# Practical aspects of the ventilation of high-speed developing tunnels in hot working environments

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## Synopsis

**The excavation of ramps and tunnels often requires high-speed development with (or without) the use of high-energy mining equipment such as loaders, dump trucks, TBMs and roadheaders.**

**This high-speed development creates a challenge in terms of providing a safe and productive working environment. For example, heat from continuously exposed surrounding rock, heat from broken rock, heat generated by mining equipment, potential inflows of hot ground water, pollution from associated diesel equipment and the distance of the advancing face from fresh through-ventilation all have to be taken into account when designing ventilation systems for high-speed ramp and tunnel developments.**

**This paper discusses methods of achieving acceptable environments at the face and along the length of the tunnel. The methodology has been successfully implemented in the development of long (up to 20 km) TBM drives in the Lesotho Highlands Project and in mining projects in hot rock using drill and blast methods as well as mechanized methods using continuous miners and roadheaders.**

**The determination of heat loads includes calculation of the heat flow within the surrounding rock, evaluation of the operating cycle of the equipment and the contribution to the overall heat load of the broken rock as it travels out of the tunnel. The determination of heat loads from surrounding rock in new tunnels required a modification of the algorithms generally used for established excavations.**

**The paper also examines the use of, for example, mobile duct and fan systems to ensure that fresh air is delivered to the specific areas where workers are located.**

## Introduction

To provide a safe and productive working environment in high-speed developing tunnels, pollutants such as heat, dust and diesel fumes must be removed by an efficient ventilation system. The best ventilation and cooling policy is generally a balance between using increased quantities of fresh air or refrigeration (or both). In a deep mine, high virgin rock temperatures mean that the refrigeration component may dominate, while in a shallow tunnel development the operation of diesel equipment may mean that refrigeration requirements are modest but significant air quantities are required for fume dilution.

In determining ventilation requirements, account must be taken of factors such as:

- ➤ Heat generated by equipment, for example, loaders, dump trucks, TBMs, locomotives
- ➤ Effect of service water
- ➤ Heat and moisture transfer from broken rock being transported in tunnel
- ➤ Heat flow from surrounding rock including moisture effects
- ➤ Effect of water pipes, including condensation
- ➤ Effect of diesel engines (including moisture)
- ➤ Ground water and drain water
- ➤ Interaction between air inside ducts and air in tunnels
- ➤ Thermal effect of fans
- ➤ Duct leakage.

A selection of some of the interesting features is discussed and two case studies, one a TBM development and the other a twin drill-and-blast heading, are used to illustrate some of the issues that need to be considered in determining appropriate ventilation systems for high-speed developments. Some conclusions regarding new approaches are also presented.

### *TBM heat*

All of the electrical power used by TBMs essentially manifests itself as heat and this is the most significant thermal input in a TBM drive. In the face zone, thermal storage takes place in the cutter head parts, surrounding rock and muck. The thermal capacity of these components results in a damping effect, which has a typical time-constant of about two hours. Thus, in determining heat loads related to power consumption, a maximum two-hour running power use is relevant (and not absolute peaks or overall averages or rated

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power). In previous work[1,2] it was concluded that the maximum average is between 40 and 55 per cent of rated capacity. The reasons for this relatively low factor are the thermal storage effects which even out the peaks and that the drive motors are loaded in a cyclical fashion during the overall cutting and advancing cycle. A significant portion of the TBM heat goes to the muck. Subsequently, the warm muck transfers heat to the atmosphere from the belts, transfer points and muck cars on its travel out of the drive. Furthermore, some of the service water leaves the cutter head zone with the muck and this has the important effect of cooling the muck.

### *Heat from surrounding rock*

In young tunnels, where hot rock is newly exposed, heat flow from the surrounding rock can be a significant thermal input. The estimation of heat flow from rock surrounding mine excavations has been well documented[3,4,5]. However, because the fundamental equations are complex, the methods have relied on interpolated approximations. Computer programs, such as Tunnel[5], have generally used approximations which are appropriate for rock surfaces that have been exposed for significantly longer periods than is the case in high-speed developments. As part of the development of new generation mine ventilation simulation software, approximations to the Jaeger and Chamalaun tables[4], valid for excavations which are newly exposed, have been produced. This significantly increases the accuracy of the procedures.

