1999.

5. SIMULATION OF THE VENTILATION AND COOLING SYSTEM OF A CASE STUDY MINE

5.1. Introduction

The basic models for airflow and air temperature simulation were developed in Chapter 4. In theory, and for other applications, these models were proven to be accurate. However, these models still needed to be tested during actual underground mine conditions.

A mine was needed for a case study to test the developed simulation models. This case study mine must have a refrigeration plant, a ventilation system and a simple layout. A gold mine near Welkom, South Africa, was chosen for this study. The mine was willing to participate and assisted in obtaining all the necessary data.

5.2. Description of the case study mine

General mine information[1]

The case study mine, the major asset of AVGOLD Ltd., is situated on the western flank of the Witwatersrand Basin, where most of the world's gold has been mined. AVGOLD's exploration efforts focused on this area and by 1993 yielded extremely encouraging results. In 1995 feasibility studies for a 45 000 tonnes-a-month mine began. In July 1996 AVGOLD increased the scope of the project to a 90 000 tonnes-a-month mine. The mine itself has a life of at least another 13 years. New resource profiles from the areas north of Target shows 65.5 million ounces at an average grade of 6,7 grams/ton which can prolong the mining operations.

The productivity of conventional gold mines equates to a typical value of 20 tonnes milled per man per month. Currently the case study mine has a productivity figure of 130 tonnes milled per man per month. The mine is continually looking to improve this figure. The mine's objective is to produce 100 000 tonnes of run-of-mine ore at a cost of less than US$150/oz by 2003 .

This 2.25 km deep gold mine's objectives can be achieved by making more extensive use of technology. The objective of this demonstration was to carry out a detailed study on the optimisation of the cooling and fan-power, in order to minimise the electricity cost and, therefore, contribute to a lower mining cost.

Case study mine systems layout

Underground refrigeration system

There is no surface refrigeration plant at the mine. All the refrigeration takes place underground. The refrigeration plant is situated on level 255 and consists of 10 refrigeration machines (chillers) each with a cooling capacity of ± 3 MW and a coefficient of performance (COP) of ± 3.5.

The water from the hot dam enters the evaporators at a temperature of 17°C and exits the evaporators at 9°C. This water is then pumped to the evaporator spray ponds at a tempo of 380 kg/s to cool the air that is destined for the workings. There are 4 evaporator spray ponds in parallel on level 255. There are also two smaller secondary evaporator spray ponds on level 276 and 280. The water that exits the evaporator spray ponds gathers in the hot dam before it is again pumped to the refrigeration plant.

From the condenser side of the chillers, water flowing at 740 kg/s, is pumped to the condenser spray ponds. There are four condenser spray ponds in parallel. The water enters the spray ponds at 46°C and is cooled by the return air from the workings to 41°C. The exit water from the condenser spray ponds is then pumped back to the condenser side of the refrigeration plant for the next cycle. The schematic layout can be seen in **Figure 5- 1**.

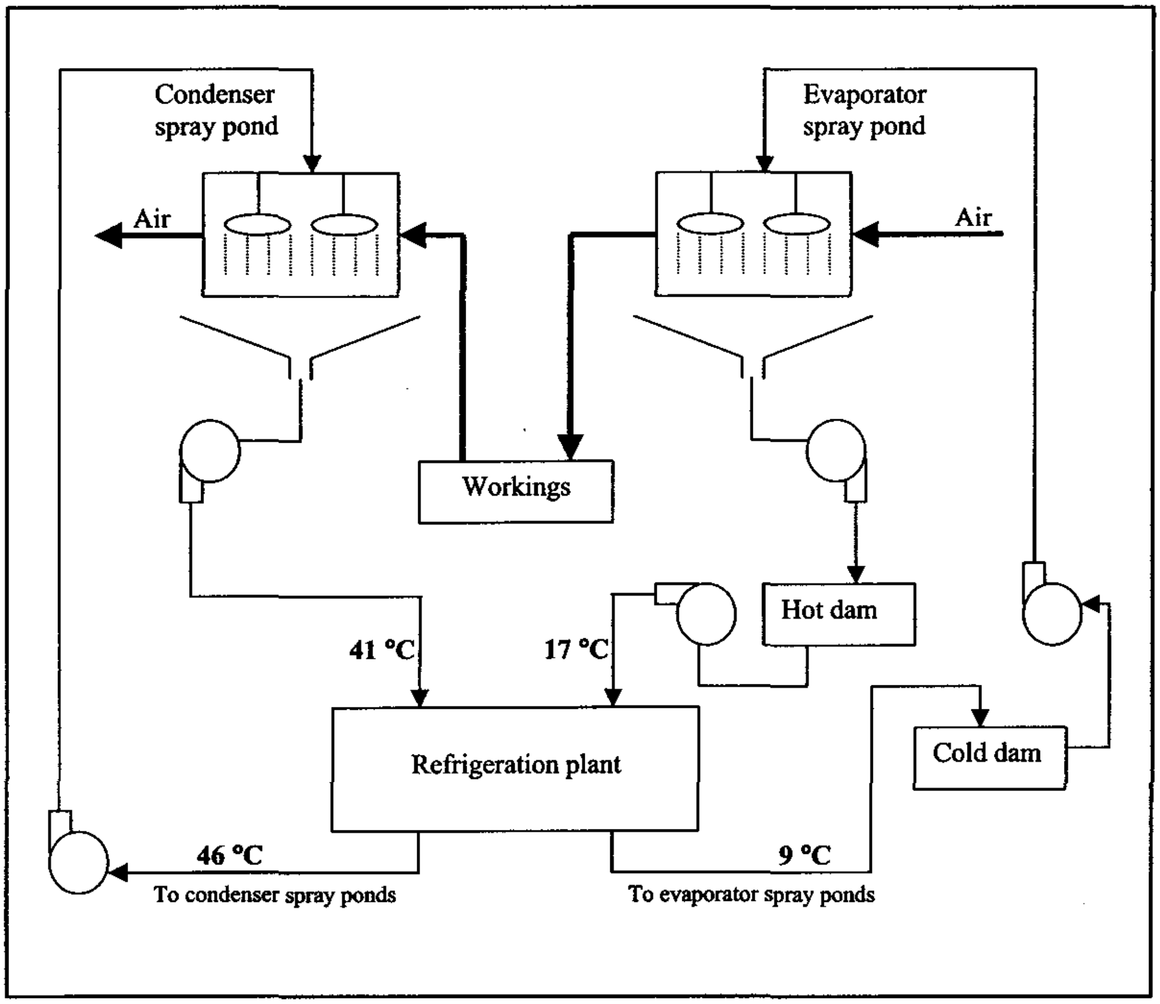


Figure 5- 1: Schematic layout of the underground refrigeration system

Underground ventilation system

A surface fan, driven by a 2100 kW electric motor, is mainly responsible for the ventilation requirements in the mine. This fan can extract air at 400 m^3/s at a pressure of 3.5 kPa. There is also one main fan on standby. The main fan is supported by two 275 kW booster fans on level 208 and four 445 kW booster fans on level 255. The schematic layout of the mine ventilation system can be seen in **Figure 5- 2**.

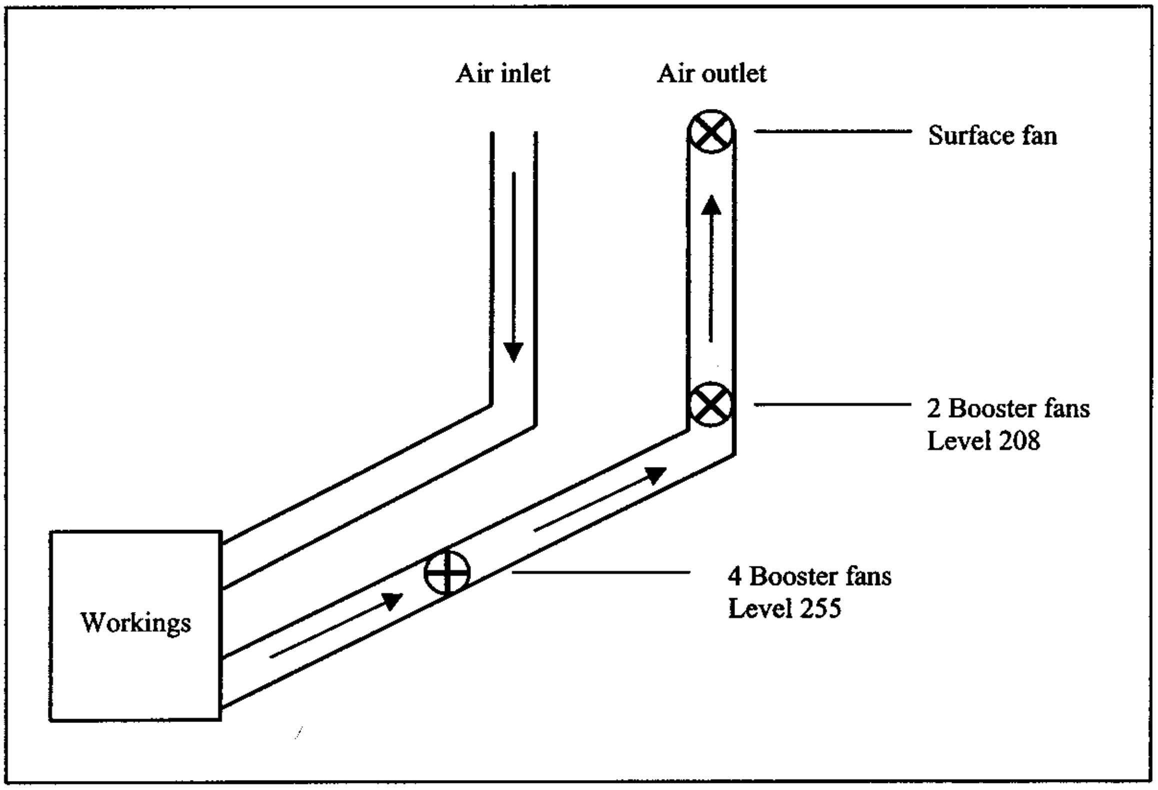


Figure 5- 2: Schematic layout of the mine ventilation system

Mine Energy audit

There are three main energy intensive systems namely refrigeration, underground pumping and ventilation. Refrigeration includes all the compressors and pumps in the refrigeration plant as well as the fans and pumps at the condenser and evaporator ponds. The contribution of each of these to the total energy consumption of the mine can be seen in **Figure 5- 3**.

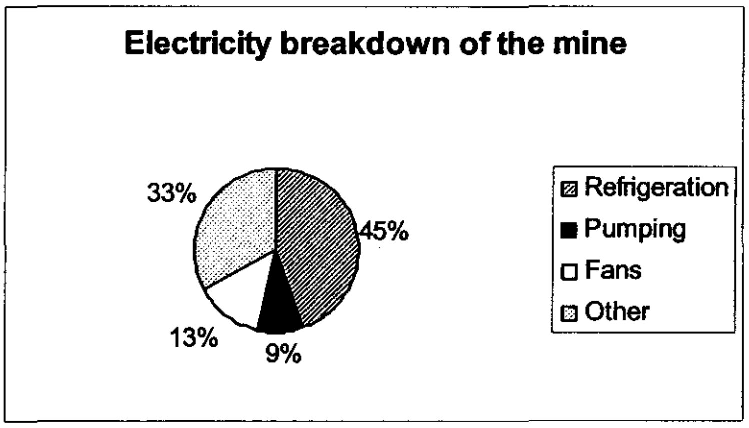


Figure 5- 3: Electricity breakdown of the mine

Other loads include all the winders, general surface electricity use, drills and rigs, crushers, and conveyor systems. The refrigeration and ventilation systems accounts for ± 58% of the mine's mining activities electricity bill.

Mine electricity tariffs and Cost

The mine is currently on the urban NIGHTSAVE tariff structure. This tariff consists of a demand and energy charge. The demand charge is only applicable during peak periods where the mine is billed per kW of maximum demand on a monthly cycle. The energy charge is calculated by taking the total energy (kWh) consumed by the mine for the month and multiply that with the c/kWh NIGHTSAVE urban energy tariff. Currently the mine pays on average R 2.8 million per month for electricity.

