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ENVIRON: A Computer Program for the Simulation of Cooling and Ventilation Systems on South African Gold Mines

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This paper describes an interactive personal computer program, ENVIRON, which simulates cooling and ventilating systems on gold mines. An example of the practical application of the program is given and proposed future developments are discussed.

The program consists of two main modules, HEATFLOW and VENTFLOW. HEATFLOW calculates the heat loads and the effect of air coolers, while VENTFLOW estimates the air flow distribution. As the calculation of the heat loads requires a knowledge of the air flow and vice versa, the two modules are run iteratively until the solution converges. The program is written in Pascal and runs on any IBM-compatible personal computer.

Introduction

As mines become deeper an accurate knowledge of the heat loads and air flow distribution throughout the mine is required in order to design optimum mine cooling systems, ensure a safe working environment and achieve maximum productivity.

A computer program, ENVIRON, has been developed which allows a complete mine to be modelled in terms of its heat sources and sinks, and at the same time allows the air flow distribution throughout the mine to be simulated.

ENVIRON has overcome the major drawbacks inherent in programs which previously existed for the determination of cooling requirements and air flow distribution on mines. Some of these drawbacks are listed here.

(a) The programs were written for mainframe computers which are generally located some distance from mines, with resultant problems of access and turn-round time.

(b) Most programs had to be executed in batch mode and thus were not at all 'user friendly'. This resulted in user resistance.

(c) The programs were generally written in Fortran IV, with the result that the code was usually not structured and did not make the most efficient use of available memory. The programs were very difficult to maintain and upgrade as improved information became available.

(d) The heat load and ventilation calculations had to be performed separately. In addition, the whole mine could not be modelled in one single exercise: the heat flow calculations had to be performed separately for each heat source or sink, with the outlet conditions from one heat source being manually entered as the inlet conditions to the next component in the air flow path.

(e) The user was constrained to a predetermined cooling strategy which did not allow for changing mining practices.

(f) The large air density variations of the ventilation air in deep South African gold mines were not taken into account.

ENVIRON consists of two main modules, HEATFLOW and VENTFLOW. The two modules have been designed in such a way that they may be run separately as stand alone programs, or as part of the ENVIRON program to perform a complete thermodynamic analysis of a mine.

The different heat sources and sinks in a mine, termed boxes, are linked together in a network representing the mine air path layout. HEATFLOW, using an air flow distribution previously calculated by VENTFLOW or manually entered by the user, determines the total heat load on the ventilation air for each of the boxes of the network sequentially. The calculations follow the same path as the air flow through the mine. The user is allowed complete freedom in devising a cooling strategy for the mine. This is achieved through taking into account the use of chilled water in stopes and development ends, and the optimum positioning of air coolers throughout the mine. VENTFLOW, on the other hand, using temperatures calculated by HEATFLOW or manually entered by the user, determines the air flow distribution pattern throughout the mine based on a mass balance. The two modules are thus accessed by ENVIRON iteratively until the solution converges.

The necessity to provide a flexible tool for the simultaneous determination of cooling and ventilation requirements on mines and the increased availability of personal computers in ventilation departments, led to the development of ENVIRON on IBM (or IBM-compatible) personal computers. The user of ENVIRON would normally have little or no computing experience, and hence the program is very 'user friendly'. To this end, the programming language chosen was Pascal, a highly structured language, which means that efficient, readable and easily maintainable code is produced. ENVIRON is fully menu-driven, makes extensive use of 'windows', supplies typical values for data required from the user and includes an on-line 'help' facility.

This paper discusses the two main modules separately and then describes some of the features of ENVIRON and an example of a practical application. Future developments are also discussed.

The HEATFLOW module

The heat sources and sinks which can be used to build up an entire mine are shown in Table 1. The user identifies the heat source and sink boxes and how they are connected on a mine air path layout.

