CHAPTER 16. SIMULATION OF CLIMATIC CONDITIONS IN THE SUBSURFACE

16.1. BACKGROUND

The complexities of the relationships that govern heat flow from the strata into ventilated underground openings are illustrated by the analyses given in Section 15.2. Indeed, the routine use of those relationships became practical only through the availability of computer assistance. The first computer programs to simulate heat flow into mine workings were developed in South Africa (Starfield, 1966). The early programs estimated strata heat flow from the Goch and Patterson tables (Section 15.2.6.), either by interpolation or from regression fitted equations that approximated those tables. Since that time, simulation programs of increasing sophistication have been developed in a number of countries. Current programs recognize the influence of boundary layers close to the rock/air interface, allow for heat sources other than the strata (Section 15.3) and predict the psychrometric effects of heat and moisture additions on the mine climate and physiological effects on workers.

A common feature of mine climate simulation models is that they are based on solutions of the fundamental equation for heat conduction (equation (15.13)), and on utilization of the dimensionless Fourier and Biot Numbers. However, the programs may vary in the manner in which they determine rock surfaces temperatures, heat transfer coefficients, and in the characterization and treatment of wet surfaces (Mousset-Jones, 1988).

Individual programs may be constrained to particular geometries of stopes or working faces, while others have been written for airways or headings. Some involve empirical relationships that are applicable only to specified layouts or methods of working. Again, some program packages allow...
combinations of airways, headings and working faces within a network structure while others are essentially "single airway" simulators that must either be run separately for each branch or used in conjunction with a ventilation network analysis package (Section 16.3.5).

This chapter is divided into two main sections. Section 16.2 outlines the logical operations of the CLIMSIM (climatic simulation) program package and is written for researchers involved in further program development or those who seek an understanding of the numerical procedures used in the simulation. Readers who are interested only in the practical utilization of a mine climate simulation package should turn directly to Section 16.3.

16.2. ELEMENTS OF A MINE CLIMATE SIMULATION PROGRAM

16.2.1. Organization of the programs

All mine climate simulations commence with the initial psychrometric condition of the air at the inlet end of the airway (or face) being defined by the user. This is normally accomplished by specifying the inlet wet bulb temperature, dry bulb temperature and barometric pressure. Under user control, the program divides the airway into incremental lengths, each of which is sufficiently short that wet and dry bulb temperatures may be assumed to be constant within the increment for the calculation of strata heat flows.

Each increment is traversed in the direction of airflow and the following parameters are calculated:
- sensible and latent heat flows from the strata and other sources
- change in moisture content of the air
- change in dry bulb temperature
- conversions between potential and thermal energies for shafts or inclined openings (autocompression)
- change in barometric pressure
- change in wet bulb temperature
- other psychrometric parameters and indices of heat stress at the exit end of the increment

The conditions for the start of the next successive increment are then defined. Each incremental length is treated in this way until the complete airway has been traversed. The following subsections outline the computational procedures involved in each of the steps listed.

16.2.2. Incrementation of airway length

The length of airway increment, $Y_i$, over which changes in temperature have no significant impact on strata heat flux will vary according to the magnitude of heat additions, the airflow and inclination of the airway. The value of $Y_i$ may be (i) fixed at some small value (say 2 to 20 m) within the program, (ii) a fixed fraction of the total length or (iii) chosen by the user.

16.2.3. Heat additions

In any incremental length of airway there will, in general, be transfers of both sensible and latent heat from one or more sources. In order to determine the corresponding psychrometric changes in the airflow, the sensible and latent heat components are each accumulated separately.

Strata heat
Let us consider the rock surface to be divided into wet and dry areas. We can then define a wetness fraction, $w$, as that fraction of total surface area that is covered or coated with liquid water. The concept of wetness fraction is discussed further in Section 16.3.1.1.
The area of wet surface within the incremental length $Y_i$ now becomes

$$A_w = 2\pi r_a Y_i w \quad \text{m}^2 \quad (16.1)$$

where $r_a = \text{the effective radius of the airway (perimeter/ } 2\pi)$

The remaining dry surface area is

$$A_d = 2\pi r_a Y_i (1-w) \quad \text{m}^2 \quad (16.2)$$

Sensible heat transfer will take place on both the dry and wet surfaces while latent heat transfer occurs at the wet surface only. The normalized strata heat flows (per square metre) may be calculated using the methods described in Sections 15.2.8 and 15.2.9.

