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Doctoral Dissertation

Anu Martikainen

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Rock Engineering

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Dissertation for the degree of Doctor of Science in Technology to be presented with due permission of the Department of Civil and Environmental Engineering for public examination and debate in Auditorium V1 at Helsinki University of Technology (Espoo, Finland) on the 1st of June, 2007, at 12 noon.

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Author Anu Martikainen

Name of the dissertation

Fog removal in the declines of underground mines in sub-arctic regions

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☐ Monograph	☒ Article dissertation (summary + original articles)

Department	Civil and Environmental Engineering
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Field of research	Mine Ventilation
Opponent(s)	Professor Andrzej Wala, University of Kentucky, USA
Supervisor	Professor Pekka Särkkä
(Instructor)	

Abstract

Fogging is a common safety hazard observed especially in the declines of underground mines located in sub-arctic regions. Fog forms when saturated air loses internal energy by mixing with a colder air stream, by simply ascending through the ventilation system of the mine, or when contact with cold wall-rock decreases air temperature.

Studies concerning fogging in underground mines are rare. Technological advances and more complete theoretical knowledge gained by research in many other fields offer possibilities for thorough fogging research in mines. This research aims to better understand underground fog formation, related parameters, characteristics, and fog behaviour.

Interviews, literature review, psychrometric and particle concentration measurements, on-site field tests of the existing fog removal methods, and developing and testing a new fog removal approach are used as research methods. The interviews show that there are methods not mentioned in the literature that are used for fog removal in mines. Case studies provide fascinating insight into fogging problems and how to solve them. From literature review the complicated behaviour of fog is uncovered, and the role of visibility, optical attenuation, and droplet size distribution studies are evaluated. Ideas concerning further research are presented according to the findings.

Basic study results demonstrate the situation in declines of three underground mines; Pyhäsalmi Mine, Orivesi Mine, and Louhi Mine in Finland. Studies concerning increasing air velocity show that the value suggested by literature to be high enough for fog dispersal, 0.25 m/s, is not nearly enough in the declines of these mines. Installing an additional fan, showed that the change in relative humidity and thus fog thickness was based on the quantity of heat the fan added to the air. Heating decreased fog thickness noticeably. Only local fog removal was observed for both methods.

Trials concerning new method development gave mainly positive results. The method is based on the water gathering effect of a net set perpendicular to the airflow. The frame and mesh installation are presented. Seven out of eight tested mesh materials resulted in a decrease of relative humidity and particle concentration. Twelve tests were completed, of which two were material combination tests. Unfortunately only two tests resulted in a noticeable decrease of fog thickness and even in these cases the efficiency was not enough for complete fog removal. The best results were received with aluminium net and a mist eliminator/fibrous filter fabric combination.

Keywords mine ventilation, fog formation, fog removal, visibility, psychrometric, particle concentration

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Tekijä Anu Martikainen

Väitöskirjan nimi

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Vastaväittäjä(t) Professori Andrzej Wala, University of Kentucky, USA
Työn valvoja Professori Pekka Särkkä
(Työn ohjaaja)

Tiivistelmä

Sumuuntuminen on tavallinen turvallisuusriski erityisesti lauhkean vyöhykkeen maanalaisten kaivosten vinoajoteillä. Sumu muodostuu kun vesikyllästetty ilmamassa menettää sisäistä energiaa sekoittuessaan kylmemmän ilmavirran kanssa, noustessaan kaivoksen tuuletusjärjestelmän läpi tai joutuessaan kosketuksiin kylmien kiviseinämien kanssa.

Sumututkimukset maanalaisissa kaivoksissa ovat harvinaisia. Tekniset edistysaskeleet ja muilla tieteen aloilla saavutettu perusteellisempi teoreettinen tietämys avaa mahdollisuuksia syvällisemmälle sumututkimukselle kaivoksissa. Tämän tutkimuksen tavoitteena on parempi sumun muodostuksen, sen ominaisuuksien sekä käytöksen tuntemus.

Tutkimusmenetelminä käytetään haastatteluita, kirjallisuustutkimusta, psykrometriaa ja hiukkaspitoisuusmittauksia, olemassa olevien sumunpoistomenetelmien kenttätutkimuksia ja vaihtoehtoisen sumunpoistomenetelmän kehittämistä. Haastatteluista selviää, että sumunpoistoon kaivoksissa löytyy kirjallisuudessa esittämättömiä menetelmiä. Tapauskohtaiset tutkimukset antavat lisätietoa sumuongelmista ja niiden ratkaisemisesta. Kirjallisuuskatsaus valaisee sumun monimutkaista käytöstä. Näkyvyyden, optisen vaimennuksen sekä pisarakokojakauman tutkimuksen hyödyllisyyttä arvioidaan. Muitakin jatkotutkimuksiin liittyviä ideoita esitellään havaintojen pohjalta.

Perusmittauksilla määritettiin sumutilanne kolmen suomalaisen maanalaisen kaivoksen, Pyhäsalmen, Oriveden ja Louhen vinoajoteillä. Ilman virtausnopeuden nostamiseen liittyvät tutkimukset paljastivat, että kirjallisuudessa esitetty suositusarvo, 0,25 m/s, on aivan liian alhainen sumunpoistoon. Puhaltimen asennus osoitti mitatun suhteellisen kosteuden ja siten myös sumun tiheyden muutoksen perustuvan puhaltimen lämpövaikutukseen. Lämmitys vähensi sumua huomattavasti. Molemmilla menetelmillä yllettiin tosin vain paikalliseen sumunpoistoon.

Vaihtoehtoisen sumunpoistomenetelmän kehittämiseen liittyvistä kokeiluista saatiin pääasiassa myönteisiä kokemuksia. Menetelmä perustuu ilmavirtaa vastaan kohtisuoraan asennetun verkon kykyyn kerätä vettä. Kehikko ja verkkoasennus esitellään. Seitsemän kahdeksasta testatusta materiaalista alensi ilman suhteellista kosteutta ja hiukkaspitoisuutta. Kahdestatoista testistä kaksi oli materiaaliyhdistelmätestejä. Valitettavasti vain kahdessa testeistä saavutettiin huomattava sumun tiheyden aleneminen. Näissäkään menetelmän tehokkuus ei yltänyt täydelliseen sumunpoistoon. Parhaat tulokset saavutettiin alumiiniverkolla ja usvanpoisto/kuitusuodatinkangasyhdistelmällä.

Asiasanat kaivostuuletus, sumun muodostus, sumunpoisto, näkyvyys, psykrometria, hiukkaspitoisuus

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Preface

This dissertation has been prepared at the Laboratory of Rock Engineering in the Helsinki University of Technology during years 2002-2007. I have had a pleasure to work with a great group of people.

I am particularly grateful to Professor Pekka Särkkä for his supervision. I am thankful for all the advise and guidance I got from my Professor during these years in the Helsinki University of Technology.

I thank M.Sc. Pekka Eloranta, Lic.Tech. Sakari Mononen, Dr. Juha Antikainen, M.Sc. Aleksis Lehtonen, Professor Emeritus Raimo Matikainen, Seija Latvala and Panu-Erkko Kaukinen for contributing to the nice working environment. I wish to extend my thanks also to all other members and former members of the laboratory whom I have had the joy to meet.

The time I spent in the spring of 2006 as a visiting scholar in the University of Missouri-Rolla was very benefial and unforgettable. I am indebted to Professor Jerry Tien, whose invitation changed the direction of my life. His contribution to my work was valuable and very appreciated.

Also other people from the Department of Mining Engineering and the Experimental Mine are acknowledged. Professors Larry Grayson, Lee Saperstein, Samuel Frimpong, and Paul Worsey are acknowledged for being supportive of my work. I thank Barbara Robertson and Tammy Shortt for their help. I also want to mention some students and graduate students. Catherine Skrzyniarz, Ryan Moyers, Joshua Chlopek, Yi Zheng, Nassib Aouad, and Oyku Selimoglu; you made me feel at home in a foreign country.

The people I have met in conferences and symposiums during my studies are acknowledged. Your interest in my topic has resulted many times in renewed enthusiasm. Also the persons answering my fogging query are acknowledged. Thank you for the valuable information.

It can’t be repeated enough that the support of the mine personnel of the underground mines participating in this research has been essential. I am grateful for everybody who has assisted me in any way. Especially I thank the hosts, Matti Pulkkinen and Ilpo Mäkinen from the Pyhäsalmi Mine, Jaakko Kilponen and Taito Ahola from the Orivesi Mine, and Jyrki Koljonen and Harri Taskinen from the Louhi Mine.

I appreciate the financial contribution received from Outokumpu Foundation and from Department of Civil and Environmental Engineering. Thank you for supporting my research.

I thank the members of my family, mom, dad, and Ismo, and my friends, especially Kirsi. Your support has been a significant part of this project. Finally I wish to express my immense gratitude for two men. Jani, your help has been extensive and versatile through this time and I can never thank you enough for it. Tristan, although you have not been in my life for long, you have been there for me already more and more often than I would have believed possible.

Espoo, May 2007

Anu Martikainen

Contents

List of Publications

This dissertation consists of an overview and the following publications:

I. Martikainen, A. L., 2005. “Comparative evaluation of fogging phenomenon in the ramp of three mines in Finland,” *Proceedings of the 8th International Mine Ventilation Congress*, July 6-8, AusIMM, Burwood, Australia, pp: 103-110.

II. Martikainen, A. L., 2006, “Alternative fog removal methods in mine ramps,” *Proceedings of the 11th US/North American Mine Ventilation Symposium*, Mutmansky, J. and Ramani, R., eds., June 5-7, Taylor & Francis Group plc, London, U.K., pp: 295-300.

III. Martikainen, A. L., 2007, “Fog mesh as an alternative fog removal method in mine ramps.” *2006 Transactions of the Society for Mining, Metallurgy, and Exploration, Inc.*, January 2007, Volume 320, pp: 38-44.

IV. Martikainen, A. L., 2007, “Fog mesh studies for fog removal,” *Proceedings of the 2007 SME Annual Meeting & Exhibit and 109th National Western Mining Conference*, February 25-28, Denver, Colorado, 4 pp.

V. Martikainen, A. L. and Marks, J., 2007, “Fogging in mines: The role of visibility, unfamiliar fog removal methods, and future research ideas.” *Journal of the Mine Ventilation Society of South Africa*, Q2, 7 pp.

VI. Martikainen, A. L., 2007, “Fog removal with a fog mesh – mist eliminators and multiple mesh systems.” *International Journal of Mining, Reclamation and Environment*, vol. 21, no.3, 14 pp.

Author’s contribution

The author has been responsible for all phases of the reported research work. The literature study, interviews, calculations, field tests, and the result analysis have been performed by the author. All articles have been prepared by the author. J. Marks provided information concerning less-well known fog removal methods, fog formation theory, and a case study for Publication V. Feedback for the main draft of Publication V was also received from J. Marks.

List of Symbols

V	Visual range
α_a	absorption coefficient
β_a	scattering coefficient
n''	imaginary part of the refractive index of the aerosol particle
n'	real part of the refractive index of the aerosol particles
λ	wavelength
r	particle radius
Q_a	Mie normalized absorption cross section
Q_d	Mie normalized scattering cross section
$n(r)$	particle size distribution
α, a, b	parameters that characterize the particle size distribution
$Ø$	required heater capacity
φ	air density
q_v	airflow
h	air enthalpy
t	temperature of air
x	the absolute humidity of air
BTU	British thermal unit
CFH	volume of air to be heated per hour
ΔT	number of degrees of temperature increase desired
€	euro
$	dollar

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1 Introduction

1.1 Background

Mine ventilation is the process of total air conditioning responsible for the quantity control of air, its movement, its distribution, and it is the most vital auxiliary operation in underground mining. It is the mainstay of the miner’s life support system. Air is necessary not only for breathing, but also to disperse and dilute chemical and physical contaminants, such as gases, dust, heat and humidity. (Tien, 1988)

Fog is a problem that combines the effect of all these contaminants. Humidity and dust are the essential prerequisites for fog formation. Mine gases, especially diesel exhaust fumes, are comprised of elements that participate in and enhance fog formation. Temperature and its changes play an important role in fog formation and in fog removal as well.

The author’s interest in underground fogging arose while preparing the M.Sc. Thesis. Fog had been present to some extent in every Finnish mine visited up to that time, but not much attention was paid to it by the author. On one very humid autumn day a mining engineer in one of the mines became frustrated when driving down a foggy decline. The question was posed: Is there anything we could do about the fog? Unable to answer, the author agreed to look into the matter. Three different ventilation textbooks were consulted, from which only two paragraphs of text describing fog occurrence underground were found in one of the three books. The extent of information, or rather the lack of it, resulted in this research. Since then, the author has continued the search for information, and tried to produce new information in order to help others who struggle with this problem.

Fog forms as the water in the cooling air condenses into droplets. This cooling is either due to a temperature decrease or to evaporation caused by radiation. When more water is condensed into the droplet than is evaporated from it, droplet grows. Droplets form around condensation nuclei that can be either particles or aerosols. The diameter of condensation nuclei is typically about 0.2 μm, but varies considerably.

Fogging is experienced commonly in mines of sub-arctic and tropical areas. Quick changes in temperature, high relative humidity of intake air, and a humid mine climate with high particle and aerosol concentrations encourage fog formation. Even if fogging is an acknowledged problem that poses a safety hazard by decreasing visibility, interest in research ceased after the 1980’s. In many mines, common ways of dealing with a fogging problem are either to tolerate the problem (Martikainen and Särkkä, 2004) or even to close the dangerous areas with extremely low visibility (Hall et al., 1989).

Fogging in underground ventilation systems occurs in two situations. First, when the strata is cooler than the dew point temperature of the incoming air and, second, due to decompressive cooling of humid return air. Due to this, fogging in ascending return airways and, especially, upcast shafts is quite common. (McPherson, 1993)

Many different methods can, however, be used for fog removal. Schimmelpfennig (1982) lists some of these in his M.Sc. Thesis as heating mine air, chemically drying humid air, refrigeration of air, use of centrifugal fan scrubbers, using cool mine water to lower the temperature and humidity of intake air, and installation of additional fans to increase air movement. Also, rerouting the air to achieve increased air velocity is mentioned in the literature. In Hall et al. (1989) the best fog minimization technique is suggested to be initially designing the ventilation system to reduce opportunities for fog formation.

Some of these methods are suitable for underground fog removal with limited problems. Others can be regarded as useless. Comments in this dissertation about the different methods are based on their suitability for usage in a decline of a mine situated in a sub-arctic climate zone.

Heating is often criticized because of the added heat to the mine environment, but in cool climates with cool or temperate underground temperatures heating does not cause problems. Unfortunately, heating consumes energy and may thus prove to be quite expensive. Also, it does not reduce the quantity of particles suspended in the air available to act as nuclei.

Cooling by refrigeration is effective, but it is the most expensive of the known fog removal methods. (Tien, 1999) In a cool climate it may also cause difficulties as the temperatures are already low and freezing should be avoided.

The fog removing effect of increased air velocity is said to be based on air mass mixing and promoting evaporation from fog droplets. In addition, an increase in airflow velocity creates a psychrometrically uniform air mass and diminishes the number of potential condensation points. Economically this method is suggested to be the most plausible solution. (Schimmelpfennig, 1982) Increasing air velocity is currently one of the most popular methods of fog removal, but its efficiency is questionable.

Centrifugal scrubbers work well in level workings according to literature, but they are not necessarily suitable for clearing declines. Their effectiveness in fog removal is based on their multiple function characteristics. They increase air velocity and reduce particle concentration and humidity.

Removing humidity by preventing leakages from rock walls and other water sources can also be used to some extent. Unfortunately treating a long ramp is expensive. As there are also open ditches and pumping stations along the decline, preventing leakages may not be enough for fog removal.

Chemical drying is considered impractical in mining industry because the amount of drying material needed is huge. Spreading the material and gathering it is also troublesome.

The above mentioned fog removal methods are used to some extent in mines experiencing fogginess. In many cases, however, achieved results have not been as good as expected, or the method has failed altogether. With careful planning, design, and installation some attempts have been successful. These fog removal methods are discussed in Publications II and III.

1.2 Research problem

All fog removal methods commonly used in mines were developed more than 20 years ago. Since then, research about fog formation and fog behaviour has introduced a lot of new information in the fields of meteorology and physics. None of this information has been used in mine ventilation.

Recent technological advances have also been largely neglected. New measurement devices enable easier testing, and more reliable results have become possible as taking a higher number of measurements and achieving more accurate values has become possible. Also, the comprehensiveness of these methods has improved.

The basics of fog formation and characteristics are quite well known, and presented in literature, but it is suggested in many references like Schimmelpfennig (1982) and Hall et al. (1989) that more research is required for better understanding of many details. The information is scattered and there are very few recent publications from the field of mine ventilation.

Comparison of the fog removal methods presented in literature is far from complete. Usually only one of the methods has been tested in one site and conclusions are based on these tests. Many different methods have not been tested in one mine and the received results compared. Also, the evaluation of one method in many different mines for comparison purposes is missing.

The proposed best way of preventing fog problems, taking the problem into account during preliminary mine planning leaves mines currently struggling with fogging without help. It is very unlikely that extreme corrective measures that affect the complete ventilation circuit will be taken even in mines with serious problems.

Typically the information concerning fog problems is based mainly on the view of the researchers. Not much on-site experience and feedback from mine personnel has been recorded or published.

No new fog removal methods have been developed or introduced during recent decades. Even information concerning unsuccessful attempts can not be found. With more thorough information concerning fog formation process, improved technology, and more complete on-site testing, new ways of approaching the problem can be developed. As the feasibility is one of the main areas of discussion when considering fog removal methods, this is kept in mind throughout this study.

1.3 Objectives

The aim of this research is to achieve a more complete understanding of underground fog formation, related parameters, characteristics, and behaviour. The latest advances in other scientific fields are considered from the point of view of mine ventilation research. Using the information to enable better understanding of the underground fog problems and fog removal is considered.

Known fog removal methods suitable for declines of Finnish mines located in a sub-arctic area are tested and compared. The objective is in receiving reliable comparison information about different fog removal methods in order to determine the feasibility of various methods relative to varying climatic conditions.

Gaining more thorough theoretical knowledge is used as the basis of developing a new fog removal method. Emphasis is placed on the practicality, feasibility, and simplicity of installing and successfully using the new method. On-site testing aims to prove the method feasible in underground mines.

This more thorough study concerning fogging in declines of underground mines aims to show that a quest for finding solutions to this problem is not in vain. Suggestions concerning future research are given based on the knowledge uncovered by this study.

1.4 Research methods

As a lot of new information is sought after concerning this research topic, many different research methods are used. A thorough literature review expands from mine ventilation to many other research fields such as cloud formation physics, meteorological sciences, and theory of water collection. Information gained by literature study is included in Publications I, II, III, V, and VI.

The main research methods are interviews of mine personnel, psychrometric and particle concentration measurements, and on-site testing of the fog removal methods. Psychrometric measurements consist of air temperature, air velocity, relative humidity, and dew point temperature measurements. Particle concentration measurements cover the large and giant nuclei size ranges. Large particles are the major condensation nuclei source for fogging. This part of the research, referred to as basic study, is presented in Publication I.