Availability of mine data

The mine has a comprehensive Supervisory Control And Data Acquisition (SCADA) system. All underground dam levels and operational pumps are logged. At the refrigeration plant the entering and leaving water temperatures, water mass flows and compressor power are logged for each chiller. For the ventilation system all active fans are logged. Logged data are available at short intervals and historical data is also available.

During the study the air temperature and relative humidity was measured at all the crucial points in the mine. These measurements were taken every minute for a period of four days.

Conclusion

The mine is well suited for this case study. The management is very keen on any savings and open to suggestions, especially as they have very challenging cost targets. The infrastructure is in place to automate the systems under investigation. Thanks to the SCADA system, most of the operational condition data is easily available.

Furthermore the refrigeration plant, as well as the underground pumping system, has large dams that can be used for energy storage. This is a pre-requisite for load shifting and electricity cost savings.

5.3. Development of a ventilation model for the mine

Airflow network

The mine underground airflow network has to be simplified and represented by a flow network as described in Chapter 3. For calculation purposes this flow network will work on the same principle as an electrical circuit. The electrical resistances are replaced by the air flow resistances through the shafts, airways and haulages. The power sources are replaced by the pressure created by the fans. The current is replaced by the amount of airflow through the airway.

The mine ventilation system was studied. With the help of the mine ventilation engineers a simplified flow network to represent the mine system was developed. This new airflow network can be seen in **Figure 5- 4**.

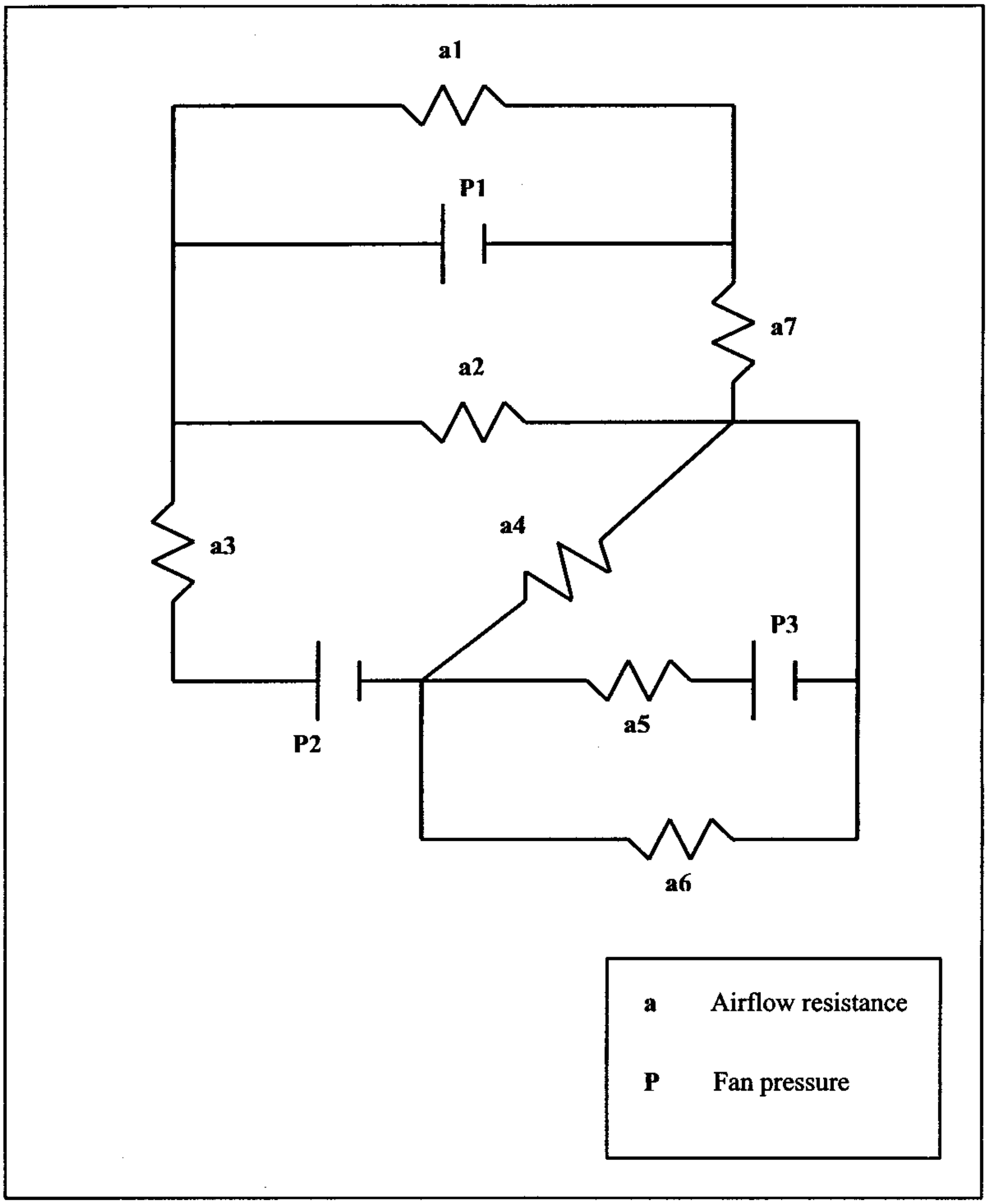


Figure 5- 4: Schematic layout of the simplified airflow network for the case study mine

(Note: The simplified airflow network is not the exact layout of the mine's ventilation system. This network only represents a simplified airflow model to calculate the airflow at specific points in the mine)

P1 = Pressure difference created by the surface fan.

P2 = Pressure difference created by the 255 level booster fans at the evaporator spray ponds.

P3 = Pressure difference created by the 208 level booster fans.

a = The airflow resistance of the airway between each node in the circuit.

(A node is where two or more of the airways come together at a common point)

Like in any electrical circuit it is now possible to generate a series of equations which can be solved simultaneously and so calculate all the unknown airflows and fan pressures in the circuit. This is done by using Kirchhoff's current laws (described in Chapter 4) but revised for airflow and air pressures.

The pressure drop through each airway is a function of the resistance of the airway and the amount of air that flows through the airway.

Pressure drop:

$$\Delta P = aQ^2$$

with :

a = Resistance of the airway

Q = Amount of airflow through the airway (kg/s)

The resistances (a1 – a7) were calculated using measured and design ΔP and Q values for each of the shafts and haulages (airways) in the mine.

There is a pressure drop through each airway. The ventilation fans must overcome these pressure drops. The pressure difference created by the ventilation fans were calculated by applying the model to each of the ventilation fans as described in Chapter 4.

The airflow and air pressures at all the crucial places in the mine can now be solved by applying Kirchhoff's laws on the circuit shown in **Figure 5- 4**.

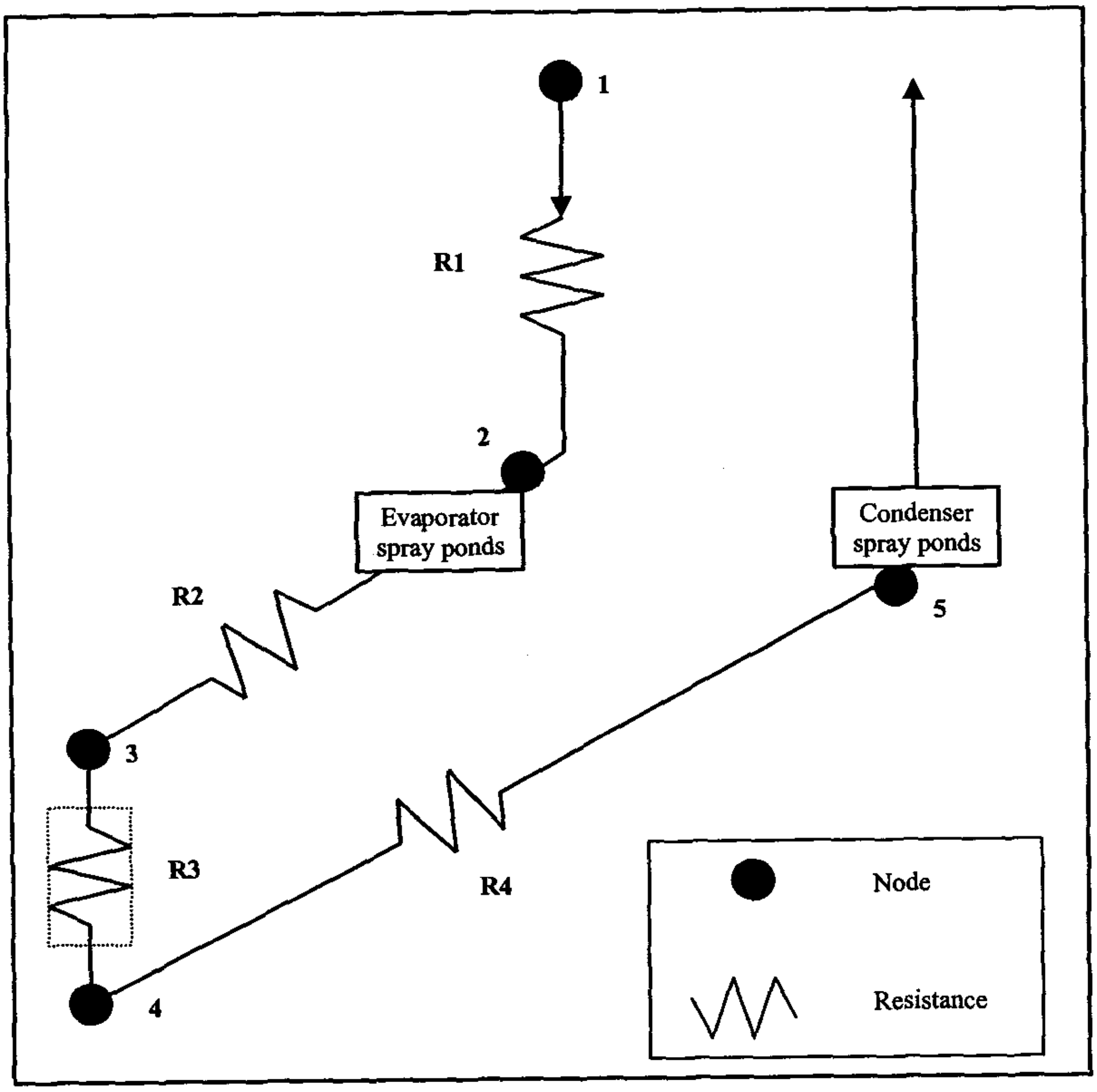


Figure 5- 5: Schematic layout, for the thermal system simulation, of the mine underground

The thermal performance of each airway (shaft or haulage) mentioned above are simulated using the energy balance equations described in Chapter 4. The basic thermal model of a shaft or haulage (airway) is shown in **Figure 4- 5.**

The energy balance of the system in **Figure 4- 5** are written as (described in Chapter 4):

$$C\frac{dT_{shaft}}{dt} = U_{shaft}A_{shaft}\left(T_{rock} - T_{shaft}\right) + m_{air}cp_{air}\left(T_{inletair} - T_{shaft}\right)$$

T_o and W_o. With the help of the psychometric formulas the wet-bulb temperature at the outlet can now be calculated. It is assumed that no mass transfer takes place.

5.5. Development of the cooling model for the mine

The simulation model must predict the inlet and outlet water temperatures to and from the refrigeration plant accurately. The model must also accurately predict the electrical energy consumption of the refrigeration plant. To ensure accurate predictions it is necessary to develop an integrated simulation model. This model will include different smaller models that will each characterise one of the components in the refrigeration system.

These components are mainly, the refrigeration machines (chillers), the condenser and evaporator spray ponds. The compressors, which are part of the refrigeration machines, are the only simulation component that consumes electrical energy. The small water pumps in the system was neglected during the simulations.

The prediction of the compressor motor electricity consumption of the refrigeration plant is essential for electricity saving calculations. To predict the realistic performance for the refrigeration plant the following have to be simulated:

- Thermal performance of the evaporator spray ponds
- Thermal performance of the condenser spray ponds.

5.6. Calibration of the mathematical models to simulate the mine

Background

Some of the developed simulation models do have various coefficients which are dependable on the exact condition or system they have to simulate. In the calibration process all the values of the unknown coefficients are calculated. To calculate these unknown coefficients, mine data was measured specially for calibration purposes. This ensure that the actual conditions of the mine are simulated.

