5.1 Introduction

Main ventilation, also termed primary ventilation, takes air from the outside atmosphere and distributes it to through the whole mine. It differs from secondary ventilation, also known as auxiliary or ancillary ventilation, which will be discussed later in Chap. 8, in that secondary ventilation takes air from the main ventilation circuit conducting it to specific areas of the mine, mainly developing zones such as faces and stopes.

Main ventilation currents can be either natural or created by powerful fans. The energy used in the main ventilation is so high that it can account for 40% of the electrical energy consumed in the mine. For this reason, ventilation calculations are of the utmost importance for the economy of the mine. Since the mine is a continuously evolving system, so is the main ventilation, which must face new challenges every day to adapt to changing environmental and circuit resistance conditions. In this chapter, we deal with the main characteristics and calculations concerning primary ventilation systems.

5.2 Mine Airflow Requirements

Among the main tasks of main ventilation we find:

- Bringing pure air in sufficient quantity to where it is required.
- Diluting, extracting or displacing toxic, asphyxiating and flammable gases.
- Diluting, extracting or displacing dust.
- Reducing or increasing as appropriate, the temperature and humidity of the mining environment.
• Reducing the transmission of infectious diseases (flu, COVID-19, tuberculosis, etc.) among workers, when necessary.\(^1\)

Table 5.1 Production factor values (\(\alpha\)) as a function of the operating method. Taken from Howes (1998)

| Exploitation method     | \(\alpha \left( \frac{\text{m}^3}{\text{s} \cdot \text{Mt} \text{year}} \right) \) |
|-------------------------|--------------------------------------------------------------------------------|
| Block caving            | 50                                                                            |
| Rooms and pillars       | 75                                                                            |
| Sublevel caving         | 120                                                                          |
| Open stoping            |                                                                               |
| • Large (\(> 5 \frac{\text{Mt}}{\text{año}}\)) | 160                                                                          |
| • Small (\(> 5 \frac{\text{Mt}}{\text{año}}\)) | 240                                                                          |
| Cut and fill            |                                                                               |
| • Mechanized            | 320                                                                          |
| • Manual tools          | 400                                                                          |

The quantity needed to ventilate the whole mine, which must comply the above-mentioned tasks, can be approximated depending on the average mine production and the mining method (Eq. 5.1) (Howes 1998):

\[
Q = \alpha t + \beta
\]  

(5.1)

where

• \(Q\): Airflow rate (\(\text{m}^3 \text{s}^{-1}\)).
• \(t\): Average annual production (\(\text{Mt a}ños^{-1}\)).
• \(\alpha\): Production factor \(\left( \frac{\text{m}^3}{\text{s} \cdot \text{Mt} \text{year}} \right) \). The factor \(\alpha\) can be obtained from Table 5.1. From this, the first idea of the precise air quantities for each operating method can be obtained.
• \(\beta\): Airflow required to ventilate the mining infrastructure (\(\text{m}^3 \text{s}^{-1}\)). This factor depends fundamentally on how the interior haulage and the primary crushing are carried out. Some references for this parameter are:
  – Transport by inclined drift without underground primary fragmentation: 50 \(\text{m}^3 \text{s}^{-1}\).
  – Skip transport and underground primary fragmentation: 100 \(\text{m}^3 \text{s}^{-1}\).

The above values increase up to 50% with the presence of conveyor belts, panzers and transfer systems.

\(^1\)For instance, silicosis is connected to a higher prevalence of tuberculosis. An example is the transmission of tuberculosis among South African miners (Hermanus 2007).
5.3 Natural Ventilation

Natural ventilation or natural draught\(^2\) is the phenomenon by which the air moves without the help of any machinery providing an extrinsic drive. This movement is based mostly on the heating owing to the geothermal gradient that the gases undergo when crossing the mine, which results in a pressure difference between downcast and upcast shafts. Other factors, such as surface winds, air self-compression, heat released by processes of oxidation, hydration and solution/dissociation, and waterfalls –mainly present in the shafts–, can also be added to the above.

![Behavior patterns of the natural ventilation of a mine based on the temperature difference at the mouths of the ventilation shafts](image)

Fig. 5.1 Behavior patterns of the natural ventilation of a mine based on the temperature difference at the mouths of the ventilation shafts

Ventilation shafts and adits which communicate with the surface at different topographic levels favour natural draught (Fig. 5.1). Therefore, if the aim is to benefit air circulation, the mouths of the downcast or intake shaft, and upcast or return shafts, should be constructed at different heights. In the past, if this was not possible, it was common to build high prismatic or cylindrical chimneys well insulated by brick walls from the outside temperature and the wind. These chimneys generated a certain thermal contrast which helped the impulsion.

At certain times of the year, natural ventilation may be interrupted since the temperature difference between shafts is not sufficient to generate airflow. Similarly, the airflow direction is usually not the same throughout the year. This is so because sometimes the air inside the mine may be hotter than the air outside, or vice versa. This is a consequence of seasonal variations between the cold and hot months. Airflow inversions can even occur due to temperature variations between day and night. For

\(^2\)Natural draught flow and natural draught pressures, respectively, refer to the air quantity and the pressure differences caused by natural ventilation.
all these reasons, natural ventilation sometimes assists the main fan and other flows against it.

The most classical approach for the calculation of natural ventilation is to consider the difference in density between the downcast and upcast air currents. However, in reality, natural ventilation is due to a transformation of heat into mechanical energy and is, therefore, a thermodynamic problem. Both approaches are taken into account in this chapter.

**Exercise 5.1** Indicate the direction of the air inside the mine for the two conditions in the figure: (a) Outdoor temperature is lower than inside the mine, (b) Outdoor temperature is higher than inside the mine.