On-site testing covers increasing air velocity by rerouting and by adding additional fans. It also includes air heating with direct electric heaters, and fog mesh tests as new-method-development -related tests. Increasing air velocity and heating are discussed in Publication II. Fog mesh tests are introduced in Publication III, and discussed further in Publications IV and VI.

Interview material is composed of experiences concerning redirecting air to different routes, increasing air velocity, and limiting water leaks in Finland. The international interview material consists of descriptions of fog problems and trials to solve them in different underground mines. Domestic interview results are presented in Publication II, and international interview material in Publication V.

1.5 Scope of the research

All on-site tests took place in Finland, which has a sub-arctic climate. These tests are limited to mine declines, as this is where fog occurs in the mines that were included in this research. Methods which are suitable for declines and in a sub-arctic climate were chosen to be studied. Due to this scope, some results may not be applicable in mines located in a tropical climate or in cases of fogging on working levels.

In the mines surveyed fogging occurs mainly or only in the ramp throughout the year. Thickness of the fog varies, and the problem is most severe usually during spring and autumn. Also during the summer, especially after heavy, warm rainfall, fog can get thick. In the wintertime air is usually quite dry, and the visibility is better since the fog is lighter. It is also typical that thickness of the fog increases during the workday and the working week. This is due to machinery usage and traffic, which increase the amount of the particles and aerosols that act as condensation nuclei in the air.

As large particles are the major condensation nuclei source for fogging, the measurements were designed to cover only large and giant nuclei size ranges. The effect and behaviour of Aitken nuclei in fog formation process is not considered in this research. The occurrence of these particles does not lead directly to fog formation. The

Aitken nuclei size is so small that they never settle out of an air mass. It is stated, however, in many references like Hudson (1993) and Jiusto (1981) that Aitken nuclei affect the condensation process, even if their role is not completely understood.

Even if information concerning the aerosol reactions is mentioned, on-site testing of this factor was considered irrelevant for this research. This was because laboratory tests of this research field are so complicated that the sudden changes of mine fog conditions were expected to prevent receiving useful results.

1.6 State of the art in underground fog removal

The most recent publication concerning underground fog removal is a case study by Calizaya et al. (2001) describing heater fan dimensioning and installation in an Indonesian mine. Fogging was observed there as a continuous fog front with a length of over 1.5 km in the declines. The visibility was reduced at worst to less than 5 m because of fog.

Ventilation surveys were conducted in order to find reasons for fogging and to determine the most feasible fog removal method. These surveys consisted of barometric pressure, dry and wet bulb temperatures, gas concentrations, air velocities, and cross sectional area measurements.

The first fog removal attempt was carried out by installing three additional fans. Unfortunately, this only cleared about 200 m. Installing additional fans in every 200 m was considered too expensive.

Fog removal methods were evaluated and found that for existing ramp infrastructure, the utilization of heater fans was the most suitable alternative. Two heater fans were dimensioned and installed 900 m apart. This resulted in eliminating the fogging problem for the entire ramp length. The achieved results were also evaluated with a climatic simulation program.

In this article the fog problem of the mine is presented precisely and extensively. The trial and error type of dealing with underground fog problems, as well as the graveness of the visibility constraints becomes very clear. This comparison of climatic simulation results with actual achieved fog removal results is the first published. However, the reason for failure of the additional fan installation was not evaluated comprehensively in the paper and comparison with other fog removal cases or studies was not performed.

The other relatively recent article by Hall et al. (1989) presents fogging problems in Canadian mines. In this paper the basics of fogging theory, preventive and corrective measures, and costs of fog removal methods are considered in a similar way to other publications. The most fascinating part of the paper describes the actual fogging experiences in seven Canadian mines. Unfortunately, the conditions are described only briefly and no measurement results are given. The most useful material to other researchers and mine planners are the design considerations of the ventilation network to prevent fogging and the information concerning direct electric heating. Also, comments about techniques for improving visibility of objects give another point of view for solving fog problems underground.

The most complete study of the topic is by no doubt the M. Sc. Thesis work of Schimmelpfennig (1982) and related article by Gillies and Schimmelpfennig (1983). In these, different conditions that lead to fogging, fog thermodynamics, and the role of particles, as well as basics of fog removal are described thoroughly. The tests presented in the Thesis were carried out at the Ozark Lead Mine, in MO, USA, and consisted of air velocity, wet and dry bulb temperature, particle concentration, and visibility measurements. The test results are presented and analyzed. The most interesting information is the measured droplet size range for fog, even if the lower end of the distribution was not recorded because of the limitations of the measurement devices. It showed a difference in the droplet size between surface fogs and those observed underground.

A limitation of this work though is that in the discussion section a generalization about the role of air velocity changes is made based on one situation only. As there are many parameters affecting fog formation, density, and dispersal, one observation can hardly be considered a rule. Installation of centrifugal fan scrubbers is suggested to be the most feasible fog removal method based on their costs and theoretical knowledge. However, no tests that would support this view or actual user experiences were presented.

1.7 Contribution

With this research a more complete picture of the fogging problems underground is obtained. Fog removal methods suitable for declines of mines located in sub-arctic areas are presented and compared based on field research. Parameters affecting fogging are measured and analyzed based on actual field test data.

Increasing air velocity as a fog removal method is ruled out by the information gained. The velocity of 0.25 m/s is shown to be eminently too low to disperse and evaporate fog droplets as suggested by literature.

Heating gave best results of the tested methods. Also, information was gained by international interviews concerning other successful fog removal cases by heating.

As none of the tested methods provided an easy and inexpensive solution to the fog problems, new method development became an option. A fog mesh method based on water collecting behaviour of nets is presented. Analysis is based on twelve tests with eight different materials.

Even if the received results showed a decrease in relative humidity and particle concentration, the most critical parameters of fogging, the effect was not enough for complete fog removal. The resistance of the mesh to airflow prohibits multiple mesh systems and a material effective enough to remove fog completely as a single layer was not found. An aluminium mosquito net came closest to acceptable values, which is why further research efforts should be concentrated on metallic nets.

Ideas concerning other possible new fog removal methods developing are also presented. Visibility studies, which are often suggested to be included in fog surveys, are shown to be impractical. Optical attenuation and droplet size distribution studies on the other hand are recommended.

Also, information about less well-known fog removal methods was gained through interviews. Ventilation system changes and defogging may prove to be successful in mines other than the ones presented as case studies. Fog removal device combinations may also prove feasible and provide a fascinating research subject.

2 Information gained by the literature survey

2.1 Fogging theory

A lot of new information concerning fogging has been discovered in many different research areas since the full-scale underground fogging survey at the Ozark Lead Mine in 1982 by Schimmelpfennig. In this section the knowledge found from literature, which was regarded as useful for the field of mine ventilation is presented. Fogging theory is discussed more thoroughly in Publication I.

The rate of droplet formation is determined by the number of condensation nuclei present. Results by Bott (1991) show delayed fog layer formation for small aerosol concentrations. High concentration of aerosols and particles in the air yield the highest vertical extent of fog above the ground and also the highest fog water content. In underground mines the particle concentration is thus a very important factor for fog formation. Decreased particle concentration results in less fog formation and decreased fog thickness.

Mattila et al (1997) studied the behaviour of simultaneous condensation in vapour mixture. They concluded that multicomponent condensation enhances significantly the growth rate of the aerosol droplet. The droplet grows faster due to two reasons. The first reason is the existence of other condensing substances and the second is the increased mole fluxes of each species. These results indicate that the problem of droplet growth, and thus fog formation, is even more complicated than earlier believed. Therefore, it is also more difficult to prohibit fogging in a continuously changing mining environment.

Saturation conditions can occur even with lower relative humidity than expected, due to the presence of soluble particles and multicomponent condensation. Also saturation fluctuations influence droplet growth. Kulmala et al (1997) found that some droplets are able to form and grow in unsaturated conditions with mean saturation ratio less than unity. This is due to saturation fluctuations, in which turbulent fluctuations result in some droplets experiencing saturations that initiate droplet growth.

2.2 Visibility theory

2.2.1 Visibility and visual range

Fog is a safety hazard because it decreases visibility. In worst cases the visibility in a fog underground 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 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)

Visibility studies pose an interesting problem when fogging is considered. On the other hand, it is impossible to say anything about fog characteristics if only visibility studies are conducted. In this research it does not matter how far a person can see in fog as the knowledge does not help in achieving fog removal, or in determining information concerning the characteristics and behaviour of fog. Another point of view is presented in Hall et al. (1989). Better lighting and usage of contrast in objects or reflective lines to gain better visibility in fog are suggested as means of combating visibility limitations caused by fog.

Gaining information about visibility in fog in order to contribute to fog removal purposes is not necessarily practical. The actual visibility parameter gives information about the resolution of the eye of a human in addition to the characteristics of the fog itself. 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. More information concerning visibility theory can be found from Publication V.

2.2.2 Optical attenuation

Optical attenuation in fog is a complex function of the droplet 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:

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

where n'' is the imaginary part of the refractive index of the aerosol particle,

λ is the wavelength in µm,

r is the particle radius in cm,

Q_a is the Mie normalized absorption cross section, and

$n(r)$ is the particle size distribution.

The aerosols scattering coefficient from Mie theory is given by:

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

where n' is the real part of the refractive index of the aerosol particles

Q_d is the 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.

2.2.3 Role of the droplet size distribution

All fog characteristics are related to the fog droplet size distribution; this may be regarded as the key parameter determining 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 droplet 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

$$n(r) = ar^{\alpha} \exp(-br) \qquad (3)$$

where $n(r)$ is the number of particles per unit volume and per unit increment of the radius r

α, a, and b are parameters that characterize the particle size distribution.

Fog droplet size variation is large. A maximum range from 0.5 µm to 100 µm is given for surface fog droplet diameters. The droplet size distribution of fog is comparable to a cloud droplet distribution. Gamma distribution is generally used to present cloud and fog droplet distributions. An example of a cloud droplet size distribution is given in Figure 1.

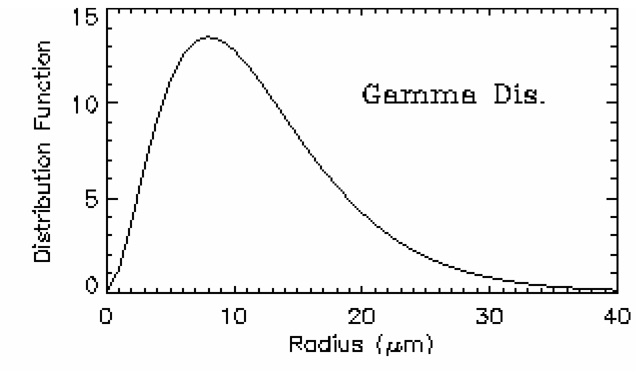

Figure 1. An example of a cloud droplet size distribution. (Hu, 1996)

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. At that time the technology was not developed enough for recording the lower end of the size distribution.

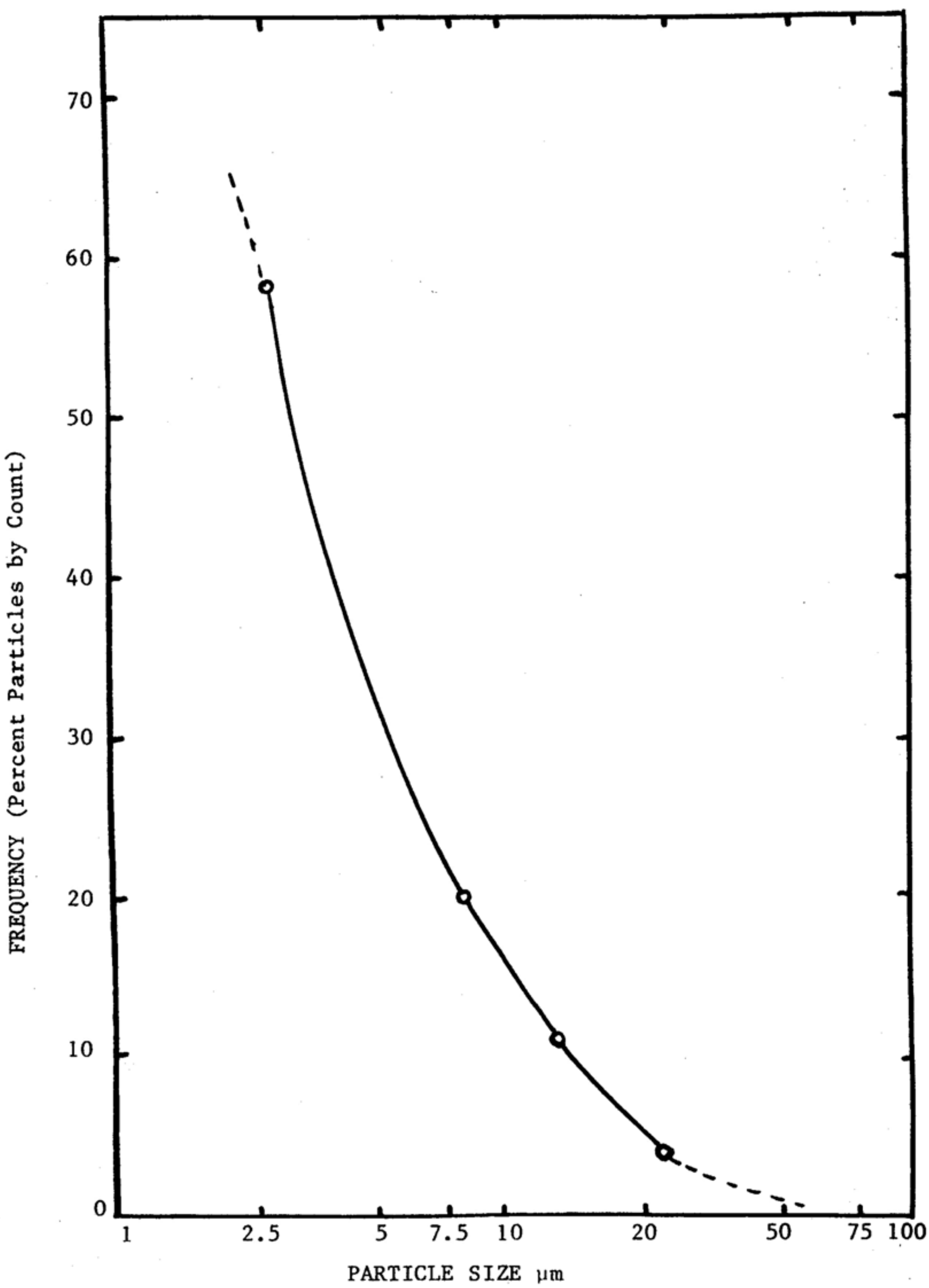

Figure 2. Fog droplet size distribution in an underground mine. (Schimmelpfennig, 1982)

Droplet size distribution of a fog is not a stable parameter. (Vasseur and Gibbins, 1996) As fog thickens, the droplets grow in size and vice versa. Also the environment, for example heat and water sources in a mine affect fog and result in changes to a fog droplet size distribution. Droplet size distribution, optical attenuation, and some future research ideas are also discussed in Publication V.

2.3 Future research ideas

The above-mentioned fog droplet size distribution and optical attenuation research are good subjects for further study. In some cases, especially when fog removal efficiency is evaluated, visibility studies may prove to be beneficial.

As automation increases in underground mines it may provide new possibilities for solving problems concerning fogging. Completely automated LHD's as well as other mobile machinery may be able to recognise rock walls through fog using other than visible wavelengths for the identification of objects.

A very interesting new material is being developed based on studies of a Namib desert beetle that gathers drinking water from morning fog. Using the water gathering technique of the beetle could lead to more efficient methods of obtaining water in arid environments and lead to improved water distillation and de-humidifying equipment says the early research concerning the beetle. (Knight, 2001) Now researchers from the Massachusetts Institute of Technology have found a way to copy the water gathering design and modify it. They can decorate a surface with any microscopic pattern of water-attracting and water-repelling areas, leading to various possible applications. (Simonite, 2006)

2.4 New method development: Fog mesh theory

While becoming familiar with the fog removal methods that are mentioned in literature, the author began considering characteristics that have not necessarily been taken into account in developing the well-known methods. It was noticed that most fog removal methods focus on humidity and rely on only that one parameter. For example, both air heating and air cooling methods are based on decreasing the relative humidity of the air mass.

As fog occurs quite frequently in Finland on the surface, the author started to pay attention to the behaviour of fog. The tendency of small fog droplets to precipitate when they come in contact with objects was noted. The idea of developing this attribute into a fog removal method surfaced.

The method is based on the adhering characteristic and condensing aptitude of water. When humid air moves over a surface, droplets are attached to it. In the case of a mesh the surface area for attachment and condensation is large. As water collects on the net, droplets join to form larger drops and fall or slide down under the influence of gravity. If the surface is cooler than the passing humid air, the water collecting effect of the surface gets even more conspicuous.

Air will penetrate a mesh set up perpendicular to the air direction and water is captured on the mesh wires. Optimal mesh size is a balance of ensuring that as much water as possible is collected, but the resistance of the mesh does not cause air re-routing. The efficiency of fog mesh will also depend on the size of droplets and air velocity.

As the fog droplets are captured, the condensation nuclei as well as other impurities get caught by the mesh with the water. The system dehumidifies the air as well as collects and removes particles from the airflow. Decreasing the number of particles in the air prohibits more fog formation and purifies the air.

In extremely dry surface areas of the earth fog meshes are used to collect water. This method is used especially on rocky coastlines. Full-scale fog collectors are typically flat, rectangular nets supported by a post at both ends, and set up perpendicular to the direction of the prevailing wind. There have been special projects all around the world especially since the 1990s to harvest fog in countries with dry climates (FogQuest, 2005). Investigations for the possibilities of this method began about thirty years ago. A full-scale fog collector is shown in Figure 3.

Figure 3. Full-scale surface fog collector, Danda Bazzar collection system. (NCDF, 2004)

Current research suggests that fog collectors work best in coastal areas where water can be harvested as fog moves inland carried by the winds. Walls are built to cover large areas and to allow air to pass through them. Typically nylon or polypropylene is used as a collector material. The materials are commonly called fog or mist eliminators. The collectors are designed for surface fogs, in which the fog droplet diameter ranges typically at least from 5 to 65 μm.

The requirements for fog collector meshes outdoors are presented as a part of United Nations Environment Programme's fog water collection information. (UNEP, 2005) If these prerequisites are compared with underground conditions, it is easy to notice the potential of an underground fog mesh system. These prerequisites are

- Frequency of fog occurrence
- Fog water content
- Wind direction
- Stability of airflow
- Topography

Usually fog tends to stay in the same areas of the mine for long periods, even for months. Water content of air is high in an underground mine because of high particle concentration. The air moves in the same direction in the decline at all times, so wind direction is stable. Air velocity and temperature are also nearly constant in most cases. Being upslope, the topography in a ramp is suitable. Fog mesh theory is presented more thoroughly in Publications III and VI.

3 Research methods and procedures

3.1 Interviews

Interviewing mine personnel was divided into two parts. In the first part Finnish professionals who work in underground mines were interviewed. A set of questions was developed to determine the extent of fogging in these mines. Questionnaires were sent to three underground mines, representing mines with different ore types in Finland. These were Pyhäsalmi Mine (zinc-copper) as a base metal mine, Orivesi Gold Mine as a precious metal mine and Louhi Talc Mine as an industrial mineral mine. Further information concerning these mines, especially detailed descriptions of their ventilation systems, is available in Pulkkinen and Martikainen (2004), Martikainen (2002), and Martikainen and Särkkä (2004).

