VENTILATION FOR SINKING VERTICAL, SUB VERTICAL AND DECLINE SHAFTS.

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Abstract

To achieve safe and healthy working conditions in shaft sinking operations, ventilation, and where necessary cooling, must be provided. These requirements are considered for sinking vertical, sub-vertical and decline shafts.

Regulatory requirements, determining air volumes and amount of cooling required, the various ventilation methods used such as force, exhaust, twin columns, air reversal using four gate systems and the equipment required to achieve this, are discussed.

Consideration is also given to the sinking of single and twin declines using diesel equipment, calculating the air volumes required to dilute pollutants and the various methods for achieving this.

Also discussed is the importance of having early ventilation design input to the overall design of the mine. In many cases ventilation can be the prime determinant for the size and configuration of the shafts or declines that have to be sunk.

Introduction

Although there are many published papers, guidelines and text books available providing clear design criteria for the ventilation of mine workings, the last technical paper that could be found specifically focused on the ventilation for sinking shafts was published in 1957 (1). This conference therefore provides a welcome opportunity what is the current best practice in the field of shaft and decline ventilation.

Virtually every shaft or decline that is sunk is different in some way, be it in the geographical location, the depth, the size, winder capacity, hoisting equipment and the amount and type of development from the shaft or decline. Thus the ventilation requirements for sinking a shaft or decline must be designed in conjunction with the overall mine design and infrastructure and the equipment for sinking in the decline or shaft barrel.

Regulatory requirements in South Africa.

The Mine Health and Safety Act no longer prescribes a minimum air requirement (formerly 0.15 m³/s/m² of face area). The regulations now refer to exposure limits.
The Occupational Exposure Limits (OEL), Ceiling Limits (OEL-C) and the Short Term Exposure Limits (STEL) have been revised to bring them into line with international norms.

"Occupational exposure limit" (OEL) means the time weighted average concentration for a 8 hour work day and a 40 hour work week to which nearly all workers may be repeatedly exposed without adverse health effects.

"Occupational exposure limit - Ceiling limit" (OEL-C) means an instantaneous value which must never be exceeded during any part of the working exposure.

"Occupational exposure limit - Short term exposure limit" (OELSTEL) means a 15-minute TWA exposure which should not be exceeded at any time during a workday even if the 8-hour TWA is within the OEL-TWA. Exposures above the OEL-TWA up to the STEL should not be longer than 15 minutes and should not occur more than four times per day.

There should be at least 60 minutes between successive exposures in this range. An averaging period other than 15 minutes may be recommended when this is warranted by observed biological effects.

For those substances for which no OEL-STEL have been specified, excluding airborne particulates, a figure of three times the occupational exposure limit is to be used when controlling short-term excursions in exposure.

"Respirable particulates" means the respirable fraction of airborne particulates.

Table 1 below gives the OEL and STEL for the gases and dusts commonly generated after blasting \(^{(2)(3)}\).

<table>
<thead>
<tr>
<th>Substance</th>
<th>OEL</th>
<th>OEL-C / STEL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ppm</td>
<td>mg/m³</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)</td>
<td>30</td>
<td>35</td>
</tr>
<tr>
<td>Carbon Dioxide (CO₂)</td>
<td>5000</td>
<td>9000</td>
</tr>
<tr>
<td>Nitric Oxide</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Nitrous Oxide</td>
<td>50</td>
<td>90</td>
</tr>
<tr>
<td>Nitrogen Monoxide</td>
<td>25</td>
<td>30</td>
</tr>
<tr>
<td>Nitrogen Dioxide</td>
<td>3</td>
<td>5</td>
</tr>
<tr>
<td>Silica dust (respirable)</td>
<td>-</td>
<td>0.1</td>
</tr>
<tr>
<td>Coal dust (respirable)</td>
<td>-</td>
<td>2</td>
</tr>
<tr>
<td>Particles not otherwise classified</td>
<td>-</td>
<td>10</td>
</tr>
<tr>
<td>Inhalable particulates</td>
<td>-</td>
<td>3</td>
</tr>
<tr>
<td>Respirable particulates</td>
<td>-</td>
<td>3</td>
</tr>
</tbody>
</table>
The OEL and STEL limits given in this paper conform to the latest internationally accepted standards.