In the calibration process the models are modified and fine tuned to simulate the case study mine exactly. Relevant measured data from the case study mine are used to calibrate each individual model. The procedures for calibration for each model will now follow:

Calibration of the fan mathematical model:

The equation for the pressure created by the fans:

$$P_{total} = K_h \rho_a n^2 D^2$$

with:

$$K_h = a_0 + a_1 K_f + a_2 K_f^2 + \ldots + a_k K_f^k$$

The a_0 to a_k the $k+1$ correlation coefficients derived from actual mine fan performance data. For the fan motor power (Pwr) the following equation are used:

$$Pwr = \frac{m_a P_{total}}{\rho_a \eta_{fan} \eta_{motor}}$$

with the fan efficiency, η_{fan}, calculated with:

$$\eta_{fan} = b_0 + b_1 K_f + b_2 K_f^{\ 2}$$

The b_0 to b_k the $k+1$ correlation coefficients are derived from actual mine fan performance data. Multi dimensional curve fittings were also done on the actual mine fan performance data. These curve fittings were done in conjunction with the above fan equations to solve fan pressures, airflow and fan power.

Calibration of the airflow model

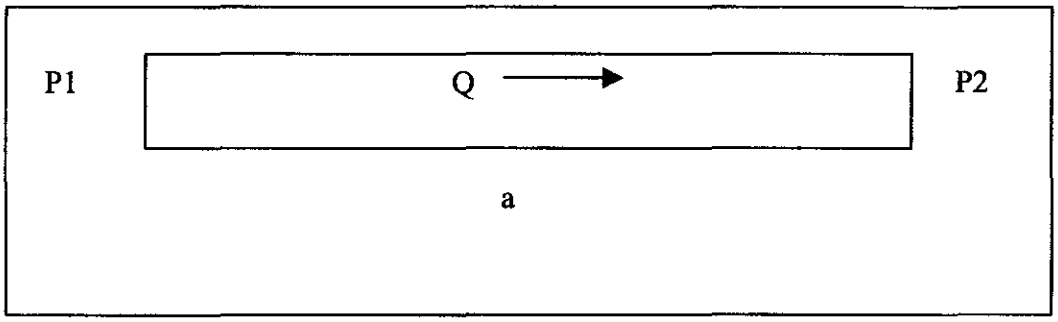


Figure 5- 7: Schematic of an airway

The equation for air pressure (P), air resistance (a) and airflow (Q) (from chapter 4):

$$\Delta P = aQ^2$$

For each airway in the mine, the inlet and outlet pressures were measured.
using:

$$a = \frac{\Delta P}{Q^2}$$

the air resistance for each airway was calculated. The mine airflow network was simplified by combining the airways in the mine (series and parallel) to create the simplest airflow network. This is the network shown in **Figure 5- 4**.

Calibration of the thermal model for the case study mine

The energy balance of the system in **Figure 4- 6** are modified and written as:

$$T_{shaft} = \frac{1}{a}\left[\left(aT^{0}_{shaft} - b\right)\exp\left(\frac{-a\delta t}{C}\right) + b\right]$$

with $$a = U_{shaft}A_{shaft} + m_{air}cp_{air}$$

and $$b = U_{shaft} A_{shaft} T_{rock} + m_{atr} cp_{air} T_{inletair}$$

In the above equations the UA, C and T_{rock} values are unknown. An optimisation solver was used to find the most accurate fixed values for UA, C and Trock for each airway. These values stayed fixed throughout all the simulations and were used in the above equations to calculate the dry-bulb outlet temperature for each airway.

The in and outlet air dry-bulb temperature and relative humidity were measured for each airway. Using the psychrometric equations, the wet-bulb temperature is calculated at each critical point. With the help of the psychrometric equations and simple curve fitting, a fixed relation was found between the dry-bulb, wet-bulb and humidity ratios for each airway in the mine. These fixed relations made it possible to calculate the outlet wet-bulb temperature at the end of the airway from knowing only the dry-bulb temperature and humidity ratio at this outlet. These relations were calibrated for each specific airway in the mine.

Calibration of the refrigeration model for the case study mine

To calculate the motor electricity (pwr) consumption of the refrigeration plant the following equation are used (from Chapter 4):

$$P_{wr} = \frac{m_{lie} m_{lic} c_p \left(a_0 + a_1 t_{lic} + a_2 t_{lie}\right) - Q_e \left(m_{lic} c_p m_{lie} - m_{lie} a_1 - a_2 m_{lic}\right)}{m_{lie} a_1}$$

Measured data was obtained at three different operating points for the chillers. This measured data included all the variables in the above equation except for the calibration coefficients a_0, a_1, and a_2 in the equation shown above. With three equations and three unknowns the values for the coefficients a_0, a_1, and a_2 was calculated.

5.7. Integration of all the models to simulate the whole mine

Backround

The airflow, cooling and heat transfer models now need to be linked to form an integrated simulation model. The air temperatures depend on all three of the mentioned models. The three models will, for each time step, supply the other models with input data. The simulation model can now predict the air mass flow, dry-bulb and wet-bulb temperatures at each crucial point in the mine. The values of these coefficients stayed fixed throughout all the simulations.

To explain the mine layout, a schematic layout in terms of the workings, spray ponds and fans are given in **Figure 5- 8**. This figure also shows the node numbers mentioned in the following section.

Linking the different models:

The following logic was followed in the calculation process:

Step 1 (see the node numbers in **Figure 5- 8**)

Node 1 to node 2:

Input temperatures:	The surface temperatures and outside relative humidity
Input Air mass flow:	Surface air mass flow which is zero
Model and function:	The airflow model will predict the air mass flow The thermal model will predict the dry-bulb and wet-bulb temperatures at the outlet of the airway at node 2.

Step 2

Node 2 to node 3:

Input temperatures:	The temperatures at node 2 as calculated in step 1
Input Air mass flow:	The air mass flow as calculated in step 1
Model and function:	The refrigeration model to predict the dry-bulb and wet-bulb temperatures at the outlet of the evaporator spray ponds.

The airflow model will predict the mass flow of air through the evaporator spray ponds between nodes 2 and 3.

Step 3

Node 3 to node 4:

Input temperatures: The temperatures at node 3 as calculated in step 2

Input Air mass flow: The air mass flow as calculated in step 2

Model and function: The workings model to predict the dry-bulb and wet-bulb temperatures at the outlet of the workings at node 4.

The airflow model will predict the mass flow of air between nodes 3 and 4.

Step 4

Node 4 to node 5:

Input temperature: The temperatures at node 4 as calculated in step 3

Input Air mass flow: The air mass flow as calculated in step 3

Model and function: The thermal model to predict the dry-bulb and wet-bulb temperatures at the outlet of the workings.

The airflow model will predict the air mass flow through the airway (node 4 to 5).

Step 5

Node 5 to node 6:

Input temperature: The temperatures at node 5 as calculated in step 4

Input Air mass flow: The air mass flow as calculated in step 4

Model and function: The refrigeration model to predict the dry-bulb and wet-bulb temperatures at the outlet of the condenser spray ponds.

The airflow model to predict the air mass flow through the condenser spray ponds (node 5 to node 6).

Step 1 to step 5 will happen for each time step. In the simulation of the case study mine a calculation was done for each minute. The result at the end of the hour (60 minutes) were then taken as the value for the hour. With this the model does 60 iterations per hour. This improves accuracy by letting the simulation calculations settle to converge to an accurate answer.

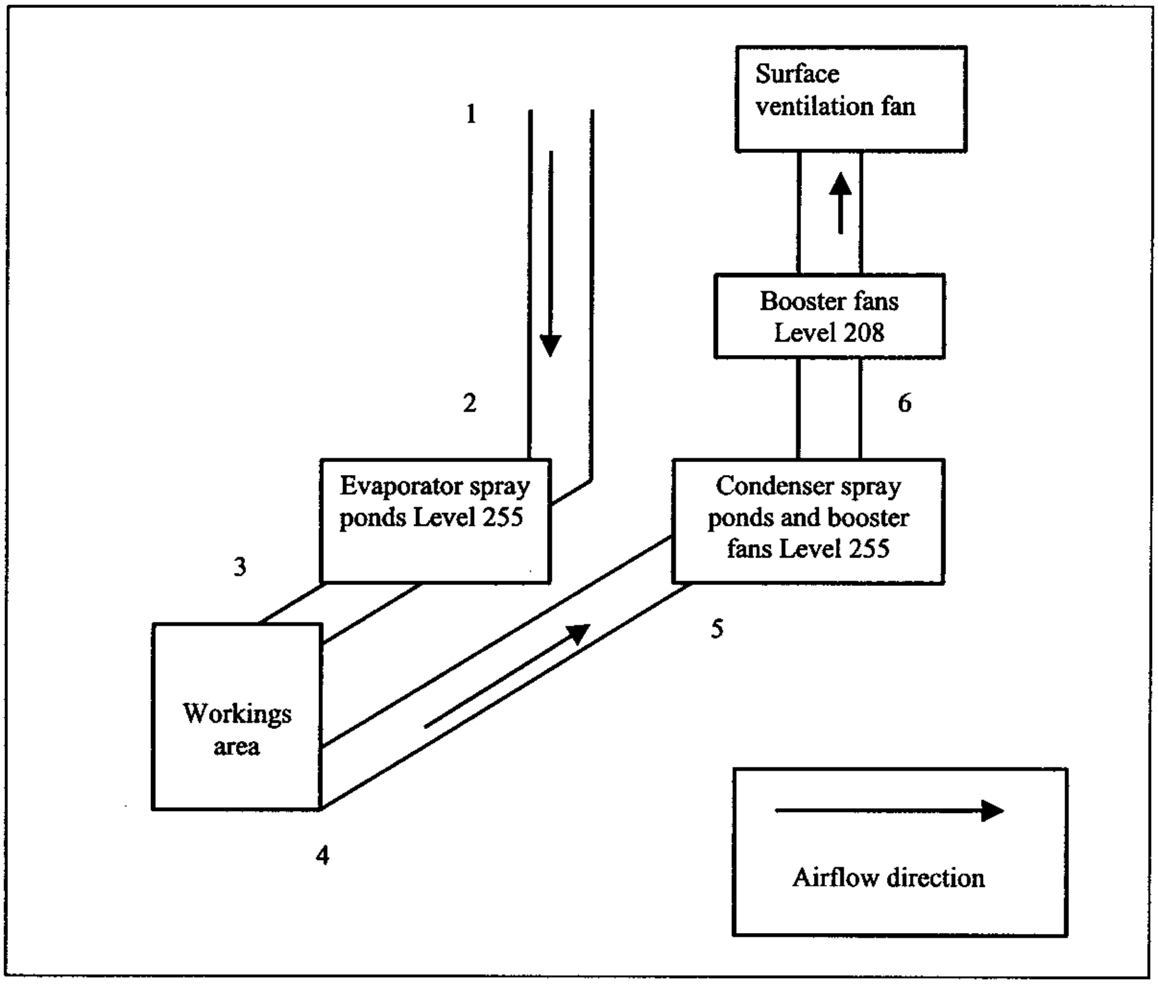


Figure 5- 8: Schematic mine layout in terms of the workings, spray ponds and ventilation fans.

5.8. Verification of the integrated simulation model

Background

After the models are calibrated and integrated into one single simulation model, it is possible to simulate the mine. The model receives input data and will then predict the air temperatures and air mass flow rates at the chosen points in the mine. These predicted temperatures and air mass flow rates are compared with the actual mine measured data over the same time period. The refrigeration and fan motor electricity consumption must also be verified.

It is important to note that a new set of data must be used to verify the simulation model. This new data must be measured under different conditions than those which were used for the calibration of the different models. The verification measurements were taken when two underground spray ponds were temporally not in use. This resulted in being able to verify the simulation models in conditions different from those which the models were calibrated on.

The most crucial environmental location in the mine is the outlet of the workings. It is here that the acceptable environmental and cooling power conditions are most difficult to maintain. This is also the point where the second set of measurements was taken for verification purposes.

Verification of the dry- and wet-bulb temperature at the workings outlet

The real dry-bulb temperature and relative humidity were measured at the outlet of the workings. These were then used to calculate the real wet-bulb temperature at the outlet of the workings. The simulation model was set up for the same conditions under which the verification data was measured.

The simulation model was then used to predict the dry- and wet-bulb temperatures at the outlet of the workings. **Figure 5- 9** and **Figure 5- 10** shows the measured versus the simulated temperatures at the outlet of the workings.