Let us denote these heat flows as follows:

- **sensible heat from dry surface:** $q_{\text{sen,d}}$ (W/m$^2$)
- **sensible heat from wet surface:** $q_{\text{sen,w}}$ (W/m$^2$)
- **latent heat from wet surface:** $q_{L,w}$ (W/m$^2$)

The strata heat flowing into the increment, $Y_i$, is then the combination of:

- **dry surface:** $q_{\text{sen,d}} A_d = 2\pi r_a q_{\text{sen,d}} Y_i (1-w) \quad \text{W} \quad (16.3)$
- **wet surface:** $q_{\text{sen,w}} A_w = 2\pi r_a q_{\text{sen,w}} Y_i w \quad \text{W} \quad (16.4)$
- **wet surface:** $q_{L,w} A_w = 2\pi r_a q_{L,w} Y_i w \quad \text{W} \quad (16.5)$

where $A = \text{surface area (m)}$ and subscripts $w$ and $d$ refer to wet and dry areas respectively.

**Machines and other sources of heat**

Here again, heat additions from operating equipment must be separated into components of sensible and latent heat. In the case of electrical plant, all of the power supplied may be considered as a sensible heat addition to the airflow, excepting any work that is done against gravity (Section 15.3.2.1). The user must supply two values representing

(a) the full power rating (kW) of the motor or device, $FPR$, reduced, if necessary, by the rate of work done against gravity, and

(b) the machine utilization factor, $MUF$, defined as that fraction of time over which, if the machine were running at full load, would consume the same amount of energy as the actual intermittent operation of the device. Hence, the machine utilization factor for a motor running continuously at full load would be 1.0.

The value of sensible heat produced by the electrical device is then given as

$$FPR \times MUF \quad \text{W} \quad (16.6)$$

**Diesel engines** produce both sensible and latent heat (Section 15.3.2.2.). Here again, the user must supply a full power rating, $FPR$ and a machine utilization factor, $MUF$, for each piece of diesel equipment. The average machine load, given as the product $FPR \times MUF$ (kW), is then converted to fuel consumption (litres/hour) using a mean empirical value (typically 0.3 litres of fuel per kW engine rating per hour). The total heat produced is then simply the fuel consumption multiplied by the calorific value of the fuel (typical value 34 000 kJ/litre).
Using the values quoted, the fuel consumed, FC, becomes

\[ FC = FPR \times MUF \times \frac{0.3}{3600} \] \text{litres/s} \quad (16.7)

and the total heat produced = \( FC \times 34 \, 000 \times 10^3 \) \text{W} \quad (16.8)

The user may, of course, specify the rate of fuel consumption directly rather than through the factors on the right side of equation (16.7). However, practical experience has indicated that most mine ventilation engineers find it more convenient to assess machine rating and utilization data than to acquire fuel consumption for individual diesel units.

In order to separate out the amount of water vapour produced by the diesel engine, the user must supply a third item of data, namely, the water/fuel ratio, \( WFR \), defined as the litres of water (liquid equivalent) produced for each litre of fuel consumed. The combustion of one litre of diesel fuel will produce between 1.1 and 1.5 litres of water. However, this may be multiplied several times by engine cooling systems and exhaust scrubbers in addition to enhanced evaporation from rock surfaces in the immediate vicinity of the machine. Values as high as 9 litres of water per litre of fuel have been reported (Mouset-Jones, 1987).

Water vapour is then added to the airstream at a rate of

\[ FC \times WFR \] \text{litres of fuel} \quad \frac{\text{litres of water}}{s} \quad \text{litres of water} \quad \text{litre of fuel} \quad (16.9)

i.e. \( \text{kg of water vapour per second} \)

The equivalent value of latent heat is given as

\[ FC \times WFR \times L \] \text{W} \quad (16.10)

where \( L = \text{latent heat of evaporation of water in J/kg} \)

while the sensible heat produced by the diesel becomes (total diesel heat - latent diesel heat) from equations (16.8 and 16.10) respectively.

**Compressed air equipment** adds no overall heat to a ventilating airstream and, indeed, can produce a small net cooling effect (Section 15.3.2.3). Such equipment is usually ignored in mine climate simulations.

Other sources of heat (Sections 15.3.3 to 15.3.8) may be specified by the user. In the general purpose climate simulators, it is left to the user to select the sensible and latent heat components. However, special purpose programs have been developed to handle cases such as ducts, pipes, cables, water channels or spray chambers located within the airway. Air coolers may be specified simply as negative heat sources.