Node numbers are assigned to the start and end points of the boxes. These numbers are used to locate the boxes correctly relative to each other within memory and to ensure the correct air flow pattern through the

TABLE 1.
Heat sources and sinks used in representing mine air path layout

Shafts
Tunnels
Stopes
Development ends
Air coolers
Fans
Hoist chambers
Spot heat sources
Shaft station areas
Subnetworks
Recirculation subnetworks
Dummy boxes

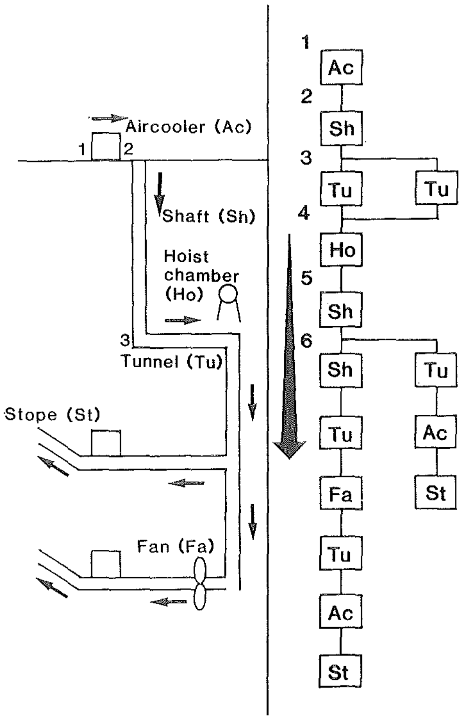

FIGURE 1. Mine airpath layout and equivalent network representation

network. The number of boxes which can be used to represent a mine is virtually unlimited.

On input of the inlet and outlet node numbers and the type of box, the program positions the box on the screen relative to the rest of the network such that the air flow path progresses down the screen. Figure 1 shows a simple mine air path layout and the equivalent network representation. Within each box, the heat flow from the rock and other sources is determined and is used to calculate an outlet air temperature for that box. This calculated outlet temperature is used as the inlet temperature for the box immediately downstream. If the air flow from more than one box joins to flow into this next box (as, for example, when air flows through two parallel tunnels and then meets), a full thermodynamic balance is performed to obtain the mixed inlet temperature. The outlet wet- and dry-bulb temperatures for a box may be overwritten by the user if more accurate data are available; the heat flows predicted for subsequent boxes are then based on these temperatures. This facility can be used to ensure that predicted values throughout the mine correspond closely with actual data. The algorithms used to calculate the heat flow in each box are described in the following section.

Algorithms used to determine heat flow to air

For each of the boxes, the calculations are broken up into three steps - firstly the determination of the overall heat flow into the box, secondly the moisture evaporation rate, and finally the change in the air condition, which is determined using standard psychrometric relationships.[1]

One of the components of the overall heat flow into a box is the heat flowing from the hot rock surrounding the excavation. Bluhm et al.[2] have reviewed the basic theory relating to heat flow from rock into underground excavations. The basic theory makes the simplifying assumptions that the excavation is produced instantaneously, that the air temperature remains constant, and that the rock is homogeneous and has a uniform initial temperature. HEATFLOW makes use of established models based on this theory and on empirical data to determine the heat flow from the rock. These models will be replaced by more accurate and detailed versions as they become available.

With regard to the moisture evaporation rate, three methods are used. Firstly, the process change is described in terms of an enthalpy/moisture ratio which is input by the user. This parameter, which describes a path on a psychrometric chart, is widely used in the air conditioning industry.[1] Secondly, the program makes use of wetness ratings. This is an approach which has been widely used in the past. The parameter used to describe the ratings has been variously known as a wetness fraction, wetness factor, wetness, equivalent wetness and footwall wetness. HEATFLOW makes use of a related parameter, the wetness rating, which, although subjective, is very flexible and can be used to correlate predicted temperatures with measured data. There are five degrees of wetness rating: bone dry, fairly dry, damp, fairly wet and totally wet. A third method is used for situations where the calculation of the moisture evaporation rate with any accuracy is difficult, for example at the stope face. In these cases the user must specify the difference between the wet- and dry-bulb temperature of the air leaving the box.

