Air quality in underground mining

Suggested adjustments for the fulfilment of the Commission Directive 2017/164

Ana Catarina Soares Gonçalves

Instituto Superior Técnico, Lisbon, November 2019

Abstract

The European Commission Directive (EU) 2017/164, published on the 31st of January 2017, has new Indicative Occupational Exposure Limit Values (IOELV) for chemical agents. The sixth article concerns the implementation of new limit-values for CO, NO and NO_2 gases in the underground mining industry. This study aims to understand the main contributors of these toxic gases and possible mitigation measures.

In the Directive, there is no indication of which methodology should be used to attain toxic gas' values. As a result, a method has been developed to gather air quality data and its further analysis. The developed method considers the assessment of all sites and operations, adaptable to all mines. The methodology is divided in three phases: characterization of the mine under analysis, measurement methodology and data analysis.

After the methodology was developed, it was applied in two case studies. In the first case, it was possible to perform direct measurements during the months of July and August 2019. Data was collected referring 20 situations allowing the understanding of the current situation in all types of sites and operations of the mine. In the second case, data was provided by the mine for further analysis. Here, the methodology was only partially implemented, and the data analysed was only related to the cleaning cycle.

Possible adjustments to meet the Directive's IOELVs and, consequently, to increase air quality by improving underground workplaces were also analysed.

Key-words: Air Quality, Underground Mining, Explosives, Diesel Equipment

1. Introduction

On January 31st, 2019, the European Union (EU) released the Commission Directive 2017/164 establishing the fourth list of indicative occupational exposure limit values (IOELV), with the purpose of increasing the health and safety of workers from risks related to the chemical agents at work. On this directive is established new limit values for the carbon monoxide (CO), nitrogen monoxide (NO) and nitrogen dioxide (NO_2). The new limits for these gases present a challenge for the underground mining industry, and so, the directive provides a transitional period ending on 21 August 2023.

The main objective of this investigation is to analyse the required adjustments on underground mining sites in order to fulfil the Commission Directive 2017/164 and, consequently, increase the air quality, improving the underground work site.

The presence of toxic gases in underground mines has several origins, but the use of explosives and diesel equipment are the main causes of most toxic gases present in this environment [1]. Depending on the mineral being explored, its extraction or reaction with the oxygen and other gases can lead to fires and, perchance, explosions, as it is the case of pyrite.

The toxic gases produced by explosives will depend on the type of explosive, the quantity of explosives used, the rock mass and the surrounding atmosphere. However, NO_x and CO are always present on the atmosphere, after blasting [2]. The CO values are higher after an emulsion blasting in comparison with ANFO; The NO values are low, almost null, after emulsion blasting unlike ANFO blasting; The NO_2 values are low with the use of both explosives, however, with the oxidizing process of NO, the nitrogen dioxide values start to increase [3][4].

Diesel equipment are one of the main sources of toxic gases. The major drawback of diesel equipment is the emission of toxic gases such as CO and NO_x, that are difficult to control [1]. Even though the pollutants emissions (CO, NO_x, hydrocarbons and diesel particulate matter) represent 0.1% of the burning diesel process they represent serious health problems to which the workers are exposed to [5].

2. Methodology

On the directive there is no indication regarding the method of measurement to understand the values of the toxic gases. Therefore, a methodology that aims to be adaptable to all types of mines, regardless the mining method, and including all situations on which the miners are exposed to the toxic gases specified by the Commission Directive 2017/164 was developed. Using this method is possible to have a detailed analysis of the areas and operations that expose the workers to the worst environments, allowing an assessment of the necessary improvements for the mine being studied.