### *Regulations governing ventilation of multi-blast development headings*

In multi-blast development headings, a recent (7 September 1999) directive from the South African Chief Inspector of Mines stipulates a force/exhaust overlap ventilation system. For a 30-minute re-entry interval, a minimum air quantity of 0,3 $m^3/s$ for every square metre of face must be delivered by a force duct to within 12 m of the face. In addition, to prevent recirculation, the total quantity of air exhausted from the end must be at least twice the quantity delivered by the force fan (i.e. at least 0,6 $m^3/s$ per $m^2$); the intake of the exhaust duct must be maintained within 30 m of the face. The current directives specify that no (butterfly) valve arrangements are permitted in development ends.

### *Dilution of diesel fumes*

There is considerable debate about the harmful effects of diesel fumes and diesel particulate matter resulting from the use of diesel equipment in mines and tunnels. Internationally, the stipulated minimum fresh air quantity to be delivered for the dilution of diesel fumes varies between 0,06 $m^3/s$ per rated kW and 1,0 $m^3/s$ per rated kW at the point of use. A general rule of thumb for this dilution factor is 0,08 $m^3/s$ per rated kW, but this is a complex issue and depends on the specific ventilation scenario, ventilation leakage and the particular machine and its application.

### *Cooling systems*

Detailed comparisons have been carried out on two general alternatives for providing refrigeration to TBM drives. First, systems in which refrigeration sets are installed on the TBM train (refrigeration sets are cooled by condenser water piped into and out of the drives). Second, systems in which refrigeration water chillers are installed remote from the face and chilled water is piped into the tunnel. The comparisons indicate that the capital and running costs of the second system are typically lower than those with in-tunnel plant. For these scenarios, air cooler units will in general be installed on the back-up of the TBM to cool the air being supplied from the main duct. A typical configuration of these coolers would be in-line closed-circuit coils. By design, any remaining required cooling can be achieved by heat transfer through pipe walls (by keeping sections of the pipe bare of insulation) and, if necessary, through air coolers installed in the tunnel. Provided that there is no ventilation leakage, the cold water pipe forms an effective and efficient long linear heat exchanger and minimizes the need for other air coolers.

## Case study 1 — Drill and blast heading in a deep mine

This case study relates to a 2 000 m twin multi-blast development heading some 4 200 m below surface. The ventilation and cooling will only be served from the start of the drive located near a sub-vertical shaft station. The critical scenario with regard to ventilation and cooling is when the drive is at a distance of 2 000 m. To satisfy the multi-blast regulations, the minimum air delivered to each face zone would be 6 $m^3/s$, while each exhaust fan would be required to draw 12 $m^3/s$ from the heading. The design parameters for the case study are given in Table I.

An energy balance was carried out using specialized software and took into account all the main heat sources including surrounding rock and diesel equipment. The overall 'design' heat loads are summarized in Table II.

For the present case study, it is assumed that an LHD with a nominal rating of 140 kW is serving both headings. The minimum air quantity for diesel dilution must therefore be delivered to both ends continuously, to enable the LHD to travel between the ends freely. Thus, a minimum air quantity of 12 $m^3/s$ would be delivered to the zone where the LHD is operating, i.e. to each face zone. The current directive

*Table I*

| | | |
|---|---|---|
| Heading dimensions | 4,5 x 4,5 | m² |
| Maximum length of drive | 2 000 | m |
| Average rate of advance [each end] | 180 | m/month |
| Barometric pressure | 130 | kPa |
| Mean air density | 1,49 | $kg/m^3$ |
| Supply ventilation temperature to drive | 24/30 | °C wb/db |
| Design wet-bulb temperature | 28,5<br>29,5 | °C in face<br>°C in tunnel |
| Service water supply | 1 | ton/ton |
| Supply water temperature | 15 | °C |
| Cleaning - LHD | 140 | kW |
| Hauling - Dump truck | 180 | kW |
| VRT | 65 | °C |

*Table II*

| | Heat source kW |
|---|---|
| Surrounding rock | 2355 |
| Fans, electrical losses, etc. | 20 |
| Diesel equipment | 470 |
| TOTAL | 2845 |

stipulating that the exhaust fan must draw at least twice the quantity delivered to the face (to prevent recirculation in the force duct system), means that the total air flow within each heading would be 24 $m^3$/s, giving a total air quantity of 48 $m^3$/s delivered to the drive. This total quantity would be adequate for the dilution of diesel fumes produced by the dump truck operating in the tunnel. Because the regulations do not allow the use of valve arrangements, it is not possible to vary the flow to a heading depending on the location of the LHD. But the use of two-speed fans would enable less air to be delivered to the faces and exhausted from the headings when the LHD is not operating. Tracking devices, which trace the movement of the diesel LHD, could be linked to the fan controls to automatically implement the necessary changing of fan speeds. However, the effect of such regular flow variation on the overall mine ventilation system would need to be evaluated.