The Mine Health and Safety Act gives a complete table of OELs and STELs for a complete range of substances.

The objective in any ventilation design to ensure that these limits are not exceeded. This is monitored by sampling.

Regulatory requirements outside South Africa

South Africa shaft sinking and contracting companies often operate outside South Africa. Many countries have their own mining regulations and obviously any contractor working in that country must comply with them. However, there are some countries that have either limited regulations or in a few instances no mining regulations at all. Applying South African regulations to circumstances where the local regulations are absent or inadequate would be considered prudent and defendable.

Design considerations

The first step in any proposed ventilation design for either a sinking shaft or developing a decline is to undertake a risk assessment to establish any risks.

The main function of ventilation is to dilute and remove gases and dust provide oxygen and to remove heat.

It should always be assumed that flammable gas (any gas or combination of gases that can burn or explode) can be encountered in mining operation. The South African legal maximum allowed is 1.4 per cent in the atmosphere. Defining “atmosphere” is somewhat subjective and is not covered in the regulations but using 150 mm in any direction from the source would be considered prudent and common and acceptable practice.

Any ventilation design should be sufficiently robust to cater for abnormal but reasonably anticipated events. For instance, if pockets of high pressure flammable gas could be intersected, then the air quantity and ventilation design should take this into account.

Any ventilation design must be capable of ensuring that persons are not exposed to dangerous or unhealthy conditions as a result of pollutants.
Vertical surface shafts

Before deciding upon the ventilation system\(^{(4)}\) to be used, consideration must be given to the overall shaft layout, to work that will be done concurrent with sinking and to work that will be done from the shaft after the actual sinking has been completed.

This usually includes station development, raise boring and achieving holings with other excavations. Consideration must also be given to the potential exposure of persons, who may be working on levels above the actual sinking operation, to airborne pollutants.

Determining air requirements

This is determined by the shaft diameter, the required re-entry time and other activities (such as development) that will be carried out during the sinking operation.

For a straightforward sinking operation, providing an air volume that is able to maintain a minimum air velocity of 0.5 m/s in the shaft has generally found to in normal circumstances to be quite adequate. A shaft 8.0 m in diameter would therefore require \(50.3 \text{ m}^2 \times 0.5 \text{ m/s} = 25.2 \text{ m}^3/\text{s}\).

To calculate the minimum fresh air quantity delivered to the face to achieve a specific re-entry time and a defined number of air changes the following example is given.

Shaft diameter: 8 m diameter (50.3 m\(^2\))
Required re-entry time: 15 minutes
Number of air changes: 8
Distance from the face to the stage when raised for blasting: 50 m

Air quantity \((Q)\) = \((\text{Air changes} \times \text{Volume}) / \text{Time}\)

\[ Q = \left(8 \times 50.3 \times 50\right) / 15 \times 60 = 22.3 \text{ m}^3/\text{s} \]

In this case the minimum air quantity required is 22.3 m\(^3\)/s

This assumes that the calculated air quantity actually reaches the shaft bottom or decline face and flows back to the exhaust column without any recirculation taking place.

Ventilation methods
The ventilation methods available are:

- Force
- Exhaust over-lap
- Force - exhaust
- Air flow reversal

**Force ventilation**
This is the simplest method for air to reach the sinking face. Air is blown down ventilation column(s) and the used air usually exits via a duct. This is shown in Figure 1.

The disadvantages of this system are that for a quick re-entry the sinking crew must travel through a plug of relatively high concentrations of gases and dust.

The deeper a shaft gets, the more dispersed the plug becomes.

Unless breathing and air filtering apparatus is supplied the practice is now generally regarded as being unacceptable from a health perspective.

The alternative is to wait until the entire shaft has been cleared of gases and dust. In relatively short shafts this may not be a problem but for a deep shaft, clearing can take some considerable time.

The layout is shown in Figure 1.
Figure 1
Force system

Exhaust overlap
In this method fresh air is drawn down the shaft and exhausted out of the ventilation column(s).