The questionnaires were analysed prior to the on-site studies in these mines. Further information was requested later based on the results and experiences received during the on-site fog removal tests and basic measurements. With the help of this additional information, the conclusions and recommendations were made.

The second part of the interviews was international. At first professionals working in the industry were interviewed personally. This resulted in a nice overview of the subject as well as case study information. For more detailed analysis supplementary information concerning underground mines was requested with a questionnaire. Results of the interviews were evaluated and compared.

Both the international and the Finnish parts included many of the same or similar questions. The international questionnaires consisted of three parts, which were basic information about the mine, information concerning fogging, and possible corrective actions taken in order to deal with the problem. The international questionnaire is presented in Appendix A.

3.2 Measurements

Measurements were taken in order to define the fog situation in each of the three mines which volunteered for the study. This information was acquired to determine whether or not drastic changes were required to remedy the situation. The thermodynamic conditions were accurately defined through by air temperature, relative humidity, and dew point temperature data. This permitted the calculation of how much the humidity should be decreased in order to accomplish fog removal. Measuring particle concentrations was also important because with high particle concentration values fog forms at a lower relative humidity and can become denser. As increasing air velocity is one of the most well-known fog removal methods, velocity values were also measured. These results were used in determining the airflow in some cases.

Air velocity and temperature measurements were performed with a hotwire anemometer, model Kimo VT200 T. The measurement range of the anemometer is from 0 m/s to 30 m/s for air velocity with the telescopic hotwire probe and from -100 °C to +400 °C for temperature based on the manufacturer’s technical data sheet. The precision of air velocity measurements is 0.01 m/s in the velocity range of 0-3 m/s and the precision of temperature measurements is 0.1 °C. The accuracy of air velocity value is

±3 % ±0.03 m/s of the reading and the accuracy of the temperature value is ± 2 % ±0.1 °C of the reading.

Humidity measurements and verification air temperature measurements were done with an Ebro TFH100 hygrometer, which measures relative humidity of 0 - 100 per cent and temperatures from -10 °C to +80 °C. The resolution of the instrument for relative humidity is ±0.1 %. The accuracy of the relative humidity, temperature and dew point temperature measurements are ±2 % of the readings. The Ebro TFH100 is designed for use in high humidity environments, like in greenhouses, so it can measure exceptionally high humidity with its normal accuracy. The air probe can be covered with a water guard in very high humidity conditions to prevent saturation. The water guard was used in the mines at all times.

An aerosol meter, DustTrak TSI 8520, with a maximum particle size range of 0.1-10 μm was used for the particle concentration measurements. The aerosol meter has a measuring range of 0.001 mg/m^3 to 100 mg/m^3 and a resolution of one per cent of the measuring range. An environmental enclosure, model 8520-1, was used to minimise error from wind conditions and water. A water trap was installed inside the environmental enclosure to collect the water during the measurements.

The measurement procedure depended on the site-specific requirements. Also, basic research and new method development had their own characteristics and thus they required slightly different measurement procedures. Information concerning measurement devices and procedures is also discussed in Publications I, II, III, IV, and VI.

3.3 Procedures concerning basic tests

The basic measurements were performed along the decline in all three mines in Finland participating in the study. Measurement points were chosen from tunnel sections with as even airflow as possible, avoiding curves, obstacles, and intersections. Measurements were taken from the bottom of the mine through to the surface. At the 1445 m deep Pyhäsalmi Mine the difference in depth between the measurement points was kept below 100 m. At the Louhi Mine, depth 230 m, the difference in depth was kept below 50 m and at the Orivesi Mine, depth 720 m, the difference in depth was at maximum 65 m. Measurement locations were marked on the tunnel walls with paint to ensure easy repeatability.

Air temperature, dew point temperature and relative humidity measurements were taken as point measurements. Air temperature values were verified with another point measurement using a hygrometer. The air velocity was taken as an average of three point measurements. The particle concentration was recorded at two minute intervals so at least 3 measurements were taken at each measurement location. The value closest to the average was chosen as a final result.

3.4 Procedures used in comparison of fog removal methods

Some information from the basic measurements was used in the evaluation and comparison of fog removal methods. This information was used primarily to evaluate the effect of increasing the air velocity by rerouting as a fog removal method.

Increasing air velocity by rerouting was studied in all three mines. The air velocity value of 0.25 m/s found in literature was suggested to result in fog scattering and successful fog removal (Schimmelpfennig, 1982). This was used as the value to be reached in the declines of these mines.

Louhi Mine was chosen as the site for the comparison study of heating and increasing air velocity with an additional fan. A location in a decline with a level connection was found suitable for the purpose due to the sufficient electricity supply for both heaters and an additional fan.

To study the effectiveness of increasing air velocity alone, an additional fan was installed in the decline-level crossroad on level +130 m. Measurements were recorded both with and without the fan operating. For comparison purposes, measurements were taken during full mine operation and after the shift.

Air heating in combination with the fan was also studied. The installation of the fan and heaters is shown in Figure 4. The heaters were not tested without the fans operating during mine operation because satisfactory results were received with the fan running and turning it off would have had a negative effect on ore transport.

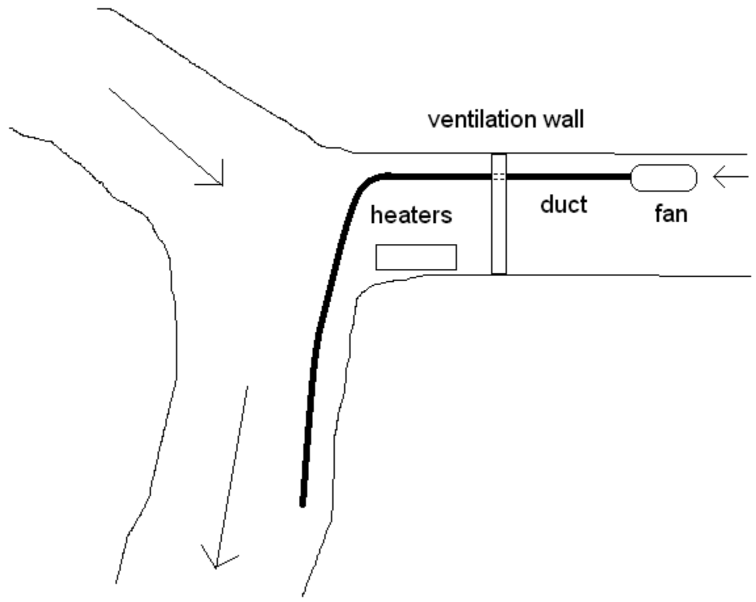

Figure 4. Installation of the fan and heaters.

The same testing equipment was used for acquiring the psychrometric values and particle concentration as in the basic measurements. The exact measurement locations, on the other hand, were chosen based on the fog removal method tested as well as the limitations caused by the testing site.

3.5 Procedures used in new method development

New method development included on-site testing at the Pyhäsalmi Mine and at the Orivesi Mine. Fog mesh was introduced as a possible new fog removal method. The measurements were performed with the same testing equipment. The measurement system was the same with the exception of measurement locations.

The chosen test site at the Pyhäsalmi Mine was in a ramp just below level +600 m, where fog is usually thick. The tunnel dimensions in the test site are about 5.5 m x 4.5 m. An old ventilation wall frame existing at the site was modified for the fog mesh installation. This rectangular opening has an area of approximately 20 m^2 that was to be covered with a mesh. Modifications amounted to simply repairing the wall frame and adding wood planks for mesh attachment. The frame structure is shown in Figure 5.

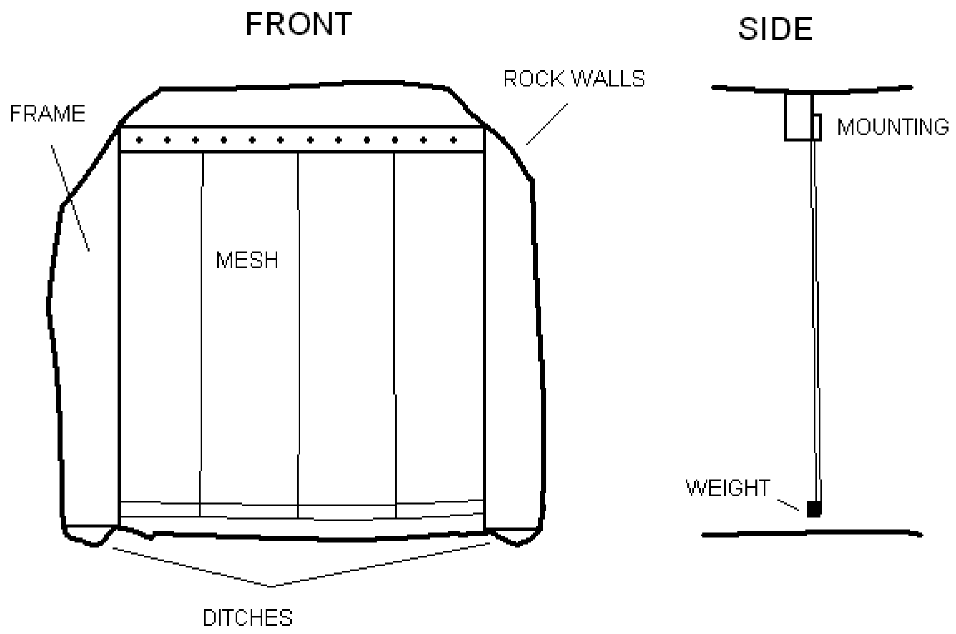

Figure 5. Frame structure and fog mesh installation.

Installation during the first tests consisted of slices of a mesh fabric, wood planks on the top of the mesh and a heavy electrical cable used as a weight on the bottom of the mesh to help keep the mesh perpendicular to the airflow. During the second tests the weight system was changed from the electrical cable to two heavy wooden planks that were placed on each side of the mesh fabric and nailed together. This way no additional wire, which could get caught to the passing vehicles, was required to attach the weight. The wood installation was also sturdier than the electric cable.

All tests were performed in the decline of both mines both downstream and upstream of the mesh frame. This was done in order to check the changes of air velocity, humidity and temperature over the fog mesh and thus to evaluate effects of the mesh. The distance from the mesh to the measurement locations was 25 m in both directions, so the measurements were performed 50 m apart.

The first test set in both mines was carried out about 30 minutes after completing the installation of the fog mesh with each material. This gave time for the airflow to stabilise and find new routes in case of resistance problems. This also demonstrated the water collecting ability of the tested mesh fabric and whether or not the water fell down the net. Each test took 10 minutes to perform in one location.

In the second test set in both mines the measurements were started 5 minutes after completing the mesh installation. Each test took 5 minutes to perform in one location. The measurement sampling rate with the aerosol meter was increased, allowing the duration to be decreased. The procedure was changed to enable a larger number of measurements with one mesh system. These tests allowed the effect of the time delay after mesh installation to be considered as a factor on the results.

The first tests consisted of testing only individual materials. Two tests with combinations of two materials were performed during the second tests.

In the second test set the number of measurements was increased from one with each material to five with each material or material combination. These measurements were taken both upstream and downstream of the mesh system as usual. The gap between the materials was about 30 cm in both material combination cases. One of the combination tests was performed at the Pyhäsalmi Mine, the other one at the Orivesi Mine.

All measurements in both mines were performed with every mesh material as well as with only the frame to develop a baseline set of measurements for comparison purposes. This allowed changes in airway resistance to be evaluated and air re-routing to be easily observed.

As the limitations of the different materials became better understood during the study, a mist eliminator material designed especially for small fog droplets was chosen as the last material to be tested. Wire mist eliminators are commonly used to collect droplets above 5 µm in diameter, the droplet sizes typical for surface fogs. When separation of smaller droplets in the 1-3 µm range is required, typical wire mist eliminators are largely ineffective because of the mesh's random structure, irregular density, and coarse fibre diameters. (Kimre, 2006)

The information concerning fog droplet size in underground mines is deficient, but because of high particle concentrations and diesel exhaust the fog droplet size can be assumed to be smaller than the droplet size of surface fogs. The only study concerning the droplet size in an underground mine shows most droplets to be extremely small (Figure 2). As the droplet size is Gamma distributed, the median fog droplet size is below 2 µm. The median fog droplet size in an underground mine is presented in Figure 6.

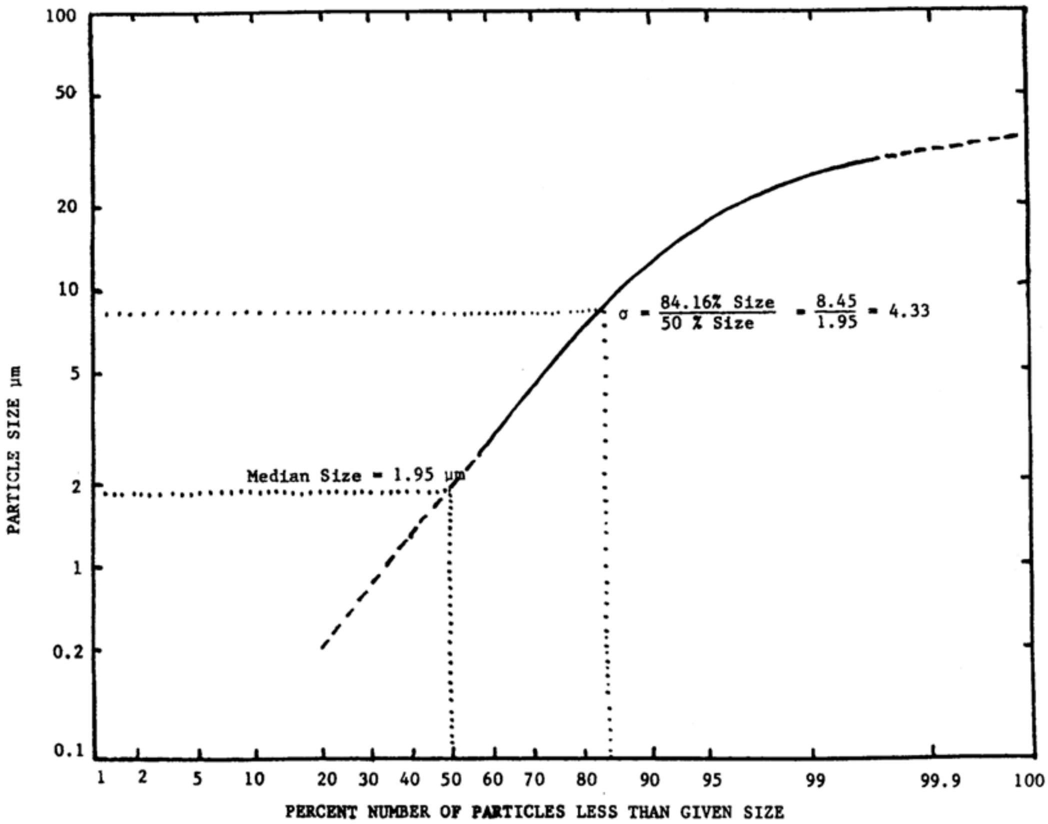

Figure 6. Median fog droplet size. (Schimmelpfennig, 1982)

4 Results

4.1 Interviews

4.1.1 General

The knowledge gathered from the mines in Finland was thorough, covering all fog-related issues from the worst fogging periods to the preventive measures and fog removal trials. The worst fogging problems occurred in mines with active operation and many noticeable water leakages or open ditches and pools. Results achieved in fog removal attempts were recorded and evaluated. In every Finnish mine that participated in the study, one or more fog removal methods had been tried out with varying success. This information is presented in detail in Publication II.

From the international interviews a lot of information was attained, even concerning methods that are not mentioned in the literature. Also, examples from successful implementation of conventional fog removal methods were received. In some mines fogging has not been problematic, while in some others the situation has been very complicated and a lot of time and effort has been put into choosing an effective fog removal method. International interviews are also discussed in Publication V.

4.1.2 Unfamiliar fog removal methods

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. (Marks, 2006)

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. (Marks, 2006) 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 at the meeting 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.

4.1.3 Pyhäsalmi Mine, Finland

Fogging is observed throughout the year at the Pyhäsalmi Mine. Conditions are typically at worst in the spring and autumn, as temperatures outside change rapidly and surface humidity is high.

Fogging has been more of a nuisance than a problem in the Pyhäsalmi Mine. This is due to the light traffic in the decline. Working levels of the mine extend from 1050 m to 1445 m beneath the surface, and shaft haulage is used for both the ore and the personnel transport (Pulkkinen and Martikainen, 2004). Only a supply truck uses the decline regularly and it has no strict schedule. Other vehicles that use the ramp occasionally are mainly for maintenance, inspection, and surveying purposes. The speed limit in the ramp is 25 km/h, but sometimes the fog has been reported too thick to enable driving according to the limit.

Fogging is observed mainly in the decline but also occurs in some old, abandoned levels where it can last almost year round. These levels have been abandoned, so this local fogging does not affect operation in any way.

The appearance of fog in the decline is not continuous, and there is usually no exact fog front in the Pyhäsalmi Mine. Several sections of the ramp are foggy, but in between there are also clear areas. In some parts of the ramp fog clouds of different sizes move upwards. As the velocity of air, relative humidity, and temperature vary along the ramp, fog thickness and fog front locations change accordingly. These variations may be caused by water seepage, pumping stations, level connections and shaft connections, which all affect the parameters controlling fog formation. Changes in fog thickness, fog front lengths, fog cloud occurrence, and locations of foggy areas also depend on factors like the climatic conditions on the surface, diesel equipment usage in the mine, and the length of a working sequence at a time.

Previous fog removal efforts in the Pyhäsalmi Mine include increasing air velocity in the ramp by re-routing and prohibiting water flow from entering the ramp. The possibility of air heating has also been discussed. In the working areas, where leakage prevention has been used, there is no fogging. It has to be mentioned though, that the area is dryer by nature and the virgin rock temperature at the working levels ranges from 20º to 22º Celsius, so the conditions there are not nearly as favourable for fogging as elsewhere. In the upper parts of the ramp where the air velocity has been increased by rerouting, the results did not reach the expectations.

4.1.4 Orivesi Mine, Finland

The worst fogging period in the Orivesi Mine is the summer, but fogging is observed during spring and autumn as well. Fog can be thick enough to prevent visibility of the rock walls surrounding the decline and thus slows down haulage speeds. Fogging has been noticed mainly between surface and level +235 m as a steady fog front. During winter fog appears in a noticeably smaller area.

In the Orivesi Mine fog appears solely in the decline. Air velocity around level +400 m is high in the decline due to the collapse of an exhaust shaft, so all exhaust air moves up the ramp past the collapsed part of the shaft. The high air velocity in the ramp is inconvenient, since dump trucks cause a disturbing pumping movement of the air. This part of the ramp is, however, free of fog.

Increasing air velocity by ventilation system changes has been attempted in order to prevent fogging, but these changes have not produced anticipated results.