Fresh air would be supplied in one of the drives and reject air returned in the second drive. The heat load will be absorbed by the ventilation air and by chilled water, which provides cooling in the face zone and in air cooler installations in the intake drive. The two heat sinks absorb the heat loads indicated in Table III.

The total air quantity delivered would be 72 kg/s (48 $m^3$/s) and the total water quantity required to achieve acceptable conditions would be 39 l/s. These are very significant resources, which would typically require 200 mm water columns (intake column insulated) and at least a 1 m duct in each heading. The force and exhaust fans would typically be rated at 18 kW and 55 kW respectively. Free-standing jet fans could be used to assist in maintaining acceptable conditions in the face zone.

The same case study was examined using an electrical LHD with the same power rating in the face zones (with the diesel dump truck operating in the drive). An energy balance was carried out using specialized software and took into account all of the main heat sources including surrounding rock and electrical and diesel equipment. The overall heat loads are summarized in Table IV.

The surrounding rock is still the dominant heat load, but note that the heat load from the equipment has dropped by 23 per cent. Also, note that no additional air would be required for fume dilution and the minimum air quantity to be delivered from the station would be 24 $m^3$/s. The lower air quantity would have a correspondingly lower ability to remove heat and more cooling water would be required. The two heat sinks absorb the heat loads shown in Table V.

*Table III*

| | Heat sink kW |
|---|---|
| Chilled water | 1760 |
| Primary ventilation air | 1085 |
| TOTAL | 2845 |

*Table IV*

| | Heat source kW |
|---|---|
| Surrounding rock | 2355 |
| Fans, electrical losses, etc. | 20 |
| Diesel and electrical equipment | 360 |
| TOTAL | 2735 |

*Table V*

| | Heat sink kW |
|---|---|
| Chilled water | 2195 |
| Primary ventilation air | 540 |
| TOTAL | 2735 |

The total air quantity delivered would be 36 kg/s (24 $m^3$/s) and the total water quantity required to achieve acceptable conditions would be 52 l/s. These are still very significant resources, which would typically require 200 mm water columns (intake column insulated) and at least a 760 mm duct in each heading. The force and exhaust fans would typically be rated at 11 kW and 22 kW respectively. Free-standing jet fans could be used to assist in maintaining acceptable conditions in the face zone.

Both the force and exhaust ducting must be maintained within a specified distance from the face and tunnelling activities may need to be suspended on a daily basis to allow ducting to be advanced.

## Case study 2 — TBM drive in a deep mine

This case study relates to a high-speed TBM drive situated some 3 000 m below surface. The ventilation and cooling will only be served from the start of the drive located near a subvertical shaft station. The critical scenario with regard to ventilation and cooling is when the drive is at the final distance of 6 000 m.

The design parameters for the case study are given in Table VI.

An energy balance was carried out using specialized software and took into account all of the main heat sources including TBM heat, surrounding rock, locomotives, shotcreting and the main duct fan power. The overall heat loads are summarized in Table VII.

One of the great benefits of using TBMs is the absence of

*Table VI*

| | | |
|---|---|---|
| TBM power rating (including cutter head motors, conveyor drives, pumps, secondary fans, etc) | 2 000 | kW |
| Cutter-head diameter | 4 | m |
| Maximum length of drive | 6 000 | m |
| Average rate of advance | 350 | m/month |
| Barometric pressure | 120 | kPa |
| Mean air density | 1,35 | kg/$m^3$ |
| Inlet air temperature to drive | 24/30 | °C wb/db |
| Design wet-bulb temperature | 28,5<br>29,5 | °C on TBM<br>°C in tunnel |
| Service water supply | 5 | l/s |
| Supply water temperature | 15 | °C |
| Hauling – electric locomotives | 3 x 45 | kW |
| VRT | 48 | °C |