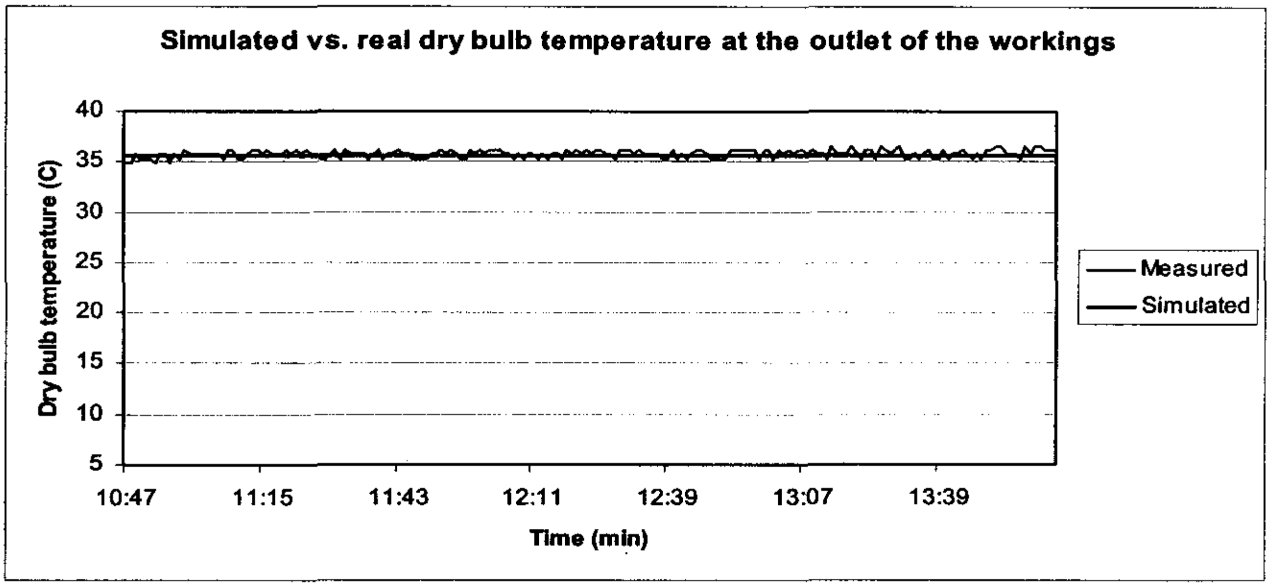


Figure 5- 9: The simulated actual and dry-bulb temperatures at the outlet of the workings.

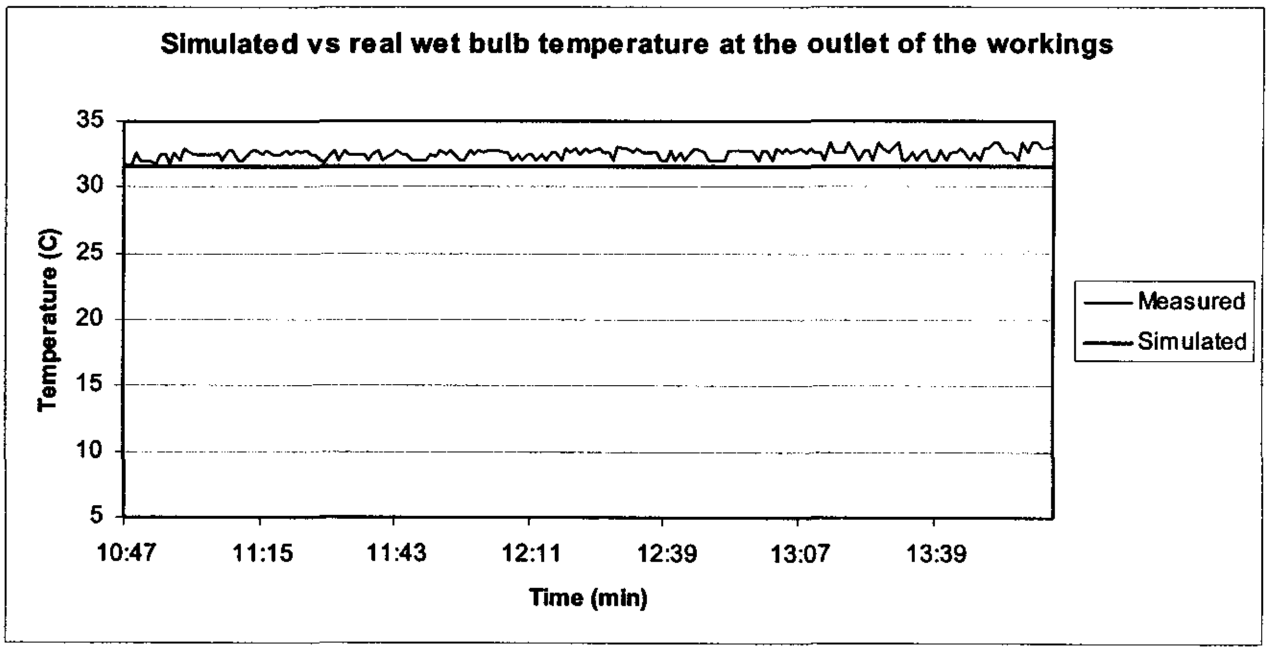


Figure 5- 10: Simulated and actual wet-bulb temperature at the outlet of the workings.

These graphs show that the model simulated both temperatures accurately.

Since the mine operates as close as it can under conditions of stability, there were no major changes in temperature during the time of measurement. Nevertheless, this verified that the model was accurate within acceptable tolerances.

Verification of the air mass flow at the outlet of the workings.

The air mass flow is constant throughout the day. The mine was not able to switch the fans off for measurement purposes. With the real fan r.p.m's and pressure differences included in the simulation model, the following results were obtained:

	Simulated	Measured (Real)
Workings air mass flow rate	274 kg/s	271 kg/s

Table 5- 1: Airflow simulation verification

Verification of the chiller compressor and fan motor electricity consumption

Compressor motor power

The simulated compressor motor power was compared with the measured compressor motor power over the same time period. See **Figure 5- 11** for compressor motor power verification. The graph shows that the compressor motor electricity consumption simulation model was calibrated accurately.

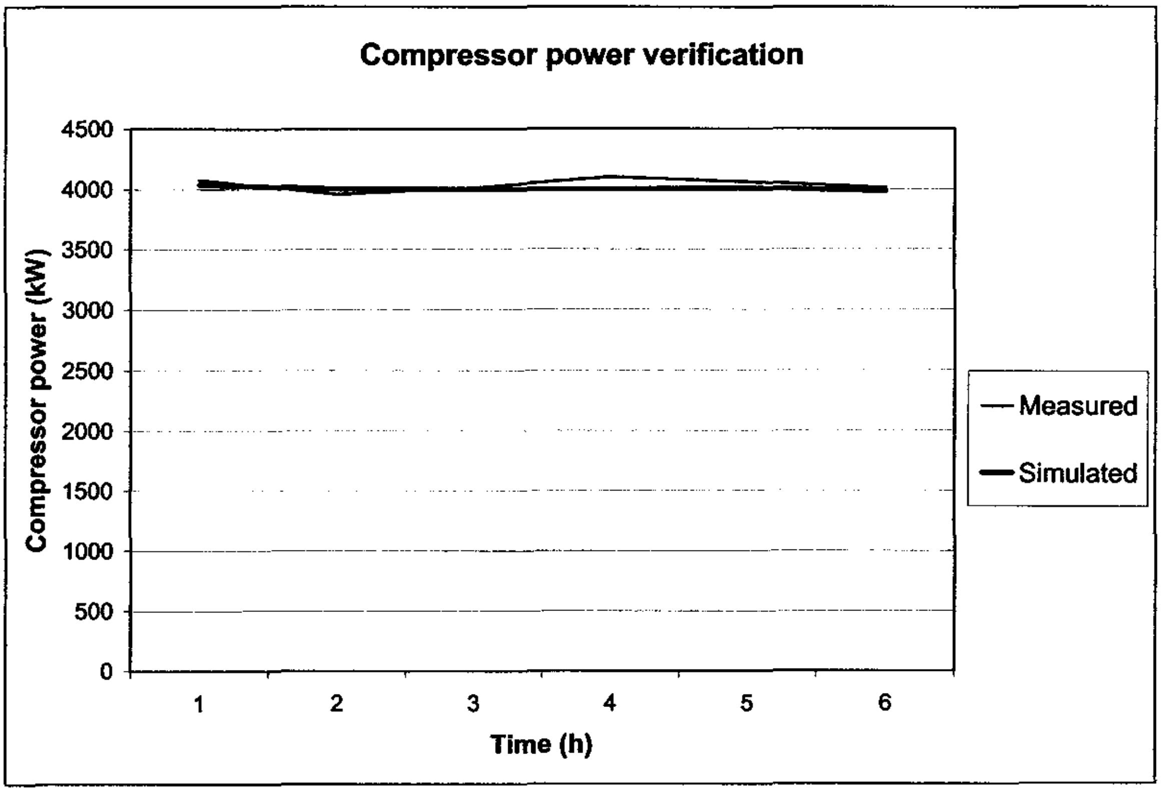


Figure 5- 11: Simulated vs. real compressor power for verification purposes.

Fan motor power

The fan characteristic curves were used to predict the performance of the fans. The motor power were calculated and compared with measured fan motor power. The result shows that the fan motor power simulation model was calibrated accurately.

	Simulated	Measured (Real)
Fan motor power	4389 kW	4317 Kw

Table 5- 2: Fan motor power simulation verification

Conclusion

Through the verification procedure the simulation model was found to be accurate. The temperatures at the inlet of the workings were predicted with an average error of 4.2%. The air mass flow was also predicted accurately. The compressor and fan power were also simulated within the acceptable accuracy limits. The simulated model is found to be accurate enough to do good simulations of the mine.

5.9. Conclusion

A new simulation tool is only as good as its ability to accurately represent the real-life situation or system. A few options are available for determining the validity of new simulation software. The best method of doing so is comparing the software results with actual, measured data from a case study mine and following a well-defined verification procedure.

One mine was selected, according to certain criteria, to test and verify the simulation software. This mine was a gold mine with an underground refrigeration system and comprehensive ventilation system. Simulations were performed and the results were compared to the measurements taken on site at the mine.

It was found that the simulation model delivered satisfactory results considering the complexity and dynamics of the systems that it was required to simulate. These models can now be used for further optimisation of the mine systems.

5.10. References

[1] Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003

6. A NEW REAL TIME OPTIMISATION MODEL FOR UNDERGROUND MINE AIRFLOW AND COOLING POWER

6.1. Introduction

Simulation of underground environmental conditions can only predict what will happen in the mine at fixed refrigeration and ventilation operating parameters. Mines currently operate their ventilation and refrigeration systems to supply fixed cooling and air mass flows. The challenge is to find the optimum air mass flow and refrigeration supply ratio that will provide an Air Cooling Power (ACP) of 300 W/m^2 at the workings. The model must be able to predict the minimum power (kW) needed for this requirement during changing mine conditions. This is extremely difficult, time consuming, and is therefore usually done by trial and error.

6.2. Need for a new optimisation model

For the purpose of this study, optimisation means finding the optimum working point of a system. In our case we need to find the optimum working point for the refrigeration and ventilation systems to supply a minimum ACP of 300 W/m^2 at the workplace using the minimum amount of electrical energy. As described above, the environmental engineers usually do this by trial and error. These trial and error procedures take a lot of time and are not effective due to daily changes in underground conditions.

An optimisation model could predict the minimum electrical energy needed by the refrigeration and ventilation systems quickly and accurately. This model would have to take into account all the environmental and other mine constraints and then carry out an optimisation over and above the simulation.

6.3. From simulation to optimisation

Once one is satisfied that the simulation model does in fact simulate the mine exactly, this simulation model can then be upgraded to also optimise the operation. The optimisation procedure will take place on top of the simulation model. It will change certain variables in the simulation, until an optimum answer has been found. The variables are for example: the fan

RPMs, compressor motor power of the refrigeration plant, etc. The values of these variables, however, are subject to certain boundaries and constraints, which are specified by the mine. They can include minimum and maximum temperatures, airflow, air velocity etc.

The basic elements of optimisation that must be considered are: the boundaries, variables, constraints and the objective function. The way each of these was handled will now be further discussed in detail.