4.1.5 Louhi Mine, Finland

The worst fogging periods in the Louhi Mine are spring and autumn. Fog in the Louhi Mine occurs as an almost stable front from the surface to level +155 m. The length of this fog front is thus about 850 m. Thickness of fog is also quite constant through this whole length.

In the Louhi Mine fog in the ramp is a safety issue. According to the personnel, one accident has probably been caused by fog reduced visibility. Fog also affects haulage speeds, but has not been taken into account in schedules.

Ventilation system changes were implemented based on a ventilation study performed in 2002 at the Louhi Mine to improve the effectiveness of the ventilation. As this increased air velocity in the decline, it was expected to reduce fogginess as well. Unfortunately fog removal was not achieved.

4.1.6 Thompson Mine and Birchtree Mine, Canada

Thompson Mine and Birchtree Mine are both located near Thompson, in Manitoba, Canada. They are nickel mines in a sub-arctic region. Mining methods used are vertical block mining and mechanized cut and fill. Thompson Mine is 1390 m deep, Birchtree Mine’s depth is about 1300 m.

Heavy fogging has been observed during winters in upcast shafts. Visibility decreases at worst to 6 – 12 m. As upcast shafts are exhausts, fogging does not cause any problems. No fog removal is used in these mines. (Laine, 2006)

4.1.7 Ekati Diamond Mine, Canada

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.

At Ekati Diamond Mine fog appeared during 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 warm air to the decline. Also, as the total flow in the decline increased the 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)

4.1.8 Kiruna Mine, Sweden

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 summer and winter 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 separately 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 winter 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 summer 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 cause 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)

4.1.9 Homestake Mine, USA

Homestake Mine was a huge gold mine in Lead, SD, USA, before its closure in 2002. 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. (Marks, 2006)

4.1.10 ”Anon” Mine, Canada

”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)

4.1.11 ”Anon 2” Mine, Canada

”Anon 2” Mine is a nickel mine with a depth of 1200 m. Mining methods used in this mine are mechanized cut and fill as well as vertical crater retreat.

Fogging in ”Anon 2” Mine occurs around the year, but summer is the worst season. Fog thickness is estimated to be moderate. Areas of fog occurrence include upcast shafts and the decline. At worst visibility decreases to about 6 m in the decline.

Fog removal method chosen for ”Anon 2” Mine is heating. Electric heaters were installed in the main ramp. The total output of the heaters is 150 kW, which was the minimum heat required based on calculations. This has resulted in significant reduction of fog and in achieving an acceptable visibility. In order to determine the required heater capacity several barometric surveys were performed in the decline at different times of the year. (Allen, 2006)

4.2 Basic study results

4.2.1 Pyhäsalmi Mine

Two measurement sets were taken at the Pyhäsalmi Mine. The reasons for this were the irregular nature of the first results, very light traffic during the measurements, and changes in the ventilation system carried out at the mine after the first measurements. Old level working connections were closed, which stabilized the airflow in the decline.

The first measurements were performed during the weekend with very little traffic. The second set of measurements took place on an active Tuesday afternoon shift.

At the Pyhäsalmi Mine, during the first tests, fog was observed between levels +300 m and +780 m as an almost continuous front. Upwards from level +300 m also a couple of moving fog clouds were noticed. The measured relative humidity values in the foggy area ranged from 75 to 81 %. Both particle concentration and air velocity values changed considerably throughout the ramp. Highest particle concentration values were observed in working levels of +1100 m and +1300 m.

In the foggy area, air velocities ranged from 0.3 m/s to 1.3 m/s and the particle concentration from about 0.4 mg/m^3 to 1 mg/m^3. The air velocity of the ramp was found to vary, due to leakage into the worked out areas. Temperature decreased from +21.5 °C in level +780 m to +15 °C in level +300 m. Humidity, air velocity, particle values, and an estimate of observed fogginess are presented in Appendix B both as a graph and in a table. The measurements were taken in the spring when outside temperature ranged from 0 °C to 10 °C during the measurements. Relative humidity on the surface ranged from 17 % to 33 %.

The second set of measurements at the Pyhäsalmi Mine, which is considered the more reliable of the two, was performed in winter with an outside temperature ranging from about -6 °C to -8.5 °C, and the relative humidity ranging from 39 % to 67 %. On this occasion, the number of measurement points was increased and the distance in depth between the points decreased to help in determining trends along the decline.

There were two different fog fronts, between levels +1010 m to level +500 m and from level +160 m almost to the surface. Within these fronts, the thickest fog was observed between levels +500 m and +780 m as well as between levels +970 m and +1010 m.

Surprisingly, the results showed very high relative humidity values in the mine, despite the surface temperature below 0 °C. Relative humidity values in the foggy areas ranged from 74 % to almost 93 %. Particle concentrations were also very high in the foggy areas, in many places exceeding the values measured in the active mining area, even when there was no traffic above level +1100 m. Air velocity values were between 1 and 1.5 m/s in the foggy parts of the ramp. From level +500 m a lot of air leakage from the ramp to old workings was attributed to causing the fog to disperse and the lowering the air velocity to near zero. Humidity, air velocity, particle concentration and observed fogginess are shown in Figure 7. All measured values are included in Appendix B.

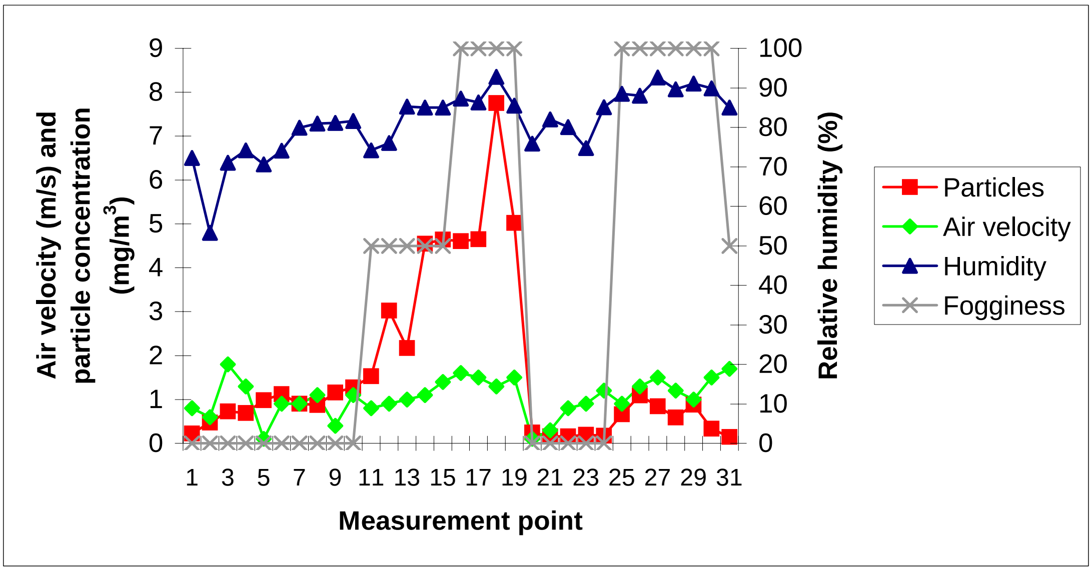

Figure 7. Results of the second basic measurement set at the Pyhäsalmi Mine.

4.2.2 Orivesi Mine

At the Orivesi Mine fog was observed in a continuous fog front reaching almost from the surface to about level +310 m. The fog disappeared then slowly when going deeper so that level +375 m was completely clear. Climatic conditions outside were warm with a temperature of about 22 °C and a relative humidity of about 50 % during the measurements.

The Orivesi Mine had the highest values of relative humidity. These high values were found in the foggy area and ranged from 92 % to 93.5 %. The air velocity ranged from 0.7 m/s to 2 m/s and the temperature in the foggy part of the ramp decreased as one approached the surface from +16.5 °C to slightly over +14 °C. The thickest fog was observed around measurement points 10 and 12, shown in Figure 8, where the air velocity was about 1.5 m/s. The complete measurement results are given in Appendix B.

Particle concentrations were the highest where the fog was the thickest and also close to the ramp portal. Probable causes for the high particle concentration near the surface were the surface wind conditions and a few passing dump trucks, which seemed to affect other measurement results in measurement point 16 as well, and scatter the fog close to the ramp exit. Humidity, air velocity, particle values and observed fogginess are presented in Figure 8.

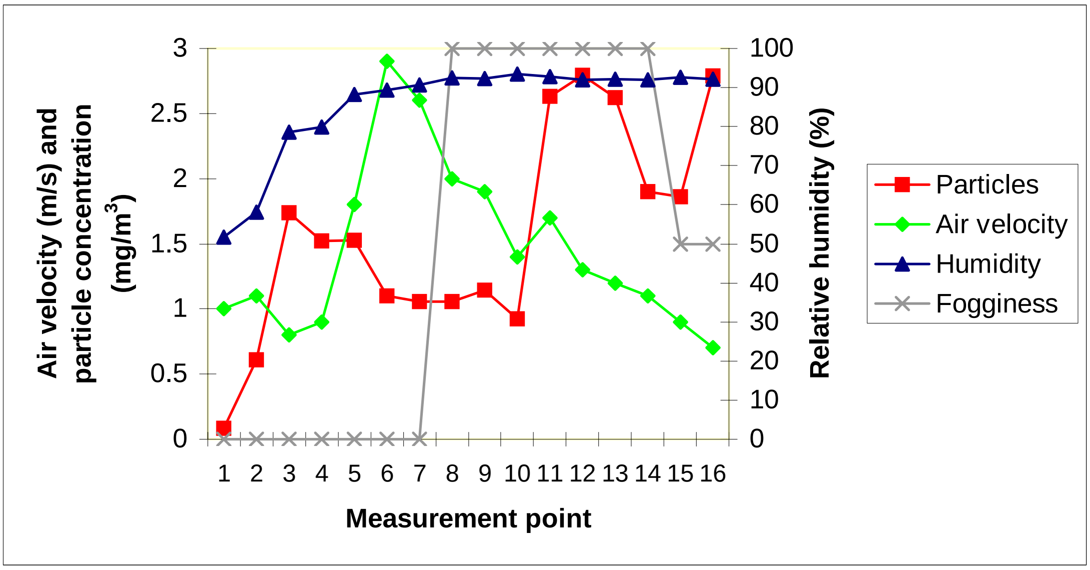

Figure 8. Results of the basic measurements at the Orivesi Mine.

4.2.3 Louhi Mine

Fog in the decline of the Louhi Mine was observed from the surface to about level +175 m, which was between measurement points 5 and 11. Relative humidity in the foggy part of the decline ranged from 80 % to 85 %. Highest particle concentrations were observed in the foggy area. Air velocities upwards the ramp ranged there from 1.1 m/s to 1.7 m/s. Temperature ranged very little around +9 °C. The weather outside during the autumn measurement day was rather stable with a temperature of about 15.5 °C and a relative humidity of 72.5 %. All the measurement results taken at the Louhi Mine are given in Appendix B. The humidity, air velocity, and particle values as well as observed fogginess are presented in Figure 9.

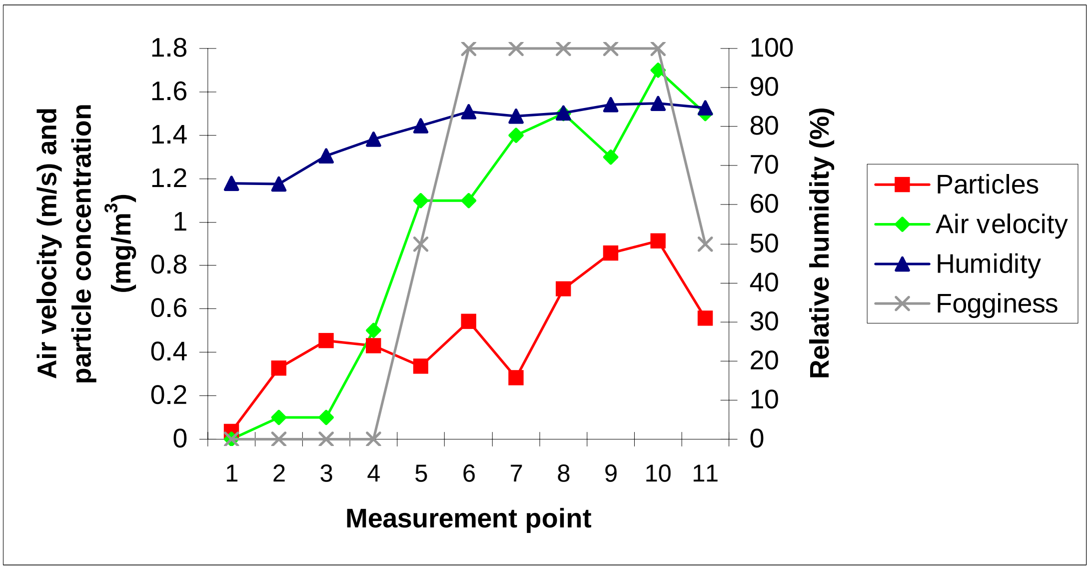

Figure 9. Results of the basic measurements at the Louhi Mine.

4.3 Fog removal method comparison

4.3.1 Increasing air velocity by air rerouting

At the Pyhäsalmi Mine the increase in air velocity resulted from closing old level connections. Previously a part of the airflow entering the ramp from the working levels had leaked from the upper parts of the decline into the old backfilled areas with old raises. At the Orivesi Mine air velocity in the decline increased because of operation progressing deeper and thus requiring ventilation changes. Fog removal was not sought after, but only hoped for as a side effect. At the Louhi Mine the situation was quite similar. Operation in areas further away from the decline led to the need for increasing the quantity fresh air. A new main fan with increased airflow was chosen and installed.

The results received from increasing air velocity by rerouting were similar in all three mines. The air velocity increased in the decline as planned in every mine. The increases in air velocity ranged from 0.1 m/s up to 1 m/s depending on the location. The literature recommended value, 0.25 m/s, was reached in every mine. Much higher values were also recorded. At the Orivesi Mine, very high air velocity values, over 2.0 m/s, were reached. Unfortunately, fog removal was not achieved anywhere. Increasing air velocity by air rerouting is mentioned in Publication I and discussed more thoroughly in Publication II.

4.3.2 Increasing air velocity by an additional fan

An additional fan was installed in the decline-level crossroad on level +130 m of the Louhi Mine. The idea was to take fresh air from the level and direct it through the ventilation wall to the decline with a duct. The fan installation is shown in Figure 4. Airflow direction is indicated with arrows. Publication II includes information concerning increasing air velocity by an additional fan.

Measurements were taken both with and without the fan operating. For comparison purposes, measurements were taken within shift with full mine operation and after the shift with minimal activity. Results are presented in Tables 1 and 2. After the shift the main fan operated only with 80 % capacity and the level working fans were turned off. This can be seen from the velocity values.

Table 1. Measurement results of increasing air velocity by an additional fan at the Louhi Mine with full operation.

Depth	Particles	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
230	0.314	0.95	9.1	84.4	6.6	none
222	0.319	1.1	8.7	87.2	6.7	none
206	0.505	1.2	9	86.7	7.2	light fog
175	0.176	1.3	8	89.8	6.5	fog
155	0.197	1.2	8	90	6.5	fog
130	0.273	1.7	8.7	89	7	light fog
110	0.296	3.1	8.9	88.7	7.2	none
70	0.366	1.5	8.9	88.6	7.2	light fog
40	0.427	1.1	8	90.8	6.7	fog

Table 2. Measurement results of increasing air velocity by an additional fan at the Louhi Mine after the shift.

Depth	Particles	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
230	0.217	0.5	8.7	86.7	6.8	none
222	0.212	0.8	8.4	88.1	6.7	none
206	0.213	1	8.2	89.3	6.4	light fog
175	0.199	0.6	8.3	88.1	6.5	light fog
155	0.173	0.9	8.4	88.6	6.5	light fog
130	0.116	1.8	8.3	88.5	6.5	light fog
110	0.122	1.7	8.5	88.1	6.8	light fog
70	0.112	1.6	8.4	88.4	6.7	light fog
40	0.105	1.2	8	89.6	6.5	fog

As the air was taken from a level, also the characteristics of the air there were considered important and thus measured. Furthermore, the effect of the fan to the airflow was studied. Results are presented in Table 3.

Table 3. The effect of fan to the airflow.

Depth	Particles	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
Fan on						
110	0.243	2.8	8.8	87.6	6.7	none
130	0.197	1.2	8.4	89.8	7	none
Fan off						
110	0.336	2	8.5	91	7.3	fog
130	0.281	2.2	8.1	90.7	6.6	fog
Duct						
Duct end			9.3	82.7	6.5	none
Fan inlet	0.039	1.7	8	87.7	6.1	none

The most noticeable change of psychrometric properties of air was recorded at the depth of 110 m. The temperature increased only 0.3 ˚C, but humidity decrease was a more pronounced 3.4 %. The increase in air velocity was somewhat less than 1 m/s.

The results showed that in passing the fan the airflow dried considerably and was heated. The temperature increased by 1.3 ˚C and the decrease of relative humidity was as high as 5 %. The heat of the fan seemed to result in evaporation of fog droplets and thus also decreased moisture content of air.

4.3.3 Heating

Heaters were installed to the level connection of level +130 m and the decline at the Louhi Mine. The placing of the heaters is shown in Figure 4. As the additional fan lowered the moisture content of the air locally, its effect was evaluated positive on ore transport and it was not removed. Instead the heater tests were performed in combination with the fan.

Heater capacity was defined based on calculations. There was no material found from the literature concerning heater dimensioning to remove humidity in an underground mine, so other types of references were used instead. Because of this two sets of calculations were done. Both gave similar results. The first set of formulas was meant for interior climate design of houses. It is presented with Equations 4 and 5:

$$\phi = \varphi\, q_v (h_2 - h_1) \qquad (4)$$

where $ø$ represents the required heater capacity in kW

φ represents air density in kg/m^3

q_v airflow in m^3/s

h_1 and h_2 are air enthalpies in kJ/kg.

Enthalpies are calculated by:

$$h = 1.006\, t + x(2501 + 1.85\, t) \qquad (5)$$

in which h is the enthalpy in kJ/kg

t is the temperature of humid air in ˚C

x is the absolute humidity of air in kg/kg

With these formulas, obtained required heater capacity was 115 kW. (Seppänen, 1996)

The other method of calculation is presented as Equation 6.

$$\frac{BTU}{hour} = 0.24 \times 0.0746 \times CFH \times \Delta T \qquad (6)$$

In this equation BTU is British thermal unit

0.24 is the specific heat of air

0.0746 is the weight of one cubic foot of air in lb/ft^3

CFH is the volume of air to be heated in ft^3/h

ΔT is the number of degrees rise desired in ˚F.

(Kennedy, 1996) After converting to SI units, a value of 106 kW was obtained.

The overall heating capacity of the installed heaters was 94 kW, which was slightly lower than anticipated from the calculations. With heating the temperature rise sought was 2 ˚C.

At the installation location, measured increase in temperature was 1.4 ˚C. Unfortunately, at the +110 m level the temperature increase was not as pronounced and only measured 0.6 ˚C. Even though the increases became smaller as distance between the installation and the measuring location became larger, the temperature was still found to increase slightly throughout the entire decline. This was not, however, enough for complete fog removal. On the other hand, the effect of heating on the measured relative humidity values was drastic. At the crossroad of +130 m the decrease of relative humidity was over 7 %. The smallest difference in relative humidity was measured near the surface. These measurement results are shown in Table 4. Results concerning heating are also presented in Publication II.