![Diagram a) Cold outside](image1)

![Diagram b) Hot Outside](image2)

**Solution**

The qualitative explanation is based on the establishing of a hydrostatic equilibrium of pressures at the height of B and B’.

In the case of Fig. (a), when it is cold outside, the air column BC on the small shaft weighs more than its equivalent in the deep shaft, which is hotter. For this reason, the air circulates from the short to the long shaft.
Conversely, in the case of Fig. (b), the air column in the small shaft (B’C’), is not capable of compensating the analogous column in on the deep shaft. Therefore, air circulates from the long shaft to the short shaft.

### 5.3.1 Calculation by the Static Method

It is a simplified calculation method. The system in Fig. 5.2, consists of two vertical shafts connected by a horizontal gallery.

The following parameters are defined in it, namely:

- \( T_1 \): Dry-bulb temperature at the inlet of the downcast (K),
- \( T_2 \): Dry-bulb temperature at the bottom of the downcast shaft (K),
- \( T_3 \): Dry-bulb temperature at the bottom of the upcast (K),
- \( T_4 \): Exhaled dry-bulb temperature (K),
- \( T_{md} \): Average dry-bulb temperature in the downcast shaft (K), and
- \( T_{mu} \): Average dry-bulb temperature in the upcast shaft (K).

The pressure of the air column at the bottom of the downcast and upcast shafts (points 2 and 3) is:

\[
P_2 = \rho(1-2)gh_d = \gamma(1-2)h_d; \quad P_3 = \rho(3-4)gh_u = \gamma(3-4)h_u
\]

So if \( P_2 > P_3 \), the air flows from 2 to 3.

The Natural Ventilation Pressure (NVP or \( P_n \)) must be (Eq. 5.2):
\[ P_n = P_2 - P_3 \] (5.2)

So that (Eq. 5.3):

\[ P_n = \gamma(1-2)h_d - \gamma(3-4)h_u \] (5.3)

Note that specific weights are not constant, that is, they depend on other variables. In order to take this aspect into account, the universal equation of perfect gases can be used: \( PV = nR_{\text{mole}}T \). This equation can be transformed to operate with mass instead of moles leading to:

\[ PV = mR_{\text{mass}}T \]

Moreover, in terms of weight, the equation can be written as:

\[ PV = WR_wT \]

Rearranging the equation:

\[ \frac{W}{V} = \frac{P}{R_wT} \]

Since \( \frac{W}{V} = \gamma \) (specific weight), replacing \( \gamma \) in the equation we have:

\[ P_2 - P_3 = h_d \frac{P_{md}}{R_{wd}T_{md}} - h_u \frac{P_{mu}}{R_{wu}T_{mu}} \]

where

- \( P_{md} \): Average pressure in the downcast shaft (Pa),
- \( P_{mu} \): Average pressure in the upcast shaft (Pa),
- \( R_{wd} \): Constant per unit mass of gases in the downcast shaft \( \left( \frac{J}{K \text{kg}} \right) \), and
- \( R_{wu} \): Constant per unit mass of the gases in the upcast shaft \( \left( \frac{J}{K \text{kg}} \right) \).

At this point, a certain humidity can be assumed for the intake depending on the climatology of the place. In the case of the return shaft, a humidity close to 100% can be admissible. With both parameters set, it is possible to obtain accurate values for \( R_{we} \) and \( R_{ws} \) from air data tables. Despite this fact, simplifications can still be made, specifically:

- To use the same value of the constant \( R \) for both the intake and return shafts.
5.3 Natural Ventilation

- To use the dry air values for \( R \). Therefore, as \( R_{\text{mass}} \) for dry air is approximately \(^3\) 287 J kg\(^{-1}\) K\(^{-1}\). Referred in weight \( R_w = 29.29 \) J NK.
- If both shafts have the same depth (\( h \)), the \( P_{md} \) is approximately equal to the \( P_{mu} \), and equal to the average pressure on the shafts (\( P_m \)).
- Finally, \( P_m \) is about 101 kPa and it is difficult to measure, so in some texts, it is simplified by the value of atmospheric pressure.

So \( P_n \) can be calculated as (e.g. Hartman et al. 1997, p. 298):

\[
P_n = \frac{h P_m}{R} \left( \frac{1}{T_{md}} - \frac{1}{T_{mu}} \right)
\]

where substituting, we have (Eq. 5.4):

\[
P_n = 0.03415 \left[ \frac{\text{NK}}{\text{J}} \right] h P_m \left( \frac{1}{T_{md}} - \frac{1}{T_{mu}} \right)
\]

The temperature close to the mouth of the downcast shaft could be quite similar to that of the air outside, thus being instable. Similarly, the temperature of the upcast shaft may resemble largely that of the interior of the mine. So \( T_{md} \) and \( T_{mu} \) are normally obtained as the mean between the temperatures that exist at the bottom of the shafts and 35 m below their respective mouths (neutral zone).

Equation 5.4 assumes that downcast and upcast shafts have an equal depth. Some considerations must then be made in the event that the mouths of the two shafts are at different heights in the topographic surface. Thus, if air enters through the longest shaft (Fig. 5.3a), the effective height is only the depth of the short shaft (\( h' \)) as the column of air located above it should have approximately the same temperature as the twin air column in the long shaft and both are compensated. Similarly, if air enters through the short shaft, the temperature contrast between columns \( A + B \) and \( C + D \) is total, and \( h'' \) should be used as the effective height (Fig. 5.3b).

---

\(^3\)For water vapour 461 J kg\(^{-1}\) K.
solution to this problem is to calculate the air density for the different columns \((A, B, C \text{ and } D)\), and with them, to establish the equilibrium of pressures.

