AIRFLOW REQUIREMENTS FOR MODERN DIESEL AND ELECTRIC EQUIPMENT

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ABSTRACT

This paper outlines some of the factors that affect the airflow required for the ventilation of modern diesel-powered equipment and of electric equipment and examines how they can be applied in determining reasonable ventilation rates for Tier IV compliant diesel equipment and for electric equipment operating in mining environments. Airflow calculations for modern diesel-powered equipment and for electric equipment are more complex and must be based on a combination of factors that are unique to each mine. Methodologies for ventilation rate determinations for each case are proposed in this paper.

KEYWORDS

Diesel mining equipment; Electric mining equipment; Ventilation; Airflow

INTRODUCTION

Traditionally, airflow requirements for production and support equipment operating in underground mines have been determined by multiplying the vehicle power by a ventilation rate that was either mandated by regulations or determined empirically from known quantities.

However, in light of the drastic reductions to diesel equipment emissions mandated by the US EPA Tier IV and EURO Stage 4 regulations, there is still a great deal of uncertainty in the underground mining industry among those responsible for the ventilation of planned new mines or the expansion of current mines. The question remains, what ventilation rates should the ventilation system designer apply for modern diesel equipment?

Also, given the ongoing development of grid/battery-electric equipment and active construction of fully electric mines, it has become critical to determine adequate airflow rates per brake kilowatt of electric engine power. One of the most important criteria for determining ventilation rates for electric equipment is the amount of heat they generate, as this is the most significant emission produced by electric equipment (which do not produce exhaust gases or particulates). Therefore, ventilation rates required to dissipate heat from electric equipment must be suitably determined for all electric vehicle fleets operating in underground mines.

This paper outlines some of the factors that affect the airflow required for the ventilation of modern diesel-powered equipment and of electric equipment and introduces methodologies for ventilation rate determinations for the two cases.

FACTORS AFFECTING VENTILATION RATE REQUIREMENTS FOR MINES

Mine ventilation systems are primarily designed to remove the contaminants of toxic equipment exhaust gases, diesel particulate matter, heat, dust and blasting fumes from the underground environment. This is accomplished by dilution of the contaminant(s) in question, removal from the affected area, or both. Dilution of dust and gaseous contaminants involves a relatively simple calculation directly proportional to the relative volumes of air and the contaminant. The removal of contaminants is dependent upon the velocity of the ventilating airstream, along with the fundamental design of the ventilation infrastructure, e.g. the location of intake/return airways, raises, etc. The transfer of heat from in-mine sources to ventilation streams, although significantly more complex in nature, is nonetheless able to be relatively accurately estimated and calculated.

Experience in ventilation planning has shown, that of all contaminant sources within modern underground mines, diesel equipment have generally taken primacy in ventilation quantity determinations; meaning that an airflow determination based on the power of the diesel fleet will be sufficient to dilute/remove all contaminants from all other sources. This is because diesel exhaust is a major source of underground air pollution, including diesel particulate matter (DPM), NO2 and heat, and because regulations tie air volumes to diesel engines. In Canada, statutory requirements of 0.063 m^3/s per kW of rated engine power are used for estimations of airflow requirements. This rule has generally been true in ventilation planning exercises except in cases of extreme heat or cold due to environmental or geological conditions based upon the physical location of the mine. However, with the drastic reductions in diesel emissions mandated by regulatory bodies (EPA Tier IV, EURO Stage IV) this may not be the case once the use of these engines and equipment become widespread in underground mines.

The application of strategic design criteria is also an important consideration when making a determination of the total airflow required for a planned underground mine. Strategic design criteria include all of those design considerations that result from the choice(s) of mine design and operation. Such design considerations include, mine layout and depth, dimensions of airways, mining method, production rate, equipment selection, and fixed facilities and infrastructure located underground. Important parameters of consideration for determining the overall airflow requirements include minimum and economic air velocities, air leakages, environmental requirements for gas emissions, dust and heat, and air conditioning requirements.

The validity of the estimated overall airflow is in most cases verified through network modelling of different planning activities and correlation with the production plans over the mine life. Benchmarking against operations with similar mining methods and production rates are also often used to validate the estimated airflow.