6.4. Optimisation boundaries, variables and constraints

The *objective function* is the value that is dependent on all the variables that must be optimised. In this case, the mine system total energy consumption (kW) is the value that must be minimised while still satisfying all of the constraints.

Boundaries are those values that are independent of any of the outputs of the model, but influence the model directly or indirectly. Boundaries may also need to be calibrated from time to time. The boundaries in this case are the amounts of air leaks through the airways and the electricity price from Eskom.

The *variables* are the values that are changed to minimise or maximise the objective function while still satisfying the constraints. In the optimisation model the fan speeds and the set point of the refrigeration plants are the main variables.

Constraints are the values that enforce the physical operational limits of the system onto the optimisation. The accurate utilisation of these limits is essential to ensure that the outputs of the optimisation are practical and implementable. The constraints applicable on every system will now be discussed.

Underground refrigeration plant

The constraints on the refrigeration plant are the number of chillers available and the cooling capacity of the entire refrigeration plant. Other constraints are the maximum water flow possible and the maximum airflow through the spray ponds.

For the case study mine there are a maximum of 5 chillers available at the underground refrigeration plant of the mine. The total maximum cooling capacity of the chillers is 18 MW. The maximum water flow through the evaporator spray ponds is 380 l/s. The maximum water flow through the condenser spray ponds is 740 l/s. There are 4 condenser spray ponds and 4 evaporator spray ponds available.

Underground conditions

The ideal and maximum wet-bulb temperatures at the outlet of the workings are 25.5 °C and 27.5 °C respectively. The ideal and minimum airflows through the workings are 270 and 225 kg/s respectively. The minimum ACP at the outlet of the workings is 300 W/m^2.

6.5. Calculation of Air Cooling Power

Air Cooling Power (ACP) is calculated using both air velocity and the wet bulb temperature in the mine. **Figure 6- 1** shows the relation between air velocity, ACP and wet bulb temperature. A mathematical model of the data in **Figure 6- 1** is needed for ACP calculations within the optimisation model. A multi dimensional curve fit was done on **Figure 6- 1** to find an equation to calculate the cooling power from air speed and air temperature.

It is important to note that, in the simulation model, all airflow calculations were done in terms of air mass flow (kg/s). The air density and the cross sectional area of the workplace was then used to calculate the air velocity in the workplace in meters per second.

The following mathematical equation was derived for ACP:

$$ACP = \left(0.3119v^2 - 3.2473v - 0.3848\right)T_{wb} + \left(-17.988v^2 + 199.55v - 5.56\right)T_{wb} + \left(244.16v^2 - 2975.6v + 704.37\right)$$

with: v (m/s) representing air velocity and T_{wb} (°C) the wet bulb temperature of the underground air.

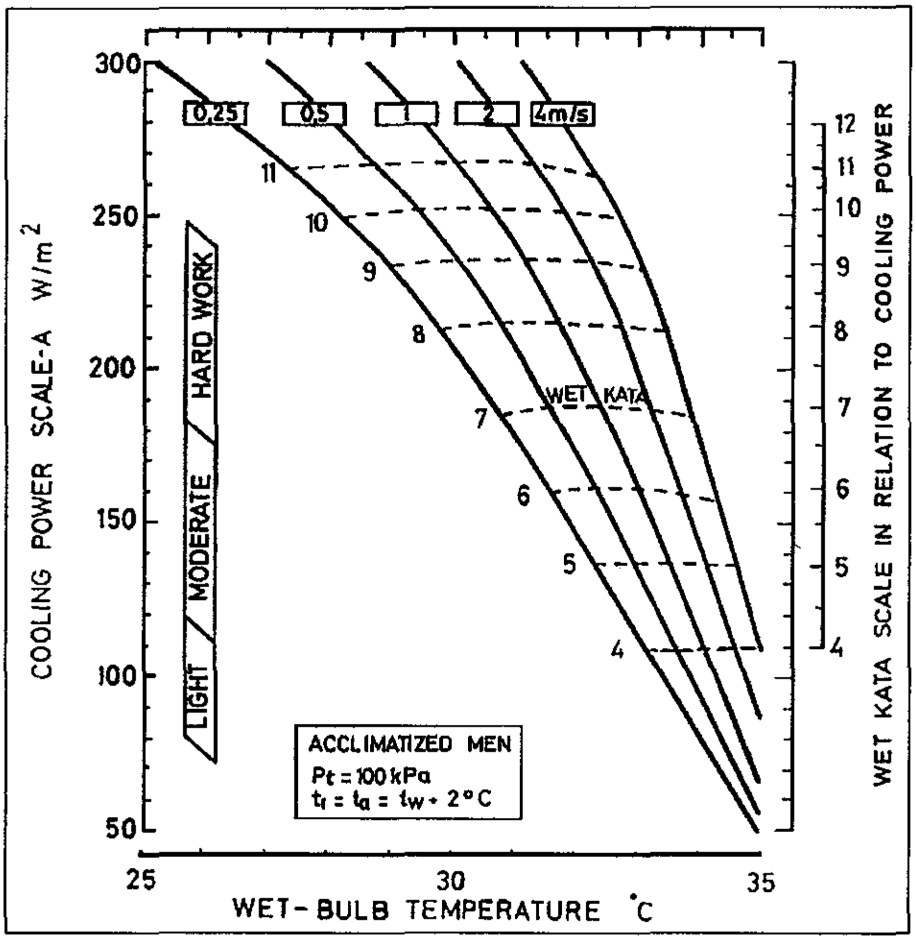


Figure 6- 1: Environmental parameters and Air Cooling Power

6.6. Optimisation of the underground airflow – refrigeration power ratio

The optimisation model will optimise the use of the refrigeration plant and fans in order to keep the workings area at the design temperature of 25.5 °C (wet-bulb) at minimum electricity cost. This involves the optimisation of the set point of the chillers and the revolution speed (RPM) of the ventilation fans.

A further optimisation study was done to limit ACP in the workings to 300 W/m^2. The model optimised the fan speeds and chiller set points to ensure that this minimum ACP be achieved at the outlet of the workings at minimum electricity cost.

6.7. How the optimisation results were obtained

An optimisation tool was applied to the already verified simulation model. In the optimisation calculations, the revolution speed of each ventilation fan, as well as the refrigeration capacity of each refrigeration plant, were set as variables. Within these constraints, the variables were changed until the desired objective was obtained. The objective for each calculation was to supply the acceptable minimum underground environmental condition whilst consuming the minimum amount of electrical energy.

At these optimum conditions, the calculated power consumed by the electrical motors that drive the ventilation fans and the compressors of the refrigeration plants were noted. The electricity consumed by these motors was then compared with the respective data measured from the un-optimised case study mine.

Optimisation procedure

Optimisation calculations were done for two different underground environmental constraints.

1. The design wet bulb temperature to which the mine currently supplies their workplace is 25.5 °C. The ventilation and refrigeration systems were optimised in such a way that the workplace is supplied with a wet bulb temperature of 25.5 °C consuming the minimum amount of electrical energy.

2. The ventilation and refrigeration systems were optimised to supply the underground workplace with an ACP of 300 W/m^2 by consuming the minimum amount of electrical energy.

The results of these optimisation calculations were noted and compared with the relative data measured from un-optimised operational data.

6.8. Optimisation results and electricity cost savings for the case study mine

Background

Through the use of the simulation models and optimisation calculations, the potential sustainable electricity savings were calculated for the case study mine.

Savings calculation

First, the simulation model was set up to simulate the mine underground operations exactly. The cost of electricity was then calculated. After the optimisation study, the cost of electricity was again calculated. These two calculated costs were compared and the difference was taken as the savings potential.

All the savings calculations were based on the NIGHTSAVE energy tariff from Eskom. The optimum cost was calculated using the cost of electricity on the actual daily energy profile measured in 2002. These savings were extrapolated to calculate the monthly savings and added together to get the potential yearly electricity cost saving.

Results

The first optimisation study was done on the compressor motor power of the refrigeration plants, and the motor power of the ventilation fans. The outlet temperature at the workings was kept at the normal mine condition of 25.5 °C. The following potential energy savings can be seen in **Table 6- 1** and **Figure 6- 2.**

	Current mine	Optimised	Energy saving
Main shaft airflow	282 kg/s	290 kg/s	
Refrigeration cooling capacity	17426 kW	16963 kW	
Refrigeration compressor power	4177 kW	3544 kW	633 kW
Ventilation fans motor power	4227 kW	3612 kW	615 kW
Total Power saving			**1248 kW**

Table 6- 1: The potential saving in fan and compressor power for a 25.5 °C wet-bulb temperature.

Table 6- 1 and **Figure 6- 2** shows how the mine can use less energy to maintain the ideal temperature of 25.5°C at the outlet of the workings. The optimisation showed that the compressor power of the chillers and fan motor power can be reduced and the fan speeds could be changed to increase their efficiencies. A continuous saving of 1250 kW could be realised throughout the day. This results in a saving of R1.48 million per year, using Eskom's NIGHTSAVE tariff for 2002.

Table 6- 2 and **Figure 6- 3** show how energy can be saved by optimising the airflow and cooling in the mine to supply a minimum air cooling power of 300 W/m^2 at the outlet of the workings. It was found that the mine had an unnecessarily high air cooling power at the end of the workings.

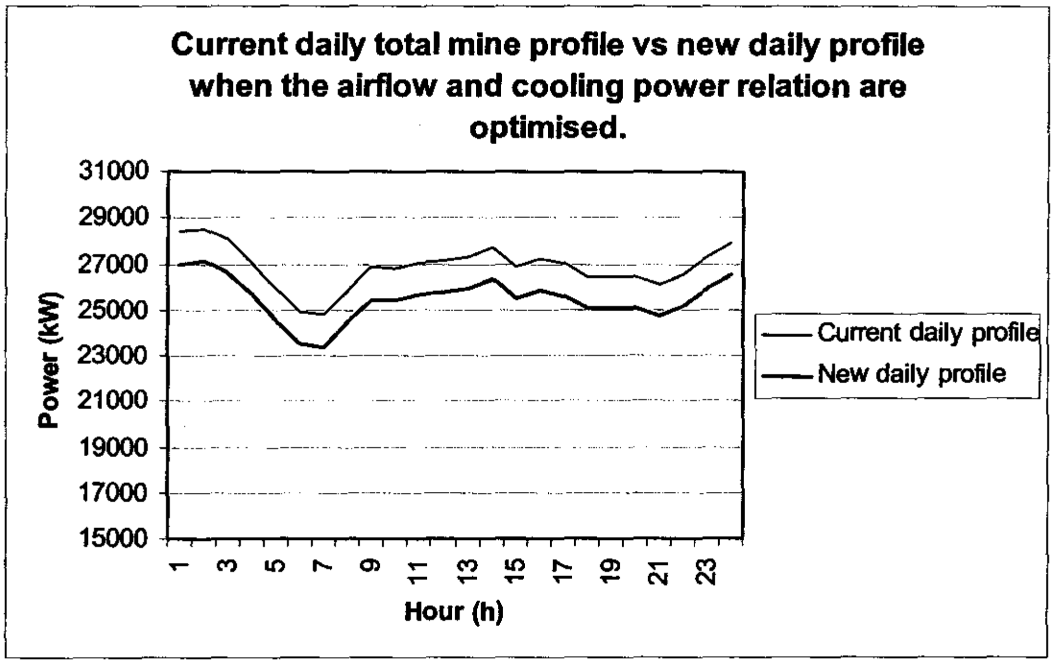


Figure 6- 2: A new daily profile for the total mine when the airflow and refrigeration systems are optimised in relation to each other.

