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Fogging in mines: The role of visibility, unfamiliar fog removal methods, and future research ideas

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ABSTRACT: Fogging problems and fog removal are discussed very briefly in mine ventilation references. Publications concerning this subject are scarce. There has been no systematic research and only a few separate case studies. Even so, many professionals have become acquainted with fogging and are eager to share their know-how. In conversations many fog removal ideas have been brought up. These ideas, the theories behind them, and reasons why these are or are not good future research subjects are presented. The often suggested visibility research is addressed. The given information includes a detailed theory section. The problems concerning visibility studies are presented as well as alternative research subjects. The most widely used fog removal methods are presented in literature quite comprehensively. On the other hand, some methods are missing completely. In this paper such methods like demisting and ventilation system changes are discussed. Case studies are presented to prove their feasibility.

1 INTRODUCTION

Fogging is a thermodynamic phenomenon that occurs in an underground mine typically when saturated air loses internal energy by mixing with a colder air stream, or by simply ascending through the ventilation system of the mine. This ascension, in accordance with first law principles, causes the air to gain potential energy at the expense of internal energy. Temperature decrease can be caused either by this internal energy loss or by the cool surroundings giving rise to heat transfer to the airway walls. Both result in condensation of water vapour from saturated air.

Discussion concerning fog removal has activated recently after almost two decades of disregard. The most common fog removal methods are presented in literature as well as their cost comparisons. Fogging theory is also already quite well documented. There are, however, many things that have been addressed only partially or not at all. For example, the information concerning user experiences is still somewhat scattered. Some fog removal methods are mentioned in discussions, but can not be found in any references. It is also worth noting that it has been a long time since a new fog removal method was developed. The time has come to take a look into the practise, the less well-known methods, and into the future of fog removal.

This article addresses many current and future research paths. The subject of poor visibility due to fogging is addressed. Poor visibility is the primary reason why fog is considered a safety problem and so is, understandably, why research is often suggested in this area. The theoretical aspects of this problem are considered and future research is suggested on that basis later on. Unfamiliar fog removal methods are also presented in much the same theoretical fashion and these unfamiliar methods are illustrated through the use of numerous case studies. In the Future Research section, this article also discusses some of the new ideas currently being studied. It also discusses the relative value of these new ideas with the intent of illustrating pathways for future research and outlines which of the ideas appear most promising.

2 VISUAL ASPECT OF FOG

2.1 *Visibility and visual range*

Fog is a safety hazard because it decreases visibility. In worst cases the visibility in fog may be only a couple of meters. It should be noted, however, that water vapour is invisible. The explanation for the visibility deterioration is that fog is composed of fine liquid droplets that cause light scattering and absorption.

Visibility depends upon the transmission of light and the ability of the eye to distinguish an object because it contrasts with the background. For dark coloured objects, light from the atmosphere is introduced into the sight path so that the object appears lighter at increasing distances. On the other hand, for light coloured objects, light is lost from the line of sight with increasing distance. In both cases the contrast between the object and the background disappears as the intensity of light from the object approaches the background value. (Marchello 1976.)

In older literature (Jiusto 1981) it is suggested that visual range represents a key index for defining fog, yet a standardized classification system does not exist. Visibility is presented by the visibility parameter (or the visual range) V, which is measured in kilometres. It is defined as being the distance to an object where the image contrast drops to 2 % of what it would be if the object would be nearby instead (Al Naboulsi et al. 2004). Another definition describes visual range as a distance at which the apparent contrast between a specified type of target and its background becomes just equal to the threshold contrast of an observer. The visual range is a function of the atmospheric extinction coefficient, the albedo, the visual angle of the target, and the observer's threshold contrast at the moment of observation. (American Meteorological Society 2006)

The visual range V is readily linked to the extinction coefficient, σ (in the visible wavelengths), which is a measure of the loss of radiation per unit distance by Beer's Law:

$$I = I_0 e^{-\sigma x} \tag{1}$$

where I_0 = radiance in the beginning; I = reduced radiance with distance caused by attenuation due to absorption; and x = distance, the meteorological range in km, which is equivalent to the visual range V in the Koschmieder expression:

$$V = \frac{|\ln 0.02|}{\sigma} = \frac{3.912}{\sigma} \tag{2}$$

where σ consists of light extinction due to particle scattering and absorption. In later equations of optical attenuation the scattering part is denoted as coefficient β and absorption part as coefficient α. (Jiusto 1981)