VENTILATION RATES FOR MODERN DIESEL MINING EQUIPMENT

Diesel-powered mining equipment contributes to four types of contaminants that must be mitigated by the mine ventilation system. Either directly or indirectly, diesel equipment produces toxic gases, particulates (DPM), heat and dust through their normal operation in mines.

A number of options and control strategies for the treatment and reduction of diesel emissions are available to industry, all of varying scopes, efficiencies, and expense. These include ventilation, fuels and fuel additives (low sulphur and ultra-low sulphur diesel, and biodiesel), emissions-based maintenance programs, engine type/specification, exhaust aftertreatment (diesel oxidation catalysts, diesel particulate filters, disposable-type filters, selective catalytic reduction), environmental cabins, administrative controls (limiting engine idle time, limiting the number of equipment allowed in a heading or drift, and remote control and automation) and personal protective equipment (respirators). Combinations of emissions control measures can be applied in order to provide the most efficient use of the allocated resources.

The most generally accepted model for determining the total airflow required for a diesel equipment fleet involves utilizing an accepted multiplier of the equipment power and with percentage reductions made for the utilization and/or availability of individual pieces of equipment. Both the values themselves, ranging between 0.045 and 1.00 m^3/s per kW, and the methods for arriving at those values (empirical derivation, statutory compliance, EQI, ALARA, etc.) demonstrate considerable variability. Whatever the method used for arriving at the multiplier, once this number has been identified, it is generally accepted that it will be sufficient to cover all four contaminant products. However, this could potentially lead to great inefficiencies whereby the amount of airflow provided was significantly more that what was required, particularly with more recent, low-emission engines. At the scale of many large mining complexes, these inefficiencies can potentially result in substantial penalties in terms of the capital and operating cost of the ventilation system. More often, the total airflow requirement for underground mines has been undersized (insufficient flow) especially in cases where the impacts of heat and dust were not considered during the design phase and ventilation rates were derived solely from bench tests by regulatory agencies.

Given the above limitations, it is proposed that the estimation of airflow requirements for modern (Tier IV) diesel equipment fleets should incorporate the separate calculation of airflow rates (Q) for each of the four contaminant products (gases, particulates, heat and dust) with the total ventilation flow rate required equivalent to whichever is greatest. The determination of airflow rates for each of the four contaminant products is discussed in the following sub-sections.

Gaseous products of combustion (POC) and DPM

For estimations of airflow requirements for Tier IV diesel equipment, it is recommended that a value of 0.025 m^3/s per kW (range between 0.022 and 0.028 m^3/s per kW) may be used for determining the airflow required for diluting gaseous contaminants and 0.010 m^3/s per kW (0.009 – 0.011) for DPM.

Heat

The determination of the total airflow required for cooling Tier IV diesel equipment is not significantly different than the determination of cooling airflow required for other diesel equipment; however, it has become an even more critical step in the ventilation planning process owing to the drastic reductions in airflow required for the dilution of exhaust gases and DPM which now render the heat generated by equipment significantly more impactful to the design calculations.

Unlike many contaminants mitigated by the ventilation system, it is not necessary to determine the maximum heat production of the equipment, and in planning exercises the average rate of heat production is generally calculated and used in determining the proper ventilation rate(s) required.

Calculating the heat production from a diesel-powered machine can be practically accomplished through the following process.

First, the Total Heat is determined based on the fuel consumption rate:

$$Q_T = f_c \times C_{diesel} / 3600$$

where,
Q_T = total heat (kW)
f_c = fuel consumption (litres/hr)
C_{diesel} = heat content of diesel (kJ/litre)

Next, the Latent Heat is calculated:

$$Q_l = V_{H2O} \times l_{H2O} / 3600$$

where,
Q_l = latent heat (kW)
V_{H2O} = volume of water production (litres/hr)
l_{H2O} = latent heat of vaporisation of water (kJ/kg)

The Sensible Heat generated is simply the difference between the Total Heat and the Latent Heat:

$$Q_S = Q_T - Q_l$$

where,
Q_S = sensible heat (kW)

Q_T = total heat (kW)
Q_l = latent heat (kW)