A climate simulation program will compute the components of strata heat for each incremental length of airway. In the case of machines or other sources of heat, the user must identify the locations of those machines or other sources. This can be accomplished by specifying either (a) a spot source, or (b) a distributed source.

A spot source will produce its heat at a fixed location and, hence, will appear in a single element of airway length. This is the type of heat source chosen for stationary pieces of equipment such as transformers, conveyor gearheads or mobile devices that move over short distances only. A distributed source, as the term implies, will spread its heat load over a distance specified by the user (e.g. length of a conveyor, hot or cold pipes, drainage channels). In a simple case, the heat will be
distributed linearly over the selected distance. A more sophisticated program may allow the heat to be distributed according to a function specified by the user.

For each increment of airway length, the simulation program will determine and sum both the sensible and latent heat components from all sources relevant to that increment. We can now refer to the corresponding summations as $\Sigma q_{sen}$ and $\Sigma q_L$, respectively, for each increment.

### 16.2.4. Change in moisture content

The apparent density, $\rho_{app}$, of the air at inlet to the airway is calculated from the psychrometric condition of the air specified by the user for that starting location

$$\rho_{app} = \frac{(P - e)}{287.04(\theta_d + 273.15)} \text{ kg of dry air per m}^3 \text{ of air}$$

(see equation (14.51))

where

- $P = \text{barometric pressure (Pa)}$
- $e = \text{actual vapour pressure (Pa)}$
- $\theta_d = \text{dry bulb temperature (°C)}$

The mass flow, $M$, of the ‘dry air’ component of the air/vapour mixture is then given as

$$M = Q \rho_{app}$$

(16.11)

where $Q$ is the known rate of airflow at inlet (m$^3$/s)

The value of $M$ remains constant along any given airway.

The rate at which water vapour is added to an increment of airway length is simply

$$\sum \frac{q_L}{L} \frac{J}{s} = \frac{kg}{s} \text{ where } L = \text{latent heat of evaporation (J/kg)}$$

The increase in moisture content of the air becomes

$$\Delta X = \sum \frac{q_L}{LM} \text{ kg/kg dry air}$$

(16.12)

Hence, if we denote subscripts 1 and 2 for entry and exit from the incremental length, then

$$X_2 = X_1 + \Delta X \text{ kg/kg dry air}$$

(16.13)

### 16.2.5. Change in dry bulb temperature and autocompression

In the absence of any fan work the steady flow energy equation (3.25) gives

$$(H_2 - H_1) - q_{12} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g \frac{J}{kg}$$

(16.14)
where \( H \) = enthalpy (J/kg)
\( q_{12} \) = heat added (J/kg)
\( u \) = air velocity (m/s) and
\( Z \) = height above datum (m)

However, equation (14.40) shows that the enthalpy term comprises a sensible heat component, \( C_{pa} \theta \), and a latent heat component, just as \( q_{12} \) involves both sensible and latent heat. As it is only the sensible heat component that affects the dry bulb temperature we can subtract the latent heat component from both the \( H \) and \( q \) terms. Then equation (16.14) can be re-written as

\[
(C_{pa} (\theta_{d,2} - \theta_{d,1}) - q_{12,sen} = \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g \quad \text{J/kg (see equation (3.33))}
\]

where \( C_{pa} = \text{specific heat for dry air (1005 J/kg °C)} \)

We must remember that \( q_{12,sen} \) is the sensible heat addition in J/kg while our earlier sensible heat summation for the increment, \( \Sigma q_{sen} \), was in Watts.

Hence, \( q_{12,sen} = \frac{\sum q_{sen}}{M} \quad \text{J/kg dry air} \) (16.15)

The increase in dry bulb temperature then becomes

\[
\Delta \theta_d = (\theta_{d,2} - \theta_{d,1}) = \left[ \frac{u_1^2 - u_2^2}{2} + (Z_1 - Z_2)g + \frac{\sum q_{sen}}{M} \right] \frac{1}{C_{pa}} \quad \text{°C (16.16)}
\]

All terms on the right hand side of equation (16.16) are known except the change in kinetic energy. This is caused only by the change in density in an airway of fixed cross-sectional area and, hence, is very small. However, it can be estimated as follows:

\[
\frac{u_1^2 - u_2^2}{2} = \frac{1}{2} \frac{(Q_1^2 - Q_2^2)}{A^2}
\]

where \( Q = \text{volume flowrate (m}^3/\text{s)} \) and \( A = \text{cross-sectional area (m}^2) \)

From equation (16.11), \( Q = M/\rho_{app} \) giving

\[
\frac{u_1^2 - u_2^2}{2} = \frac{1}{2} \frac{M^2}{A^2} \left[ \frac{1}{\rho_{1,app}^2} - \frac{1}{\rho_{2,app}^2} \right] \quad \text{J/kg} \quad (16.17)
\]

A difficulty arises here in that \( \rho_{2,app} \) requires a knowledge of the psychrometric conditions at the exit end of the increment. These are still unknown. However, as the change in kinetic energy is a very weak parameter, satisfactory results are obtained by using the change in air density established for the previous increment in equation (16.17). For the first increment in the airway, the kinetic energy correction may be ignored without significant loss of accuracy.