Also, a general equivalence between the extinction coefficient and liquid water content of the fog is worth noting. The Trabert equation shows the connection:

$$V = \frac{2.6kr}{LWC} \tag{3}$$

where visual range V is presented in m, r is the droplet radius in µm, liquid water content LWC is shown in g/m^3, and k is the approximation relation, which varies typically from 1 to 3 depending on the width of the droplet spectrum. (Jiusto 1981)

In a Canadian research (Hall et. al 1989) liquid water contents of fogged air in three mines are presented. Liquid water contents of 0.5 g/kg to 3 g/kg of air are said to reduce visibility to less than 10 m and prevent mining.

Gaining information about visibility in fog in order to contribute to fog removal purposes is, however, not necessarily practical. The actual visibility parameter gives information about the resolution of the human eye in addition to some characteristics of the fog itself. It is true that fog removal success can be evaluated best by a visibility study. Unfortunately, exact information concerning the characteristics and behaviour of fog, which is essential as the basis of developing successful fog removal methods, cannot be attained by a visibility study.

As visibility is said to depend on the transmission of light, let us consider light. Light is defined in a strict sense as the region of the electromagnetic spectrum that can be perceived by human vision, i.e., the visible spectrum, which is approximately the wavelength range of 0.4 µm to 0.7 µm (Institute for Telecommunication Sciences 2006). Even if the visibility parameter itself is problematic, attenuation of the visible electromagnetic waves, light, in fog is directly related to the physical parameters of fog.

2.2 *Optical attenuation*

Optical attenuation in fog is a complex function of the drop size distribution, density, extent, refractive index, and wavelength. In dense fog conditions, however, attenuation is practically wavelength independent. Mine fogs thick enough to require fog removal can always be regarded as dense fogs in comparison with surface fogs.

Attenuation in fog can be predicted from Mie theory in the visible wavelength region, as the droplet size is of the same order as the wavelength. From Mie theory, the absorption coefficient due to atmospheric aerosols per unit path length is given by:

$$\alpha_a(\lambda) = 10^5 \int_0^\infty Q_a\left(\frac{2\pi r}{\lambda}, n''\right)\pi r^2 n(r)dr \qquad (\mathrm{km}^{-1}) \tag{4}$$

where n'' = imaginary part of the refractive index of the aerosol particle; λ = wavelength; r = particle radius; Q_a =Mie normalized absorption cross section; and $n(r)$ = particle size distribution. The aerosols scattering coefficient from Mie theory is given by:

$$\beta_a(\lambda) = 10^5 \int_0^\infty Q_d\left(\frac{2\pi r}{\lambda}, n'\right)\pi r^2 n(r)dr \qquad (\mathrm{km}^{-1}) \tag{5}$$

where n' = real part of the refractive index of the aerosol particles; and Q_d = Mie normalized scattering cross section. (Deirmendjian 1969)

If particle size distribution and water refractive index are known, the extinction efficiency can be calculated. It is defined as the extinction cross section of a droplet normalized with respect to its geometrical cross section. It depends on the fog droplet diameter and the considered wavelength, although wavelength dependency is rather weak at optical wavelengths. (Kruse et al. 1962) The extinction cross section of a particle is the area which, when multiplied by the incident energy, gives the total power taken from the incident electromagnetic wave. The energy is partly scattered and partly absorbed as Mie theory predicts.

2.3 *Role of the droplet size distribution*

All fog characteristics are related to the fog droplet size distribution, which may be regarded as the key parameter for accounting for the physics of fog. Propagation of electromagnetic radiation through fog is affected by absorption and scattering by the suspended droplets, and therefore attenuation by fog strongly depends upon the actual drop size distribution. Several analytical models have been proposed to describe fog droplet size distributions. The most commonly used representation is the gamma distribution. It is expressed as

$$n(r) = ar^{\alpha} \exp(-br) \quad (6)$$

where $n(r)$ is the number of particles per unit volume and per unit increment of the radius r and α, a, and b are parameters that characterize the particle size distribution.