The associated temperature rise in the ambient air across the machine is a function of the flow rate of air:

$\Delta T = q / (m_{air} \times C_p)$

where,
ΔT = Temperature Change (K)
q = heat (kW)
m_{air} = mass flow rate of air (kg/s)
C_p = specific heat of dry air (kJ/kgK)

Often this equation is changed slightly to solve for the ventilation rate necessary to limit the temperature increase across the machine to a certain point, or to ensure that conditions do not reach the design criteria for stop-work temperature. Note that the mass flow rate of air should be converted to a volume flow rate using the air density in order that a proper comparison to the other ventilation rates can be made:

$VR = v_{air} / P_{machine}$

where,
VR = ventilation rate (m^3/s per kW)
v_{air} = volume flow rate of air (m^3/s)
$P_{machine}$ = machine power (kW)

Now it is possible to both calculate the heat added to the mine environment and establish criteria for evaluation and comparison based on the other contaminant products of the diesel equipment fleet.

Mineral dust

The dust created by new low-emission diesel-powered equipment does not vary significantly from that generated by older equipment, instead the examination of how much airflow is required to remove the hazard has become more important based on the reduction(s) in airflow required for other contaminant products (i.e. gases, DPM). As long as mechanical equipment is utilized to break, load and transport material in underground mines, dust will be generated at the sites where the mineral is disturbed, and it will be equally important to eliminate, minimize or remove this hazard from the ambient underground environment as long as there are people present in these areas.

Although many forms of dust control in underground environments exist, including the extremely effective use of water sprays and dust filtration units, ventilation remains the most commonly used means of diluting and removing mineral dust from the underground environment. Respirable dust settles from the airstream at an almost negligible rate, and should be controlled via dilution in a manner similar to other gaseous contaminants. In the case of larger particles it is primarily the airflow velocity that dictates the distance and time the dust particles will be entrained in the air stream (McPherson, 2009). If the airflow velocity is too great, then additional dust particles can be picked up by the ventilating air.

The minimum airflow velocity in areas where diesel equipment is in operation should be 1 m/s. A further benefit of an airflow velocity of at least 1 m/s in development and production locations such as loading points and muck bays is that it also contributes to a significant airflow penetration distance into areas that are not part of the primary ventilation circuit.

Selecting appropriate airflow velocities for design criteria can also prevent the stratification of exhaust gases and respirable dust within mine entries where diesel equipment is operating. Homotropal ventilation should also be considered along haulage routes to further minimize the generation and propagation of harmful mineral dust underground.

Ultimately, since dust control in modern underground mining environments usually incorporates a combination of active and passive installations including but not limited to the ventilation system, using the minimum velocity requirement alone for dust control (which assumes dust is addressed solely by the ventilation system, i.e. no water sprays, etc.) may lead to overestimating the ventilation requirement. Alternatively, the minimum requirement associated with one drift based on airflow velocity may not be sufficient when there are multiple vehicles operating in that drift. Therefore, minimum velocity should only be used as the governing criteria in areas where no other dust control measures are in place and only one piece of diesel equipment is expected to be in operation.

Case application

A test case featuring an actual piece of mining equipment is presented to demonstrate the application of the proposed method in determining airflow requirements based on individual derivations for the contaminants of gaseous POC, DPM, heat and dust.

The LHD selected for this comparison is the commercially available Sandvik LH517 powered by a Volvo TAD1361VE 285 kW Tier IVi engine. This LHD has a rated capacity of 17,200 kg in its 7 cubic meter bucket and is approved for use in underground mines by NRCan under CSA M424.2-90 (non-gassy mines). Minimum drift dimensions of approximately 5 m wide by 6.5 m high are required for this loader to achieve full mobility.

The results of the total required airflow determination for the test LHD using the various methods of calculation are shown in Table 1.

Table 1. Calculation of required Tier IVi LHD airflow

Method of Determining Airflow	Total Airflow (m^3/s)	Ventilation Rate (m^3/s per kW)	Percent of Greatest (%)
Gaseous POC	8.0	0.028	24.6
DPM	3.1	0.011	9.5
Heat	21.4	0.075	65.8
Dust	32.5	N/A	100

When compared with current methods (required airflow of 18 m^3/s at a ventilation rate multiplier of 0.063 m^3/s per kW), the required flow is actually higher for a Tier IV engine.