Initially, it is necessary to do a theoretical approach with the objective of contextualizing the circumstances and gain in-depth insight of the mine under analysis. Posterior to this analysis, it is required to understand where the new limits for toxic gases are not being fulfilled and which are the contaminants' producers, through a practical approach. Subsequent, this study is conceivable to reach adjustments to accomplish the Commission Directive, adapted to each case. The methodology process is illustrated in Figure 1:

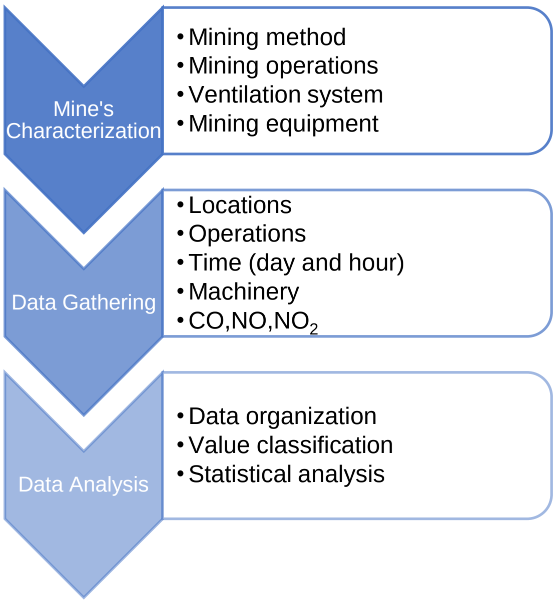

Figure 1 - Methodology

The mine's characterization aims to adapt the other phases of the methodology to the mine in study. The characterization should be made following the parameters mentioned in Figure 1.

Regarding the data gathering, a practical approach, measuring the toxic gases at the site, is crucial for the study of solutions, therefore, the gas' analysis should be done on a normal performance of the mine. It is necessary to select development areas, stopes and other locations where the workers stay for more than 15 minutes. Posterior to the choice of the locations, the operations performed at the sites, to which is necessary the presence of workers, should be identified. The measurements should conciliate the locations with the operations performed at the site. To have a complete analysis, the data must be collected for, at least, the time of one cycle of each operations. During the data gathering, it should always be indicated the parameters described in Figure 1 and which is the source of energy from the working machines, if the auxiliary ventilation is on, and, if there are any other contributors of toxic gases at the site.

After the data gathering, it is imperative to evaluate the results. This data analysis will be divided in three main phases: data organization, value classification, statistical analysis, as represented in Figure 1. The data organization will create a homogeneous data base for further comparison; to simplify the analysis, the data should be separated, firstly by location, and after by operation. After the data organization, it is necessary to understand when the new limits are not respected. For an easier interpretation, the data should be identified by the colour scheme displayed in table 1.

Table 1 - Identification of data range

CO (ppm)	**NO_2** (ppm)	**NO** (ppm)
$[0 , 20]$	$[0 , 0{,}5]$	$[0 , 2]$
$]20 , 100]$	$]0{,}5 , 1]$	> 2
> 100	> 1	

- Green: fulfilment of the TWA limit

If the values are green, the location/operation are not a preoccupation to the mine, since the TWA limits are followed, therefore it follows the directive.

- Yellow: fulfilment of the STEL limit

If the values are yellow, it is necessary to identify for how long; if the time the values are above the TWA limit does not surpass the 15 minutes, than the location/operation is in accordance with the directive, otherwise, it should be a concern for the mine.

- Red: unfulfillment of both limits

If the values are red, the location/operation does not comply with the directive, and so, the mine needs to do adjustments, regarding the location itself or the operation.

To do the statistical analysis it is fundamental to choose a representative period, in order to compare all the situations during the same amount of time, creating a more coherent statistical analysis. The representative period should be decided taking into consideration the operation that takes less time to finish. When chosen the period, all operations should include all the situations that occur related to the operation under analysis (e.g. during drilling should be selected a period that includes the jumbo's movement (use of the diesel engine) and the drilling (use of the electric engine)) . For each situation should be calculated the maximum, minimum, average, standard deviation and coefficient of variance. If the maximum and/or minimum are too distinct from the average, this will allow an identification of abnormal situations, that need to be identified. The standard deviation will allow to understand if the values spread out from the average, that is, if the average is the usual values the workers breathe in. The coefficient of variance will enable the comparison between locations/operations. Additionally, to the statistical analysis, the production of graphics will assist the data interpretation: Ppm vs Time (figure X) and Ppm vs Operation (figueX).