Fog droplet size variation is large. A range from 0.5 μm to 100 μm is typically given for surface fog droplet diameters, but experimental records of the smaller end are rare. The drop size distribution of fog is assumed to be comparable to a cloud droplet distribution. An example of a cloud droplet size distribution is given in Figure 1. The only research in which fog droplet size distribution has been measured in a mine was conducted in 1982 by M. Schimmelpfennig. This fog droplet size distribution is presented in Figure 2.

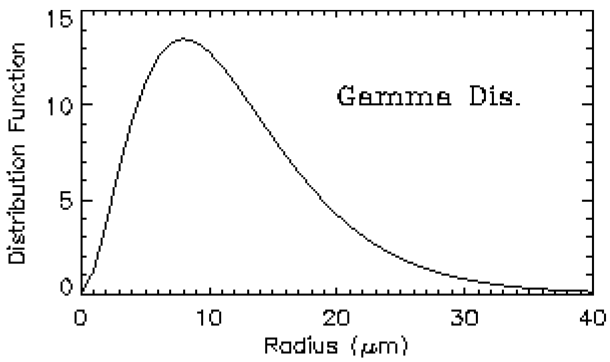

Figure 1. An example of a cloud droplet size distribution (Hu 1996).

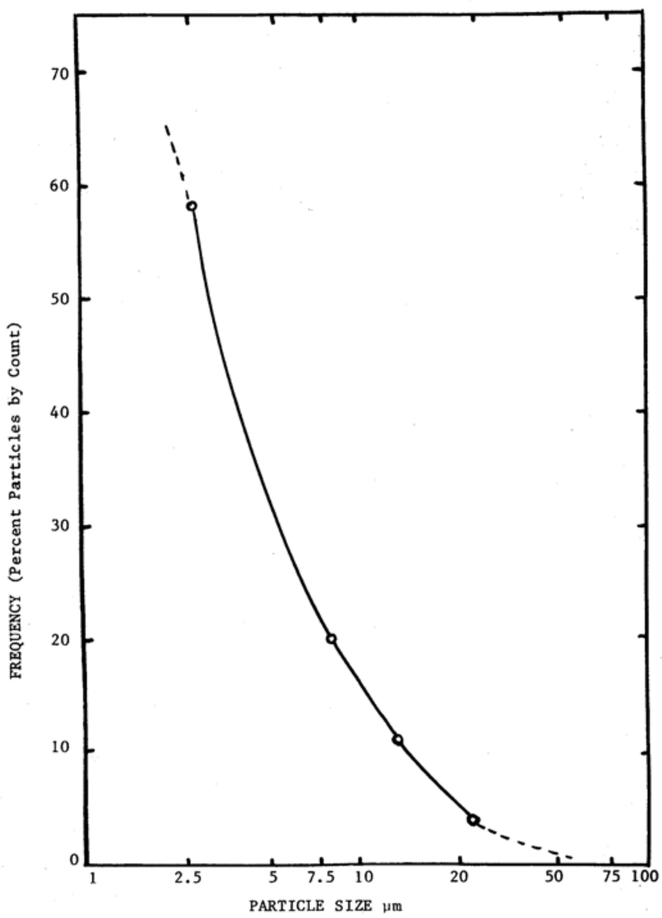

Figure 2. Fog droplet size distribution in an underground mine (Schimmelpfennig 1982).

Droplet size distribution of a fog, however, is far from being a stable parameter. It can change with the location and, at the same location, with time. (Vasseur & Gibbins 1996) As fog thickens, the droplets grow in size. Also the environment, for example heat and water sources in a mine affect fog, and result in fog droplet size distribution changes.

3 IDEAS FOR FURTHER RESEARCH

3.1 *Fog lights*

In more than one discussion the idea of improving visibility by using fog lights instead of striving for fog removal has been brought up. This approach is founded in Rayleigh scattering law. It says that scattering is always greater at the short wavelength end of the visible spectrum than at the long wavelength end. Thus, to obtain the greatest penetration of light through fog, you should use the longest wavelength possible. Red is considered unsuitable, so as a compromise yellow is used instead.

