Simulation Techniques for the Optimization of High Capacity Refrigeration in German Coal Mines

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To improve the climatic environment underground the German coal mining industry has installed refrigerators with a capacity of 300 MW cooling power. One third of this total is accounted for by central refrigeration plants with more than 5 MW capacity. The central refrigeration comprises three stages: mechanical cooling, transport and distribution of chilled water via pipelines and exchange of heat in the air coolers. Of these three stages only the mechanical generation of chilled water has been resolved satisfactorily. Transport (including distribution) and exchange require further technical research.

The Mining Institute of the Aachen University of Technology has done extensive studies on this subject, concentrating on controlling the flow of chilled water according to demand in the mine. Additionally, the favourable exchange in the air coolers is taken into account. The studies are based on a model mine which simulates the conditions in deep coal mines in Germany.

The simulation program represents firstly the condition of the mine air at the location of the air being cooled, then the heat exchange in the air cooler itself, and finally the transport of the chilled water from the central refrigerator to the consumer. The program also reproduces the seasonal and operational changes in conditions of mine air as well as different air cooler designs. A regulated distribution of chilled water is also suggested. Finally, estimations of costs can be made as an aid for further planning.

Introduction

Central refrigeration is described as a stationary installed plant with a cooling power of 5 MW or more, supplying several working places at the same time. The generated coolth is carried by a chilled water circuit, which distributes the coolth to the different working points where, in air coolers, it is transferred to mine air. Nowadays the mechanized generation of chilled water has been solved satisfactory, but transport and distribution and particularly exchange of heat in the coolers need further improvement.

Within the boundaries with support of the DFG (German Research Community), the Mining Institute of the Aachen University of Technology has undertaken extensive studies in developing techniques for a better transport, distribution and transfer of coolth. The proposals have been illustrated by a model and proved with simulation techniques.

In some cases German coal mines use water spray coolers in addition to common heat exchangers (Figure 1). In the water spray cooler the
chilled water is sprayed into the air current so that chilled water and air are in immediate contact. In contrast the chilled water and the air are separated in the heat exchanger by a metallic wall. The most important advantage of the water spray cooler is its insensitivity to dust in the mine air. Its greater construction size is a disadvantage in providing the same cooling power.

To aircondition a working area different locations of coolth transfer are possible, as shown in Figure 2. These include the district, the start of exploitation and shortly in front of or behind the face. For technical reasons the possible locations are limited. The efficient refrigeration of longwall faces has to date proved impossible. Even in front of or behind the face the cooling power is restricted by the narrowness of the drive.

At the start of the district, stationary heat exchangers are working successfully with a high reliability.
Changes in the mine air conditions are caused by the seasonal rhythm of temperature and air humidity on the surface, by the advance of the working areas as well as by different phases in the operating cycle. For economic cooling the heat content of the chilled air should be constant. This can be attained by regulating the chilled water circuit and the air current. The heat content of the chilled air should be chosen in such a way that even under the most disadvantageous circumstances the air cooling is sufficient. At night and at weekends the cooling power can be half the normal.

**Simulation model**

The above mentioned considerations have been tested in a simulation model which represents the climatic and operational conditions of deep German coal mines (Figure 3).

A flow of 500 cubic metres per second of fresh air is distributed at the bottom of the double shaft and courses through the different workings up to the level above. The wasted air is exhausted to the surface through the two outer shafts. The air current in a coal face is limited by its cross section and by the permitted maximum air velocity of 4.5 metres per second. In order to limit the maximum effective temperature to 29°C on a coal face, the necessary quantity of coolth can be determined by climate calculation. The need for coolth for the other underground roadways has to be estimated only.
Western district
Shaft west
Development
Face 1 west
Face 2 west
Face 3 west

Central double shaft
Development
Face 1 east
Face 2 east
Face 3 east
Preparation
Work in course of withdrawal

Eastern district
Shaft east

FIGURE 3. Mine layout for simulation model

FIGURE 4. Central cooling plant

Cooling tower
Chilled water circuit
Pre-cooler
Surface
Toe-in
Backflow
Shaft circuit
High/low pressure heat exchanger
II level
RF = Refrigerator
RF 1
RF 2
RF 3
RF 5
RF 4
Backflow
Mine circuit

MINING: VENTILATION
The cooling water is generated in a central cooling plant consisting of several refrigerators. Three refrigerators and one pre-cooler are located on surface, connected by a shaft column with two other refrigerators and one high/low pressure heat exchanger underground. The water warmed up in the mine is cooled first in the underground high/low pressure heat exchanger. Then it is cooled to 3°C by the underground refrigerators which also transmit their waste heat to the shaft circuit. The water in the shaft circuit is returned where it is first in the pre-cooler and then in the refrigerators. The chilled water is then piped underground into the mine circuit.