Table 4. Measurement results with heaters on and off.

Depth	Particles	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
Heaters on						
230	0.678	0.9	9.3	82.9	6.5	none
222	0.69	1	9.2	83.7	6.6	none
206	0.667	1	9	86	6.5	none
185	0.509	1.4	8.6	88.4	6.6	light fog
130	0.338	1.4	9.6	84.9	6.8	none
110	0.299	2.3	9	87.2	6.9	none
70	0.244	2.3	8.7	89.1	6.7	none
40	0.336	1.2	8	91.6	6.8	light fog
Heaters off						
230	0.577	0.8	9	87.8	7.2	none
222	0.678	1	8.3	90.6	7	none
206	0.543	0.7	8.3	91.2	7.1	light fog
185	0.592	1.4	8	91.8	6.9	light fog
130	0.413	1.7	8.2	92	7.1	none
110	0.334	2.2	8.4	89.3	6.9	light fog
70	0.211	2.4	8.4	93	7.4	fog
40	0.265	1.3	7.8	92.7	6.9	fog

The heaters caused a temperature increase, which resulted in fog removal as the relative humidity of the air decreased. The changes in the dew point temperature are most probably due to the evaporating effect of the heaters.

4.4 Fog mesh study

4.4.1 Mesh materials and their costs

In this study eight different materials were tested. Each one of these materials was tested individually. However, three of the materials were also tested in material combinations. The tested mesh materials are presented in Figures 10-17.

Only one of the tested materials was designed for fog removal use. The other seven materials were developed for other purposes entirely. Three of the tested materials are mosquito nets, two are used for filtering, one is designed for plant protection, and one is for greenhouses. The mesh materials are introduced more closely in the order, in which they were tested. All costs are given for 25 m^2 of material as well as in a cost per square meter of mesh fabric both in dollars and euros based on the exchange rate of 1.25 in June, 2006.

A grey mosquito net made of thin metallic wires and coated with plastic was tested first. The holes of the mesh are rectangular and the mesh size is 1.4 mm. The material seems to be pressed, as individual wires can not be detected. The cost of this material was $1200 (1500 €) or $48 (60 €) per square meter.

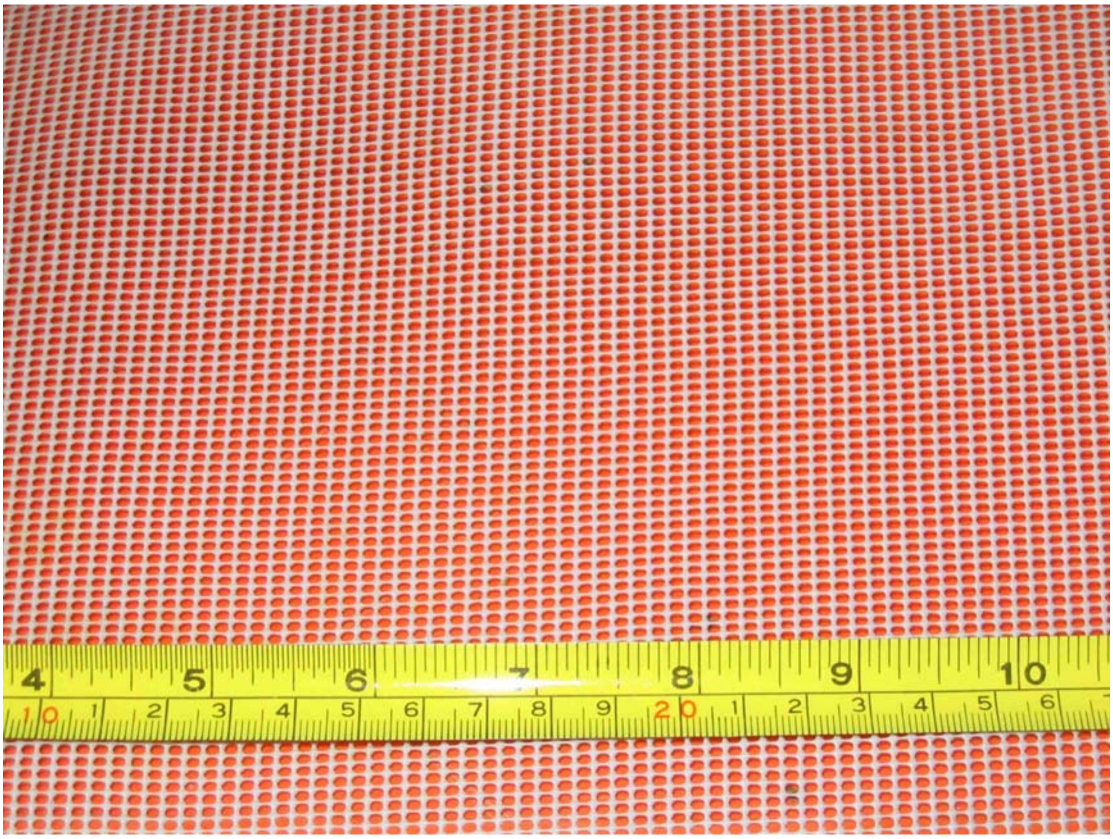

Figure 10. Grey mosquito net.

Another mosquito net tested, called white mosquito net, is thinner and made completely of plastic with a mesh size of about 1.0 mm. The threads are extremely thin and interwoven. The price of the white mosquito net was on total \$180 (225 €) or \$7.2 (9 €) per square meter.

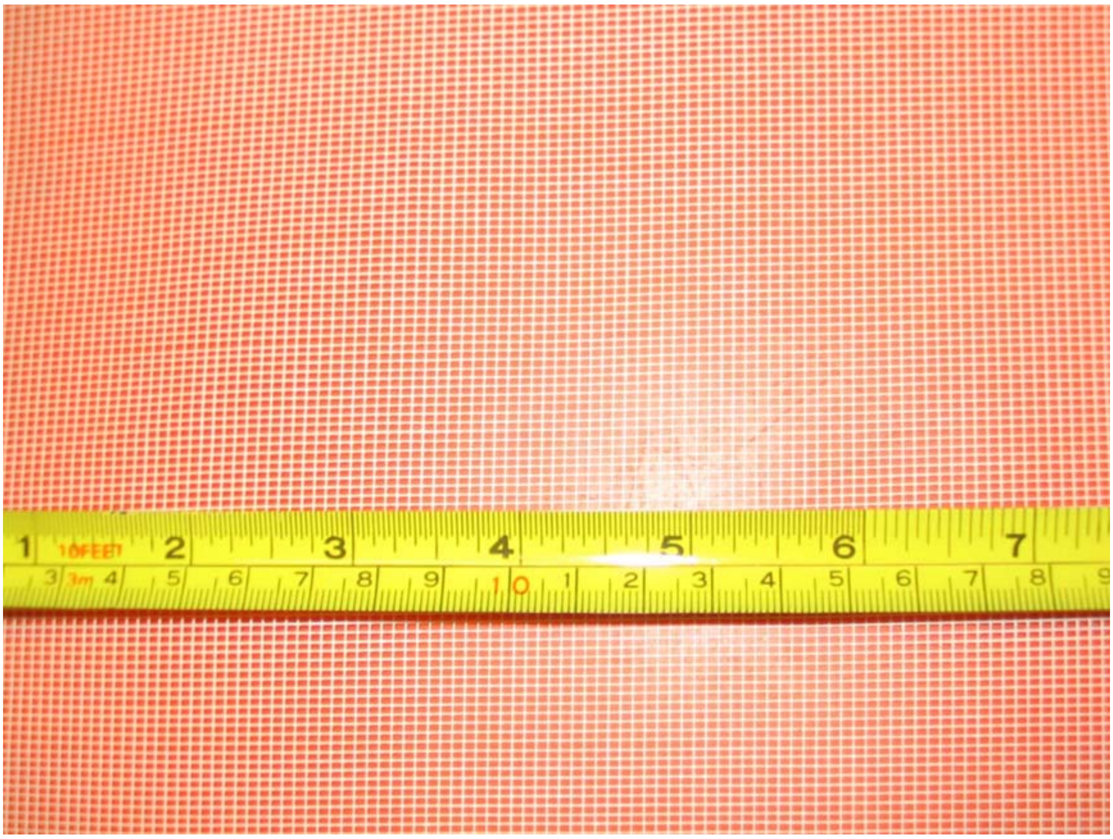

Figure 11. White mosquito net.

The third net is designed to protect bushes and trees from the sun or cold. This mesh is made of woven plastic bands. These bands are 1 mm wide. The mesh consists of triangular holes with a height of 7 mm and the length of the shortest side of 3 mm. This material was very cheap with a price of only \$30 (37.5 €) or \$1.2 (1.5 €) per square meter.

Figure 12. Plant cover net.

The fourth material is a 1 cm thick filter fabric for air cleaning. The filtering efficiency or the grade of the fabric is G3. The volume of the filter fabric is 20.2 litres per square meter and the weight 0.25 kg per square meter. This material costs about \$200 (160 €) or \$8 (6.4 €) per square meter.

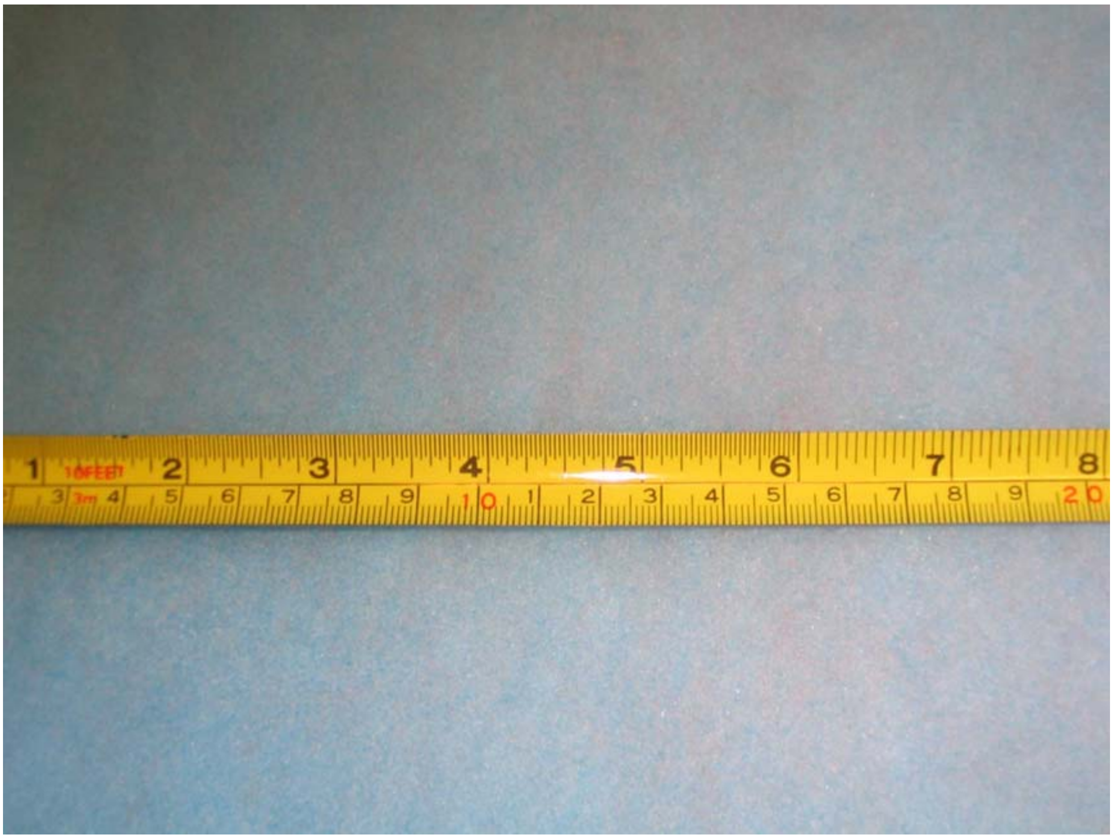

Figure 13. Filter fabric G3.

The fifth material is a fibrous filter fabric used typically for underground water filtering named Bidim S02. Fibrous filter fabric Bidim S02 is designed for segregation and protection of soil as well as for water filtering purposes in geoconstruction. This material is made of bound fibres with a thickness of 1.5 mm. The average weight of the fabric is 0.1 kg per square meter. The price of Bidim S02 was estimated as \$31 (25 €) or \$1.3 (1 €) per square meter.

Figure 14. Fibrous filter fabric Bidim S02.

The sixth material is a plastic greenhouse net. The plastic greenhouse net is white and has vertical perpendicular square holes of about 4 mm diameter. The perpendicular threads of the net are pressed together, so the material looks two-layered. This material costs about $56 (45 €) or $2.3 (1.8 €) per square meter.

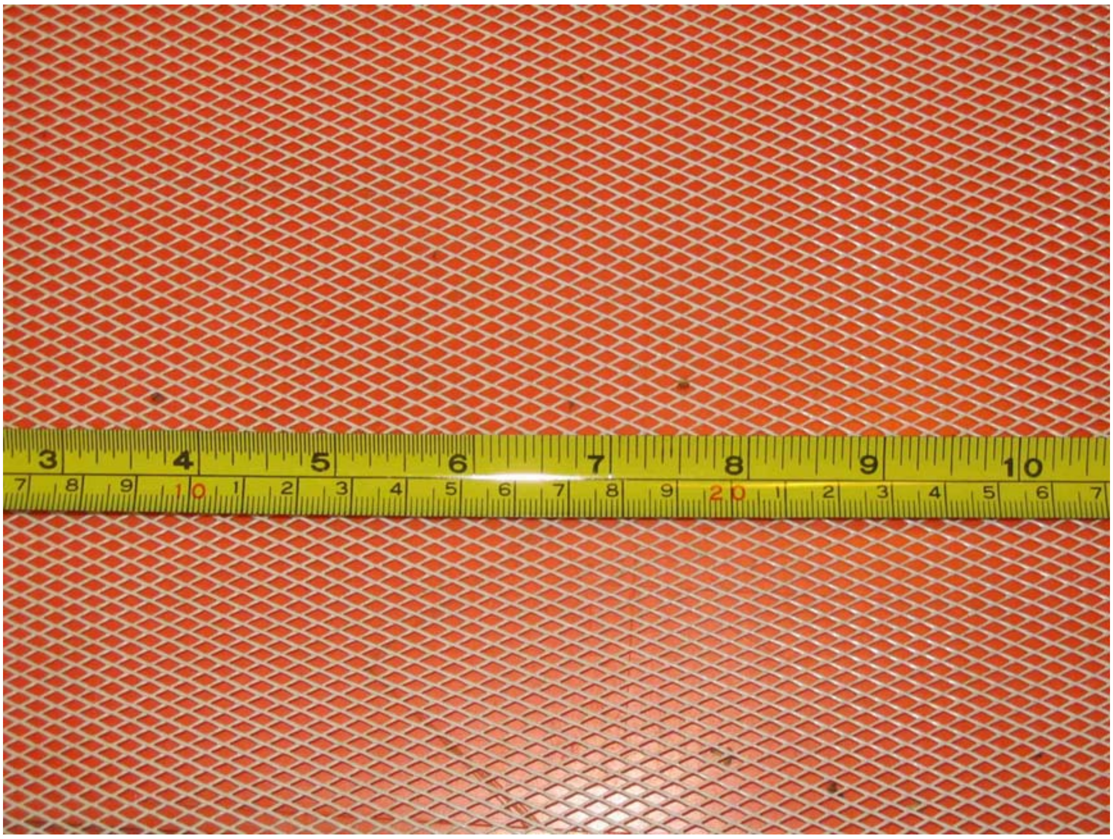

Figure 15. Plastic greenhouse net.

The seventh material is a dark grey aluminium mosquito net covered with a thin paint layer. Aluminium net has a hole diameter of 1.2 mm. The material is composed of extremely fine woven aluminium threads. This material costs about $1038 (830 €) or $41.5 (33.2 €) per square meter.

Figure 16. Aluminium mosquito net.

The eighth and last tested material is a mist eliminator pad. The chosen mist eliminator, by Kimre, is made of polypropylene. The material has been described as ladder-like or honeycomb-like and is comprised of three-dimensionally interlocked plastic monofilaments. Style 4/96 was used in the tests. The price of the material was $4400 (3520 €) or $176 (141 €) per square meter. Fog mesh materials and their testing are discussed in Publications III, IV, and VI.

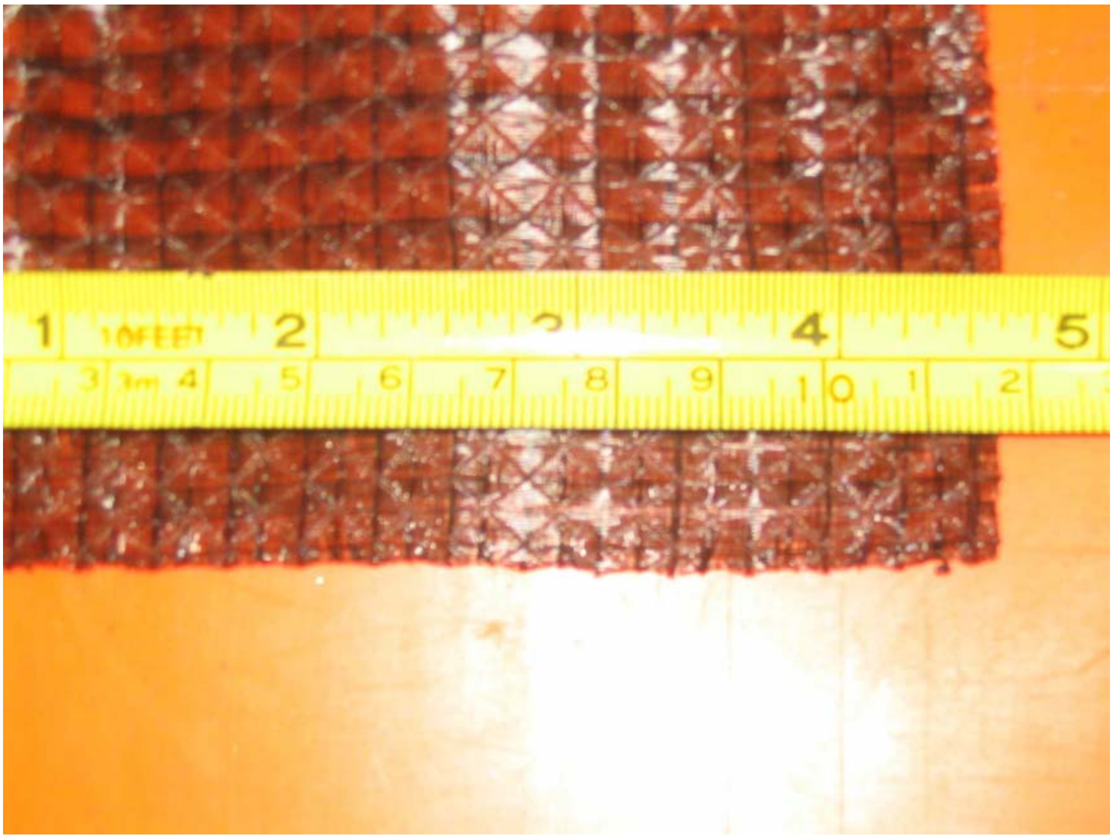

Figure 17. Mist eliminator.