Equation (16.16) then enables the change in dry bulb temperature, \( \theta_d \), to be determined, having taken into account both the sensible heat added and the change in elevation. The dry bulb temperature of the air leaving the increment is simply

\[
\theta_{d,2} = \theta_{d,1} + \Delta \theta_d \quad \text{°C (16.18)}
\]
16.2.6. Change in barometric pressure

In the absence of a fan the variation in absolute pressure of the air, $P$, is caused by
(a) the conversion of mechanical energy into heat causing a frictional pressure drop, $p$, and
(b) changes in elevation ($Z_1 - Z_2$).

The effect of changes in moisture content on barometric pressure through any single element
remains small provided that the incremental length is not excessive.

The frictional pressure drop is given by Atkinson's equation (5.2)

$$\rho = \frac{k}{Y_i} \frac{\text{per}^A u^2}{2} \text{ Pa}$$  \hspace{1cm} (16.19)

where $k = \text{Atkinson's friction factor (} \rho_f/2 \text{ kg/m}^3 \text{) and per = airway perimeter (m)}$

This can be converted into the work done against friction

$$F_{12} = \rho / \rho_m \text{ J/kg}$$  \hspace{1cm} (16.20)

where $\rho_m = \text{mean air density in the increment (} \text{kg/m}^3 \text{). Here again, } \rho_1 \text{ may be used for the first increment then, subsequently, } \rho_m \text{ extrapolated from the previous increment.}$

Assuming polytropic flow through the incremental length of the airway, the steady flow energy
equation written in the form of equation (8.1) gives

$$R_m (T_2 - T_1) \frac{\ln(P_2 / P_1)}{\ln(T_2 / T_1)} = \frac{u_2^2 - u_1^2}{2} + (Z_1 - Z_2) g - F_{12} \text{ J/kg}$$  \hspace{1cm} (16.21)

The gas constant is given as

$$R_m = \frac{287.04 + 461.5 X}{1+X} \text{ J/kg K} \text{ [see equation (14.14)]}$$

where $T = \text{absolute dry bulb temperature (} \theta_d + 273.15 \text{ K)}$
and $X$ and $\theta_d$ are the mean values for the increment.

The outlet pressure, $P_2$, remains the only unknown in equation (16.21) and, hence, may be
calculated.

16.2.7. Change in wet bulb temperature

The psychrometric condition of air is completely defined if any three of its psychrometric properties
are specified. At the exit from the incremental length of airway, the moisture content, $X_2$, the dry bulb
temperature, $\theta_d$, and the barometric pressure, $P_2$, have now all been determined. All other
psychrometric parameters can then be calculated from the equations given in Section 14.6.

In particular, the wet bulb temperature, $\theta_w$, may be found from the following equations.

$$X_2 = \frac{S_2 - 1005 \theta_d}{L_w + 1884 (\theta_d - \theta_w)} \text{ kg/kg dry air}$$
where \( S = L_{w,2} X_{s,2} + 1005 \theta_{w,2} \) J/kg dry air

\[
L_{w,2} = \left( 2502.5 - 2.386 \theta_{w,2} \right) 1000 \text{ J/kg}
\]

\[
X_{s,2} = 0.622 \frac{e_{sw,2}}{P - e_{sw,2}} \text{ kg dry air/kg}
\]

and \( e_{sw,2} = 610.6 \exp \left[ \frac{17.27 \theta_{w,2}}{237.3 + \theta_{w,2}} \right] \text{ Pa} \)

In this sequence of equations, \( \theta_{w,2} \) is the only unknown independent parameter. Hence, by assuming an initial value, the equations may be cycled iteratively until a value of \( \theta_{w,2} \) is found that satisfies all the equations simultaneously.