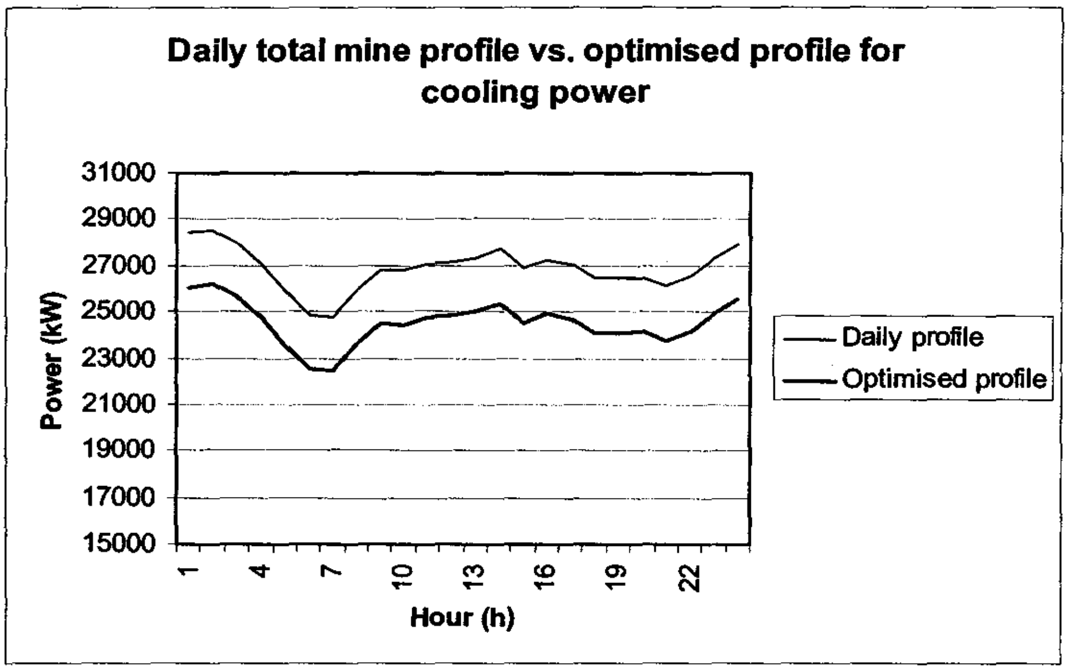


Figure 6- 3: The daily total mine profile of the mine vs. the optimised profile for cooling power.

	Current mine	Optimised	Energy saving
Main shaft airflow	282 kg/s	251 kg/s	
Refrigeration cooling capacity	17 426 kW	14 387 kW	
Cooling power	422 W/m^2	300 W/m^2	
Refrigeration compressor power	4177 kW	3389 kW	788 kW
Ventilation fans motor power	4227 kW	2616 kW	1611 kW
Total Power saving			**2399 kW**

Table 6- 2: The total energy saving for an optimised cooling capacity of 300 W/m^2.

The model showed that a reduction in fan motor power and refrigeration compressor motor power was possible. During the optimisation, the wet-bulb temperature at the outlet of the workings was set to 30.3 °C. With an airflow of 251 kg/s, the minimum cooling power of 300 W/m^2 was realised. The potential saving was calculated at 2400 kW for the day. This yields a monetary saving of R2.55 million per year using the NIGHTSAVE energy tariff of Eskom for 2002.

6.9. Conclusion

Without changing the current mine environmental conditions, the model managed to reduce the electrical energy needed for this condition by 1250 kW. By changing the conditions further to supply only 300W/m^2 at the workplace, the model managed to reduced the electrical energy needed by 2400 kW per day.

It must be stated here that this saving is not necessarily a *net* saving, since capital equipment investments, such as variable speed drives, may have to be made to realise the savings. However, it was clearly demonstrated by these simulations and optimisation calculations, that significant savings in energy costs may be possible.

7. INTRODUCTION TO FUTURE IMPLICATIONS OF THE NEW OPTIMISATION MODEL

7.1. Introduction

This chapter deals with the possibility of extending this new model to new energy management fields. The storage of thermal energy in underground mines is discussed, and how the new model can be applied to assist with efforts to better utilise this energy. This can be done by means of remote energy management.

7.2. Thermal energy storage

South Africa's main electricity supplier is now making Real Time Pricing and "time-of-use" tariffs more desirable for its clients. Clients will be able to realise more savings on their electricity bills when they shift their electrical energy load from peak periods to off-peak periods. Needless to say, the client must be able to do this without affecting their current production rates, or the health and safety of their employees. Thermal energy storage can be the answer for these clients, especially for deep underground mines.

Cool thermal storage was first used commercially in the 1940's in buildings that only required cooling for limited portions of the day or week, such as theatres, churches, and dairies. The goal of these applications was to downsize air conditioning and refrigeration equipment. As the price of air conditioning equipment dropped in the 1950's and 60's, and central air conditioning became more popular, the primary incentive for employing cool storage shifted to energy cost savings and peak load management.

In deep, hot, South African mines, thermal storage is also needed. Since electricity now costs more during peak periods, mines need to store cold energy during off-peak periods for the use during peak periods. New mines are designed with huge chilled dams, so that cold water can be stored in these dams during off-peak periods. During peak periods this water is then used and the refrigeration plants can be switched off or cut back to reduce electricity consumption.

Another method of thermal storage is the storage of thermal energy in underground air and rock. Although this happens automatically by standard underground cooling, it is possible to use this stored energy during peak periods. In the future, the new model developed in this study can be extended to explore the potential of utilising stored thermal energy in deep underground mines.

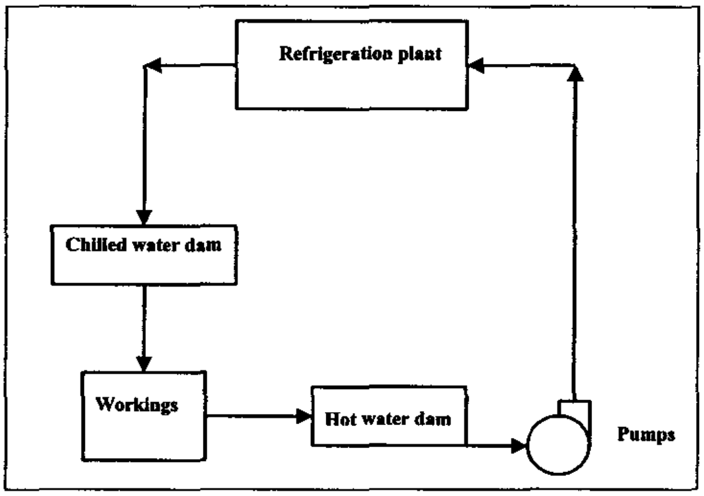


Figure 7- 1 Schematic layout showing the chilled water dam in an underground mine.

The continuous cooling of air and rock in underground mines also leads to the storage of thermal energy in these two mediums. This thermal energy in the air and rock can be used to supply the mine underground with cool thermal energy during high cost electricity peak periods. **Figure 7-2** shows schematically how this thermal energy is stored. In this figure the cooled rock and cold air represents the thermal energy in the mine.

The new model can be applied to explore the possibility to use stored thermal energy in underground air and rock to keep the mine environment and conditions acceptable during peak times.

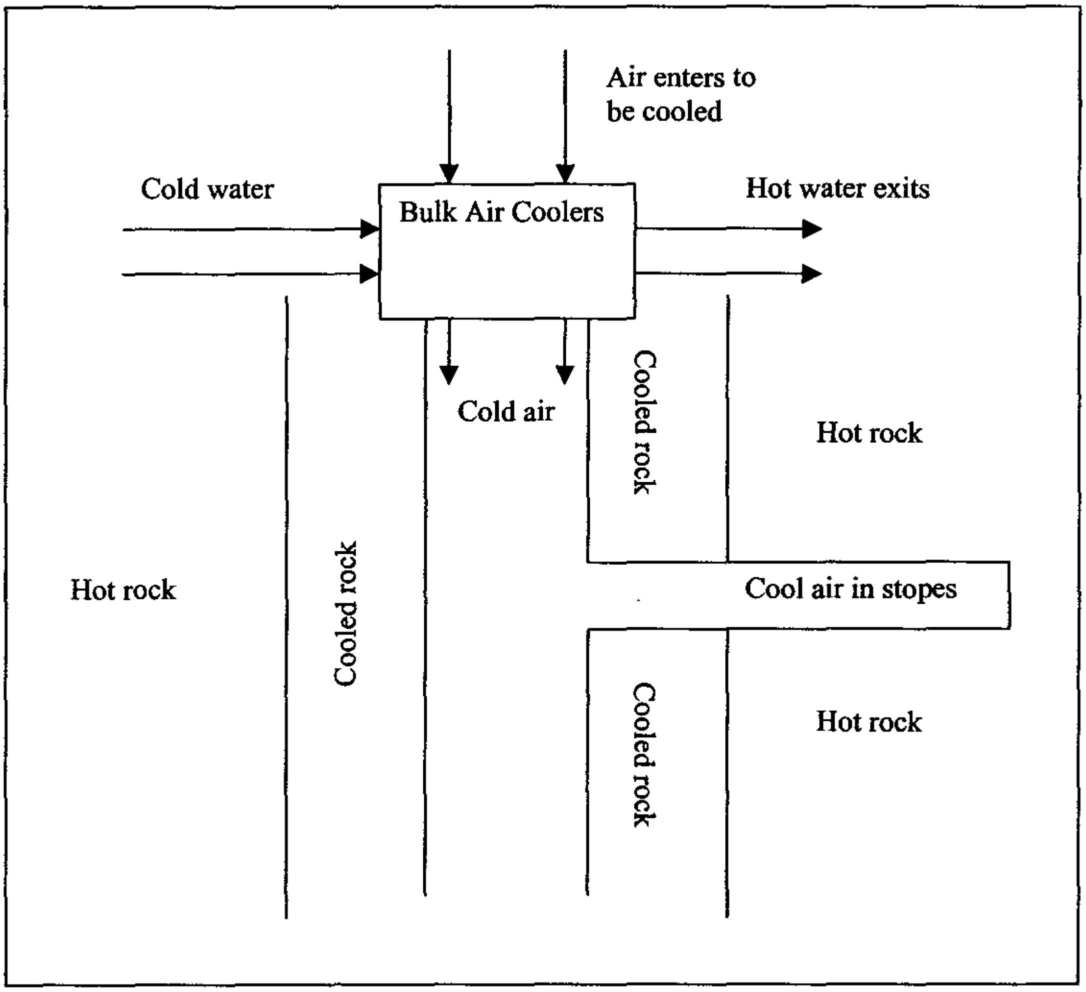


Figure 7- 2: Schematic of how thermal energy is stored in underground air and rock

7.3. Time-of-use electricity tariffs

In the future, the new model can also be applied for better energy management on mines. Under changing mine conditions, the new model must be able to accurately predict the cooling power, wet-bulb and dry-bulb temperatures in the workings.

The model can therefore predict the required performance of the refrigeration plants and the ventilation fans, within specifications, to supply the workings with the correct amount of cooling power using the minimum amount of electrical energy. Currently the model can only predict steady state conditions and have to be revised for dynamic simulations.
With electricity prices changing hourly, the future model can be extended to supply the

workings with the correct amount of cooling power 24 hours per day at the minimum electricity cost taking into account the high electricity cost during peak times.

The optimisation model will automatically change the ventilation fans and refrigeration plant performance to cool the mine more than is required during off-peak times. During peak times the off-peak storage of thermal energy in underground water, rock and air will be used to cool the mine down using the minimum electrical energy.

Example

Assume a Real Time Pricing (RTP) tariff for the day as seen in **Figure 7- 3** below:

Hour	RTP [c]
1	6
2	6
3	6
4	6
5	6
6	7
7	12
8	17
9	19
10	17
11	12
12	18
13	11
14	8
15	8
16	9
17	10
18	8
19	26
20	74
21	30
22	8
23	8
24	7

Figure 7- 3: Typical RTP signal from Eskom. The price values are in cents.

In the mornings from 12 am to 6 am the electricity prices are low. From 7 to 12 am there is a morning peak where the electricity price is high. From 10 am to 6 pm the price is lower but from 6 pm to 9 pm the highest peak prices occur. From 10 pm to 12 am the prices are lower again.

During off-peak times the performance of the ventilation fans and the refrigeration plant must be combined to cool the mine down more than what is necessary. The cold water dam must also be filled to the maximum. During peak times the cold water dam as well as the cold air in the mine will be sufficient to keep the underground conditions acceptable.

The following figures will explain this clearly:

Figure 7-4 shows how the dam level of the chilled water dam at the mine will change as the electricity price changes during a day. When the electricity price is low, the refrigeration plant can operate at full capacity to supply the dam with as much cold water as possible. During higher electricity prices, the cold water in the dam is used while the refrigeration plant will run below capacity as far as possible.

By doing this the refrigeration plant will operate at full capacity during off-peak periods and use minimum electricity during peak periods. The success of this depends on the capacity of the chilled water dam and the quality of insulation of the chilled water system.