The algorithms for each of the boxes are described below.

Shafts

The change in air condition is determined by considering the effect of adiabatic compression, heat flow from the surrounding rock and the heat flows associated with artificial sinks or sources (for example,water pipes or power cables).

The effect of linear heat sources or sinks is calculated from the input value of the total heat transfer and the enthalpy/moisture ratio describing the process change of the air due to this heat source.

In determining the heat flow from the rock, the shafts are assumed to be circular in cross-section, to have no variation in surface temperature around the perimeter and to experience radial heat flow only. Any moisture on the surface is considered to be evenly distributed around the perimeter which may have varying degrees of wetness. The heat flow model is based on the work of Jaeger and Chamalaun,(3) and details of the shaft geometry and age must be input.

Tunnels

The change in air condition between the inlet and outlet of a tunnel is determined by considering the effects of the heat flow from the surrounding rock together with the heat associated with artificial sources or sinks. The tunnel may be horizontal or inclined and, where necessary, adiabatic compression is taken into account.

The effect of linear heat sources, as would result from the use of diesel locomotives, drains, hot and cold water pipes and so on, is calculated directly from the input value of total heat transfer and the enthalpy/moisture ratio describing the process change of the air due to this heat source. If the tunnel contains any spot heat sources (or sinks) the user is required to divide the tunnel into several tunnel boxes with the heat sources or sinks inserted in between and treated as separate boxes.

The effect of the heat flow from the rock is calculated by assuming the tunnels to be rectangular in cross-section with surface moisture on the footwall. Figure 2 schematically illustrates the boundary conditions and the heat flow processes taking place simultaneously in tunnels. The heat flow is calculated using a model based on the work of Hemp,(4) which was developed from a data base of finite difference solutions and an interpolation scheme.

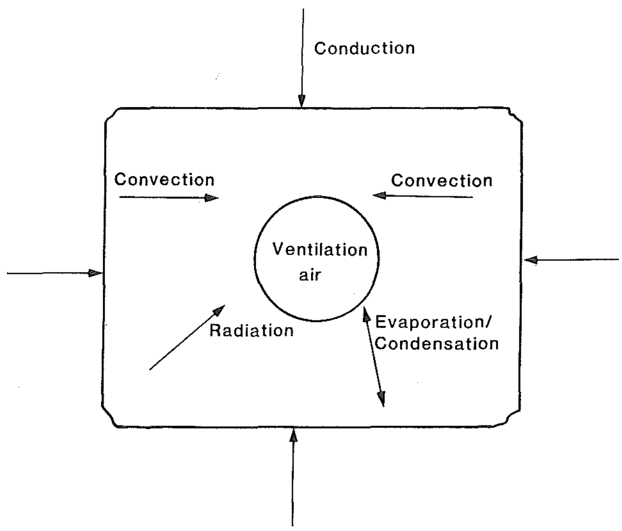

FIGURE 2. Schematic of heat flow processes in tunnels

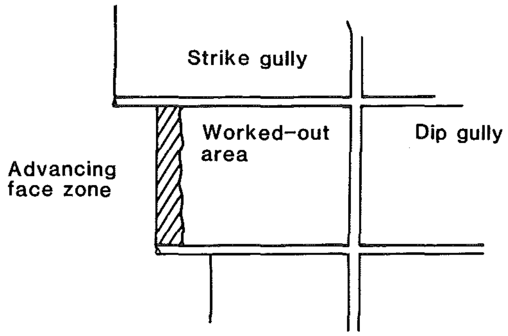

FIGURE 3. Layout of part of stope

Stopes

In modelling a stope, the overall layout is divided into the production zone (which is characterized by wet rock surfaces and high air velocities), the worked-out area and the reef developments (Figure 3). A variety of different stoping layouts is possible and depend on the geometric parameters that are input. Both scattered stoping and different longwall arrangements are possible. The heat flow from the rock is calculated on the basis of one-dimensional conduction in parallel slabs, with the broken rock being assumed to leave the stope at the inlet dry-bulb temperature of the ventilation air.[5] Other heat sources that are accounted for are men, machinery, explosives and the heating and cooling effects of fissure and service water. Additionally the effects of backfill can be modelled by reducing the heat flow from the worked-out area by the fraction that is backfilled.