However, this is not true for fog, as Rayleigh scattering law can be used only when the particle size is much smaller than the wavelength. Instead of Rayleigh theory, Mie theory applies. Mie theory scattering and absorption have been explained earlier in the text. As scattering of visible light in fog is essentially wavelength independent, yellow fog lights will not give any more illumination in fog than any other visible lights. (Bohren 2006)

The fog lights used in cars are based on a carefully considered aiming of lights or on such a design that decreases backscatter. Fog lights are marketed for example by telling that they will shine a bright beam of light low down and to the sides of the car. This aiming is explained to eliminate the dangerous glare that occurs when high beams are used in fog. (Race pages 2006) Compensation for the loss of light by absorption can be made by the use of stronger lights, but in some circumstances, additional lights can be degrading to a system because of the increase in backscatter. So the use of high beam headlights in most cases causes worse viewing conditions than low beam headlights. (ROV Committee 2006) This is, however, probably a more suitable subject for further study in car manufacturing industry than in mining.

3.2 *Visibility studies*

It is often suggested that visibility studies be included as a part of fog removal research. Unfortunately, visibility is a problematic parameter as explained earlier in this text. Due to the difficulty of visibility studies and research on optical attenuation, droplet size distribution studies would be more practical methods of gaining information about fog behaviour and characteristics and developing new fog removal methods.

3.3 *Droplet size distribution studies*

As little as a decade ago, droplet size distribution measurements of fog were very difficult to perform due to the technical difficulties involved and thus were extremely rare. Even in those rare cases of successful measurement, the range of the measurement device was not large enough to cover the complete size distribution. With an advanced technology and theoretical knowledge about the subject, droplet size distribution studies could be continued in mines having fog problems. Further droplet size distribution studies of fog in mines have already been suggested by Schimmelpfennig (1982) and Hall et al. (1989). With droplet size distribution information, many other fog parameters can be calculated or predicted. These studies are becoming more practical. For example KLD Labs provides droplet size distribution measurement devices (KLD Labs 2006). Many other devices based on the latest technological achievements have become available lately as well.

3.4 *Fog mesh*

A study concerning a new approach to fog removal is currently underway. It is based on the adhering characteristics and condensing aptitude of water. This study looks at a situation in which humid air moves over a surface, fog droplets get attached to it and water condenses into larger droplets. Nets made of different materials are tested in order to define their fog droplet collecting capacity. Droplets then fall or slide down the mesh fabric. The results received from the first field tests and measurements are promising. They show a decrease in both relative humidity and particle concentration. (Martikainen 2007a, b) This research continues.

3.5 *Fog removal device combinations*

A very frequently appearing topic in conversation is combining different fog removal devices. Combinations of a heater and a fan, a scrubber and a fan, a fan, scrubber, and a demister, as well as a refrigeration unit and a scrubber have been brought up. The combinations most likely to work well could be chosen for further study. Different combinations should be tested and their performances measured. Their feasibility in different fog conditions could be estimated based on the measured values. The most effective combinations could then be put to use.

4 LESS WELL-KNOWN FOG REMOVAL METHODS

4.1 *Demister units*

One rarely mentioned method of de-fogging involves drawing foggy air through a demister-plenum-fan unit. The demister must be located ahead of the fan on the intake side so that the liquid water droplets can impinge on the demister blades and dribble out. The air then goes through the fan, which pressurizes and heats it up, further evaporating any moisture, and giving the discharged air a wet-bulb depression. The more water removed by the demister, the greater the wet-bulb depression created by the fan. Demister units are recommended for heavily fogged air. The unit can stand alone, or it can do double duty by either boosting airflow through a section of the circuit or by sending the air through a duct. For booster duty, the demister must be located in a bulkhead. For example Pneumafil and Schauenburg manufacture portable demister units.

4.2 *Ventilation system changes*

Ventilation system changes have been mentioned in many discussions as a potential fog removal method. Depending on the mine and its fog problems, different approaches can be used. These include changing airflow balances, mixing or separating airflows with different psychrometric properties, and rerouting airflows.