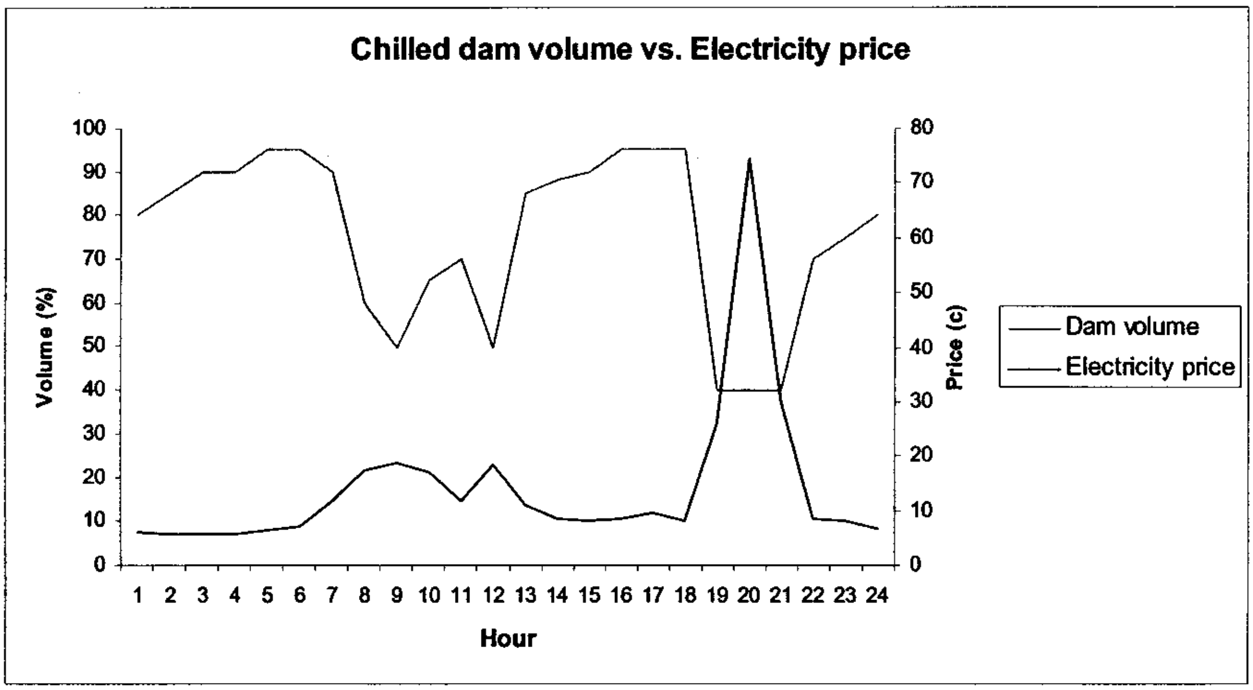


Figure 7- 4: Simulate changes in the level of the chilled water dam as the electricity price changes throughout the day.

Figure 7- 5 shows the amount of electrical energy (Power in kW's) absorbed by the ventilation fans and the refrigeration plant to supply the mine with acceptable cooling power. During the off-peak periods the mine is supplied with excessive cooling power to cool the mine down. During peak periods the ventilation fans and refrigeration plant must supply only the minimum necessary to ensure that the cooling power does not drop below 300 W/m^2 at the workings.

This means that for example 320 W/m^2 is supplied during off-peak times. This high cooling power will cool the mine down and store cold energy in the underground air and rock. During peak times, the ventilation fans and refrigeration plant will only, for example, need to supply an average of 280 W/m^2 during the peak period.

This can be controlled in real time by measuring the cooling power in the workings and then signal the ventilation fans and refrigeration plant to use the minimum amounts of electrical energy to ensure the correct environmental conditions at the workings. **Figure 7- 6** shows how the supply of cooling power at the workings can change as the electricity price changes throughout the day.

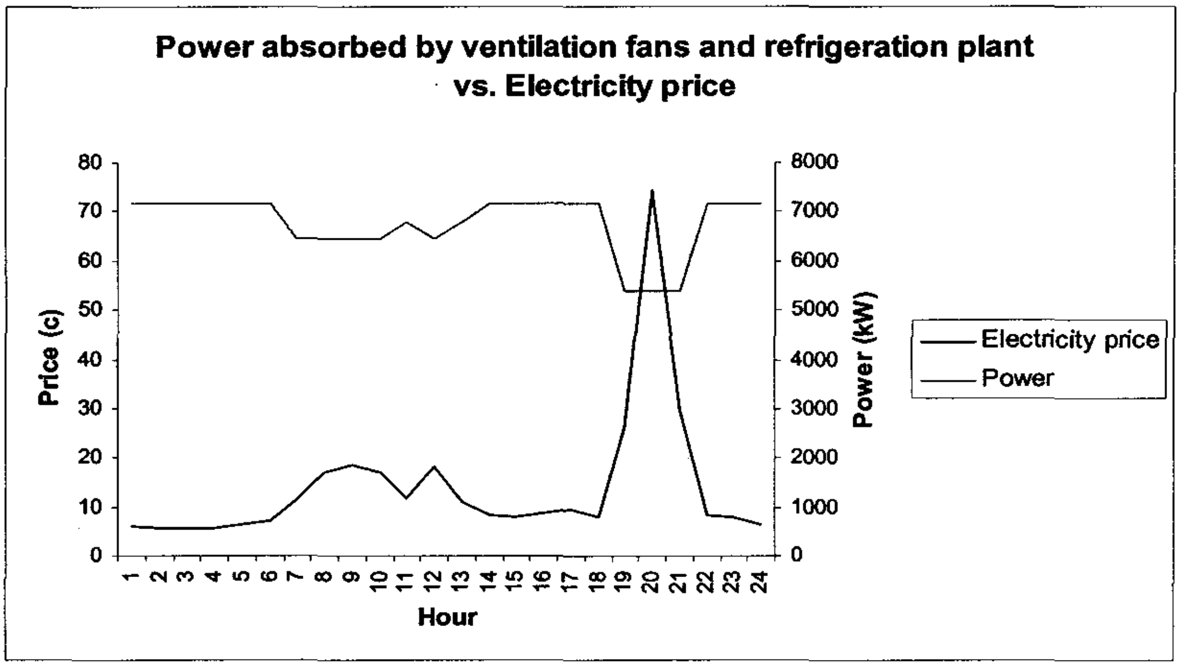


Figure 7- 5: Simulated changes in the power usage of the ventilation fans and refrigeration plant as the electricity price changes throughout the day.

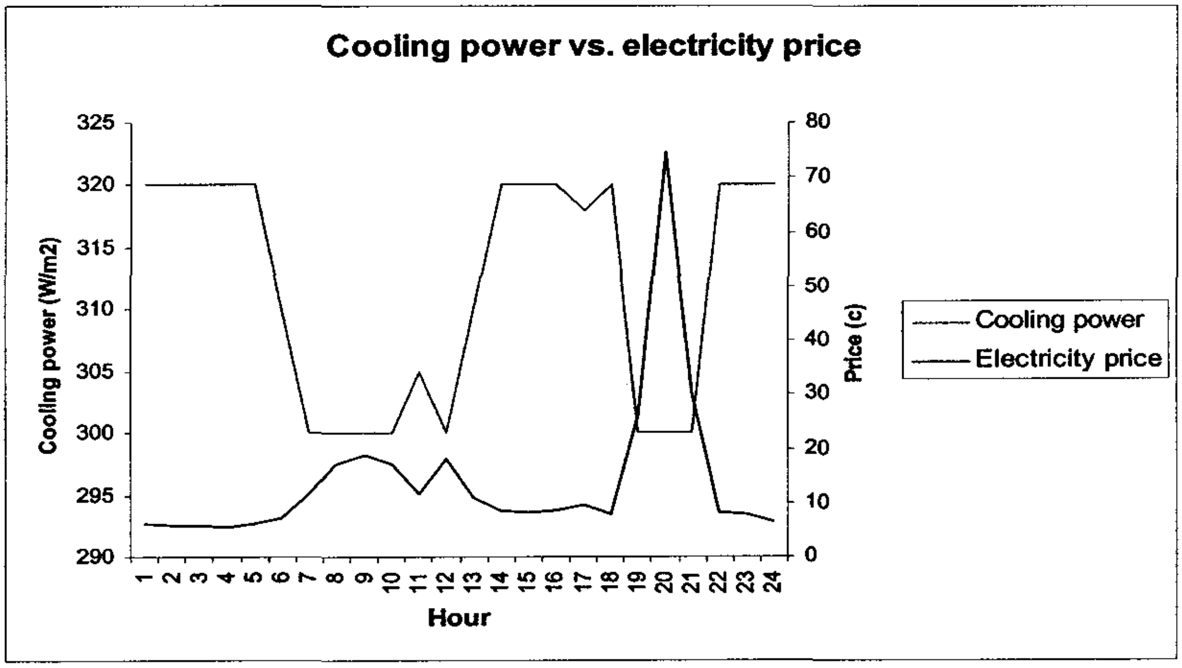


Figure 7- 6: Simulated changes in the cooling power as the electricity price changes throughout the day.

7.4. Remote energy management

At the moment, in most South African mines, a mine control room is used to monitor the conditions underground. A Supervisory Control and Data Acquisition (SCADA) system is used to collect data from underground for display on a computer screen in the control room. The control room operator can monitor the underground conditions from the computer screen and operate the respective equipment from above ground via the SCADA.

This operator needs to watch all the mining equipment like the fans, pumps, refrigeration plant etc. and control them to operate, as far as possible, only in off-peak times. This is a big task for any operator. Experience in this field has shown that the operator cannot always manage this and, because of the human factor, an operator solely for energy management is therefore not a viable option.

To eliminate the human factor, a new product has been developed in South Africa. This product is called Real time Energy Management System (REMS). This system combines current mining conditions, constraints and boundaries into computer control of the mine equipment, in "real time", in order to operate only in off- peak conditions, taking into account an hourly changing electricity price.

This intelligent control system makes use of underground storage capacities to shift electrical load from peak to off -peak periods. Currently REMS is only used to control refrigeration plants and clear water pumps, making use of water storage capacities.

The new model that has been developed in this study, contributes to new efforts made by the engineering industry to control the ACP in a mine. The proposed system will control the ventilation fans as well as the refrigeration plant automatically, to supply the ACP in the workplace at the lowest electrical energy cost.

7.5. Conclusion

Thermal storage during specific periods is already being used in buildings. However the mining industry does not yet use this process to its maximum potential. In the future, the new model developed in this study, can assist with new efforts to explore the maximum thermal energy storage potential in a warm underground mine and be able to do this automatically by means of remote control.

8. CONCLUSION

8.1. Summary and conclusion

The objective of this study was to develop a simulation and optimisation model to calculate the combined optimum working point for the environmental control system of an underground mine.

By gathering information on electricity consumption of the mining industry and future electricity tariff changes, it was found that the proposed optimisation model will be financially beneficial to the mining industry as well as to the electricity supply industry.

A study of underground mine environmental practice showed that the wet bulb temperature and ACP are the two criteria to which mines control their underground air quality. The underground environmental condition will be acceptable if the ACP does not exceed 300 W/m^2 at the workplace.

A secondary objective of this study was to gather information on simulation techniques and available simulation software for the engineering industry. The method of simulation was studied and applied later on in this study. The gathered information showed that comprehensive software tools do exist but they are not specifically designed for ACP optimisation in underground mines.

An easy-to-use simulation model to simulate underground mine environmental conditions was therefore developed. The new simulation model was tested in an actual case study mine. Using real mine data, the simulation model was calibrated and verified. The model was proved to be accurate for the case study mine.

The simulation model was then used for optimisation calculations. By taking into account all the environmental system boundaries and constraints, the calculations showed the following:

- To maintain the *same* underground environmental conditions as those with which the mine is currently supplied, the ventilation and refrigeration systems could be optimised to save the mine 30 000 kWh per day. This could save R1.5 million per year on electricity costs.

- However, if the mine's operating practices were changed to supply the underground workplace with only the accepted ACP of 300 W/m^2, the mine could save 57 600 kWh per day, which translates to a saving of R 2.55 million per year.