A force fan and column, handling slightly less air than the exhaust quantity is installed to blow air directly onto the shaft bottom. This fan and column must be placed so that there is an overlap of at least 12 m between the intake of the force fan and the intake of the exhaust column.

This method requires that the force fan be moved regularly or be installed on the stage with a sacrificial canvas tube used to force air to the shaft bottom. This installation can run into problems as follows:

- Insufficient power on the stage.
- Insufficient room on the stage.
- Normal axial type mine fans cannot be used. These fans are designed to operate horizontally and if they are installed vertically, the bearing life is severely shortened. Thus a special fan is installed on the stage.
- High levels of noise.

Generally this method is considered the least practical.

The layout is shown in Figure 2
This method has one column permanently forcing and one column permanently exhausting. The exhaust column should handle approximately 1.5 times the amount of air than the force column. This is to ensure that the shaft barrel remains in fresh air.

In addition, the force column outlet must be closer to the sinking face than the exhaust to ensure that air is directed onto the face and that the force air does not short-circuit directly into the exhaust column.

This system is generally the most practical.
The layout of this system is shown in Figure 3
Airflow reversal
This involves changing a force column to exhaust mode after the blast. This is usually done using a 4 gate system. This ensures that good ventilation is available on the face for normal operations and contaminated air is removed after the blast. However, care must be taken that there is sufficient turbulence in the air at the face to disperse the pollutants up into the exhaust column.

As an alternative to a 4-gate system a separate exhaust fan can be installed with an air switch-over mechanism.

The principle of operation of a 4-gate system is shown in Figure 4.
Development from the shaft.
When developing from a sinking shaft the ventilation design must be capable of catering for both the sinking and the development required. A practical method is to have the total quantity of air exhausted to be sufficient to cater for all the development and to have a standard exhaust-overlap system in the development ends. Alternatively an air reversal system can be useful when cutting stations as the blasting can be made to coincide with the sinking blast.

When stations are developed it is not uncommon to use diesel powered equipment.

As the ventilation requirements for the various development possibilities are so diverse they should be designed on an individual basis rather than trying a ‘one size fits all’ approach.

There are a number of common problems that arise with shaft sinking ventilation arrangements. The major one being leakage due to improper installation and by damage. Leakage can be difficult to find and remedy as accessing ventilation columns can be difficult in a sinking shaft as it means raising the stage.
The recommended type of column available is 2 or 3 mm “Corten” with FEMA type joints. Another advantage of this type of column has a significantly lower resistance than conventional development ducting. Installing a protection piece of heavier gauge steel on the end of the column(s) is effective to prevent damage from the blast and from stage movement.

Development of declines

Declines are developed either from a surface portal or as sub vertical excavations. The latter are becoming more popular as new and existing mines wish to mechanise for production efficiency or to extend their operations and life without the expense of a full blind sinking operation.

Most commonly, developing declines are ventilated using flexible force ducting, as this is very easy to install. Often declines either spiral or zigzag down. This offers opportunities for ventilation purposes as an exhaust raise bored hole can be often put in place to maximize efficiency of the ventilation system particularly with respect to re-entry times.

Another option could be to put in twin declines. This has several advantages. One decline can be used as an exhaust until the permanent upcast facilities have been established. One decline can serve as the second (or emergency) outlet to the other in both the sinking and permanent state.

Figure 5 shows the ventilation layout for twin decline development.

Figure 5
Twin decline development
Diesel powered equipment. The diesel mining fleet is usually the determinant when developing declines or doing development off sinking shafts.

The pollutants and the OEL relevant to diesel exhaust emissions are given in Table 2.