This example clearly illustrates the profound changes in the total airflow determination caused by the addition of heat and dust as design criteria. While it may be possible to justify a reduction in the airflow required for dust control provided that other design features (e.g. water sprays) are added to the area in question, the mitigation of heat (the next highest airflow requirement) remains a concern and could even be exacerbated by the addition of water to the local environment (raising the humidity and ultimately the wet-bulb temperature).

Despite the significant reductions made in the gaseous POC and DPM emissions of the Tier IVi engine, the overall airflow required has not significantly changed, and may even be increased in cases where the critical design parameters of heat and dust were not previous considered.

VENTILATION RATES FOR ELECTRIC MINING EQUIPMENT

It is seen by many that electric equipment could greatly reduce the volume of air needed to ventilate an entire mine as well as individual headings because they do not emit many of the contaminants found in diesel exhaust. Because of the exponential relationship between power consumption and air volumes, this could greatly reduce the amount of power required for mine ventilation as well as the capital cost of ventilation infrastructure. As heating and cooling costs are also directly linked to air volumes, the cost and energy intensity of heating and cooling the air would also be significantly reduced.

The only emissions produced by electric mining equipment are heat and dust, and therefore, required ventilation rates are based on the determination of the effective dissipation of heat from electric equipment provided that minimum airflow velocities or other dust control measures are implemented as described for diesel-powered equipment. It is still critical to ensure dust and blasting fumes can also be adequately addressed by the ventilation system. Since dust is often successfully controlled through the use of water sprays and operational practices, it may not be considered a major factor in determining airflow requirements. Thus the heat generated by the electric engines would be the main factor governing airflow requirements, as long as the reduced airflows are still able to effectively clear blasting fumes and maintain minimum airflow velocities.

Additional sources of heat including heat from the rock strata, autocompression, the oxidation of ores, mobile equipment, auxiliary fans, pumps, compressed air, hoists, conveyors and intentional heating of the air during winter, should also be considered although they may not have a large impact on the ventilation systems.

In general, electrically-powered equipment produces only about one-third of the heat that a comparable diesel-powered vehicle does. More specifically, considering that reasonable proxies for the efficiencies of diesel engines and electric motors could be 37% and 92% respectively, then it can be stated that electric equipment should produce about 40% of the heat per kW of brake power output. In this case it is important to note that brake power output refers to the work done and not to the nameplate size of the engine or motor.

In practice, other sources of underground heat also need to be managed by the air supply. As well, the airflow in headings needs to be high enough to mitigate airborne dust and to clear blasting fumes in a reasonable amount of time. Due to these additional concerns, only a 40% to 60% reduction in airflows seems necessary and practical assuming no major changes in the design philosophy of underground ventilation systems.

Given a reduction in mine airflows of 40% and a reduction in drift airflows of 50%, then the power consumption of the main fans and the auxiliary ventilation system should drop by upwards of 80% and 70% respectively. Additionally, it is likely that the height of mine workings can be reduced by at least 0.3 m due to a reduction in the standard diameter of ventilation tubing.

Ignoring additional sources of heat and other concerns, discussed above, the amount of air required for ventilating electric equipment needs to be based on how much power it consumes throughout the shift. Effectively this means the airflow needs to match the utilization, load factor and nameplate power of the motor because all of the work done, except for work done against gravity and work recaptured through regenerative braking, is converted to heat. Thus, the design of ventilation systems should take into account additional heat loading from charging batteries underground, and heat reductions from regenerative braking and any significant work done against gravity, like hauling ore and waste rock upramp.

In a fully electric mine, supplying only enough air to address heat emissions from electric mining equipment will not be sufficient. Either, airflows will need to address all heat emissions, or cooling capacity will need to be incorporated into the ventilation system to manage some portion of the heat load.