If the ventilation circuit permits, potential active foggy regions in mines should be ventilated with downcast fresh intake air. Downcast air will not fog up in normal circumstances because of its low relative humidity and particle concentration. Unfortunately, the mining plan may not permit ventilating airflows to downcast through active areas. In addition, freezing during winters may prohibit using downcast air in areas susceptible to fogging.

The idea of changing the balance of cold and warm airflows that arrive in foggy areas is based on that in the collision point of airflows with different temperatures, the dew point may be reached. In these cases psychrometric charts should be consulted in order to define the eligible conditions.

5 CASE STUDIES

5.1 *Ekati Diamond Mine*

Ekati Diamond Mine is located in the sub-arctic climate region in Canada. Mine depth ranges from 100 m to 600 m. Mining methods used in different mining areas are open benching in Koala North, sublevel retreat in Panda and sublevel caving in Koala.

In Ekati Diamond Mine fog appeared in the winter. Fogging problems in the decline were severe with visibility decreased at worst to 2-3 m. Fog was created at the bottom of Koala North decline from which there are accesses to all 3 mines. There warm air from Panda and Koala mixed with cold air from Koala North. Even if Koala North is in permafrost, Panda and Koala are not, so the resulting fog from the colliding airmasses was not ice fog.

The fog problem was solved by slightly decreasing inflow of cold air to the decline and considerably increasing inflow of a warm air to the decline. Also, as the total flow in the decline increased air velocity in the previously fogged area increased. The change in air volumes and proportions of warm and cold air did not cause any additional costs. (Holod 2006)

5.2 *Kiruna Mine*

Kiruna Mine in Sweden is a large iron ore mine. Mining method in Kiruna is sublevel caving. The depth of the mine is 1180 m. Kiruna Mine is located in cold sub-arctic climate zone.

Fog occurs in Kiruna Mine during summers and winters in the decline and the exhaust shafts of the mine. The decline is used as a secondary exhaust. Fog is estimated to be thick, and both types of fog, normal and ice fog, have been observed. Visibility can decrease during a fogging situation to as low as 2 meters.

Summer and winter fogging problems of the decline are considered separate, because they are caused by different reasons. Thus they are also dealt with separately and with different fog removal methods. Fogging in the exhaust shafts is not problematic.

During winters humid air from the decline with a temperature of approximately +4 ºC meets the cold air outside, which can go down to -35 ºC. The fogging problem is concentrated at the mine entrance. The lower the temperature outside, the more fog problems occur. Two single fans are used for fog removal on each side of the drive-way in the decline, close to the mine entrance. The fans are 30 kW, low pressure fans with a 150 cm diameter. The mine personnel say that the fans are probably only mixing the air rather than moving it. This method meets the requirements set for a fog removal system.

During summers humid air travels up the decline and as it cools due to auto decompression, fog forms. The temperature during summer in the mine is about +18 ºC in the bottom of the mine and at about +8 ºC 500 m underground where fog appears. This problem is partly taken care of by traffic. Vehicles moving and mixing the air causes fog to disappear. Also, taking more fresh air to the decline at different levels is used successfully for fog removal in these occasions.

Costs of the fog removal are low. In winters operational costs result from electricity usage of fans. The fog removal fans use approximately 90 kW for 8760 hours/year. (Bolsoy 2006)

5.3 *Homestake Mine*

Homestake Mine was a huge gold mine in Lead, SD, U.S. before its closure in 2002. Mine operated for over 126 years. Nowadays, Homestake Mine has a visitor center that provides surface tours. Homestake mine reached almost 2.5 km in depth. (Homestake Visitor Center 2006)

Fogging became an occasional problem on several of the upper level ramp systems. Intake air flowed up a series of active ramps to exhaust. While upcasting these ramps, visibility reduction caused by fog formation was enough to be a concern to LHD operators.

The first attempt to mitigate the fog was to downcast the air through the ramp. The intake on the upper level was opened, and the exhaust was closed off. Then, the intake was closed on the lower level and the exhaust opened. The reversed airflow cleared up the fog in the area.