Only the total heat flow to the air stream is predicted, with no differentiation being made at present between sensible and latent heat components; that is, no attempt is made to predict the evaporation rate independently. The outlet moisture content of the air is determined from the difference between the wet-bulb and dry-bulb temperature at the outlet of the stope, which is input by the user.

Development ends

In HEATFLOW, development ends are treated as boxes with single inlets and single outlets. Three types of development end may be modelled: two of these are single tunnel developments, with forced or exhaust ventilation and the third is a twin development, where one tunnel is used as an intake and the other as a return airway. The change in air condition is determined by considering the heat flow from the rock, the effect of both service and fissure water and any other artificial heat sources or sinks that might be present. In evaluating the flow of heat from the rock, the development end is divided into two areas. The first of these includes the face and first 50 m of tunnel. In this region the model of the heat flow from the face, broken rock and standing rock is based on the work of Whillier and Ramsden.[6] The remaining area of the tunnel is treated like a new tunnel.

The model calculates the total heat flow into the development end and does not differentiate between sensible and latent heat components. The outlet moisture content is determined from the difference between the wet-bulb and dry-bulb temperature at the face zone, which is input by the user.

Air coolers

The heat transfer in air coolers is determined from either an estimate of the cooling duty or an estimate of the outlet air temperature. The air leaving the cooler is assumed to be saturated.

Hoists

The heat load due to the operation of hoisting machinery is assumed to be a proportion of the rated power. Only sensible heat transfer is taken into account, and all of this heat is transferred to the air at the location of the hoist.

Fans

The entire power input to a fan is dissipated as heat which manifests itself in the air stream as sensible heat.

Spot heat sources

Provision is made for spot heat sources such as electric motors or pumps. In this case latent as well as sensible heat is taken into account.

Shaft station areas

Within about a 200 m radius of a shaft there are many interlinking tunnels and excavations and also numerous installations of heat generating equipment. Besides the major plant installations which include hoists, refrigeration machines, booster fans and main dewatering pumps, there are also many smaller scattered items of equipment. The larger individual items of equipment affect the environment substantially and should be treated as separate boxes within the network. The shaft station box is included to model the smaller items and the maze of excavations. The user estimates the length of all the tunnels and also the total average power of all machinery in the shaft station area. The model defines an equivalent tunnel and the heat flow from the rock surrounding the excavations is determined using the Whillier and Ramsden(6) approach for tunnels. All the air leaving the shaft at the station is considered to absorb the combined heat load.

Sub-networks

Sub-network boxes can be used to give a clear, simple representation of a complicated sub-region of a mine when only the inlet and outlet conditions of the sub-region are required as part of an overall layout. The details of the sub-region are viewed independently. The only restrictions placed on the use of a sub-network box are that the network being represented does not contain any other sub-network boxes and it must have only one inlet and one outlet.

Controlled recirculation of ventilation air is modelled using the recirculation sub-network box.

The VENTFLOW module

The VENTFLOW module is used to determine the ventilation flow rates throughout the mine and hence those applicable to each of the boxes discussed above (each box becomes either an airway, a fan, a regulator or an equivalent airway). There are numerous ventilation network programs available (7,8) but most do not take advantage of developments made in modern computer technology. In addition many are not designed to accommodate changes in psychrometric properties in deep mines, where significant air density and temperature changes occur. Also many of the existing programs are proprietary. The need for a ventilation network analysis module, which was compatible with HEATFLOW, led to the development of VENTFLOW. The module can also be run as a stand alone program.