3. Case Studies

After the development of the evaluation methodology for the analysis of the current situation on the mines, was requested the availability of mines to put in practice said methodology. It was possible to put it in practice in two case studies. The two mines represent very different scenarios (such as the mineral mined, the mining method and its dimensions) making them unfeasible to compare, however it is possible to find some common issues, regarding the fulfilment of the Commission Directive 2017/164.

Case Study 1

On the first case study, it was possible to do direct measurements throughout the months of July and August of 2019, mostly during the first shift (from 7 am to 3 pm); nonetheless, others were done during the second shift (from 3 pm to 11 pm). It was possible to acquire data from 20 situations. The measurements were made by accompanying the miners through the different areas and operations; the measurement equipment was calibrated outside the mine and after taken inside where it was positioned, always near the workers, in order to have better comprehension and the real levels to which the workers are exposed to, for at least one cycle of each operation. The cleaning operation was an exception, regarding the measurement process, since the measuring equipment was transported by the driver of the LHD; this allowed to have the complete data of a cleaning cycle.

After the measurements previously described, the data gathered was organized, and the values of CO, NO_2 and NO were classified based on the information displayed in table 1. Posteriorly to the previous organization, a representative period of 30 minutes was selected for every operation at each location. This period was selected by considering a consecutive time that represented all the activities done at each operation. The selected period possibilitates a comparison between all operations.

Case Study 2

It was also possible to study another mine, presented on the case study 2. On this case study the methodology was only partially implemented, and the data obtained was only from the cleaning cycle. This case study allowed the characterization of the atmosphere during the cleaning operations and evaluate which were the problems associated with this process.

The data was gathered by the mine's team during the month of April and May of 2019. The data gathering for this case study did not go entirely according to the measurement method.

The data was measured during the operations involving the cleaning process: loading, hauling and dumping. The measurements were made during the first and second shift, and most of them included information for the entire 8-hour shift.

After the measurements previously described, the gathered data was organized, and the values of CO, NO_2 and NO were classified based on the information displayed in table 1. As mentioned, the data was measured for an entire shift, therefore, it was used the whole time period for statistical purposes.

4. Results

The research demonstrates a correlation between some situations and reach the following conclusion: The most critical situations are watering and cleaning. The concentration of gases during watering are mainly influenced by the type of location, the type of explosive and the blast-clearance time. Regarding the cleaning operation, the highest gas' concentration will also depend on the location, the machine used, the effectiveness of the watering operation, and consequently on the type of explosive.

The stopes are the areas where the accumulation of gases is the greatest. The main ventilation and the auxiliary ventilation have an influence on the concentration of gases at these areas. However, the expansion of stopes can reach great distances from the main galleries, creating a difficulty for their ventilation.

The type of explosive is directly related with the gases produced. When emulsion/hydrogel is used, the quantity of NO_x on the air posteriorly to the detonation, is much lower, especially when comparing with the emissions from ANFO.

The blast-clearance time is important to clear most of the toxic gases after blasting. However, if the auxiliary ventilation is not turned on or if it is not well placed, the blast-clearance time (independently of the time used) will not clear the air.

Considering the use of diesel equipment, it is possible to understand that in areas where there are diesel engines working, the values of NO increase, even after the machinery leaves the area and despite secondary ventilation being on. Even though cleaning was the operation where this situation was most critical, on other operations, such as, drilling and use of auxiliary vehicles, the increase of NO_x, especially NO, is notable.

The ventilation has a great influence on the dilution of the gases. An increase or adjustment on the main ventilation will contribute to a higher effective dilution of toxic gases. However, this decrease of gases may not be enough.