4.4.2 Mesh tests

In the first mesh evaluation, four materials, namely grey mosquito net, white mosquito net, plant cover net, and filter fabric G3 were tested at the Pyhäsalmi Mine. Only one of these materials, filter fabric G3 and three others, namely Bidim S02, plastic greenhouse net and aluminium mosquito net were subsequently tested at the Orivesi Mine in the search for optimal mesh characteristics. The eighth material, mist eliminator, was tested in both of these mines. Combinations of two materials were also tested at both the Pyhäsalmi Mine and at the Orivesi Mine. The material combination tested at the Pyhäsalmi Mine consisted of the mist eliminator and the grey mosquito net. The material combination tested at the Orivesi Mine had again the mist eliminator but this time with Bidim S02. With both material combinations the mist eliminator fabric was placed upstream of the second fabric.

At the Pyhäsalmi Mine, testing of the first four materials took two days. Two materials and the baseline were tested during the first day and the last two material tests were performed during the second day of testing.

The results varied depending on the mesh material, as expected. Unfortunately the fog situation also varied significantly during the measurements. Fog moved in clouds as pulses through the test site. Sometimes there was almost no fog at all and at its most severe condition the fog thickness was only considered moderate. At no time during the tests was fog observed to be thick. The quality of the airflow at the test site was inconsistent with slight variations in both air velocity and relative humidity. This was taken into account in result evaluation.

The baseline measurements gave a good basis for result comparison. The biggest difference between the upstream and downstream measurements was observed in the air velocity value. This resulted from a smaller cross-sectional area of the tunnel upstream of the mesh frame. The particle concentration as well as the relative humidity were also slightly higher upstream of the frame. This shows that in the test site fog may start forming or observed fog gets slightly thicker. The temperature upstream slightly decreased as expected.

The first material, grey plastic covered metallic mosquito net, was found to be extremely wet even if there was not much fog at the test site at the time of the measurements. Thin water streams were running downwards on the net. During the measurements with this fog mesh the measured air velocities were slightly higher than the baseline measurements. This air velocity pulse carried a lot of particles with it. Over the mesh the air velocity decreased only slightly. A decrease in relative humidity was noticeable. The measured particle concentration also decreased considerably.

With the second material, white plastic mosquito net, all measured values were slightly decreased in comparison with the baseline readings. At the time of measurements there was some fog, but not much. The mesh fabric was relatively dry after the 30-minute waiting period and throughout the measurements.

The woven plastic plant cover net was wet after the waiting period and lowered the relative humidity a considerably more than the white, thin plastic mosquito net. The temperature was the only value that did not change over the mesh like all the other values, which decreased somewhat.

Filter fabric was the only one of the materials which caused notable air-rerouting as the air velocity values dropped considerably. The decrease upstream of the mesh was as much as 50 %. Also it seemed that most of the particles were carried through the other route. Temperature stayed stable over the mesh. The most remarkable change in relative humidity was achieved with this material. The fabric was completely wet already before the ending of the 30–minute waiting period. Water did not, however, fall or run down, but seemed to get collected in the fabric making it extremely heavy and difficult to operate.

All tested fog meshes worked to decrease humidity and particle concentration as expected and planned. Temperatures either stayed the same over the mesh or changed only slightly. Measurement results are presented in Figures 18 and 19, and in Appendix C.

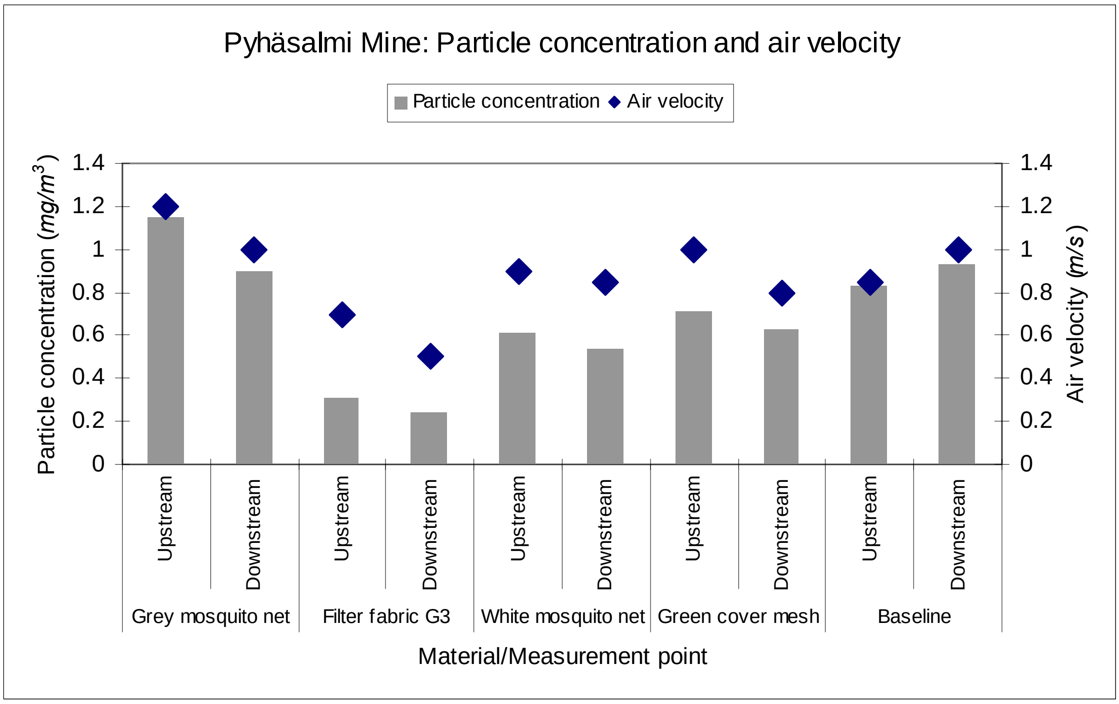

Figure 18. Particle concentration and air velocity of the first mesh test set at the Pyhäsalmi Mine.

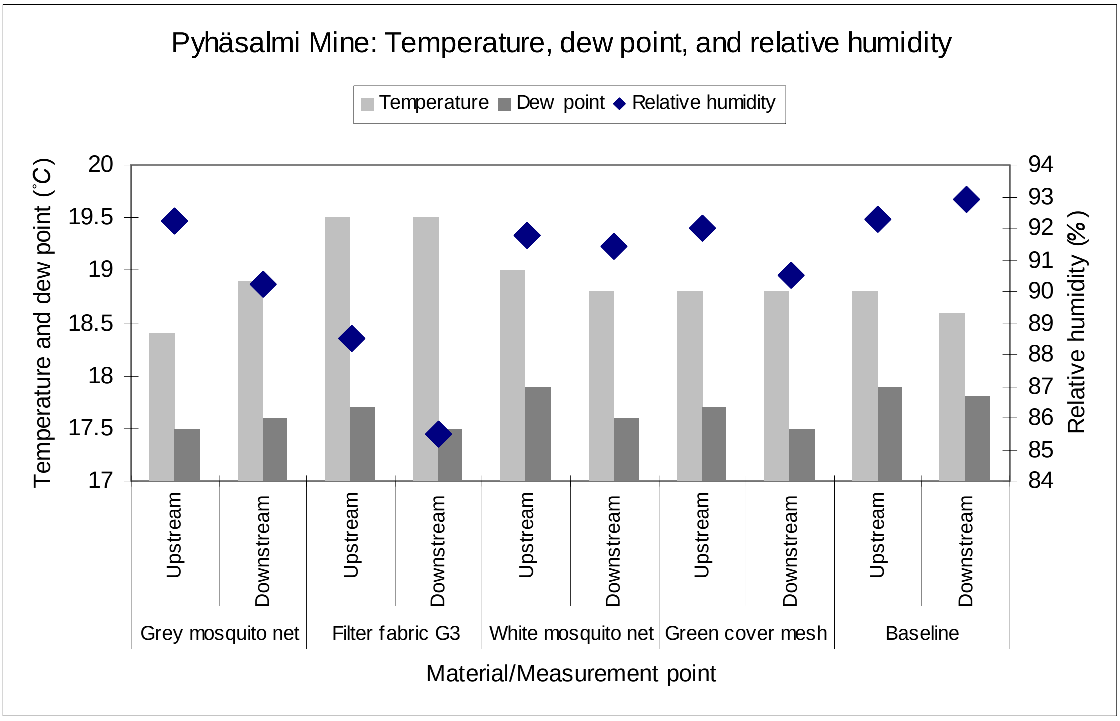

Figure 19. Temperature, dew point, and relative humidity of the first mesh test set at the Pyhäsalmi Mine.

The second set of tests evaluating the mesh combination also took two days to perform. Three tests were performed on the first day. The mist eliminator, the combination of the mist eliminator and the grey mosquito net as well as the baseline measurements were done. The only test left for the second day was the one with a grey mosquito net.

The baseline values showed that particle concentrations and psychrometric conditions obtained from the Pyhäsalmi Mine during the second set of tests were comparable with the previous results. The only value that had changed dramatically since the first test set was the air velocity. This was caused by changed exhaust fan settings, which resulted in increased airflow in the decline. The baseline was recorded first, so the slightly lower relative humidity than with any of the meshes is explained by this. Also, the baseline values had highest variations of relative humidity and particle concentration.

The performance of the grey mosquito net was of the same order in both trials. In the previous tests the measured relative humidity decrease was 2 %, while a value of 1.9 % was measured during the second trial. The decrease of relative humidity by the mist eliminator was about 0.8 %, which was, unfortunately, much lower than expected. The combination of the mist eliminator and the mosquito net resulted in worse performance than of the mosquito net by itself, together they only showed slightly over a 1 % relative humidity decrease, which was unexpected. On the other hand, the combination worked better than the mist eliminator alone. The averages of the results are shown in Figures 20-22 with calculated standard deviations as error bars. The complete measurement result set, averages and variances are presented in Appendix D.

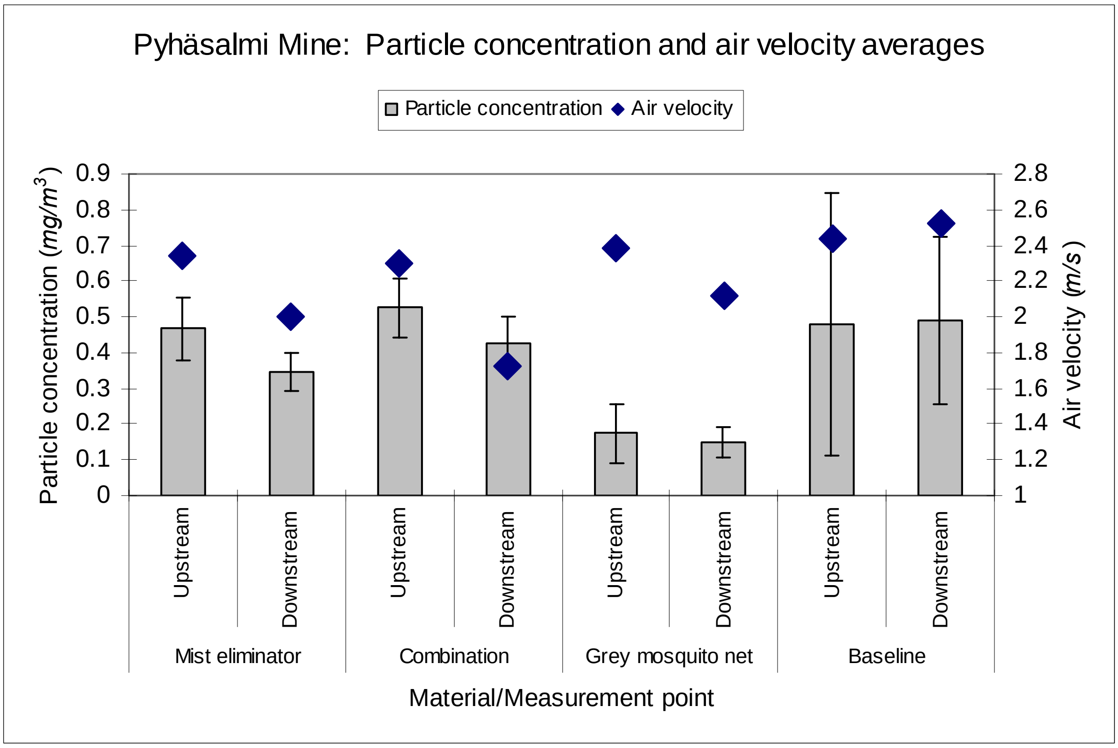

Figure 20. Particle concentration and air velocity averages of the second mesh tests at the Pyhäsalmi Mine.

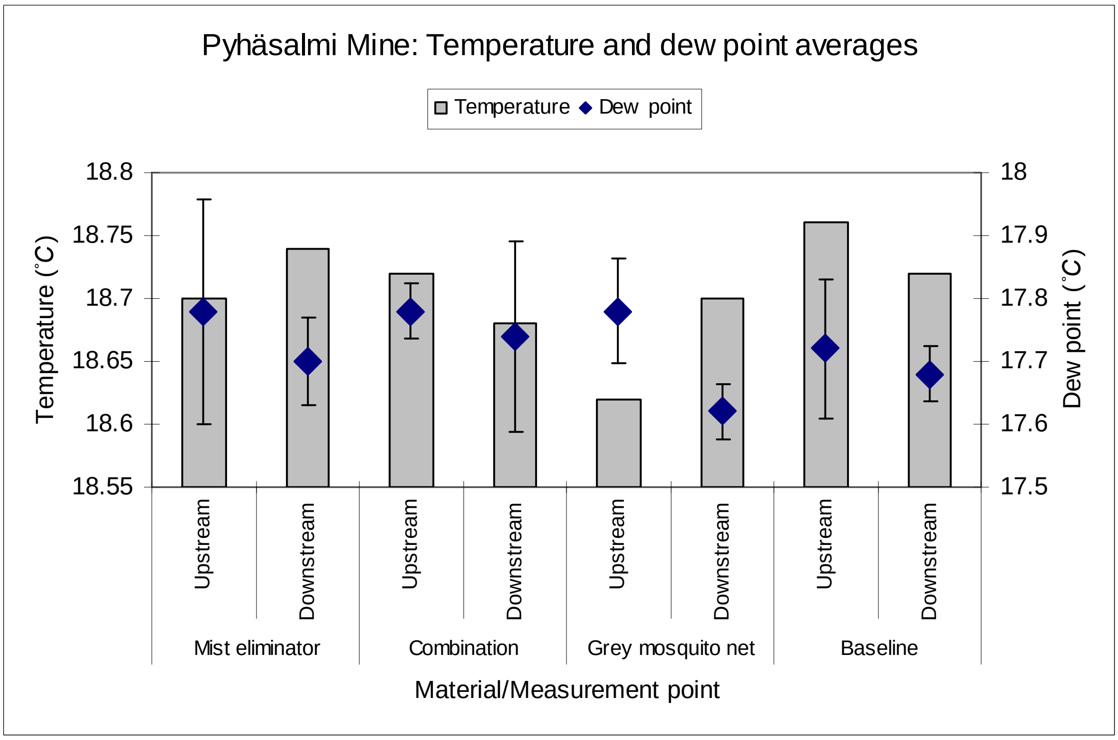

Figure 21. Temperature and dew point averages of the second mesh tests at the Pyhäsalmi Mine.

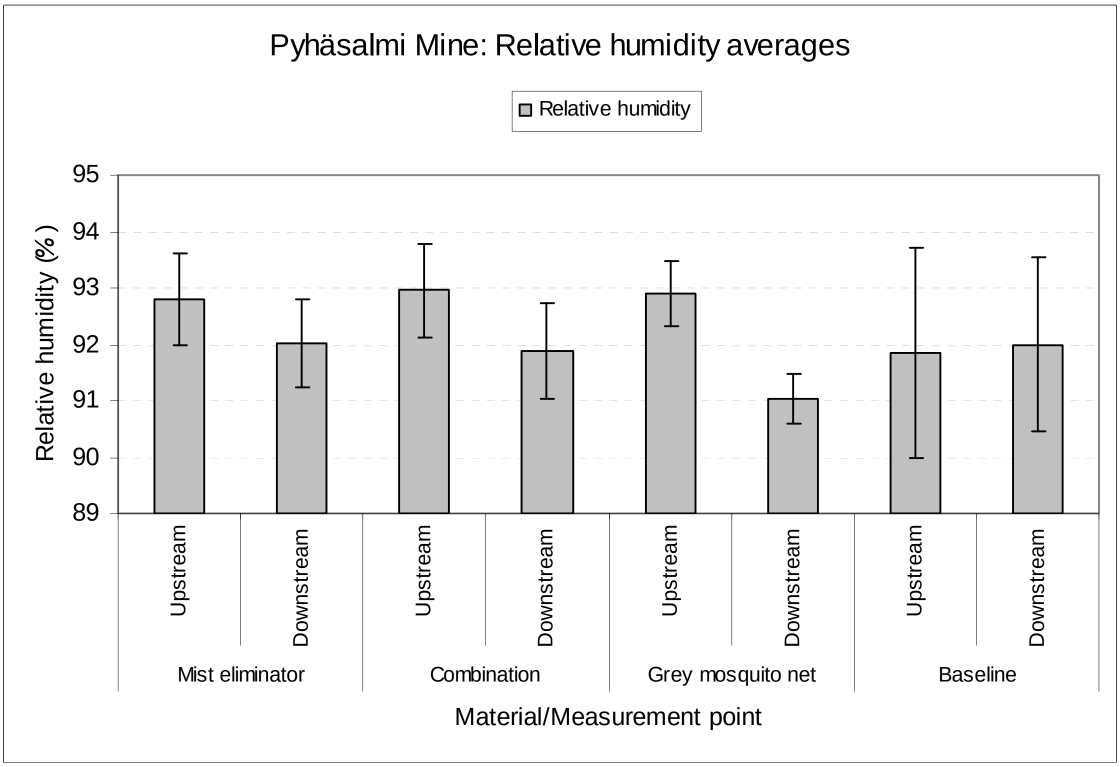

Figure 22. Relative humidity averages of the second mesh tests at the Pyhäsalmi Mine.

At the Orivesi Mine the first tests were performed during two days. In each day, two materials were tested as well as the baseline. The fog was uniform and its thickness was moderate. The largest fog droplets were visible with the naked eye. Noticeable changes were not observed during the tests. The results of the first tests at the Orivesi Mine are presented in Figures 23-26 and in Appendix C.