In VENTFLOW, the Hardy Cross (9) network analysis procedure is applied to the solution of mine ventilation networks. Essentially this procedure is a trial and error method which does not require the solution of the large matrices associated with a mine ventilation network. A network of nodes and branches is established to simulate the air flow paths through the mine and each branch is assigned a resistance value. A pressure source or fixed flow is specified in one or more of the branches; the solution yields the distribution of air flow through all branches of the network.

The network solution is based on a fluid analogy to Kirchhoff's laws. Firstly, the mass flow rate is conserved at all the nodes, and secondly, the total pressure drop in traversing a closed path (or mesh) is equal to zero.

The pressure drop, P, of an individual branch with a resistance, R, and a mass flow rate of $\dot{m}$ is given by:

$$P = R\dot{m}^n \qquad [1]$$

The exponent, n, can take any value in the range 1,75 - 2,2, depending on the nature of the flow. The user is allowed to specify the value of this exponent for each branch (most other programs use a value of n = 2 for the whole mine).

VENTFLOW computes all the airflows through the fans, airways and regulators. The user is allowed to fix the flow in certain airways to achieve the required airflow distribution. This is a useful feature during preliminary runs to determine the required fan duty before selecting fans. Control of air flow distribution in a mine is achieved by booster fans and regulators.

Fan characteristics are usually supplied by manufacturers in the form of a pressure/ volume curve measured at standard density. The data points are read from the operating region of the fan curve and a regression polynomial is fitted through the points. This allows the fan to be placed at any position within the network, with density changes in the air being accounted for automatically.

In simple incompressible flow models, the effect of a natural ventilation pressure is usually incorporated by adding constant pressure fans to appropriate branches in the system (usually the shafts). Since the values of temperature and elevation for each node of the network are part of the input data, VENTFLOW calculates a natural ventilation pressure for each mesh automatically.

The accuracy of the network solution is strongly dependent on the resistance value assigned to each airway. The user may choose one of three methods of describing airway resistances. Firstly, Atkinson's friction factor may be used. Secondly, the user may describe the airway in terms of physical dimensions and surface roughness from which a friction factor is calculated.(10) Finally, measured values of pressure drop and airflow across an airway may be input.

Shock losses due to bends or changes in area are modelled as an additional equivalent length of airway.

Air flow through worked-out areas or leakage through ventilation doors can be modelled as flow in the laminar regime by setting the exponent in Equation [1] equal to unity. In this case airway sizes are not known and the resistance value must be determined by measurement.

The ENVIRON program

The program is fully menu-driven. A brief explanation of each menu option is displayed as the cursor highlights the option. In the 'defaults' option, typical values for the current run are set. For example, a shaft diameter fixed in this option will cause any shaft box created to default to this value. In addition, global parameters such as surface barometric pressure can also be set in this option. During the input of the details of a box, default values are displayed and may be altered by the user. The user is not allowed to leave the input form until all necessary parameters (that is, those parameters for which no default value is provided) have been entered. The program checks that all parameters are within specified limits.

Once the network has been entered, the user may move the cursor from box to box and enter the 'Edit' mode to alter parameters or view results.

During the calculation stage a status window indicates the progress of the calculation. On completion of the calculation the status window contains a summary of the heat and air flow details for each box.

Provided the auto-save flag has been set in the defaults option the current network is automatically saved to disk every 5 operations during the editing and box creation stages. The network may be manually saved to disk at any other time.

The network data and the results may be printed or stored on disk as an ASCII file. Various reports may be generated depending on the detail required by the user.