Case study 2's data, suggests the implications of cabins, in the vehicles, on the decrease of the miner's exposure to toxic gases. Although this protective measure does not protect the workers fully, it does help lower the contamination level. The implementation of cabins to achieve the new IOELV, can be discussed as if it should be a valid measure to be taken.

The studies validate the hypothesis regarding the main producers of the toxic gases under analysis, being the explosives and the diesel equipment. On the case study 1 is possible to understand the difference between ANFO and emulsion. Although it was possible to show, on both studies, the contribution of the diesel equipment with toxic gases to the mine's atmosphere, due to the lack of available data, the results cannot confirm the moments where the diesel equipment produced the highest values of toxic gases and how adjustments on these equipment can decrease the toxic gases production.

From the case studies' analysis, it is possible to conclude that on some situations, the Directive is not fulfilled, at the moment. Therefore, it is required to do some adjustments on the mines until de end of the transitional period (21st of August 2023). The economic value of the adjustments can vary deeply, depending on the alterations made. The suggestions presented were made without detailed evaluation studies, and so, the proposal is to adjust the measures and control the results, moving to larger measures if the results are not enough. It is important to consider the mine's characteristics, since these are directly related with the effectiveness of the adjustments.

Therefore, three types of solutions are presented:

- Adjustments of immediate mitigation

The adjustments for immediate mitigations, aim to describe low-cost solutions especially dedicated to the critical situations, identified on the case studies.

The most critical areas are the stopes and development areas, since they are classified as "bag end", that is, the air does not move enough to decrease the contaminants. The implementation of secondary ventilation can improve the air quality at these areas

Regarding the drilling operations, there are only toxic gases when the jumbo's diesel engine is on. To decrease the exposure to toxic gases produced by the jumbo, the equipment should always be turned off when someone is connecting the cables and/or needs to be in the back of the vehicle. Another possibility is to change the direction of the exhaust pipe to the side or the bottom of the equipment, decreasing the direct exposure of the miners when connecting the cables.

One of the most critical situations is during the watering of the faces. The blast-clearance times should be used to clear the air, through a methodologic implementation of auxiliary ventilation. The auxiliary fan should be installed on the main gallery, where the air is fresh and free from contaminants, so the air moved to the face is always clean. The sleeve attached to the secondary fan should be positioned to move the air inside the stopes and be adapted according to the enlargement of the faces, assuring that it is installed as close as possible without being damaged by the blasting. Immediately after blasting, the auxiliary ventilation should be turned on.

Concerning the toxic gases related with use of diesel equipment, it should be done a regular maintenance and a tight control over the emissions. The use of catalysts filters on the machines can filter the CO and the NO_x.

- General adjustments

The general adjustments focus on solutions that have been tested on the case studies and have been proven to decrease the exposure of the workers to toxic gases.

The power given to the main fan will directly influence the amount of air moved into the mine. The increasement of the main ventilation will raise the quantity of fresh air inside the mine. On the case study 1 was possible to compare the same work area after an increase of the main ventilation after the detonations; this study showed that after the increasement of the main ventilation, the toxic gases at the area had a very significant reduction

The use of explosives has a great impact on the toxic gases released on the mine. Through the knowledge acquired on the theorical framework and in the case study 1, is possible to conclude that emulsions are the explosive (currently on the market) with less NO_x emissions.

The use of vehicles with cabins can be discussed whether it can be used to achieve the Directive or not. However, on case study 2, was possible to analyse the exposure of the workers during the cleaning operation when they are working inside a machine with a cabin. The cabin permits the worker to have a more controlled environment, since the air-condition allows a control of the temperature and a decrease the exposure to toxic gases. Nevertheless, were still found some peaks of exposure even inside the cabin.

- New technology adjustments

The new technology adjustments aim to present solutions related with the development of new technologies, from solutions that have been put recently on the market, to ideas of solutions that can be done hereafter.