In the underground workings the chilled water is transported and distributed by separate water circuits. In the simulation model different locations of air coolers can be taken into account, as well as different cooler designs. This makes it possible to compare the costs of various alternatives.

The simulation of the cooling plant serves for cost calculation purposes and for the final review of the proposals for improved coolth transport and distribution. The necessary programs are written in Fortran 77.

The calculation is divided into two steps. In the first, the climatic situation, the coolth requirements and the cold water circuits in the mine are simulated. In the second, the electric power consumption at the central cooling plant is determined. The weekly consumption of coolth and electric power can be established by calculation of three key values: the maximum and minimum coolth requirements during the production shift and the
Main program: 'The Mechanical Climatization in the Simulation Model'

Start of the program
Definition of the variables
Initialization of the start values from the data file

<table>
<thead>
<tr>
<th>Opening of the go files and result files</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calling of the subprogram 'Simulation'</td>
</tr>
<tr>
<td><strong>Contents:</strong></td>
</tr>
<tr>
<td>- Imitation of the mines' climatic situation</td>
</tr>
<tr>
<td>- Determination of the needed coolth quantity</td>
</tr>
<tr>
<td>- Computing of the currents of chilled water and mine air</td>
</tr>
<tr>
<td>- Imitation of the cold water circuits</td>
</tr>
</tbody>
</table>

| Calculation of the total cooling power   |
| of the total ventilator power            |
| of the total cold water pumping power    |
| of the massflow in each circuit         |
| of the backflow temperature in each circuit |
| of the total massflow of cold water      |
| of the demand for cold at the cooling plant |
| of the total backflow temperature       |
| of the heat transfer along the pipeline  |

<table>
<thead>
<tr>
<th>Transfer of the results to go files</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 runs a week (twice during the exploitation shift, once for the nightshift)</td>
</tr>
<tr>
<td>52 runs a year</td>
</tr>
<tr>
<td>Mapping of formatted tables and back up of the values in the result files</td>
</tr>
</tbody>
</table>

**FIGURE 6.** Flowchart of the main program: The Mechanical Climatization in Simulation model

necessary quantity of coolth at night and over weekends. Assuming three production shifts a day, the first two key values correspond to fifty hours a week. For the rest of the week only half of the cooling power is demanded. This situation is represented by the key value 'night shift'.

The Mechanical Climatization in Simulation model

Figure 6 presents the flowchart of the main program called 'The Mechanical Climatization in the Simulation Model'. After opening up the definition of variables and the opening of several files, the main program starts to work. First it backs up the number of the day and the sign for the wanted key value. To simulate one year the program must iterate 156 times: 52 weeks per year multiplied by three key values a week.

After calling and starting the subprogram called 'Simulation', the position of the coal face and the roadways for the chosen day is calculated (Figure 7). Subsequently the dry bulb temperature and the
Subprogram: 'Simulation'

| Determination of the location of the coal face or kind of drive at the day z |
| Determination of the dry bulb temperature and the mine air’s steam content |
| Exploitation with the lowest need of coolth |
| yes | no |
| Correction of the climatic values at the extension | % |
| Calculation of the heat content of the to be chilled mine air |
| Determination of the need of coolth out of the heat content, command and air current |
| nightshift |
| yes | no |
| cooling power = 0.5 * coolth requirements | cooling power = coolth requirements |
| cooling power g.t. 50 kW? |
| yes | no |
| % | cooling power = 0 |
| 12 runs (one per location) |

Three iteration runs (temperature in the cold water toe-in in the first run only estimated)

| 12 runs (one per location) |
| cooler design? |
| one stage spray cooler | two stage heat exchanger |
| Subprogram: spray cooler I | Subprogram: spray cooler II |
| Subprogram: heat exchanger |
| Calculation of the cold water current and the ventilator power |
| Calculation of the toe-in temperature in the subprogram: 'Pipeline' |

Back to the main program

FIGURE 7. Flowchart for subprogram Simulation

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steam content in the mine air is computed for all the twelve points of heat transfer. The starting point for this process is the yearly trend of climatic values on surface which is determined statistically (Figure 8).

Using the climatic values the heat content of the mine air can be enumerated. The local coolth requirements as well as the cooling power are determined by the difference of the heat content and the characteristic of the regulation, which has to be multiplied with the local mass flow of the mine air. The subsequent calculation only takes into account those areas of mine air with a necessary cooling power of more than 50 kW. After having finished the calculation of the cooling power for all twelve locations of coolth transfer, the program computes the necessary ventilation power and the currents of cold water and air.