If the difference of the inverse of temperatures from Eq. 5.4 is operated obtaining the common denominator, we have:

\[
P_n = 0.03415 \left[ \frac{N K}{J} \right] h 101,300 \left( \frac{T_{mu} - T_{md}}{T_{md} T_{mu}} \right)
\]

Then \(T_{md} \cdot T_{mu}\) can be replaced by its possible values, which range\(^4\) within 273–293 K (Eq. 5.5), therefore:

\[
P_n = 0.04 \left[ \frac{\text{Pa}}{\text{C m}} \right] (T_{mu} - T_{md})h
\]

For this reason, McElroy (1935) and Borisov et al. (1976), indicated that 44 Pa of natural ventilation pressure are generated for every 10 °C difference between the average temperature of the shafts for every 100 m of effective height. Some NVP values depending on depth and temperature are given in Table 5.2.

| \(h_m\) (m) | 5     | 10    | 20    | 30    |
|-------------|-------|-------|-------|-------|
| 200         | 50    | 100   | 190   | 280   |
| 500         | 120   | 240   | 500   | 710   |
| 1000        | 240   | 480   | 950   | 1400  |

**Question 5.1** Pressures have been measured at each of the points indicated in the mine in the figure. Determine an expression as the sum of the given pressures for the calculation of the NVP of the mine.

\(^4\)Note that other temperatures within the range of possible values do not significantly vary the result.
Answer

As can be seen, the NVP is the pressure difference at the bottom of the downcast and upcast shafts. In this case, both come together at the same depth, thus:

\[ P_n = \Delta P_A + \Delta P_B + \Delta P_C + \Delta P_D - (\Delta P_E + \Delta P_F) \]

As indicated in the previous question, air can circulate in different directions depending on the difference in temperature between inside and outside the mine, thus changing the sign of NVP.

**Exercise 5.2** The ventilation of a mine takes place through two vertical shafts of 600 and 400 m. The conditions in them are monitored automatically, recording average temperatures of 2 °C in the mouth and 9 °C at the bottom for the long shaft, and 17 °C at the mouth and 12 °C at the bottom for the short shaft. It is also known that the pressure at the average depth of both shafts is 108.475 kPa. You are asked to:

(a) Estimate the NVP of the system.

(b) Comment on the direction of the airflow and the temperature measurements provided in the problem statement.

**Solution**

(a) Firstly, average pressure must be estimated for the midpoint of the air columns in the shafts. This value could be slightly higher than the atmospheric pressure. As this value is supplied, 108.475 kPa is used directly.

Secondly, the average temperatures of the downcast and upcast shaft are calculated:

\[ T_{md} = (5.5 + 273) \text{ K} = 278.5 \text{ K} \]
\[ T_{mu} = (14.5 + 273) \text{ K} = 287.5 \text{ K} \]

These values can be substituted in Eq. 5.4:

\[ P_n = P_2 - P_3 = 0.03415 \left[ \frac{NK}{J} \right] hP_m \left( \frac{1}{T_{md}} - \frac{1}{T_{mu}} \right) \]

An airflow direction can easily be assigned considering that the air outside is colder than inside the shafts. In such a case, the air enters the system through the short shaft, then it is more appropriate to assume a height of 600 m corresponding to the depth of the long shaft. However, it is a common practice to use the mean values, therefore:

\[ P_n = 0.03415 \left[ \frac{NK}{J} \right] \left( \frac{400 + 600}{2} \right) m \cdot 108.475 \text{ Pa} \cdot \left( \frac{1}{278.5 \text{ K}} - \frac{1}{287.5 \text{ K}} \right) \]

\[ P_n = 208.2 \text{ Pa} \]

Checking by the approximated formula:

\[ P_n = 0.044 \left[ \frac{Pa}{C \text{ m}} \right] (T_{mu} - T_{md}) \left( \frac{h_d + h_u}{2} \right) \]

We have:

\[ P_n = 0.044 \left[ \frac{Pa}{K \text{ m}} \right] (287.5 - 278.5) \text{ K} \left( \frac{600 + 400}{2} \right) m = 198 \text{ Pa} \]

(b) As a conclusion, it can be deduced that the NVP in this mine is low. This is due to the rapid increase in temperature throughout the long shaft, the low increase in temperature towards the outlet in the short shaft as well as the short effective height of the latter. This first approach points to an unstable equilibrium which makes inversions frequent.\(^5\)

As the direction of the airflow is given by the increase of temperatures in the circuit (from colder to hotter), there would be no discussion about its direction. However, there are grounds for suspecting that some measurements could be incorrect. Thus, temperatures at the bottom of the long shaft and at the mouth of the short shaft could be lower and higher respectively than those supplied by the problem statement.

---

\(^5\)In cold and shallow mines (<400 m), natural ventilation is unreliable. In other words, it does not guarantee that there is an adequate NVP, nor that it takes place in the required direction.
5.3.2 Calculation of the Logarithmic Formula Method

Despite the simplifications in the previous section, pressure does increase with depth, and its increase takes place in a nonlinear manner. In order to consider this fact, the following expression was developed. A height differential \( \mathrm{d}L \), of a dry air column of height \( h \), increases the hydrostatic pressure at its base \( A \) by a value \( \mathrm{d}P \). Therefore, establishing the balance of forces, we have:

\[
A \, \mathrm{d}P = \gamma \, A \, \mathrm{d}L
\]

where \( \gamma \) is the specific weight of air. This value can be obtained from the general gas equation, therefore:

\[
A \, \mathrm{d}P = \frac{P}{R \, T} \, A \, \mathrm{d}L
\]

where

- \( R \): Constant of gases (per unit mass) \( \left( \frac{J}{K \, kg} \right) \).