Clearly, theses savings are not net savings, since some capital investments may have to be made to realise them. This may include additional control instrumentation and variable speed drives for the fans. Should the mine wish to implement these findings, a separate cost/benefit study would have to be done. This was outside the scope of this study. However, what this study showed unambiguously, was that there were large potential savings to be realised in the optimisation of a mine's underground environmental control systems. In each individual case, the new optimisation model could be applied, and both potential savings and implementation costs calculated. This would enable the mine owners to make a business decision.

Looking to the future, a brief study on RTP, thermal energy storage and remote energy management was done. This showed that a model such as the one developed, in this study could contribute to automatic real time energy management.

8.2. Contributions to the field

This new model, which can not only simulate but also optimise the supply of underground environmental conditions, will assist mines to institute better energy management. This will lead to lower electricity cost for the mining industry, as well as assist Eskom to improve the management of its generation and reticulation facilities.

The fact that energy savings translate to less environmental stress and reduced greenhouse emissions is a fortuitous coincidence. However, this study was designed specifically with the financial gain of the mine operators in mind. For this reason, the secondary impacts, such as environmental benefits, have not been quantified.

8.3. Recommendations for future work

The new model has only been tested at one case study mine. The environmental conditions at this mine did not change rapidly nor frequently, which seems to be the norm in the industry. However, it may be that a mine with a more dynamic, unstable environment would wish to do a similar study. In that case, the model could be applied here and tested to see whether it is rigorous enough for such a condition, and some adjustments may well have to be made.

With some modifications, the new model can also be applied to new Real Time Price offerings from Eskom. It will be able to identify an operating point for the refrigeration and ventilation systems to supply 300 W/m^2 for the workers, in real time, at the lowest electricity cost. The model can set the operating point to cool the mine extra during off peak periods and then use this stored cold energy to maintain 300 W/m^2 during peak times, thus using less electricity.

New intelligent control can also be obtained to control the refrigeration and ventilation systems automatically from a computer. Technically advanced mines can already control the environmental operations from the surface using a SCADA system and a control operator. In the near future, the environmental control operator can be assisted by an intelligent computer driven system which will be able to calculate and apply the optimum combination of environmental control and energy management.

9. BIBLIOGRAPHY

Chapter 1

[1] The Economics Advisory Unit of the Chamber of mines, ***The South African mining industry fact sheet***, Tel. +27 11 498 7100, www.bullion.org.za, 2002.

[2] Lynch, R., ***An energy overview of the Republic of South Africa***, US Department of Energy, Office of Fossil Energy, FE-27/ Germantown Building, 1000 Independence Avenue SW, Washington, D.C. 20585-1290, USA, October 2003.

[3] Pickering, R.G.B, ***Deep level mining and the role of R&D***, SAIMM, Vol. 96 no. 5, September/October 1996.

[4] Mbendi, Information for Africa, South Africa: Gold mining overview, http://www.mbendi.co.za/indy/ming/gold/af/sa/p005.htm, 23 September 2003.

[5] Ramsden, R., **Mine cooling towards the 21st century**, Journal of the Mine Ventilation Society of South Africa, September 1990.

[6] Chadwick, J., ***Deep Mining***, Mining Magazine, January 1997

[7] Haase, H., ***The potential for cost reductions by reducing heat loads in deep level mines***, Journal of the Mine Ventilation Society of South Africa, March 1994.

[8] van der Walt, J., Pye, R., Pieterse, H., Dionne, L., ***Ventilating and cooling of Barricks Meikle underground gold mine***, Mining Engineering, April 1996.

[9] Bailey-Mcewan, M., ***Use of the "chiller" computer program with conventional water chilling installations on South African gold mines***, Journal of the mine Ventilation Society of South Africa, Vol 44 nr.1, January 1991

[10] Stroh, R.M, ***Energy conservation with mine refrigeration systems***, Electricity tariffs and metering (ETAM) and Management and Auditing of Electrical Energy (MAFE), Johannesburg, 13 March 1992.

[11] Marais, D., ***Mine ventilation society alive to the challenges of a new era***, S.A Mining World, Vol. 13, no. 8, September 1994.

[12] Statistics SA, ***Gross Domestic Product, Third quarter 2001, P0441***, Private bag X44, Pretoria, 0001, Tel. +27 12 310 8304, www.statssa.gov.za, 2001.

[13] Eskom NEWS, page 2, May 2003.

[14] Edward J, O' Neal, P.E., ***Thermal storage system***, Achieves operating and first-cost savings, ASHRAE Journal, April 1996.

[15] Kintner-Meyer, M., Emery, A.F., ***Optimal control of an HVAC system using cold storage and building thermal capacitance***, Energy and Buildings, December 1994.

[16] Huang, W., Lam, H.N., ***Using genetic algorithms to optimise controller parameters for HVAC systems***, Energy and Buildings, January 1997.

[17] Ben-Nakhi, A.E., Mahmoud, M.A., ***Energy conservation in buildings through efficient A/C control using neural networks***, Department of Mechanical Engineering, College of Technological Studies, Kuwait, May 2002.

[18] Zaheer-uddin, M., Zheng, G.R., ***Optimal control of time-scheduled heating, ventilating and air-conditioning process in buildings***, Energy conversion and Management, 41 (2000).

[19] Yang, K.H., Su, C.H., Hwang, R.L, ***The analysis on intelligent control strategies of a thermal energy storage air-conditioning system.***

[20] Usta, N., Ileri, A, ***Computerised economic optimisation of refrigeration system design***, Energy Conversion and Management, Volume 40, page 1089-1109,1999.

[21] Matthews, E.H., et al., ***New software for dynamic simulation of mine cooling and ventilation,*** Temm International, Contact no. (+27 12 991 5110)

[22] Delport, G.J., Lane, I.E., ***Electricity cost management in mining***, Power engineering Journal, August 1996.

[23] Lilic, N., et al., ***An expert system for mine ventilation system analysis, Department of Mining Engineering, Faculty of Mining and Geology***, University of Belgrade, Yugoslavia, February 1997.

[24] ENVIRON- ***A comro computer program for the full thermodynamic analysis of a mine environment***, Information leaflet-43, Chamber of mines of South Africa, Research organisation library. For further information: The Director

Environmental Engineering, COMRO P.O Box 91230, Auckland Park, Tel. (011) 726-3020.

[25] VUMA, http://www.vuma.co.za, CSIR, PO Box 395 Pretoria 0001 South Africa, Tel. + 27 12 841 2911.

[26] Webber, RCW., ***Determining the Physical and Economic impact of Environmental Design Criteria for Ultra-deep Mines***, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, University of Pretoria, page 28, 2000

[27] Really cool ventilation system saves Rustenburg's Turffontein, Mining Mirror. August 1998.

[28] MacPherson, M.J., ***Mine ventilation planning in the 1980's***. International Journal of Mine Engineering, Volume 2, page 191-202, 1984.

[29] Els, R, ***Potential for load shifting in ventilation and cooling systems***, Thesis is presented in partial fulfilment of the reguirements for the degree of Master of Engineering, University of Pretoria, page 70, 2000.

[30] Swart,C., Webber, RCW. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003.

Chapter 2

[1] National Electricity Regulator, ***Electricity supply statistics for South Africa 1999***, page 4, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 1999.

[2] Els, R., ***Energy evaluations and load shift feasibility in South African mines,*** Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the University for Christian Higher education, 2003.

[3] Gcabashe. T.S., ***Eskom Annual Report 2001: Eskom Chief Executive section***, Eskom, P.O. Box 1091 Johannesburg, 2001.

[4] Gcabashe. T.S., ***Eskom Annual Report 2000: Eskom Chief Executive section***, Eskom, P O Box 1091 Johannesburg, 2000.

[5] Conradie, D., Eskom, ***Eskom's retail pricing plan: 2002***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[6] Conradie, D., Eskom, ***Eskom Tariffs 2002: NightSave***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[7] Conradie, D., Eskom, ***Eskom Tariffs 2002: MiniFlex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[8] Conradie, D., Eskom, ***Eskom Tariffs 2002: Ruraflex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[9] Conradie, D., Eskom, ***Eskom Tariffs 2002: MegaFlex***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[10] Mkhwanazi, X.H., ***Annual Report 1999/2000: National Electricity Regulator***, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, **www.ner.org.za**, p. 12, 2000.

[11] Mkhwanazi, X.H., Speech on "***The changing regulatory environment during electricity supply industry reform***", to the South African Institute of Electrical Engineers, 8 February 2001.

[12] Radebe, J., MP, ***Policy Framework: An Accelerated Agenda Towards the Restructuring of State Owned Enterprises***, Pretoria, 10 August 2000.

[13] Chalmers, R., ***Eskom's reshaping plans are on track***, Business Day, 28 February 2002.

[14] Department of Minerals and Energy, ***White Paper on Energy Policy for Republic of South Africa***, pp. 28 – 46, DME, Private Bag X59, Pretoria, 0001, Tel: +27 12 317 9000, December 1998.

[15] Mkhwanazi, X.H., ***Electricity market scenarios study***, Report no. NER 01-2001, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, **www.ner.org.za**, 2001.

[16] Department of Minerals and Energy, ***EDI Restructuring update***, Electricity Regulatory Journal August 2001, p.1, NER, PO Box 40343, Arcadia, 0007,

Republic of South Africa, Tel: +27 12 401 4600, **www.ner.org.za**, 2001.

[17] National Electricity Regulator, ***NER licenses South Africa's second IPP***, Electricity Regulatory Journal September 2001, page1, NER, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, **www.ner.org.za**, 2001.

[18] Eskom, ***Demand Side Management's Information Guide for Energy Services Companies***, Eskom, P O Box 1091, Johannesburg, 2000, www.eskom.co.za, 2002.

[19] NER, ***An Integrated Electricity Outlook for South Africa***, National Electricity Regulator, PO Box 40343, Arcadia, 0007, Republic of South Africa, Tel: +27 12 401 4600, www.ner.org.za, 2002. *(Document was only available for a few months till April 2002 for public discussion and planning)*

[20] Africa, A., ***Eskom: Demand Side Management, Short to medium term demand side strategy***, National Energy Efficiency Conference, 17 July 2001, VW Marketing Conference Centre, Midrand, South Africa, http://www.dme.gov.za/, 2001.

[21] Claassen, D.T, ***New procedures to reduce cost in HVAC systems,*** Thesis submitted in fulfilment of the requirements for the degree Philosophiae Doctor in Mechanical Engineering at the Potchefstroom University for Christian Higher education, 2003

Chapter 3.

Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003

[1] COMRO, 1991. ***Heat stress management: A comprehensive guideline.*** Chamber of Mines Research Organisation, User guide No. 22, Johannesburg.

[2] MacPherson, M.J., 1984. ***Mine ventilation planning in the 1980's.*** International Journal of Mine Engineering, Volume 2, page 191-202.

[3] Stewart, J., 1989. ***Practical aspects of human heat stress.*** In: J. Burrows, R.

Hemp, W. Holding and R.M. Stroh (Eds.), Environmental Engineering in South African Mines, page 535-567. Johannesburg, The Mine Ventilation Society of South Africa.

Chapter 4

[1] Bouwer, W, ***Dynamic integrated simulation of mine thermal and energy systems***, Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001.

[2] Law, A.M., Kelton, W.D., ***Simulation modelling and analysis***, McGraw-Hill, 1991

[3] Vladimirescu, S., Zhang, K., Newton, A.R., Pederson, D.O., ***SPICE Version 2.5 User's guide***, Berkeley, CA, 94720.

[4] Stoecker, W.F., ***Design of Thermal Systems***, McGraw Hill, 3rd Edition, page 349-352, 1989.

[5] Taljaard, J.L.F, ***Simplified mathematical models of specific system components for thermal simulation software***. Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001.

[6] Swart, C., ***Integrated simulation of heat transfer networks***. Thesis presented in partial fulfilment of the requirements for the degree of Master of Engineering, Potchefstroom University for Christian Higher Education, 2001

[7] Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003

[8] von Glehn, F., ***Simulation and control of mine ventilation and cooling systems,*** Journal of the mine Ventilation society of South Africa, July/September, page 91, 1999.

Chapter 5

Swart,C., Webber, RCW 2004. ***A Demand Strategy versus a Supply Strategy for Ventilation, Cooling and Pumping Requirements for Deep Mines,*** Symposium, Computer Applications in the Mining Industry (CAMI), Calgary Canada, September 2003.