When considering the heat produced by electric mining equipment, equipment utilization and average motor load(s), airflows in the range of 0.020 to 0.035 m^3/s per brake kW would be considered appropriate for electric equipment. However, it should be stressed that these rates will not be appropriate for electric equipment with non-average load factors and that ultimately airflows need to be based on the power consumed by the equipment and any additional heat loading intended to be addressed by the air supply. As such, ventilation rates for electric equipment averaging 0.045 m^3/s per kW are recommended. It should be noted that the airflow rates provided for electric equipment should not be compared directly with flow rates for diesel equipment as motor sizes for electric equipment are typically smaller than engines in comparable diesel equipment. The overall reduction in flow volume for electric equipment is actually greater than it would appear given a direct comparison of flow rates.

DISCUSSION

In general mine ventilation is required in order to dilute and remove the following contaminants:

1. toxic equipment exhaust gases
2. diesel particulate matter (DPM)
3. heat
4. dust
5. blasting fumes

Diesel engines and the combustion of hydrocarbons are primarily responsible for the first two sources of air pollution underground and contribute a large component of the third. Alternatively, electric mining equipment does not produce any toxic exhaust gases, no DPM from combustion and much less heat. Although implementing electric equipment will reduce the first 3 categories of pollution, it will still be critical to ensure dust and blasting fumes can also be adequately addressed by the ventilation system.

Concerning dust, even with the use of very clean engine exhausts (Tier IV), dust can be produced in such large quantities that it could easily require more air than current regulations mandate (0.063 m^3/s per brake kW) to completely dilute and remove it from the workplace. However, it is noted overall dust is often not a major factor in determining airflow requirements because it is often successfully controlled through the use of water sprays and operational practices. Instead, if and when diesel engine exhaust is sufficiently clean to have little impact on air quality, then the heat generated by the engines would be the main factor governing airflow requirements.

Assuming that the introduction of electric equipment will permit airflows supplied by the auxiliary ventilation system to be reduced, as long as the reduced airflows are still able to effectively clear blasting fumes and operational practices are still able to effectively mitigate airborne dust, then it can be assumed that the main consideration governing airflow requirements will be heat production in the underground environment.

For modern diesel and electric equipment, ventilation airflows are based on the amount of airflow required to dilute and clear the heat produced by mining equipment. Furthermore, heat from other sources also need to be accounted for, as well as whatever air is required for mitigating dust and clearing blasting fumes from active development and stoping areas.

CONCLUSIONS

Diesel mining equipment

Given the significant reductions in the emissions of diesel-powered mining equipment, it seems highly unlikely that total flow calculations for future mines and mine expansions will continue to be calculated based simply on engine power. In this paper, a solid case is made demonstrating that heat and dust from diesel equipment should be considered and included in making calculations of this nature. It has also been demonstrated that the 90% reductions in emissions associated with Tier IV diesel engines will not result in 90% reductions in ventilation rates and total airflow quantities that many anticipated. Even with drastic reductions in the gaseous and particulate emissions realized by Tier IV engines, the heat generated by those engines mandate a ventilation rate that is not significantly lower than what is commonly used today. Based on the heat production of diesel engines, the analysis showed ventilation rates that varied from approximately 0.06 m^3/s per kW to 0.094 m^3/s per kW over the range of input parameters likely to be encountered in most mining scenarios with a rate of 0.075 m^3/s per kW for ‘average’ conditions.

Electric mining equipment

Considering the likely operating efficiencies of electric motors and diesel engines, it can be determined that electric equipment produces only 40% of the heat produced by diesel equipment. Based on estimated heat emissions of electric mining equipment, it is postulated that without diesel equipment underground, ventilation volumes could be reduced by as much as 40 to 60%. Ventilation rates for electric equipment averaging 0.045 m^3/s per kW are thus recommended (note that the recommended flow rate appears conservative as electric motors tend to be smaller than diesel engines). Considering that reductions on the recommended scale would reduce power requirements for the ventilation system by 70% or more and that lower flowrates could be problematic due to issues with respirable dust, blast clearance times and heat, it is likely that airflows cannot be reduced further and there would be few incentives to do so. In the end removing diesel equipment from the underground does not eliminate the need for ventilation and therefore ventilation systems as they are currently designed and operated will remain a necessity for underground mines for the foreseeable future.

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