As mentioned before, watering is one of the operations the miners are exposed to the higher values of gases. To eliminate the miner's exposure can be used a remote-control watering device. The miner controlling it would be on a well-ventilated area and not exposed to any toxic gases and free of the danger of falling rocks. Although there are no equipment available on the market for this operation to be remote controlled, the technology is already available to create this robot: the robot should be equipped with a camera, allowing the miners to control it, to see where the machine is at all times and a tank of water with sufficient dimensions to water at least the face (with the tank it is not necessary to be connected to a hose and it is able to move without restrictions); the wheels should be a continuous track, so it can move easily on a fresh blasted face; the robot should water resistant and able to resist the impact from rock falling.

The use of electric vehicles is an option that will eliminate the emissions of gases resultant from the diesel burning.

The battery-powered vehicles can be applied to all type of mining methods and to all vehicles (LHD, loaders, dumpers). The autonomy of the battery may vary according to the manufacturer, vehicle size, vehicle load and effort that it is put to. The battery's technology is being widely developed with improvements that increase the batteries' autonomy and/or an easy battery swap technology.

The cable-powered vehicles can only be used in some types of mines and in some vehicles. The size of the mine will influence largely its possible use; on small mines, the use of cable equipment is easier. The easiest mining methods for the use of this technology are room & pillar and caving, since, usually, the vehicles do the same short-distance trajectory using LHDs. The loader can also be cable-powered, if is towed to the other faces or has a diesel motor to move to the next face. The dumpers cannot use this technology, since this vehicle do long distances and the cable would not allow a great movement.

The trolley-powered vehicles can only be used in caving, since the structure necessary for this technology is very hard to install; since in caving the entire extraction structure is prepared from the beginning, the catenary can be installed right away. On other mining methods, the use of trolley-vehicles can be used has a hybrid, that is, in the main galleries the catenaries are installed and, in the stopes, and development areas the vehicles use diesel or a battery. This technology can be used in LHDs and dumpers, since these are the machines that move.

Although the vehicles related with cleaning are the most pollutant, personal vehicles, such as, tractors or pick-up vans, can also be adapted or replaced. As seen on the case study 1, the tractor was the main contribute for toxic gases during the charging of the explosives, and so, changes on this machine could decrease the exposure of the miners to the gases.

The increasingly stricter requirements from the governmental institutions and the concern with the miner's health and safety will result in stricter regulations. The advance in the technologies and, the adaptation of the mines to them, seems to be an inevitable path.

5. Conclusions

This research aimed to understand the current situation at European mines and the measures necessary to be taken to fulfil the

Commission Directive 2017/164 Article 6. Based on the theorical and practical analysis, it can be concluded that the main producers of toxic gases on underground mines are the explosives and the diesel equipment; the type of explosive influences the quantity of gases released during blasting, usually the emulsion releases less NO_x. The results also indicate that the main and secondary ventilation are directly correlated with the dilution of the contaminated air; an increase on the main ventilation will affect directly the dilution, even inside the stopes, and an adjusted auxiliary ventilation can be enough for a complete dilution after blasting. Nonetheless, on the study was possible to identify the diesel burning as a substantial contributor of toxic gases, but it was not possible to understand the components, from diesel equipment, that contribute the most and how to adjust the diesel equipment.

On the Directive there is no indication regarding the method of measurement or analysis of the toxic gases. Consequently, it was relevant to develop a methodology of measurement and analysis to answer the research question. There are many factors that contribute to the presence of toxic gases on a mine's atmosphere, and the methodology aimed to create a method that allows to compare, not only the locations, but also the different operations that are performed in the locations. Through the methodology developed was possible to analyse how different operations and how different locations contribute to the levels of the toxic gases under analysis, and all the factors that change.

Further research is needed to determine the relationship between the machinery components and the emission of toxic gases and how additional adjustments could decrease the emissions. Additionally, to better understand the implications of the adjustments presented, a study might be required to institute the solutions on a mine and analyse their effectiveness.

This study allowed the search and implementation of a measurement and analysis methodology that will enable the comprehension of the current situation at the mines and that can be implemented posteriorly to the adjustments to confirm their effectiveness and the fulfilment of the Directive.

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