In another mining section, the circuit did not permit reversing airflow. To remove the fog from this area a demister unit was designed. It consisted of a commercial demisting panel, followed by a droplet fallout zone, a plenum, and a 30 kW fan. The unit defogged about 15 m^3/s and delivered the air up the ramp in 1.07 m brattice cloth duct to the working headings being driven off the ramp. Thus, the defogger unit served two functions: defogging the air, and delivering it to auxiliary-ventilated headings. The demister installation resulted in successful fog removal. Unfortunately psychrometric measurements taken of the unit's performance were lost when the mine was deactivated.

5.4 *"Anon" Mine*

"Anon" Mine is located in the province of Quebec, Canada. A fogging problem was noticed in the exhaust shaft of "Anon" Mine. This prohibited the use of the exhaust shaft for men and materials handling and consequently limited production skipping in the intake shaft.

To investigate this problem, environmental monitors for air temperature, relative humidity, and barometric pressure were installed at selected points. A site visit was used to inspect the problem further and to obtain a more detailed evaluation of the psychrometric conditions throughout the mine.

The psychrometric survey of the mine, performed in 2000, showed that the exhaust air leaving the mine was already under saturated conditions by virtue of the air temperature naturally decreasing as it ascends the exhaust shaft. This caused some degree of fogging to occur and could only be avoided if the air was heated or dehumidified prior to ascent. Considering the volume of air to be treated these methods were not practical in "Anon" Mine. However, if the operations requiring visibility in and around the exhaust collar can be scheduled to when the airflow is significantly reduced, these methods may have some potential.

Furthermore, when the air is discharged at surface, the natural stack effect of this air to continue ascending tends to draw cold air into the building. This cold air becomes entrained with the warm air and extensive fog formation results. Depending on surface wind conditions this fog could be driven into work areas within the head-frame building. Based upon the survey observations, it is doubtful that the moisture content of the air could be suitably reduced such that when it comes in contact with colder surface air, especially in winter, that saturated conditions and hence the fogging would be eliminated.

Despite this, the severity of the conditions at the collar can be controlled if the interaction between mine's saturated warm exhaust air and cooler surface air is limited. This can be achieved if the warm humid air and the cold surface air can be kept apart. Due to the need for access to the shaft this separation could be best achieved with air curtains. Should the air curtain method be used, the cold air flow towards the air column exiting the exhaust shaft should be prevented. Also the air used for the air curtain should be warm enough so as not to cool the exhaust shaft air to ensure efficient operation of the air curtain.

Even with the installation of an air curtain, the shaft discharge air's stack effect will draw cold air in through other openings. This may continue to cause fogging. If this still proves to be a problem then the headframe structure surrounding the discharge column will have to be sealed to stop the infiltration of cold air.

There is no information whether the suggested fog removal method based on the study was adopted for use in "Anon" Mine or not. Also the information concerning the possible success of the method is unobtainable. (Hardcastle 2006)

6 CONCLUSIONS

Even if fogging is a common problem, fog and its parameters have not been thoroughly studied in mine environments. It is remarkable that so much information concerning fogging and especially fog removal in mines is obtained from discussions and not from publications. Attention should be paid to this oversight in the mining community in order to ensure proper distribution of knowledge through publication to the advantage of everyone.

Based on the technological advances as well as better theoretical knowledge of fog, opportunities for fog study and development of new fog removal methods are abundant. In this text a selection of ideas for further research are presented.

Often suggested visibility studies do not necessarily provide useful information for fog removal purposes. However, optical attenuation studies based on the visibility theory may prove to be worthwhile, and the most promising direction for future research seems to be droplet size distribution study.

Currently ongoing research about fog collecting meshes has given promising results. This new fog removal method idea is based on the adhering characteristics and condensing aptitude of water. All results received from this study will be published.

Fog removal device combinations provide also a fascinating research subject. Based on combination developing and field tests their practicality and effectiveness can be defined.

The presented case studies give a glimpse of the fog problems and the more unfamiliar solutions found in some underground mines. These less well-known methods may prove feasible also in other mines, especially in the ones with similar fog problems and similar thermodynamic conditions.

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