Simplified:

\[
\mathrm{d}P = \frac{P}{RT} \, \mathrm{d}L
\]

Integrating between the pressure at the top of the downcast shaft \( P_1 \) and the pressure at the bottom \( P_2 \), for a depth of the shaft \( h \), and considering the temperature as an integration constant \( T_{md} \), we have:

\[
\int_{P_1}^{P_2} \frac{P}{P} \, \mathrm{d}P = \int_0^h \frac{h_d \, \mathrm{d}L}{RT_{md}}
\]

Therefore, the pressure at the base of the downcast shaft is (Eq. 5.6):

\[
\log P_2 = \log P_1 + 0.03415 \frac{h_d}{T_{md}} \quad (5.6)
\]

In a similar way, the pressure at the base of the upcast shaft can be obtained (Eq. 5.7):

\[
\log P_3 = \log P_1 + 0.03415 \frac{h_u}{T_{mu}} \quad (5.7)
\]

where

- \( h_u \): Depth of upcast shaft (m), and
- \( T_{mu} \): Average temperature of the upcast shaft air (K).
Therefore, the Natural Ventilation Pressure \((P_n)\) is (Eq. 5.8):

\[
P_n = P_2 - P_3 \tag{5.8}
\]

Note that the same pressure \((P_1)\) has been assumed outside both shafts. Note also that these calculations have been simplified to a static problem while the problem is actually dynamic due to air movement.

**Exercise 5.3** Calculate natural ventilation pressure for the mine in the figure.

\[
\begin{align*}
P_1 &= 101,400 \text{ Pa} \\
T_1 &= 10 \degree \text{C} \\
T_2 &= 20 \degree \text{C} \\
T_3 &= 45 \degree \text{C} \\
P_4 &= 100,000 \text{ Pa} \\
T_4 &= 37 \degree \text{C}
\end{align*}
\]

**Solution**

\[
\begin{align*}
\log P_2 &= \log P_1 + 0.03415 \frac{h_d}{T_{md}} = \log 101,300 + 0.03415 \frac{1100}{\frac{10+20}{2} + 273} = 5.1360 \\
\log P_3 &= \log P_4 + 0.03415 \frac{h_u}{T_{mu}} = \log 100,000 + 0.03415 \frac{1100}{\frac{37+45}{2} + 273} = 5.1196
\end{align*}
\]

\[
P_n = P_2 - P_3 = (1.3677 - 1.3170) \times 10^5 = 5068.57 \text{ Pa}
\]

The value obtained corresponds to a very high NVP.

### 5.3.3 Calculation by the Thermodynamic Method

The air inside the mine is heated, resulting in an addition of energy which causes potential and kinetic energy changes, as well as friction losses in the air mass. If this energy refers to the unit of air mass, it is called *Natural Ventilation Energy (NVE)*.

The NVE can be simply obtained if the values of the pressure and the specific volume of the airflow are available at the following locations (Fig. 5.4, left), namely: topographic surface \((A)\), bottom of the downcast shaft \((B)\), exit from the stopes \((C)\), exit to the outside of the upcast shaft \((D)\).

The above data can be represented on Cartesian axes of absolute pressure versus specific volume \((P - V_e)\). In this case, if it is assumed that there is no heat exchange
with the walls of the shafts, the adiabatics $AB$ and $CD$ are formed. In the same way, the isobar corresponding to the external pressure $DA$ is observed. The highest heat incorporation to the air mass ($BC$ curve) takes place in mining stopes. However, in well developed mines it is possible to assume that the heat flow to the air mass is zero, giving rise to an adiabatic process, which is also isothermal ($T_B = T_C$).

The Natural Ventilation Pressure ($NVP, P_n$), from a static point of view, is the $PB-PC$ difference. The ABCD area corresponds to the NVE (Fig. 5.4, right). If the NVE is multiplied by the density of the air ($\rho$), the work per unit volume is obtained, or in other words, the NVP (Eq. 5.9):

$$ P_n = NVE \rho \quad (5.9) $$

where

- **NVE**: Natural Ventilation Energy (J kg$^{-1}$), and
- **$\rho$**: Air Density (kg m$^{-3}$).

The determination of the pressure at each point can be made by means of an aneroid barometer, while the specific volume can be approximated by the expression (Eq. 5.10):

$$ V_e = \frac{287.1 \ T}{1000(P - P_v)} \quad (5.10) $$

where

- **$T$**: Dry-bulb temperature (K),
- **$P$**: Barometric pressure (kPa), and
- **$P_v$**: Vapour pressure of water (kPa).
Bearing in mind the equations for an adiabatic system with self-compression of air (Eq. 2.9), Voropaev (1950) stated that: “The work performed by 1 kg of air in a natural ventilation system can be approximated with the area of a closed contour in a coordinate system depth-temperature \((h-T)\), divided by the absolute temperature of its centroid\(^6\)” (e.g. Novitzky 1962, p. 211) (Eq. 5.11):

\[
P_n = \frac{S}{T_c} \rho
\]  

(5.11)

where

- \(P_n\): Natural ventilation pressure \((\text{NVP})\) \((\text{kp m}^{-2})\),
- \(S\): Surface of the figure \((\frac{\text{kp m}}{\text{kg K}})\),
- \(T_c\): Centroid temperature \((\text{K})\), and
- \(\rho\): Air density (usually taken as 1.25 kg m\(^{-3}\)).

The limitations of the above expression in the presence of a fan have been discussed by Lepikhov (1975).

Surface decomposition can be systematized by the shoelace formula. This procedure consists of defining a polygonal surface from a series of lines determined by pairs of points \((x_{i-1}, y_{i-1}), (x_i, y_i)\) of a Cartesian coordinate system. In this nomenclature, \(i\) is the point number. It is important that the last point in the series coincides with the first for the polygonal to be closed. Also, in order to not complicate the method, the coordinates defining the polygonal should not produce line crossings.