Additional features are the HELP and PSYDE functions which may be accessed at any stage except while the calculations are being performed. The HELP function provides additional information and examples about the parameter at which the cursor was positioned when the facility was invoked. For example, guidance is given on the choice of the value of the exponent, n, in Equation [1]. Ventilation engineers often need to determine the psychrometric properties of an air stream: for example, given the wet- and dry-bulb temperature and the barometric pressure, it may be necessary to determine the energy content of the ventilation air. The PSYDE function will display the remaining psychrometric properties on input of any three valid parameters; this obviates the need to access separate charts, tables or calculators.

Example of program application

In this section a design study which was carried out using ENVIRON is described.

The study was conducted to determine the effects on heat and air flow of backfilling on an existing shaft system.(11) Three cases were compared. The first of these was a control situation which modelled the existing system. The second case examined the effect of backfilling on the cooling and fan power requirements while maintaining the same air quantity as in the first case. In the third case the effect of backfilling on both the air quantity and the fan power required was examined. It is for this type of study, in which the results of several design changes are required rapidly, that ENVIRON is extremely useful and necessary. A diagrammatic representation of the shaft system is shown in Figure 4.

The strategy followed in solving the problem is shown in Figure 5. Using a fixed air flow rate in the upcast shaft, the existing air flow and temperature distribution throughout the network were modelled by inserting booster fans and regulators and by adjusting artificial heat sources and wetness ratings. The upcast fan was selected by ensuring that the required pressure (determined using the fixed flowrate in the upcast shaft) was available at the operating point. The changes required to model each of the remaining two cases were easily implemented; for instance, to simulate the backfilling of all stopes to a 5 m fill-to-face distance, the resistances of the stope 'airways' were altered. The program was then re-run and showed that the design change resulted in a significant drop in stope temperatures and increased face velocities. The total cooling requirement, based on a maximum wet bulb temperature of 28°C, was reduced by about 30% to 21 000 kW. The fan pressure and power to maintain the design air quantity increased by 32%. The study showed that to maintain the original stope temperatures and face velocities, the cooling duty and fan power could be reduced.