<table>
<thead>
<tr>
<th>Pollutant</th>
<th>OEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>5000 ppm</td>
</tr>
<tr>
<td>Carbon monoxide (CO)</td>
<td>30 ppm</td>
</tr>
<tr>
<td>Nitric oxide (NO)</td>
<td>25 ppm</td>
</tr>
<tr>
<td>Nitrogen dioxide (NO₂)</td>
<td>3 ppm</td>
</tr>
<tr>
<td>Sulphur dioxide (SO₂)</td>
<td>2 ppm</td>
</tr>
<tr>
<td>Diesel particulate matter (DPM)</td>
<td>Not specified</td>
</tr>
</tbody>
</table>

Prescribed, minimum and recommended air to diesel power ratios worldwide vary considerably, from as low as 0.023 m³/s/kW for low sulphur fuel with specific “name plated” engines as determined by the diesel emissions laboratory at CANMET-MMSL in Canada, a legislated minimum volume of 0.05 m³/s/kW for major vehicles in Western Australia, to a legislated 0.1 m³/s/kW for all vehicles in Russia and most former Soviet Union countries.

There is currently no legislated minimum air quantity for diesel equipment in South Africa. Accordingly, it is recommended that a ratio of 0.075 m³/s/kW rated power and, taking into account leakages and activity factors, be used at the point of use. This ratio has been found in practice to provide adequate ventilation to dilute exhaust particulates and gases. In arriving at this figure it is assumed that low sulphur diesel fuel, catalytic converters and particulate filters will be used and that the maintenance of modern diesel equipment will be of a good standard.

Thus a LHD with a 150 kW engine would require (0.075 x 150) = 11.3 m³/s. It is generally assumed that the largest (or single) vehicle in an end should be given a ventilation factor of 1. This will cater for full power use when digging in and accelerating away with a full load.

Where multiple vehicles are in use in series the following formula may be applied:

- Largest vehicle a ventilation factor of 1.
- Second largest vehicle a ventilation factor of 0.75.
- Remaining vehicles a ventilation factor of 0.5 each.
An example of such a calculation is given below.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>kW</th>
<th>0.075</th>
<th>Factor</th>
<th>m³/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>20 tonne truck</td>
<td>240</td>
<td>0.075</td>
<td>1</td>
<td>18.0</td>
</tr>
<tr>
<td>LHD</td>
<td>185</td>
<td>0.075</td>
<td>0.75</td>
<td>10.4</td>
</tr>
<tr>
<td>Utility vehicle</td>
<td>80</td>
<td>0.075</td>
<td>0.5</td>
<td>3.0</td>
</tr>
<tr>
<td>Drill rig</td>
<td>40</td>
<td>0.075</td>
<td>0.5</td>
<td>1.5</td>
</tr>
<tr>
<td><strong>Total air required</strong></td>
<td></td>
<td></td>
<td></td>
<td><strong>32.9</strong></td>
</tr>
</tbody>
</table>

It should be remembered that this air is required at the point of use and leakage must be taken into account.

**Common problems**

**Sizing of ventilation columns**
These are based on the quantity of air required and the fan pressure that can be applied. The greater the pressure for a given air quantity the higher the power required. This can be a major consideration with power costs and availability at remote sites where electrical power must be generated.

Table 3 gives a comparison between two 1.0 m diameter flexible ducts both 1500 m long handling 15 m³/s and 20 m³/s, respectively, each with 1 per cent leakage per 100 m.

| Table 3: Comparison of fan power requirements |
|-----------------------------------------------|-----------------------------------|
| Column 1 | Column 2 | Units |
| Air intake quantity | 15.0 | 20.0 | m³/s |
| Column diameter | 1.000 | 1.000 | m |
| Column length | 1500 | 1500 | m |
| K (friction) factor | 0.0030 | 0.0030 | Ns²/m⁴ |
| Leakage of air per 100 m (ave) | 1 | 1 | % |
| Shock losses | 100 | 100 | Pa |
| Fan Pressure required | 4147 | 7295 | Pa |
| Face quantity | 12.9 | 17.2 | m³/s |
| Fan input power required (75 % overall efficiency assumed) | 82.9 | 194.5 | kW |

As can be seen, an extra 111.6 kW would be required to get another 5 m³/s of air into the same sized column. Assuming the same leakage factor and shock losses, this figure drops to only 4.3 m³/s extra air delivered at the face.