For each cooler design a special subprogram is used. To determine the power of a cooler the subprogram makes use of five thermodynamic service conditions: the dry bulb temperature, the cold water temperature at the entry, the dry steam content at the entry, and the two mass flows in the cooler. The cold water temperature initially can only be estimated. To avoid serious errors the toe-in temperature is computed using cold water mass flow which is known after the first run. For this purpose the subprogram called 'Pipeline' determines the coolth transfer from the cooling plant to the location along the pipelines.

Using the new value of the cold water temperature the calculation is repeated. After this loop has been passed for the third time the cold water current and the ventilator capacity are known for every location and control returns to the

![FIGURE 8. Yearly trends, dry bulb temperature and content of steam in mine air during the production shift](image-url)
main program (Figure 6).

Two further subprograms are necessary to determine all the capacities, mass flows and temperatures which are described in the flow chart shown as Figure 6. The first calculates the power consumption of the cold water pumping station, the other the coolth transfer along all chilled water pipelines. For this geographical data as well as technical data concerning current and coolth are stored in the computer.

In the subprogram called 'Cold Water Pumping Station' for every pipe system the calculator searches for the path of the greatest pressure drop and determines the necessary power at the pump. In the subprogram called 'Coolth Transfer' it computes the heat absorption of the cold water or heat emission through the air coolers and back to the cooling plant.

The main program finishes with instructions to provide formatted tables and to back up the results in files.

The Central Refrigeration model

The second main program is called 'Central Refrigeration' (Figure 9). It computes the electric power consumption for the previously determined 156 key values of coolth requirements. The program regards different power inputs at equal coolth requirements by determining an average consumption of electric power. For this reason the necessary rated capacity is computed for all the wet bulb temperatures occurring in the file of the month concerned.

After the start of the program the calculator reads the need for coolth at the central cooling plant, the flow of chilled water in the mine and the wet bulb temperature on the surface. The calculation starts by determining the heat transfer in the high/low pressure heat exchanger (Figure 4). Later, the waste heat of the refrigerators underground is computed. This heat is transported by the shaft circuit and extracted again in the cooling plant on surface. After having determined the heat, extracted by the pre-cooler, the computer calculates the cooling power of the three refrigerators on the surface.

To be able to calculate the refrigerators’ rated capacity in terms of cooling power, the working temperature and the utilization of the plant’s several subprograms are necessary.

The cooling power of the machines underground and on the surface is distributed with the aim of minimizing the energy required at the electric drives. Moreover, a refrigerator’s need for constant working temperatures and the varying efficiency depending on working temperature and utilization have been considered. A further subprogram serves to calculate heat transfer at the pre-cooler.

The simulation is finished after having calculated the average electric power consumption for all 156 key values.

Finally, characteristic data are determined, for example the capacity factor of coolth production as well as the average coolth and...
# Main program: 'Central Refrigeration'

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</table>

156 runs (52 weeks with 3 key values)

- Determination of the need of coolth and the cold water current in the mine
- 15 - 20 runs (depending on the number of the wet bulb temperatures of the relevant month on the surface)
- Calculation of the heat transfer in the high/low pressure heat exchanger
- Determination of the necessary cooling power underground
- Distribution of the cooling power into the underground refrigerators, No. 4 and No. 5
- Calculation of the condensation heat and the warming up of the chilled water in the shaft circuit
- Calculation of the heat transfer in the pre-cooler
- Distribution of the cooling power into the refrigerators on the surface, No. 1 to No. 3
- Calculation of the power consumption of the central cooling plant as a whole
- Calculation of the main electric power consumption

Calculation of the characteristic values: capacity factor and average value of the consumption of the coolth and energy, etc.

Mapping of the formatted tables and back up of the values in result files

**FIGURE 9. Flowchart of the main program: Central Refrigeration**
energy consumption for the year.

Conclusions
Using the above described program for simulation and cost calculations permits one to evaluate proposals for improved transport and distribution of coolth.

In this manner it was found that the model mine's overall costs for the year for air cooling could be lowered from DM 12.6 million to DM 10.6 million by regulation of the cooling power at the coolers. Moreover, it became clear that in the case of high demand for coolth with stationary coolers, water spray coolers are to be preferred to common heat exchangers. The latter are cheaper in the case of low demand for coolth and mobile location.

Finally, the research establishes the following point: air conditioning in the intake airway of a working place can be achieved more cheaply if the coolers are located at the entry to the working place than if they are located short of the coal face, even if the need for coolth is higher in the first case. To place the coolers at the entry of a district only leads to a decline of costs if several locations are to be cooled and if the biggest part of the chilled mine air is coursed through workings which have to be airconditioned.

References