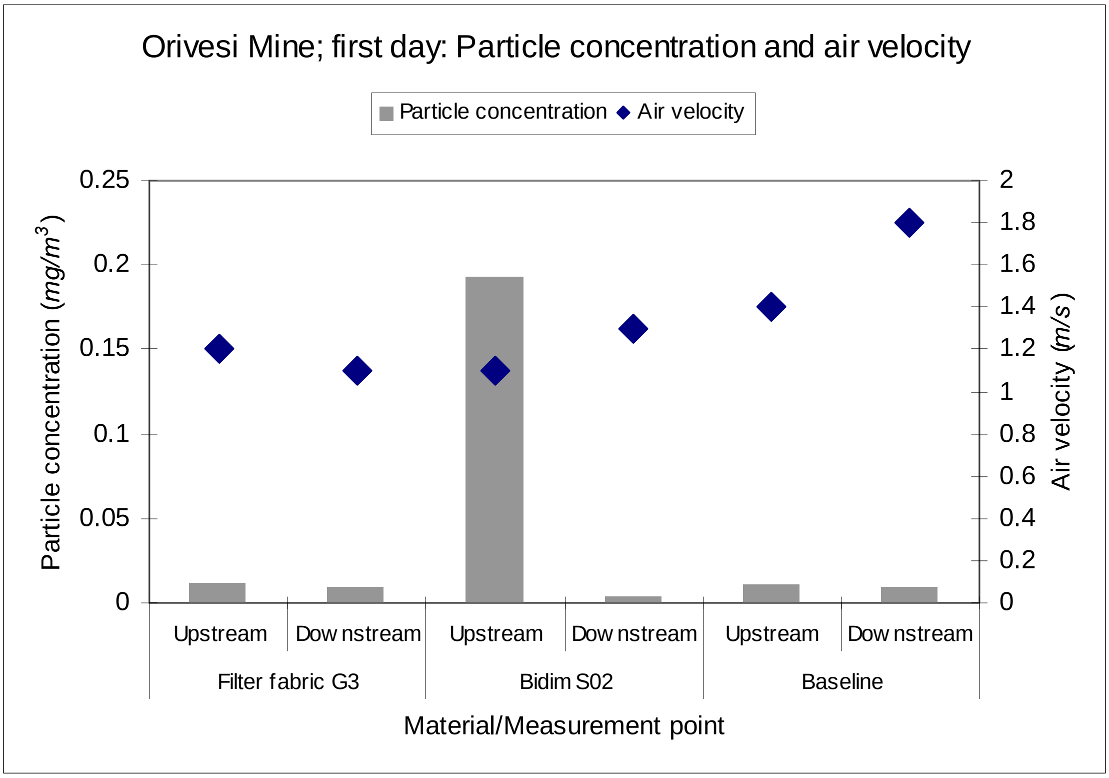

Figure 23. Particle concentration and air velocity of the first mesh test day at the Orivesi Mine.

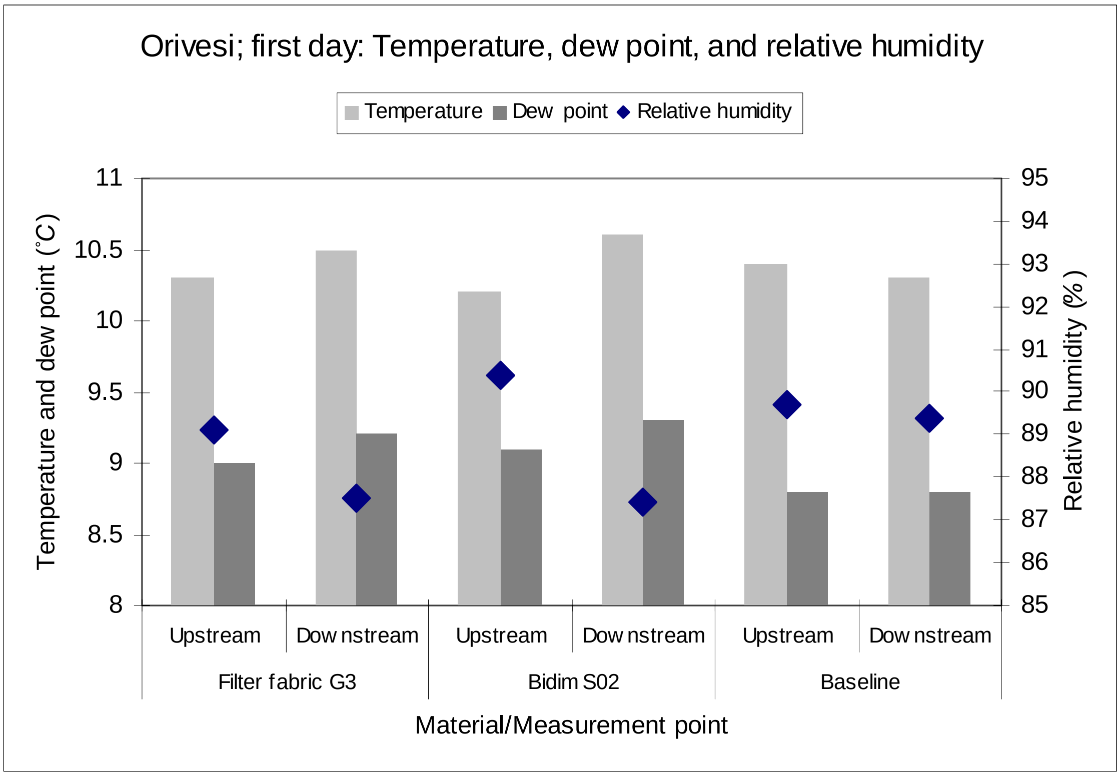

Figure 24. Temperature, dew point, and relative humidity of the first mesh test day at the Orivesi Mine.

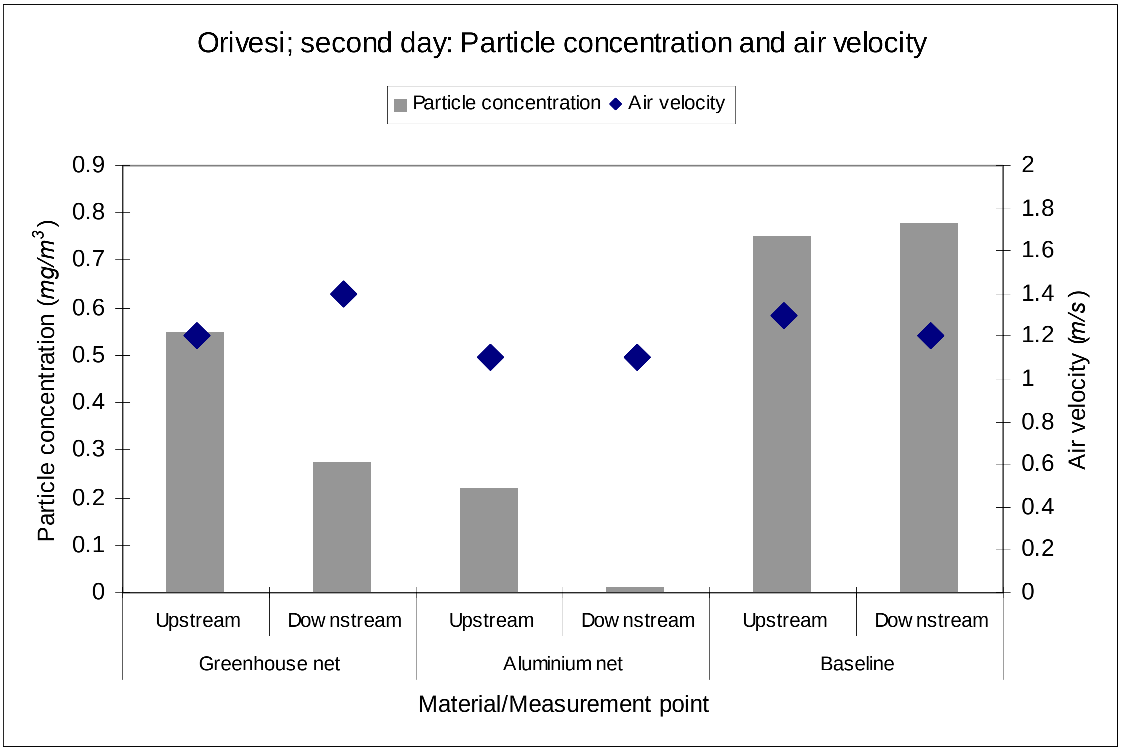

Figure 25. Particle concentration and air velocity of the second mesh test day at the Orivesi Mine.

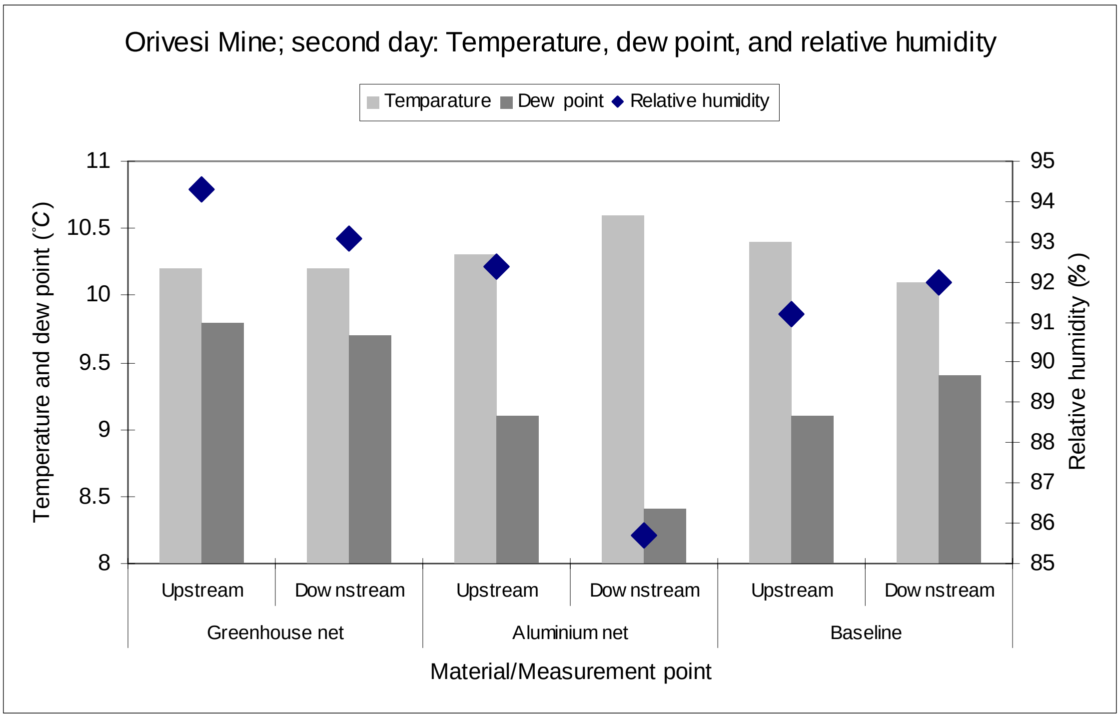

Figure 26. Temperature, dew point, and relative humidity of the second mesh test day at the Orivesi Mine.

Filter fabric G3 behaved as at Pyhäsalmi. It collected a lot of moisture, but it soon became heavy and saturated with water. Air velocity decreased, especially upstream of the mesh. Air temperature and dew point temperature were quite stable. As there were few particles in the air, almost no change was observed in particle concentration.

Fibrous filter fabric Bidim S02 lowered relative humidity noticeably, as much as 3 %. Air temperature and dew point temperature remained quite stable across the mesh. Air velocity decreased somewhat, but the downstream values were higher than with the filter fabric G3. Bidim S02 gathered a lot of moisture and water was observed to trickle down the material.

The white plastic greenhouse mesh decreased the particle concentration quite well, but otherwise it was considered to be the worst material tested yet for fog removal purposes. It actually collected droplets on both sides of the mesh and inside mesh holes as well. This caused the air flowing through the mesh to actually gain moisture and caused a thickening of the fog all around the mesh. None of the water drained off of this mesh. The measured relative humidity values were higher than without a mesh and also the dew point temperature rose.

Installing the aluminium mosquito net resulted in the best fog removal values. The decrease in relative humidity was 6.7 % and a change in dew point temperature was also noticeable. Water drainage was good, as it flowed down the net in streams. The aluminium mesh also collected a lot of particles. With this material a change in fog thickness was observed downstream, where the fog became lighter.

The second set of tests was performed in one day, during which the baseline was measured, both materials were tested individually, and the material combination was also tested. The measurements were started with the baseline in the morning, so the fogginess was expected to increase during the day with operation.

At the Orivesi Mine air velocity had increased at the test site since the previous tests. With the operation now active, more fans were now turned on in the mine, resulting in higher air velocities. Temperatures and dew points were higher too because of the operation as well as the warm weather outside. The relative humidity compares well with the prior results.

Obtained mesh and mesh combination results show the relative humidity consistently decreasing with each mesh and mesh combination tested. All materials unfortunately also decreased the air velocity notably.

It can be seen that fibrous filter fabric Bidim S02, which performed very well in previous tests with a 3 % decrease in relative humidity, only reached about 1 % decrease in this trial. The maximum particle value obtained was almost twice as high as in the previous tests. This increase in particle concentration must have caused a decrease in the average fog droplet size, thus decreasing the efficiency of the mesh.

The mist eliminator fabric decreased the relative humidity by about 0.8 %. However, it affected the dew point noticeably.

The mesh combination resulted in a visibly decreased fog thickness. Neither of the two materials of the combination used individually could attain this by themselves. In this case the combination was the most efficient with a relative humidity decrease of about 1.2 %. It did not, however, reach a decrease similar to the sum of the single meshes that would have been 1.6 %. Reaching this value was not expected, as decreasing the original value is bound to change the situation so that a slightly lower efficiency is to be expected. Also, the mesh combination had a distinct effect on the dew point. The averages of the results are shown in Figures 27-29. The variances and standard deviations were calculated and the standard deviations of the most important parameters are given as an error estimation for each result. All measurement values, averages, and variances are shown in Appendix D.

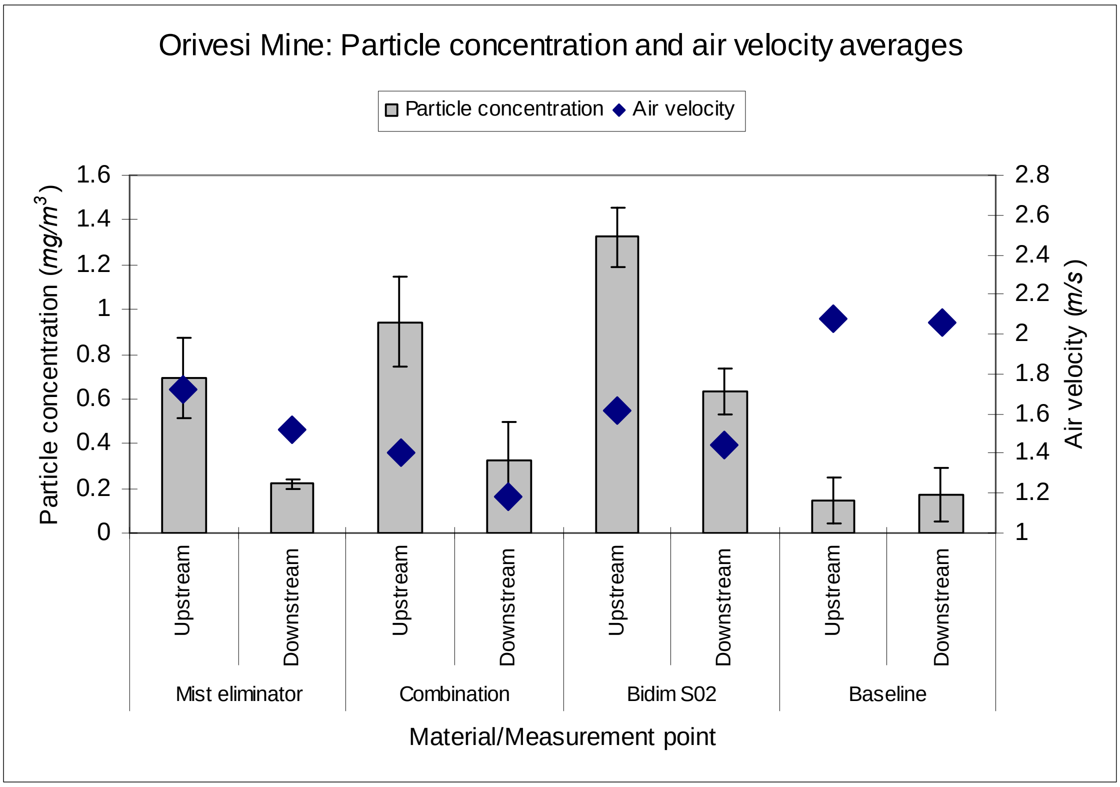

Figure 27. Particle concentration and air velocity of the second mesh test set at the Orivesi Mine.

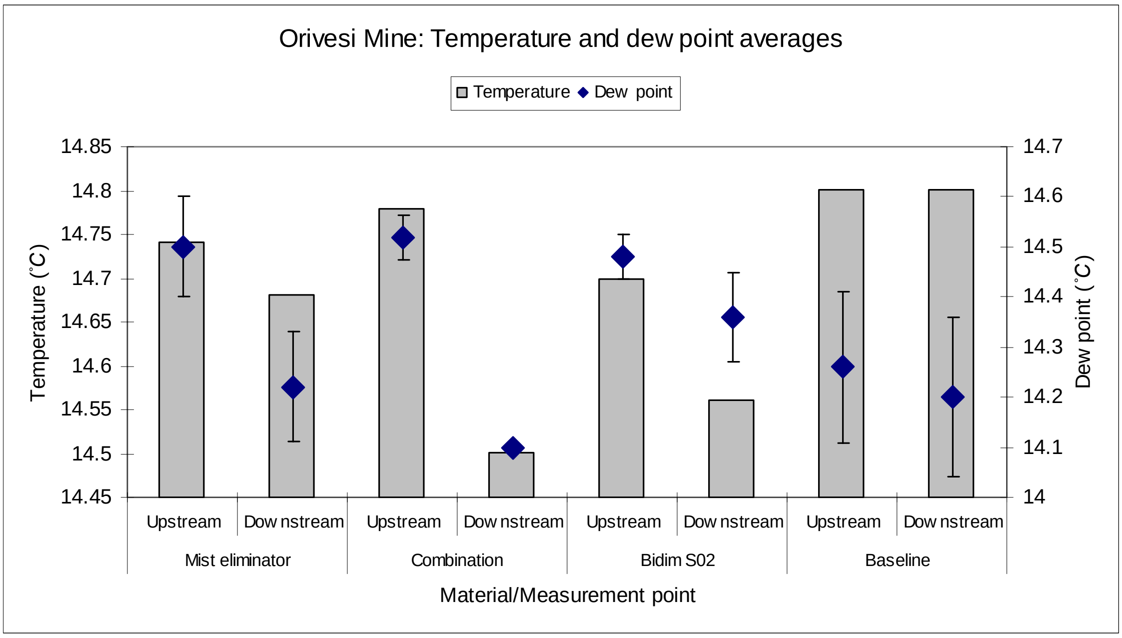

Figure 28. Temperature and dew point of the second mesh test set at the Orivesi Mine.