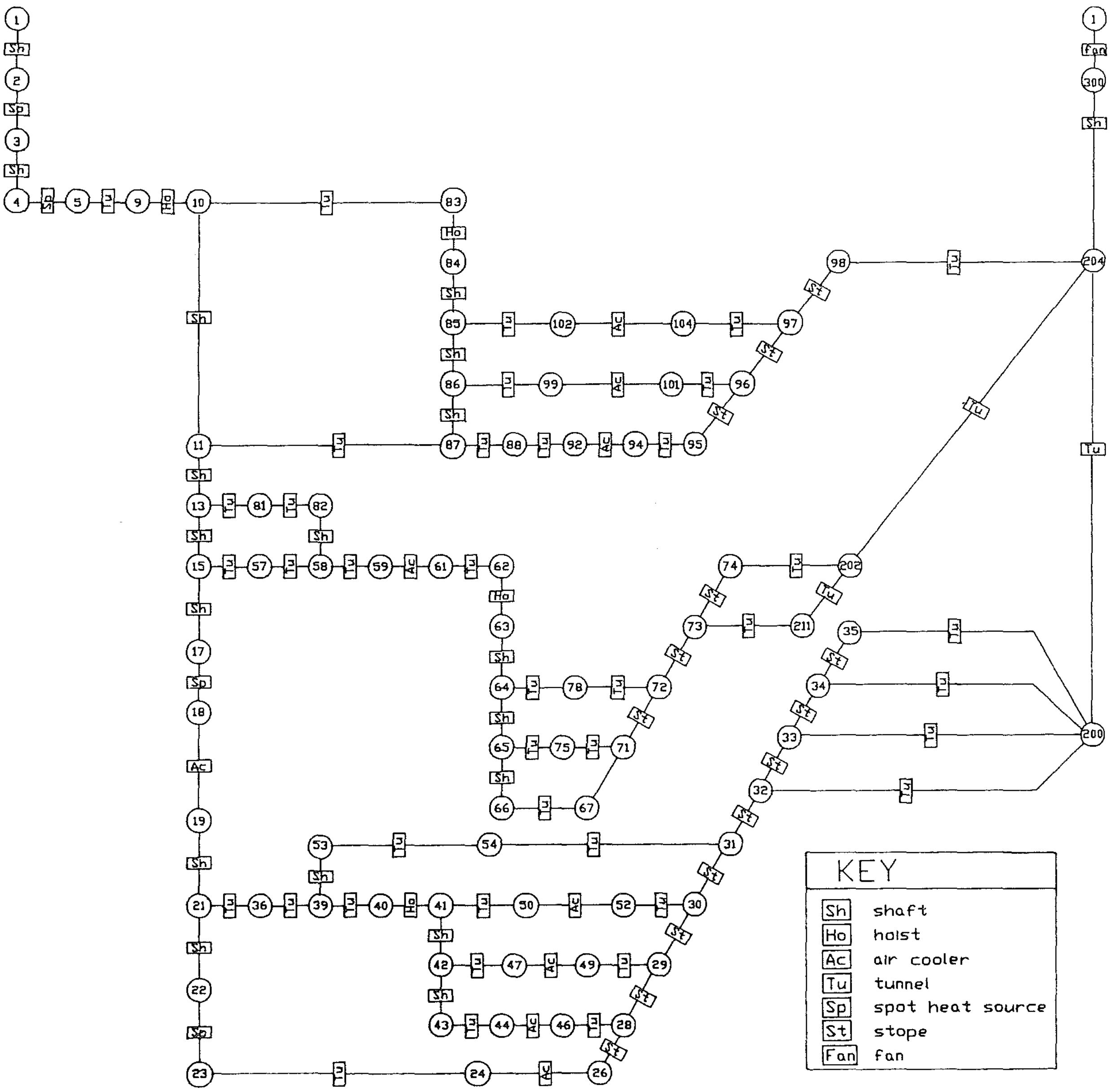

FIGURE 4. Network for example of program application

Future developments

Comments from users on all aspects of the program are being collated and future releases will contain improvements based on these comments. Users of the separate HEATFLOW and VENTFLOW modules have reported very good agreement with measured results. Other developments being undertaken are listed below.

(a) The inclusion of graphics input/output routines will enable data to be entered directly from mine plans using digitizers and will enable networks with relevant air flows and temperatures to be plotted.

(b) Modifications will allow the program to automatically devise a mine cooling strategy by inserting air coolers (in the most practical and efficient locations) whenever the air temperature rises above a user-specified maximum.