16.2.8. Relative humidity and saturation conditions

One of the psychrometric variables that may be calculated for each incremental length of airway is the relative humidity, defined as

\[
rh = \frac{e}{e_{sd}} \text{ (see equation (14.54))}
\]

where \( e = \) actual vapour pressure (Pa) and \( e_{sd} = \) saturated vapour pressure at dry bulb temperature (Pa)

If the result of this calculation is a value exceeding unity (supersaturation) then this indicates that condensation will take place. Such condensation will occur on all surfaces with a temperature less than that of the air wet bulb temperature and also as a fog within the airstream. Indeed, the former will occur even if the relative humidity is less than 1.0. If the computed psychrometric variables indicate supersaturation, then the heat of condensation released causes the dry bulb temperature to rise until saturation is attained at the same level of enthalpy as the original supersaturation condition. This is approximated closely by setting the revised dry bulb temperature equal to the current value of wet bulb temperature.

16.2.9 Indices of heat stress

Some mine climate simulators go beyond predicting variations in psychrometric conditions to include one or more of the indices of heat stress. These fall into two main groups:

(a) indices that can be determined from measured or predicted climatic parameters (e.g. effective temperature, ET, or wet bulb globe temperature, WBGT). These are sometimes referred to as ‘empirical indices’.

(b) indices that are based on physiological responses of the healthy human body to an actual or predicted environment for a specified work rate and type of clothing (e.g. Mean Skin Temperature, MST, sweat rate, or Air Cooling Power, ACP). These are often called ‘rational indices’.

The methods used within mine climate simulators to determine most of these indices are described in Section 17.4.
16.3. USING A MINE CLIMATE SIMULATOR

The first stage of commissioning a mine climate simulation system is to obtain a program package that provides the required features. The pointers given in Section 7.4.5 for network simulation packages apply equally well here. Secondly, for any given airway or network of airways, the data must be assembled. There is a much greater variety of information required for the prediction of psychrometric conditions along each airway than for the ventilation network analyses described in Chapter 7. Furthermore, some of those data may, initially, be of uncertain precision. Hence, the correlation exercises that must precede employment of a climate simulator for long term planning will often involve modifications of the initial data.

This section deals with data preparation, correlation trials, the procedures involved in running a mine climate simulator, and design exercises that can be carried out with the assistance of such program packages.

6.3.1. Data preparation

The parameters that influence heat flow into a subsurface airway were introduced in Section 15.2.1. The following subsections deal more specifically with the data that must be quantified for each airway in preparation for a mine climate simulation.

16.3.1.1. Physical description of airway

Geometry. The parameters required are airway length, cross-sectional area, perimeter, and levels below a surface datum of both the inlet and exit ends of the airway. It is normally assumed that the cross-sectional area, perimeter and gradient each remain constant throughout the length of the airway. Should there be significant deviations in any of these parameters then the airway should be divided into two or more sub-lengths for simulation.

Friction factor. The roughness of the airway lining is normally quantified as the Atkinson friction factor (Section 5.2).

Age. The program package may allow the age of each end of the airway to be specified separately. The age of each simulated increment of airway length is then computed assuming a uniform rate of drivage. This feature takes into account the time taken to develop the airway and is particularly useful for advancing headings.

Wetness fraction. This parameter was introduced in Section 16.2.3 as the fraction of airway surface that is covered or coated with liquid water. However, we have not yet discussed the actual distribution of water over the surface. Furthermore, although the strata heat flow analyses of Section 15.2 considered both dry and wet surfaces, the solution of the basic equation for heat conduction assumed radial heat flow. In a simple case of a square airway with a completely wetted floor but dry sides and roof, the wetness fraction would be 0.25. However, the heat flow through the rock would no longer be radially symmetric.

The concept of wetness fraction as originally introduced by Starfield in 1966, envisaged the wetness to be spread uniformly over the surface. With a surface that is damp but not completely covered in water, asperities on the rough surface may be dry on their peaks but with liquid water in the troughs. This water may be emitted through capillaries in the rock matrix or from discrete fractures before spreading out by a combination of surface capillarity and gravitational forces. The temperature of this type of surface will then take a value lying between those of the completely dry and completely wet surfaces analyzed in Section 15.2 and, hence, be dependent upon the degree of wetting.

In practice, the wetting of airway surfaces is usually far from uniform. Within a single airway there may be surface areas varying from completely wetted to visually dry. Mack and Starfield (1983) proposed an "equivalent wetness factor" for such circumstances, this being defined as the wetness
fraction over a uniformly wetted surface that would give the same rates of heat and moisture transfer as the actual surface of non-uniform wetness.