The area of each element defined by coordinates is calculated as:

\[
A_n = x_i y_{i-1} - x_{i-1} y_i
\]

Then the total area of the closed polygonal is:

\[
A = \frac{1}{2} \left| \sum A_i \right|
\]

The centroid of any triangle is given by the following expression:

\[
X_g = \frac{1}{3} (x_1 + x_2 + x_3)
\]

\[
Y_g = \frac{1}{3} (y_1 + y_2 + y_3)
\]

**Exercise 5.4** The figure represents the scheme of a simplified mine with sidehill shafts. The data corresponding to the coordinates of each point are included in the table. You are asked to:

\(^6\)The centroid or barycenter is a geometric concept which defines the centre of symmetry of a geometric figure. For a body with uniform density, it coincides with the centre of masses.
(a) Calculate the centre of gravity of the surface $h-T$ by the shoelace formula.
(b) Determine the NVP by the Voropaev method.

\[
\begin{array}{|c|c|c|}
\hline
\text{Point} & \text{Temp. } T \text{ (°C)} & \text{Depth } h \text{ (m)} \\
\hline
A & 6 & 50 \\
B & 10 & 175 \\
C & 16 & 175 \\
D & 15 & 0 \\
E & 5 & 0 \\
\hline
\end{array}
\]

Solution

(a) First, the $h-T$ diagram is constructed with the data from the statement. Thus, the diagram is broken down into geometric figures of a known centre of gravity:

According to the above, the areas would be\(^7\):

---

\(^7\)Note that since temperature differences are to be measured, it makes no difference whether the graph is in °C or in K.
Then, the total surface $S_T = 1437.5 \text{ kp m} / \text{ kg K}$.
The coordinates of the centres of gravity of the individual surfaces are then:

\[
T_c = \frac{\sum_{i=1}^{5} S_i T_i}{S_T} = 11.26^\circ \text{C}
\]

Then the NVP is obtained as:

\[
P_n = \frac{S_T}{T_c} \rho = \frac{1437.5 \text{ kp m} / \text{ kg K}}{(273 + 11.26) \text{K}} \times \frac{1.25 \text{ kg}}{\text{m}^3} = 6.3 \text{ kp m}^2/
\]

(b) The centre of gravity can be also calculated for the above case by the shoelace formula, e.g. for the decomposition of the figure as:
### 5.3 Natural Ventilation

| Triangle | \( T_i \) (°C) | \( h_i \) (m) | Centroid coordinates | \( T_{i-1} \cdot h_i - T_i \cdot h_{i-1} \) | Area of the triangle |
|----------|----------------|--------------|---------------------|---------------------------------|-------------------|
|          |                |              | \( T_{cg} \)     | \( h_{cg} \)           |                  |
| 1        | 5              | 0            | –                   | –                              | 250               |
|          | 15             | 0            | 0                   |                                |                   |
|          | 6              | 50           | 750                 |                                |                   |
|          | 5              | 0            | 8.67 16.67 –250     | 250                            |                   |
| 2        | 6              | 50           | –                   |                                |                   |
|          | 15             | 0            | –750                |                                |                   |
|          | 10             | 175          | 2625                |                                |                   |
|          | 6              | 50           | 10.33 75.00 –550    | 662.5                          |                   |
| 3        | 15             | 0            | –                   |                                |                   |
|          | 10             | 175          | 2625                |                                |                   |
|          | 16             | 175          | –1050               |                                |                   |
|          | 15             | 0            | 13.67 116.67 –2625  | 525                            |                   |

**Weighted mean values**

- \( T_{cg} \): 11.26
- \( h_{cg} \): 80.07
- Total area: 1437.5

Or, also:

![Diagram](image)

### Triangle

| Triangle | \( T_i \) (°C) | \( h_i \) (m) | Centroid coordinates | \( T_{i-1} \cdot h_i - T_i \cdot h_{i-1} \) | Area of the triangle |
|----------|----------------|--------------|---------------------|---------------------------------|-------------------|
|          |                |              | \( T_{cg} \)     | \( h_{cg} \)           |                  |
| 1        | 5              | 0            | –                   | –                              | 250               |
| (continued) |
5.3.4 Measuring Natural Ventilation

Method of the Ventilation Door

One of the most commonly used methods is to measure when the fan is switched off, the pressure difference on both sides of a closed ventilation door through which the entire mine airflow passes (Fig. 5.5a). This door is usually located at any point between the downcast shaft and the upcast shaft. In this case, it is possible to measure the pressure difference between the bottom of both shafts (Fig. 5.5b) (Hatman et al. 1997, p. 302).

---

| Triangle | $T_i$ ($^\circ$C) | $h_i$ (m) | Centroid coordinates $T_{cg}$ | Centroid coordinates $h_{cg}$ | $T_{i-1} \cdot h_i - T_i \cdot h_{i-1}$ | Area of the triangle |
|----------|------------------|----------|-------------------------------|-------------------------------|---------------------------------|----------------------|
|          |                  |          | $T_{cg}$                      | $h_{cg}$                      |                                 |                      |
| 1        | 15               | 0        | 0                             |                               |                                 |                      |
|          | 16               | 175      | 2625                          |                               |                                 |                      |
|          | 5                | 0        | 0                             |                               | $-875$                          | 875                  |
| 2        | 5                | 0        | $-$                           |                               |                                 |                      |
|          | 16               | 175      | 875                           |                               |                                 |                      |
|          | 5                | 50       | $-250$                        |                               |                                 |                      |
|          | 5                | 0        | 9.00                          | 75.00                         | $-250$                          | 187.5                |
| 3        | 6                | 50       | $-$                           |                               |                                 |                      |
|          | 16               | 175      | 250                           |                               |                                 |                      |
|          | 10               | 175      | 1050                          |                               |                                 |                      |
|          | 6                | 50       | 10.67                         | 133.33                        | $-550$                          | 375                  |
| Weighted mean values | | | | | **11.26** | 80.07 | Total area | 1437.5 |