Another consideration in determining column sizes and numbers is the clearance required to operate other equipment such as sinking stages, trucks and other vehicles in the excavation. These have to be worked out for each case.
Heat loads

Generally, a surface shaft in South Africa, in the course of being sunk to about 1500 m does not experience problems with heat. Where heat can become a problem is on sub vertical and tertiary shafts and in surface shafts and declines being sunk in tropical conditions, or deeper than 1500 m or in areas with high geothermal gradients.

Heat can also be a problem in specific areas of development where diesel equipment is in use or where an inflow of groundwater at high temperature is found. These however can be dealt with.

The following factors must be taken into account:

- Depth of excavation (auto-compression of the air).
- Surface virgin rock temperature.
- Geothermal gradient of the host rock.
- Thermal characteristics of the rock.
- Size of excavation (area of rock exposed to the air).
- Ground water inflow rate and temperature.
- Broken rock.
- Diesel equipment.
- Fans.
- Pumps.
- Other mechanical and electrical equipment
- Compressed air columns.
- Pump columns.

In order to design for heat loads, it is necessary to know the cooling capacity (or lack of it) of the intake air. This entails the knowing the air quantity and the psychrometric conditions (temperature, humidity and barometric pressure) of the intake air and of the desired conditions of the reject air.

With this information, a thermal balance can be calculated which will reveal how much, if any, cooling will be required.

A thermal balance for any mining operation would consist of the cooling capacity of the air with any refrigeration required, being equal to the total heat load.

Total heat load consists of Mining heat load and the autocompression heat load.

Mining heat load =

- Heat from rock + Heat from ground water + Heat from equipment.

- + Autocompression heat load =
  Mass flow of air x Autocompression depth x Autocompression.

- Cooling capacity of the air =
  Mass flow of air x difference in enthalpy between the intake and reject air.
Where the cooling capacity is greater than the total heat load additional cooling is not required, where the total heat load is greater the difference must be made up by additional cooling normally provided by refrigeration.

There are several computer programs available that will calculate this. These programs also allow changes in the ventilation and cooling strategies to be tried out and optimized.

Up-front ventilation planning

When a mine or section of a mine is in the planning stage it is essential to have ventilation input from the very beginning.

Table 4 below gives the recommended for air velocities in various excavations.

<table>
<thead>
<tr>
<th>Type of excavation</th>
<th>Air speed range (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equipped downcast shafts</td>
<td>8 ~ 12</td>
</tr>
<tr>
<td>Unequipped upcast shafts</td>
<td>15 ~ 22</td>
</tr>
<tr>
<td>Raise bored holes</td>
<td>15 ~ 22</td>
</tr>
<tr>
<td>Declines with vehicles</td>
<td>5 ~ 8</td>
</tr>
<tr>
<td>Intake declines equipped with conveyors*</td>
<td>5</td>
</tr>
<tr>
<td>Intake airways equipped</td>
<td>5 ~ 8</td>
</tr>
<tr>
<td>Return airways unequipped</td>
<td>8 ~ 10</td>
</tr>
</tbody>
</table>

* The air speed over the conveyor should not exceed 5 m/s, for example if the conveyor is traveling at 2 m/s against the airflow then the airflow should not be above 3 m/s.

Frequently shafts and declines have to be sized on the ventilation requirements as opposed to their carrying capacity for hoisting or for vehicles. There are examples where the entire strategy to access the ore body has been determined on ventilation and second (emergency) outlet considerations.

Conclusions

For any new shaft or decline development the ventilation system should be designed to meet the requirements to achieve the sinking and development requirements and to cater for the pollutants, gases, dust and heat that could be encountered in that operation. The temptation to work on the premise that the design was alright for the last shaft and this one is similar so the same one will be used must be avoided.

In the current environment of health and safety in the mining industry any ventilation design and risk assessment should be specific and defendable should the need arise.
References
(1) J C Jacobs The ventilation of sinking shafts and development at Buffelsfontein Gold Mining Co Ltd. Journal MVS of SA October 1957.
(2) Mine Health and Safety Act Regulations – Hazardous Chemical Substances, Guideline Tables
(3) Dr M Taylor African Explosives Ltd – Personal communication.
(4) A F Lane Private Consultant – Personal communication.