Values of wetness fraction can be established for existing airways through correlation exercises (Section 16.3.2). Furthermore, ventilation engineers who are experienced in running a climate simulation package become adept at estimating wetness fractions by visual inspection of airways in much the same way that they can estimate friction factors from the appearance of surface roughnesses. Wetness fractions seldom fall below 0.04, even in airways that appear quite dry.

For planned but yet unconstructed airways, the wetness fraction may be estimated from previous experience of mining within that same geologic formation and at similar depths. If no such data are available then hydrologic studies and the projected use of service water can provide an indication of the potential average wetness of future workings. For particularly important projects including underground repositories for hazardous wastes, test drivages within the relevant horizon(s) will provide invaluable data regarding the migration of moisture from the strata.

16.3.1.2. Condition of airflow at inlet

Most mine climate simulators assume that the airflow and psychrometric condition of the air at inlet have remained constant since the airway was driven. In the majority of cases this gives acceptable results because of the thermal flywheel effect (Section 15.2.2). Variations in the surface climate are usually well damped by the time the air reaches the working areas. If the transients that occur along intake airways are of concern then methods that employ the principles of superposition are available for such analyses (Hemp, 1982).

The inlet data required for conventional non-transient simulators are simply airflow, barometric pressure, and wet and dry bulb temperatures. Satisfactory results for hot mines can be obtained by assuming mean summer (not extremes) atmospheric conditions on surface.

16.3.1.3. Thermal parameters and other heat sources

The data in this category comprise:

Rock thermal conductivity:
It is the effective thermal conductivity of the strata that should be specified. It is preferable that this parameter should have been established through in-situ tests as described in Section 15.2.10. If values are available from laboratory samples only, then corrections may be necessary to obtain the effective thermal conductivity that actually pertains underground (Mousset-Jones, 1988). Here again, correlation trials with a climate simulator are valuable in establishing values of effective thermal conductivity.

Rock thermal diffusivity:
This can be measured directly in-situ as well as by laboratory methods. However, it is normally satisfactory to determine thermal diffusivity indirectly as

$$\alpha = \frac{k_r}{\rho_r C_r} \text{ m}^2/\text{s}$$

(see equation (15.13))

where $k_r = \text{ effective thermal conductivity W/(m°C)}$

$\rho_r = \text{ rock density kg/m}^3$ \and

$C_r = \text{ specific heat of the rock J/(kg°C)}$

Virgin rock temperature and geothermic step (Section 15.2.4):
The combination of VRT at the inlet of the airway and the rate at which rock temperature increases with depth allows the VRT to be determined for each increment of length along a non-horizontal
airway. These parameters may be determined from temperature logs taken from boreholes. In the case of a downcast shaft, the inlet VRT should actually be the rock temperature sufficiently far below the surface to be unaffected by variations in the surface climate. This is usually between 10 and 20 m.

Heat sources other than the strata:
The location of every machine or other source of heating or cooling and the distance over which it extends must be specified. The magnitudes of both the sensible and latent heat components should be quantified either directly or indirectly by identifying a machine type (Section 16.2.3).

16.3.1.4. Physiological parameters (Worker data)

For mine climate simulators that predict a physiological index of heat stress (see Section 16.2.9), two more sets of data are requested. One of these includes the metabolic work rate in Watts per square meter of body surface and the typical posture (body view factor) of a worker. The second set of physiological factors involves the thermal resistance of the clothing ensemble and the increase in body surface area associated with that ensemble. Fortunately, all of these parameters can be entered in a user-friendly fashion simply by choosing from lists of work activities and types of clothing (see Table 16.1).

16.3.2. Correlation tests

All simulation packages should be subject to correlation tests in order to verify that they do, indeed, simulate the real system to the required accuracy prior to their being employed for planning purposes. The accuracy of data must also be verified by site-specific correlation trials. This is true for ventilation network analysis (Section 9.2.3) and is also the case for mine climate simulation studies.

Due to the uncertainty that may be associated with some of the data, correlation trials of mine climate simulators should include sensitivity runs involving those input parameters of uncertain accuracy. Experience has shown that such correlations conducted for a few airways in any mine can not only highlight previously unidentified sources of heat and humidity but also provide a range of typical data values that may be tested against other airways until sufficient confidence has been established to embark upon planning studies.