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![Fig. 5.5](image-url) Measure of natural ventilation with the door closed

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### 5 Main Ventilation
5.3 Natural Ventilation

Turning the Main Fan Off and On

The natural draught can be estimated from measurements taken in the main fan drift with the main fan off and operating. Thus, when the fan is on and the surface airlock, also termed shaft cover is closed, the resistance is:

\[ R = \frac{P_v + P_n}{Q_v^2} \]

where

- \( P_v \): Pressure supplied by the fan, and
- \( Q_v \): Flow rate with the fan running.

Afterwards, the main fan is turned off, the fan drift is closed with a damper, and the shaft cover is open. Then, we have:

\[ R = \frac{P_n}{Q_n^2} \]

with:

- \( Q_n \): Flow rate with the main fan off (flow rate supplied by natural ventilation).

Therefore:

\[ \frac{P_v + P_n}{Q_v^2} = \frac{P_n}{Q_n^2} \]

Finally (Eq. 5.12):

\[ P_n = P_v \frac{Q_n^2}{Q_v^2 - Q_n^2} \quad (5.12) \]

Exercise 5.5 The upcast shaft in a mine registers an airflow rate of 800 m\(^3\) min\(^{-1}\) when the depression developed by the main fan is 6000 Pa. When the fan stops the flow in the upcast shaft, it reduces to 250 m\(^3\) min\(^{-1}\). Determine the value of the NVP in this mine.

Solution

If the fan is on, we have:

\[ R = \frac{P_v + P_n}{Q_v^2} = \frac{6000 \text{ Pa} + P_n}{\left(800 \frac{\text{m}^3}{\text{min}}\right)^2} \]

When the fan is stopped:
\[ R = \frac{P_n}{Q_n^2} = \frac{P_n}{(250 \text{ m}^3/\text{min})^2} \]

Equalizing:

\[ \frac{P_n}{(250 \text{ m}^3/\text{min})^2} = \frac{6000 \text{ Pa} + P_n}{(800 \text{ m}^3/\text{min})^2} \]

Therefore:

\[ P_n = 6000 \text{ Pa} \frac{(250 \text{ m}^3/\text{min})^2}{(800 \text{ m}^3/\text{min})^2 - (250 \text{ m}^3/\text{min})^2} = 649.35 \text{ Pa} \]

**Operating the main fan at two different speeds**

In this case, the resistance is the same for both speeds. Therefore, for the main fan drift we have:

\[ R = \frac{P_{v1} + P_n}{Q_1^2} = \frac{P_{v2} + P_n}{Q_2^2} \]

where the subscripts 1 and 2 represent the two rotation speeds to which the motor fan is subjected.

So, in this case, the \( P_n \) will be (Eq. 5.13):

\[ P_n = \frac{P_{v1} Q_2^2 - P_{v2} Q_1^2}{Q_1^2 - Q_2^2} \quad (5.13) \]

**Exercise 5.6** The main fan in a mine moves 1000 m\(^3\) min\(^{-1}\) of air operating at a pressure of 8000 Pa. When its rotational speed is reduced, the flow drops to 700 m\(^3\) min\(^{-1}\) and the pressure developed is 3500 Pa. Determine the NVP of this mine.

**Solution**

For the first rotation velocity, we have:

\[ R = \frac{P_{v1} + P_n}{Q_1^2} = \frac{8000 \text{ Pa} + P_n}{(1000 \text{ m}^3/\text{min})^2} \]

For the second velocity:
\[ R = \frac{P_{v2} + P_n}{Q_2^2} = \frac{3500 \text{ Pa} + P_n}{\left(700 \text{ m}^3/\text{min}\right)^2} \]

Equating:

\[ \frac{8000 \text{ Pa} + P_n}{\left(1000 \text{ m}^3/\text{min}\right)^2} = \frac{3500 \text{ Pa} + P_n}{\left(700 \text{ m}^3/\text{min}\right)^2} \]

Finally:

\[ P_n = 823.53 \text{ Pa} \]

### 5.4 Forced Ventilation

When air is supplied to a certain space using mechanical devices called fans, a forced ventilation system is being used. Depending on the location of the ventilation shaft with regard to the ore deposit, two types of forced ventilation are distinguished: \textit{central} and \textit{boundary}.

#### 5.4.1 Central Ventilation

In this ventilation system, also referred to as \textit{bidirectional}, downcast and upcast shafts are very close together and located in the centre of the mineral deposit (Fig. 5.6). It is characterized by the movement of air from the centre of the mine to the stopes, and to return through the ventilation galleries to the upcast, which, as has been already indicated, is located in the centre of the mineral deposit. In this case, the upcast shaft can be used for the extraction in parallel with the downcast shaft. It is a common ventilation system in medium-sized mines. Some of the main advantages and disadvantages of this system are set out below (Novitzky 1962, p. 254).

**Advantages**

- Grouped installations, and
- It is more convenient in the early stages of the mine.

**Disadvantages**

- This system increases the resistance of the circuit a lot, which is more evident as the mine increases.
Short-circuits can occur as fresh and foul airways are very close to each other and sometimes they are almost parallel. Short-circuits usually occur near the shafts where the pressure is maximum.\(^8\)

- An accident in a shaft, for example, a collapse can affect the other as both are very close to one another.
- The resistance of the mine can increase when the air has to cover the same distance twice (downcast shaft to stopes and stopes to upcast shaft).