(c) An improved model for ventilation and heat flow in the stoping zone is being

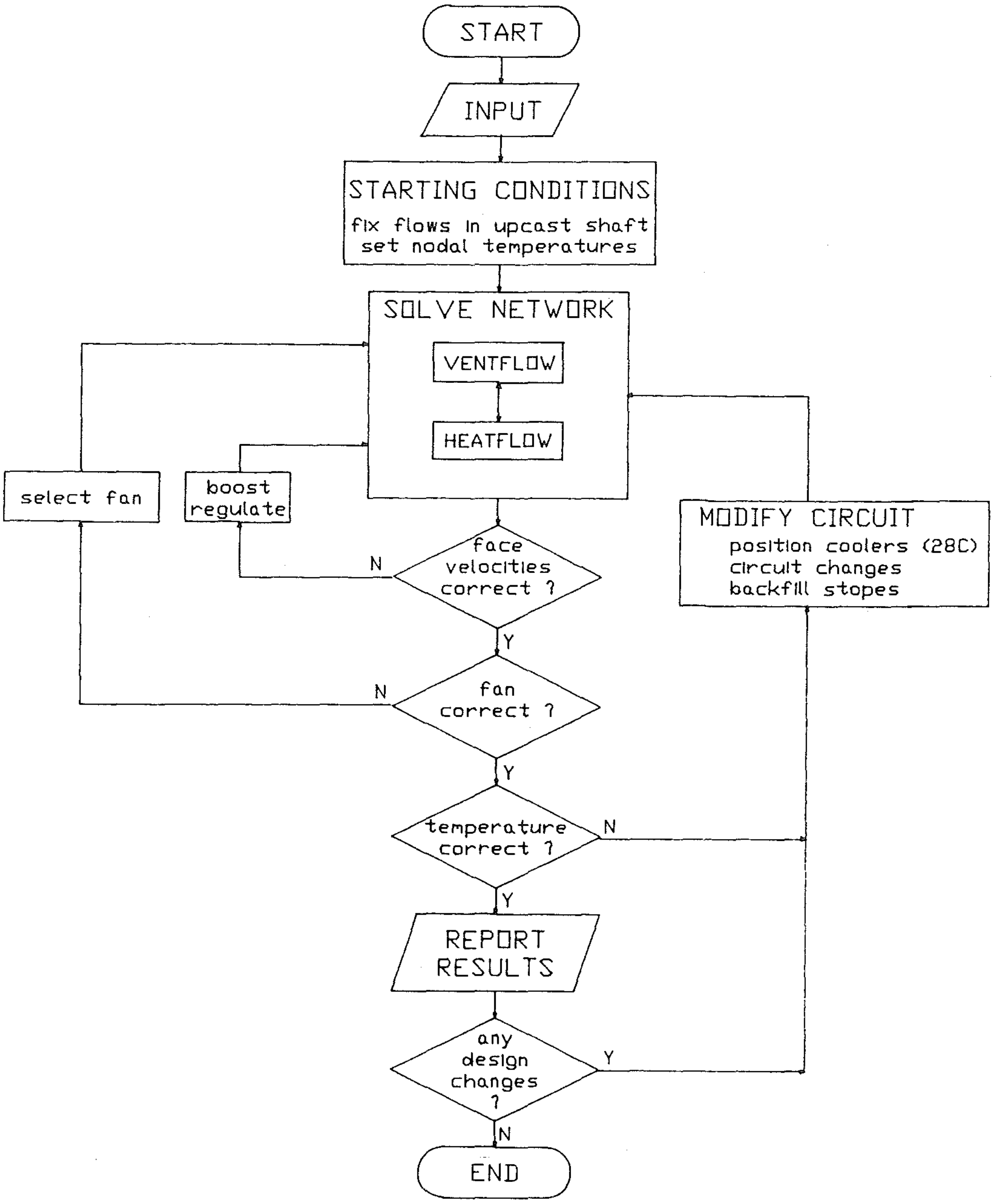

FIGURE 5. Flowchart for example program

developed whereby the stope is built up in terms of components such as the face area, worked-out area, types of panel boundaries and discontinuities.

(d) Additional theoretical work and field measurements are being undertaken to test and improve the models for heat load calculation incorporated in the HEATFLOW module.

(e) Because of the interaction of the air-flow network with water networks by way of heat exchangers, pipes and drains, it is necessary to incorporate a model of the water network to obtain a broader picture of the overall process.

(f) An 'expert system' which will aid in the design of mine layouts will incorporate ENVIRON.

Conclusions

The program described in this paper will afford the ventilation engineer far greater flexibility and control over the design of mine refrigeration and ventilation systems than has been possible with previous programs. It is intended that the user requires minimum effort in implementing the program. Time-consuming and error-prone data preparation has been obviated by requiring that the user enter fundamental parameters only. Once a mine model has been established and validated for an existing mine, it is a simple task to study the effects of proposed changes.

In addition to being a useful planning tool, the program has a data structure flexible enough to be used as a research tool to simulate the effects of different design strategies on the ventilation system. The program is continuously being upgraded to increase its applications and to take into account changes in mining practices and improvements in modelling techniques.

Acknowledgement

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Nomenclature

$\dot{m}$ air mass flow rate (kg/s)

n exponent in Equation [1]

P pressure drop in an airway (Pa)

R airway resistance $(kg\ m)^{-1}$