There is a definite procedure to follow in conducting sensitivity studies and correlations of climatic simulation output with actual conditions in a mine. The airways chosen for initial correlation should each be well established and continuous with no intermediate additions or losses of airflow. Any gradient from horizontal to vertical is acceptable provided that it remains uniform along the length of the airway. The primary trials should seek to provide correlation between computed results and the effects of strata heat and, perhaps, autocompression. Additional sources of heat that can be quantified easily, such as metered electrical equipment, may also be included. However, the initial trials should avoid airways that contain diesel equipment or open drainage channels. Such sources of heat should be subject to secondary correlation runs.

Careful measurements of airflow, barometric pressure, and wet and dry bulb temperatures should be made at the intake end of the correlation airway. Additional wet and dry bulb temperatures should also be taken at about 100 m intervals along the airway. All of the other parameters required as input (Section 16.3.1) should be ascertained or ascribed initial estimated values.

In comparing the computed output with observed temperatures, attention should be focused first on the wet bulb temperatures. If there is a consistent divergent trend between the computed and measured values then it is probable that a continuous heat source has been over or underestimated, or perhaps even omitted entirely. A check should be carried out on the depths of the airway ends and their corresponding ages (if less than two years). Sensitivity runs should also be made to test the effect of thermal conductivity.
If the observed wet bulb temperatures do not show a smooth trend then the reasons for discontinuities should be investigated. There may be occurrences such as leakage of air or other fluids from old workings, machine heat, or increased inflow of fissure water. Correlation exercises provide a valuable educational experience in tracing sources of heat in the mine.

When reasonable correlation (+1 °C) has been obtained for the wet bulb temperature, attention should be turned to the dry bulb temperature. Any remaining deviations of this parameter will almost certainly be due to the evaporation or condensation of water. If the deviation shows a consistent trend then it is likely that the wetness factor has been wrongly assessed. Sensitivity runs on wetness factor will test for such a condition. More localised deviations may be caused by inaccurate assessment of the water vapour produced by diesel equipment, or the effects of dust suppression sprays.

Having followed this correlation procedure over a series of airways, the ventilation engineer will have built up a store of information on the values and dispersion of heat sources in his mine. He will also have determined a range of in situ values for thermal conductivities, wetness factors and contributions of heat and humidity from mechanized equipment. At that stage, forward planning studies may be initiated with confidence levels that have been established through the correlation procedures. Climatic simulations then provide an invaluable tool of unprecedented detail in planning environmental control for hot underground facilities.

16.3.3. Case Study

For clarity of explanation, this case study involves a single airway rather than a sequence of branches. Figure 16.1 illustrates a 500 m inclined airway descending from 450 to 530 m below a surface datum. The airway contains a diesel unit of output rating 175 kW working at a mean rate of 60 per cent full load, an air cooler of 200 kW cooling capacity and a conveyor expending 230 kW along its length from the midpoint to the exit of the airway. The complete data for the airway have been assembled under the categories given in Section 16.3.1 and are shown in Table 16.1. The order and format of the input data depend upon the particular software package being used.
Table 16.1 Input data for the case study as requested by the CLIMSIM mine climate simulator. The shaded boxes are screen prompts. The values are entered by the user.

The tabulated results of the simulation are shown in Table 16.2. Here again, the form of the output depends upon the program employed. The CLIMSIM package used for this case study allows any of the computed variables to be produced in graphical form. Figures 16.2 and 16.3 are computer plots of the variations in air temperature and relative humidity respectively. The effects of the diesel unit, cooler and conveyor are shown clearly. Despite the influence of autocompression and strata heat, evaporation in this rather wet airway results in an initial decrease of dry bulb temperature.

Figures 16.4 and 16.5 show the variation in mean skin temperature of the workforce and the wet bulb globe temperature respectively. The mean skin temperature is seen to exceed the limit (for the prevailing climatic conditions) at which workers may begin exhibiting the effects of heat stress. This occurs at about 440 m from the beginning of the airway. An interesting feature of the mean skin temperature graph is the increase in its slope at 368 m from the entrance, even though there are no additional heat sources at or after this location. This is the point at which the average healthy worker becomes fully covered in perspiration. As his body can no longer increase its cooling by further wetting of body surface area it attempts to maintain thermal equilibrium by additional increases in skin temperature (ref. Section 17.3 and Figure 17.6). This effect is not reflected by empirical indices of heat stress such as wet bulb globe temperature or effective temperature as these are determined solely by the condition of the airflow and do not indicate physiological response.