### 5.4.2 Boundary Ventilation

In *boundary ventilation*, also known as *radial, side, unidirectional* or *diagonal ventilation*, the air goes from the downcast to the stopes and from the stopes to the upcast, which is located at the limits of the concession (Fig. 5.7). All this takes place without returning to the centre of the mine.

**Advantages**

- Shafts well separated, which means that an eventual accident in one does not affect the other.

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\(^8\) *Air short-circuits* can be understood as those roads of low or null resistance where the air flows with more facility unbalancing the systems and the desired circulations of the air in the mine. They can also be produced by the opening of doors which should normally be closed.
5.4 Forced Ventilation

Fig. 5.7 Diagonal ventilation. Modified from Fritzsche (1965, p. 712)

- In this system, several upcast shafts are possible, so the air can enter through one and leave diagonally through several of them. This fact results in higher security of the ventilation system.
- More stable ventilation.
- The same level can be divided and used for the air intake and return.
- Shorter circuit, and therefore, less resistant, thus the mine can be operated with less depression.
- Resistance circuit is most constant as it is independent on whether the work is in the central or border areas of the concession.

Disadvantages
- In mines where firedamp is present and requiring significant ventilation airflows, several upcasts have to be built, with the high costs that this entails. The existence of these shafts is not a complete disadvantage as, in the long run, they also facilitate the movement of personnel, materials and rescue equipment.

5.5 Airflow Generation Systems

5.5.1 Depression System

Generally, the most commonly used system is depression ventilation. This configuration has the following advantages and disadvantages (Tien 1978; Hartman et al. 1997, p. 526):
Advantages

- The haulage galleries are kept free of dust and gas, allowing workers to have a cleaner working atmosphere.
- It simplifies the action of the rescue teams if fires or explosions occur. This is because fresh air is in the access route, which makes it easier to instal equipment and materials.
- The system can be more energy efficient. For this purpose, gradual expansion outlets (*evasés*) should be used in the main fans which lower air discharge velocities and improve static efficiency.
- In a mine with firedamp, as this gas has a lower density than air, this system favours its evacuation to the exterior.

Disadvantages

- In winter, the temperatures can be very low in the mouth of the intake shaft making it difficult to work in them, and may even lead to equipment malfunctions due to freezing.
- It may be more difficult to detect a fire on the conveyor belt.
- Dust generated by transport in the downcast, as well as fires in these areas, can reach the stopes.
- Dirty air and dust pass through the fan and may affect its normal functioning.
- Firedamp escapes from the already abandoned areas of the mine can be drawn towards the centre of the mine with the subsequent problems.

5.5.2 Blower System

Blower ventilation causes air movement resulting in an overpressure in the area to be ventilated. It has the following advantages and disadvantages (Tien 1978; Hartman et al. 1997, p. 527):

Advantages

- While the fan is running, coal seams are under high pressure thus reducing the gases emanating from them. Although this fact is debatable, at least in the case of firedamp.
- The systems and areas through which air enters the mine are heated by the main fan, thus preventing their freezing.
- Fire outbreaks are more obvious.
- The fan receives clean air, which extends its useful life.
- These types of fans are cheaper as they have a smaller diffuser.

Disadvantages

- It may hinder mine rescue efforts by tending to push contaminating gases into escape routes.
• Shock pressure losses are higher in blowing than in depression systems.

Taking all this into account, the preferred system for the main ventilation is depression, assisted by several booster fans distributed inside the mine.

5.6 Direction of Transportation

The direction of air circulation is also strongly conditioned by the direction of transport inside the mine. According to this, two systems are distinguished: anti-tropic and homotropic. In the former, the movement of air and materials transported from the mine to the outside takes place in the opposite direction. Whereas, in the latter, the direction of the airflow and the materials transported outside the mine coincide.

In general, the homotropic is the preferred one, as it raises less dust and heat, and gases generated inside the mine are expelled more easily. Moreover, this system also allows for a better management of eventual fires that take place in the mine slope.

Another factor to take into account is the inclination of the stopes. Ascensional ventilation is the most common in inclined stopes (Fig. 5.8). This system is used to:

Fig. 5.8 Ascentional air circulation in a mine stope

• Take advantage of the ascensional force due to the heating of the air that takes place in them. This natural draught allows for some air circulation even in the event of the main fan stopping.
• Facilitate the evacuation of firedamp as it is lighter than air.
• Decrease the arrival of dust in the transport galleries.
For all these reasons, this system is compulsory in many regulations mainly in coal mining. In order to make the ventilation ascend, the downcast shaft must be at least as deep as the upcast shaft so as to prevent part of the ventilation from descending.

*Descensional ventilation* is also possible when a more compact system is needed. In this case, it is normal to also move the materials in the same direction to operate in a homotropic system.

**Exercise 5.7** The image represents the ventilation systems of two metal mines. The following manometric pressures have been measured:

Scheme (a): $-1200, 0, -2100, -2400, -1500, (\text{Pa})$

Scheme (b): $-680, 0, 0, 0, -500, 450 (\text{Pa})$

You are asked to:

(a) Indicate which type of ventilation system each figure corresponds to.
(b) Place the static and absolute pressures on the graph in their corresponding place.

**Scheme (a)**

**Scheme (b)**

**Solution**
5.6 Direction of Transportation

Scheme (a): Central ventilation. 1: 0, 2: −720, 3: −1200, 4: −1500, 5: −2100, 6: −2400 (Pa)
Scheme (b): Diagonal ventilation. 1: 0, 2: −500, 3: −680, 4: +450, 5: 0 (Pa)

In order to locate the absolute pressures add 101,300 Pa to all the previous values.