*Table VII*

| | Heat source kW |
|---|---|
| TBM power as heat | 1040 |
| Surrounding rock | 900 |
| Main tunnel fan power and auxiliary fans | 270 |
| Lights, cable losses, etc | 100 |
| Electric locomotives | 90 |
| Shotcrete/coverdrilling equipment, etc | 80 |
| TOTAL | 2480 |

*Table VIII*

| | Heat sink kW |
|---|---|
| Chilled water | 1825 |
| Primary ventilation air | 655 |
| TOTAL | 2480 |

blasting fumes and related re-entry issues. In taking full advantage of this, a completely different approach to that traditionally used in ventilating high-speed development ends can be adopted. It is possible to use a force ventilation mode of operation and achieve the following benefits:

- Use of flexible, low friction, low leakage ducting that can be supplied in lengths of up to 200 m
- Use of duct cassettes, which allow an automatic advance of duct. This is only possible with flexible ducts, and solves the problem of maintaining follow-on ducting at high face advance rates
- Use of a single main fan station at the start of the drive rather than numerous staged fans along the drive. The duty of the fan station must be upgraded as the length of the drive and the length of the force ducting increases.

The analysis shows that the optimum ventilation system would make use of a ducted force ventilation system from a main fan station located at the start of the drive. The required ventilation flow in the main duct would be 23 m$^3$/s (11 m$^3$/s would be delivered to the TBM back-up train, which extends to 300 m from the face) and this would be achieved by a nominal 1,2 m duct system. The heat load will be absorbed by the ventilation air and by chilled water, which provides cooling in the face zone, in air cooler installations and via the supply and return pipes. The two heat sinks absorb the heat loads shown in Table VIII.

The main duct will deliver primary ventilation to the TBM back-up train and the air will be cooled by heat exchangers installed on the train. Secondary fans then circulate the cooled air to the front of the TBM train through appropriate ducting installed on the train. The total air quantity delivered at the main fan station would be 30 kg/s (23 m$^3$/s) and the total water quantity required to achieve acceptable conditions would be 45 l/s. These are very significant resources, which would typically require 200 mm water columns (intake column insulated) and at least a 1,2 m duct in the tunnel.

## Observations and conclusions

A number of important issues are highlighted in the case studies.

- Different combinations of ventilation air and cooling water will remove the heat loads in developing tunnels. The final selection of an air quantity and a water flow rate will usually be dictated by factors such as the minimum air quantity required for dilution of diesel fumes, the available space for ducting and cost of fan power, pump power and refrigeration power.
- Detailed comparisons have shown that capital and running costs of a system in which cold water is piped into the tunnel from a refrigeration water chiller located remote from the face are significantly lower than systems in which a refrigeration set is installed on the TBM train.
- Notwithstanding the development of more efficient, cleaner burning diesel engines and fuels, the operation of diesel equipment in a heading implies that significantly more air is required to ensure dilution of diesel fumes, than is the case of a heading in which only electrical equipment is utilized.
- Current South African regulations do not allow force ventilation systems in multi-blast developments. The advantages of using flexible force ducting that is continuously extended as the face advances thus cannot be realized.
- The rate of advance achievable in a single TBM drive is about twice that possible in a drill and blast heading. Additional advantages of TBM developments are the absence of blasting fumes and related re-entry times.
- In a carefully designed system, the use of staged fans along the length of a drive can be avoided if large ducts with low friction and low leakage characteristics are used. Maintenance of any duct system to minimize pressure losses and leakage is critical.
- The use of two-speed fans in multi-blast headings in which diesel equipment is operating will enable the flow rate in the heading to be varied, depending on whether the equipment is running or not.
- Very large ventilation and cooling resources are required. Typically these would include at least 1 m ducts, an insulated chilled water supply, auxiliary (force/exhaust overlap) fans and jet fans. An important issue that must be addressed with a high level of priority is maintaining the exhaust and force ducts close to the face, particularly in view of all of the other activities taking place in the heading, such as, rock bolting, shotcreting and even possible insulation of rock surfaces for future strategic airways.

Although the above case studies have specifically focused on deep mining operations, the principles have been well established/proven in long surface tunnelling operations.

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