The actual reaction of workers on approaching the onset of heat stress or a full coating of perspiration will be behavioural, i.e. reducing the work rate via less strenuous activity or more frequent rest periods, and/or discarding clothing. Figures 16.6 and 16.7 show that the mean skin temperature can be maintained below the relevant limit throughout the airway either by reducing the metabolic work rate from 200 to 185 W/m² or by wearing shorts rather than thin trousers.
### Diesel heat source at 100 m, sensible heat = 147.41 kW, latent heat = 149.74 kW

Spot heat source at 175 m, sensible heat = -200.00 kW, latent heat = 0.00 kW

Linear heat source starts at 250 m, length = 250 m, sensible heat = 230.00 kW, latent heat = 0.00 kW

Strata heat totals: sensible heat = -68.03 kW, latent heat = 164.87 kW

Other heat totals: sensible heat = 177.41 kW, latent heat = 149.74 kW

Metabolic rate = 200 W/m², Skin temperature limit value = 34.98 °C

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#### Table 16.2 Tabulated CLIMSIM output for the case study. This is shown at 20m intervals for conciseness but is computed at 2m intervals as requested in the input data.
Figure 16.2 Graphical output for wet and dry bulb temperatures along the airway.

Figure 16.3 Graphical output for relative humidity along the airway.
Figure 16.4 Graphical output for average mean skin temperature of workers along the airway.

Figure 16.5 Graphical output for Wet Bulb Globe Temperature along the airway.
Figure 16.6  Mean skin temperature with metabolic work rate reduced to 185 W/m².

Figure 16.7  Mean skin temperature with workers wearing shorts and short-sleeved shirt.
16.3.4. Organization of mine climate simulation exercises

The flow chart given on Figure 16.8 illustrates the procedure for investigating variations in the air temperatures, humidities and indices of heat stress throughout a ventilation network. From the results of a ventilation network analysis, one or more routes should be selected through the system. These may commence at an air intake point on surface, proceed through shafts, intake airways, work areas and return passages back to surface. Routes should be chosen that may be expected to produce the severest psychrometric conditions. Climatic simulations may then be conducted along successive branches throughout the selected routes.

The input shown on Figure 16.8 may be supplied by manual interaction with the climate simulation package as illustrated in the case study of Section 16.3.3. Alternatively, the input may be drawn from data files that have been assembled over a period of time, again, either manually or as a result of previous simulations. Such files may also be used or amended by other program packages. For example, the airflow for each individual branch may have been determined from a ventilation network analysis package (Sections 7.4 and 9.1). Similarly, branch inlet temperatures and pressures will have been produced by climate simulations on upstream airways.

Figure 16.8 indicates that the computed results from a mine climate simulation should be reviewed with respect to the selected heat stress indices (Chapter 17) or other climatic criteria relevant to the particular study. Should these criteria not be met then the program should be rerun successively in order to investigate means of reaching the desired standards. Parameters that may typically be amended are airflow, airway size or lining, reduction in machine power (for example, replacing diesels by electrical equipment), the installation, siting and cooling capacities of heat exchangers or the attire and workrate of personnel. Sensitivity studies should also be run to test the influence of any input parameters that may be of questionable accuracy.

The convenient editing features of modern climate simulators allow individual items of input data to be updated with very few keystrokes and the program re-run within a matter of seconds.

There will usually be several ways of meeting the climatic criteria. Again, the procedure may be cycled successively to investigate alternative arrangements. This sometimes necessitates going back to re-evaluate an upstream airway.

16.3.5. Interaction with Ventilation Network Analysis packages

Figure 9.1, introduced in Chapter 9 to illustrate the systems analysis of subsurface ventilation planning, shows the relationships of climate simulations to ventilation network exercises. While the initial airflows used in climate simulations may have been produced by VNET exercises, it might have been necessary to amend those airflows during the climate investigations in order to meet set criteria. The sizes and linings of some airways may also have been altered, affecting their resistances. In those cases, it becomes necessary to re-run the network analysis package in order to revise fan duties and other consequential effects throughout the ventilation system.

Where the installation of cooling plant has proved to be necessary during the climate simulation exercises, the airflow requirements should be reviewed most carefully in order to approach an optimized combination of ventilating and cooling costs while, at the same time, providing airflows capable of diluting other airborne contaminants (Section 9.3) (Anderson, 1986).

Programs have been developed that combine the functions of ventilation network analysis and climate simulation. However the volume and variety of both data and output can become daunting to the user. Practical experience of ventilation engineers leads to a preference for separate program packages for network analysis and climate simulation while, at the same time,
maintaining the efficiencies of rapid transfer of information between data files. This also allows manual modification of those files whenever required and establishes firmer control over the design process by the planning engineers.

**Figure 16.8 Climatic planning procedure.**
Bibliography