5.7 Ventilation on Demand

Ventilation on Demand (VOD) is a system by which ventilation can exactly adapt to real ventilation needs. This means (Dicks and Clausen 2017):

(a) Ventilating only the zones of the mine when ventilation is needed. This is equivalent, in most cases, to the active zones of the mine.
(b) If ventilation in a mine zone is necessary airflow requirements may change over time.
(c) Not all auxiliary systems are required simultaneously.
(d) Probably the original design criteria have been exceeded so changes are necessary. This is the opposite of the “set and forget” policy.
(e) Non-active periods usually require less ventilation.

Ventilation on Demand can be carried out at 5 different levels (Tran-Valade and Allen 2013), namely:

1. User control: It is based on the manual control of fans and regulators to be adapted to the ventilation requirements.
2. Time of day scheduling: Actions over fans and regulators are not carried out manually but on a pre-set schedule.
3. Event-based: Changes in the ventilation system correspond with certain activities and events, e.g. blastings or a mine fire.
4. Tagging: The airflow is distributed inside the mine depending on a tag and tracking system which provides real-time location of the personnel and vehicles.
5. Environmental: Making use of modern-day computer software to continuously monitor the concentration of gases (Atmospheric Monitoring System, AMS). For this system to work, it is essential to have: (a) gas and flow sensors, (b) personnel and machinery tracking devices indicating their location at any given time, (c) fan control systems (motors with variable-frequency drive), and (d) qualified personnel.

The airflow diminution consequence of VOD results in a significant energy consumption reduction (Jahir et al. n.d.). Some studies indicate that VOD can save up to 50% on ventilation costs (Wallace et al. 2015).
5.8 Ventilation and Exploitation Method

The fundamental factors to consider in the selection of an exploitation method are morphological, geotechnical and economic. In addition, as each method must be ventilated differently, ventilation may, in some cases, influence the selection of the method. Any mining engineering textbook in which mining methods are studied will provide a detailed account of the particulars of the ventilation system to be used for each of them. The ventilation of the most common mining methods is explained afterwards for illustrative purposes.

For example, in the case of pillar-supported methods, the most characteristic is that of room and pillars. This method generates large horizontal extensions, of complex ventilation in which diesel equipment is the most common. The method implies the installation of auxiliary fans in the faces, although it is still frequent to direct the air with line brattices. It shows two variants: the bidirectional or in W and the unidirectional or in U (McPherson 1993, p. 106). In the first one, the air enters through the centre of the exploited zone and exits through both sides (Fig. 5.9a). In the second, air enters from one side, is directed one after the other to all the faces, and returns through the other side (Fig. 5.9b). One of the main disadvantages of the U-system is that the air is loaded with toxic gases as it sweeps the faces, thereby

![Fig. 5.9 Ventilation of active faces in the operation of rooms and pillars by means of deflectors: a) bidirectional system (W); b) unidirectional system (U)
decreasing its ability to renew the air. The W system, on the other hand, requires more line brattices to be executed and the pressure losses are greater.

Another pillar-supported method is the sublevel stoping. In this method, the ventilation is achieved by injecting air through the production level where the gases from the Load Haul Dump (LHD) diesel chargers accumulate (Fig. 5.10). This air ascends mainly through the raises which connect to the upper level and are drifted to the different sublevels where the blasting fumes accumulate. From the sublevels, the air enters the stope and after sweeping, it finally reaches the upper level.

As far as artificially supported methods are concerned, cut and fill and shrinkage stoping are some of the most characteristic.

Multiple configurations come under the category of cut and fill. In any case, its general layout is very similar to that of the sublevel stoping method. Thus, fresh air is injected from the transport level to the stopes via raises, and from there it reaches the upper level from where it is incorporated into the general mine ventilation (Fig. 5.11).

Regarding shrinkage stoping, the ventilation is also very similar to that of the previous methods. The stope is flanked by pillars, which, in turn, are surrounded by two raises: one for access and the other for evacuation. The air ascends from the transport level through the access raise and sweeps the stope (Fig. 5.12). The foul air comes out through the evacuation raise and is conducted towards the upper level where it is incorporated into the general circulation of the mine.

With regard to the cave mining methods, as is the case of panel caving, we will focus on its current variant: block caving, of analogue ventilation system. In order to ensure the significant amounts of precise ventilation flow at the production level,

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9The general principle of ascensional ventilation for the stopes is followed.
10This method uses pillars or filled material as a support.
these methods have a network of ventilation galleries located about 15–30 m below it (Fig. 5.13). Fresh air is circulated from the injection galleries to the production level through raises. After the sweeping of the production level, the air is conducted again by means of raises to the air extraction level (McPherson 1993, p. 113). An excellent review of block caving ventilation systems can be obtained from Calizaya and Mutama (2004).

Another intermediate method between artificially supported and unsupported is longwall mining. The most commonly used ventilation method is the U-shaped system. Under this system, the air enters through the entry route to the face, sweeps it, and travels back through the return path to the general circulation (Fig. 5.14).
In addition, there is usually a purge system with its own fan which separates CH₄ from the previous circuit. A particularly up-to-date review of ventilation techniques in coal mining can be found in Gillies and Wu (2013).

From the point of view of ventilation, coal mines can be divided into sections or ventilating districts. These are independent ventilation units into which the mine is divided to avoid enrichment in noxious gases and dust, but above all, in firedamp. Their main function is to prevent ventilation air enrichment in the above-mentioned gases as a consequence of it crossing the stopes successively. Districts are considered as being independent when they have only the main inlet and outlet airways in common (e.g. MIE 1985). By main airways, we refer to those galleries or shafts in which circulating air has not already passed through an active stope (Fig. 5.15).
Fig. 5.15  Schematization of the division by ventilating districts of a mine

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