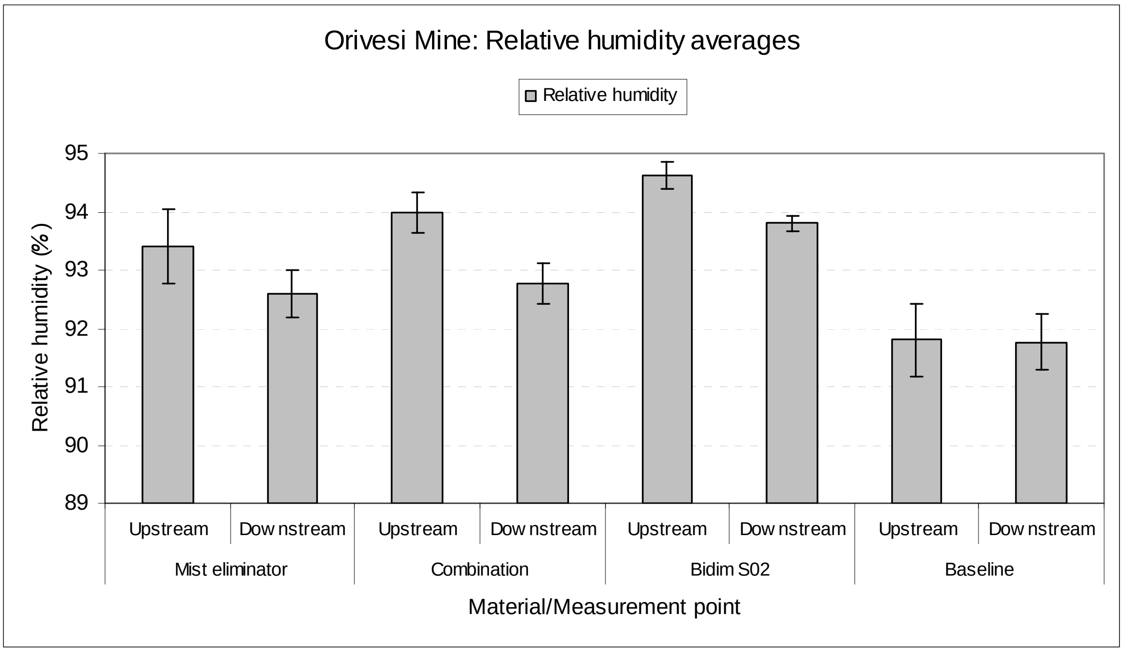

Figure 29. Relative humidity of the second mesh test set at the Orivesi Mine.

5 Result analysis

5.1 Interviews

From the interviews it can be perceived that fogging problems are common experiences in mines, especially in sub-arctic regions. The problems are typically solved individually, depending on the case. In some situations the chosen fog removal method is based on a psychrometric study, but also trial and error is quite common practice.

The most typical area of fog occurrence is the decline. In all three Finnish mines fog was observed in the decline. In four out of seven international cases fog formed in the decline. Every one of these mines is located in a sub-arctic region. The severity of the fog problem depends on several variables and is thus not easy to solve. In all these cases the decline is used as an exhaust.

Successful fog removal methods included ventilation system changes by changing airflow balances and reversing airflow, demisting, heating, and fan installation. The fan installation was located at the entrance of the mine, which has to be taken into account in the method success evaluation.

The international heater installation case study concerning “Anon 2 Mine” is not the only one with acceptable fog removal results the author has heard of. Anonymous information concerning three other Canadian mines in which heating has been chosen as a fog removal method was also received from two informants. Unfortunately, permission to present these as case studies was denied. However, it can be mentioned that heating decreased notably the fogging problems, which occurred in the declines of these mines.

5.2 Basic study

The results show that the fogginess compares well with high measured relative humidity and particle concentration values. Air velocity, on the other hand, does not seem to have much of an effect on fogging. Based on the theory, fogginess should decrease with increasing air velocity, but that does not seem to be true. Especially the results from Louhi Mine give almost the opposite impression. Also the second measurement set taken at the Pyhäsalmi Mine points to the same conclusion. As the results from the Orivesi Mine show a different situation, it can be stated that air velocity is not a critical value when considering fog removal in the declines.

Air velocity of 0.25 m/s is not enough in the ramps of the surveyed mines to scatter the fog, or to prohibit fogging. Air velocities as high as 2 m/s were measured in areas filled with thick fog. The measurement results obtained from the Orivesi mine show that with a temperature dew point spread of only about 1 °C, no fog is observed with air velocities above 2.5 m/s. In this situation, the air velocity in the ramp is nevertheless so high that pumping effect caused by moving vehicles becomes problematic.

From the measurement results it can be seen that a difference of about 3 °C between the measured temperature and the dew point temperature is enough to prohibit fog formation in the climate of these mines. If this is true also in other underground mine climates, this temperature-dew point spread could be used as a guideline in determining the requirements for fog removal devices. More research to confirm this would be beneficial. Achieving this temperature-dew point spread in a decline of an underground mine depends on many site specific characteristics of which the most important is the airflow.

Highest particle concentrations were measured throughout the basic study in the foggy areas of the declines in all three mines. Fog needs condensation nuclei to form so the particle concentration values observed in the foggy areas were expected to be high. An interesting observation is, however, that in many cases particle concentration values are much higher in the foggy areas than in the areas with no fogging, even without the influence of traffic or any other particle sources in many cases. This indicates that fog actually restricts the settling of particles and particle movement to the areas with unfavourable conditions for fog formation and that way prevents fog from scattering. At least the studied large and giant condensation nuclei tend to stay in the air of the foggy area. This way fog there continues to form easily, even if there are minor changes in other influencing parameters.

5.3 Fog removal method comparison

5.3.1 Increasing air velocity

Increasing air velocity by rerouting air gave poor results in each one of the three mines. Everywhere in the foggy areas the measured air velocity was above 0.25 m/s, which should have been enough for fog removal. Actually, air velocity increased up to 1 m/s in most areas of the declines in all mines. In some places 2 m/s was reached and thick fog was still observed.

Best air rerouting results were obtained accidentally at the Pyhäsalmi Mine as most of the humid air escaped from the decline to the old workings and thus took the fog away from the ramp entirely. Unfortunately the air velocity in the decline dropped close to zero, which was not appreciated. The air re-entered the decline some hundred meters above with lower humidity. It was concluded that either the filling of the old workings was adsorbent or water condensed on the cool surfaces of the filling material and rock surfaces while working its way through.

Increasing air velocity by an additional fan gave interesting results at the Louhi Mine. The effect on fogging was easy to notice close to the fan installation site, especially upwards the decline. The fog disappeared on level +110 m and got lighter in the nearby measurement points in both directions. Also the air velocity increased locally. Unfortunately this positive effect did not cover the whole decline.

It can be seen from the received results that the humidity decreasing effect as well as the increase in temperature by the fan corresponded exactly with the heating capacity of the fan. The calculated temperature of the united airflows of 14 m^3/s from the fan and of 46.8 m^3/s from lower levels on level +130 m was 8.376 ˚C when the measured value was 8.4 ˚C. The correlation was similar for the relative humidity. To define the correspondence for the humidity the Mollier diagram was used. It is shown in Appendix E.

The effects of air mass mixing and promoting evaporation from fog droplets could not be specified or proved to result from the increased air velocity by the additional fan. The measured changes were caused by the dehumidifying effect of the fan motor acting as a heater.

The effect of the fan on the airflow was presented in Table 3. It can be seen that close to the fan, with the fan operating and locally removing the fog, decreased particle concentrations were measured.

The most positive results concerning increasing air velocity were received from international interviews. At the Ekati Diamond Mine good fog removal results were received as the air velocity increased. Fog removal was achieved by slightly decreasing inflow of cold air to the decline and considerably increasing inflow of a warm air to the decline. As the total flow in the decline increased air velocity in the previously fogged area increased. In this case, however, fog removal is more likely based on the change of psychrometric properties of the airmass than on the air velocity change.

In Kiruna Mine the fogging problem is concentrated at the mine entrance where warm air from the decline collides with the cold surface air in the winter. 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 mine personnel say that the fans are probably only mixing the air rather than moving it. This type of air mixing at the entrance was also mentioned to clear the air from fog at the Louhi Mine.

During summer, fogging occurs in the decline at the Kiruna Mine. Vehicles moving and mixing the air cause the fog to disappear. Vehicle movement typically causes momentary local changes. Especially in areas where only a slight change in psychrometric parameters is enough to dissolve the fog, heating and air mixing effect of a vehicle may prevent fog formation or result in fog removal.

Also, taking more fresh air to the decline at different levels is used successfully for fog removal in these occasions at the Kiruna Mine. In this case the same applies as in the case of Ekati Diamond Mine. Fresh air carries less humidity and particles, so changing the air mass balance to less humid and less dusty results in fog removal.

5.3.2 Heating

Heating tested at the Louhi Mine enhanced the humidity decreasing effect of the additional fan and increased temperatures all along the decline. The installation location of the heaters was ideal, as the relative humidity decreased in every measurement point. Unfortunately the target value was not reached. The reason for failure to remove fog completely was that the calculations for the heater dimensioning were very basic and did not take into account all factors that affect the temperature. For example leakages, rock thermal conductivity and virgin rock temperature were not taken into account at all in any of the formulas. As all these effectively decrease the temperature, it is easy to understand why the heater capacity was not sufficient.

The worst leakages were observed between the measurement points of 40 m and 70 m, where the smallest decrease of relative humidity was measured. Also, other measurement results correspond well with the observations.

Higher particle concentration values without heating than with heating were observed in the decline between levels +110 m and +206 m. The occurrence of high particle concentration in foggy areas compares well with the results obtained from the basic tests. The results of the basic tests showed the highest particle concentrations in the foggy areas. As heating decreased fogginess, the largest particles acting as condensation nuclei were able to settle thus decreasing the measured airborne particle concentration.

5.4 Fog meshes

5.4.1 General

The twelve fog mesh tests, of which two were mesh combinations, gave interesting results. Eleven of the twelve tests resulted in decreased humidity and particle concentration. In one test, a negative effect on fogging was observed.

The meshes in which at least one of the components was a metal generally had the best performance. The best results obtained were with the aluminium mosquito net at the Orivesi Mine. The best result from the tests at the Pyhäsalmi Mine were with the grey mosquito net, which is also coated aluminium.

These good results obtained with aluminium mesh were considered to be a consequence of the thermal conductivity of the material. Being a metal as compared to some of the other materials, the thermal conductivity of aluminium is high. The high thermal conductivity of the aluminium mesh allows the fabric to experience quick, small temperature changes. With a turbulent airflow and a moderate air velocity lower temperature pulses affect the mesh. The cooler the surface of the mesh relative to the environment the more moisture it is able to collect. These meshes also tended to show significant water run off.

An important result was also observed from the testing of the white plastic greenhouse mesh. This material appeared to be unsuitable, resulting in an even worse fogging situation than originally observed. This shows that not just theoretical knowledge is enough, but on-site testing, and careful planning are of extreme importance in developing fog removal methods.

The temperature difference between dew point temperature and air temperature was about 1 ˚C without a mesh during the first tests at the Orivesi Mine. This was also the case with both filter fabric materials. It was observed that with white greenhouse net this difference decreased to less than 0.5 ˚C. In the case of the aluminium net, the difference increased to more than 2 ˚C. The previously mentioned 3 ˚C temperature-dew point spread in fog free areas measured during basic tests was not reached, but with the aluminium net fog thickness reduced visibly.

In the mesh tests air re-routing due to an increased resistance to airflow was expected. However, it was only significant at the Pyhäsalmi Mine with only one of the tested materials, the filter fabric G3. Although this could be overcome, this material was also impractical because of its water retention characteristics. Making it difficult to manipulate consequently, it can be ruled out as a fog removal mesh underground.

The mist eliminator pad did not perform as well as expected based on the theoretical values. This was partly due to the low air velocities and partly due to the small fog droplet size. One of the reasons is also the light liquid loading that has caused liquid holdup on the polypropylene meshes and thus inefficiency in other applications as well (McFarland and Ortiz, 1984).

The performance of the meshes does not correlate with the mesh prices. The most expensive mesh, the mist eliminator, did not give good enough results to justify the high cost. The aluminium net gave better results out of the two quite expensive metal meshes than the grey mosquito net despite the lower price. Although, the best results were achieved with the aluminium net and mist eliminator combination. White mosquito net and filter fabric G3 were in the same average price category, but unfortunately neither of them performed well. The performance of plant cover net, which had a very low price, was mediocre. The third cheapest greenhouse net is completely unsuitable for fog removal. On the other hand, the second best performer at the Orivesi Mine, fibrous filter fabric Bidim S02, was the cheapest of the materials. The price-performance ratio of Bidim S02 was the best.

Based on the experiences with mesh installations a system that could be lifted away from the traffic, like some air curtain systems, would be beneficial. Also, even if this method could not be used in the decline because of problems with traffic, maybe it could be used in levels with minimal traffic. Another possible way to improve the performance of the mesh method without traffic problems could be a close-to-wall mesh installation. In such a system a layered mesh with a large effective area could be attached to the rock walls. Unfortunately, the efficiency could be affected by size of the open area in the middle of the tunnel.

5.4.2 Evaluation based on calculations and simulations

The measured air velocity values show that the materials cause different resistances. Some materials changed the air velocity more than others. In lack of pressure data another method of analysing the resistances was applied. Ventilation simulation models were used in order to study the resistances of the materials in more detail.

A model of the ventilation system of the Orivesi Mine was created in 2002. At that time the Orivesi Mine was in full operation. The ventilation model is discussed in detail in Martikainen (2002). This model was updated to correspond to the standby situation found at the time of the first measurements. The model was again modified to represent the situation of the operation during the second measurement set.

After updating the model for the standby situation fixed resistances were tested on the location of the mesh. The approximate resistances of the materials were found by iteration. Iteration was continued until the added resistance resulted in the measured air velocity values. The resistances of the airway with the frames only as well as without a frame were also calculated to evaluate the resistance effect of the frame. For easy comparison some standard resistance values of the simulation program are also given. These are presented in Table 5. The estimated resistances of meshes as well as airflow information and pressure loss values are given in Table 6.

Table 5. Resistances of the frames and constants of the simulation program.

<table>
<tr><th colspan="4">Resistances (Ns²/m⁸)</th><th colspan="2">Constants</th></tr>
<tr><th colspan="2">Comparison values</th><th colspan="2">Airway resistances without mesh</th><th colspan="2">Modeling constants</th></tr>
<tr><td>Muck pile</td><td>1</td><td>Frame 1</td><td>0.0002</td><td>k (kg/m³)</td><td>0.01</td></tr>
<tr><td>Flaps</td><td>2</td><td>Frame 2</td><td>0.0003</td><td>Shock as equivalent length (m)</td><td>5</td></tr>
<tr><td>Brattice</td><td>3</td><td rowspan="2">No frame</td><td rowspan="2">0.0001</td><td rowspan="2">Length of airway (m)</td><td rowspan="2">1</td></tr>
<tr><td>Steel door</td><td>10</td></tr>
</table>

Table 6. Resistance, airflow, and pressure loss estimates of the first mesh measurement set at the Orivesi Mine based on the simulation model.

Material	Mesh resistances	Airflows	Airflow reduction	Pressure loss
	Ns^2/m^8	*m^3/s*	*%*	*Pa*
Baseline		30.4		
Filter fabric G3	0.30	26.9	12	217
Bidim S02	0.19	29.1	4	161
Baseline		26.7		
Greenhouse net	0.03	26.1	2	21
Aluminium net	0.12	24.9	7	74

In the model the exhaust air balance changes slightly because of the added resistance of the mesh. A fraction of the air moves from the incline to the exhaust air shafts because of the increased resistance with every mesh. In case of filter fabric G3 with the highest resistance the amount of air to move over to the shafts is below 5 m^3/s, which is less than 15 % of the airflow in the decline. With other meshes even lower airflow reductions were observed.

The model edited to represent operation also gave good results concerning the resistances of meshes and mesh combinations. The resistance estimates compared well with the results from the standby model. In this case the effect of the frame was not studied as the resistances in the standby model were negligible in comparison with the mesh resistances. On the other hand, in this case the air rerouting was more prominent than observed without simulation. With the highest resistance, resistance of the combination, almost 40 % of the airflow moved to the shafts. Even with the mist eliminator, which had the lowest resistance, the amount of air moving to the shafts was almost 25 % of the total airflow of the decline. The simulated resistances, pressure losses, airflows and reductions are shown in Table 7.

Table 7. Resistance, airflow, and pressure loss estimates of the second mesh measurement set at the Orivesi Mine based on the simulation model.

Material	Mesh resistances	Airflows	Airflow reduction	Pressure loss
	Ns^2/m^8	*m^3/s*	*%*	*Pa*
Baseline		51		
Mist eliminator	0.12	39	24	183
Combination	0.30	32	37	301
Bidim S02	0.17	36	29	225

The model created for the Pyhäsalmi Mine in year 2003 was first updated to represent the situation of the first measurement set and then again to represent the situation at the time of the second measurements. The notable increase in the air velocity naturally signified also a considerable increase of airflow in the decline. The estimated resistances compared well with the Orivesi Mine model results. Also airflow reduction percentages were well in line with results received from the models of the Orivesi Mine. The results received from both simulation models with all mesh materials are shown in Table 8.

Table 8. Resistance, airflow, and pressure loss estimates of the mesh measurements at the Pyhäsalmi Mine based on the simulation model.

Material	Mesh resistances	Airflows	Airflow reduction	Pressure loss
	Ns^2/m^8	*m^3/s*	*%*	*Pa*
Baseline		21.6		
Grey mosquito net	0.10	18.6	14	33
Filter fabric G3	0.28	14.5	32	59
White mosquito net	0.05	19.6	9	19
Plant cover net	0.07	19.1	12	26
Baseline		68.0		
Mist eliminator	0.22	50.6	26	564
Combination	0.59	43.8	36	1131
Bidim S02	0.16	52.5	23	442

Absolute humidity and water-air mixing ratios were calculated for both measurement set results based on the measurement results and pressure estimates obtained from the simulation models. The barometric pressure on level +164 m at the Orivesi Mine was 102.9 kPa and the barometric pressure on level +600 m at the Pyhäsalmi Mine was 108.5 kPa based on the simulation model. Stable pressure conditions were assumed for the calculations. The accuracy of the measurement results was enough to show changes also in these calculated values. The most remarkable change showing the fog removal effect of the meshes was received with the aluminium net. Absolute humidity and mixing ratios are presented in Tables 9-10. In the case of the second measurement sets the given values are averages of the five calculated values for each measurement point. Absolute humidity and mixing ratio values of aluminium net and mist eliminator-fibrous filter fabric Bidim S02 combination are underlined to highlight the results of these best performing systems.

Table 9. Calculated absolute humidity and mixing ratios for the first mesh measurement sets.

	Absolute humidity		**Mixing ratio**	
	g/m^3		*g/kg*	
Pyhäsalmi	upstream	downstream	upstream	downstream
Grey mosquito net	14.5	14.4	11.4	11.4
Filter fabric G3	14.9	14.4	11.8	11.3
White mosquito net	15.0	14.8	11.8	11.6
Plant cover net	14.9	14.6	11.7	11.5
Baseline	14.9	14.8	11.7	11.7
Orivesi, 1st day	upstream	downstream	upstream	downstream
Filter fabric G3	8.6	8.5	6.8	6.8
Bidim S02	8.6	8.5	6.9	6.8
Baseline	8.7	8.6	6.9	6.9
Orivesi, 2nd day	upstream	downstream	upstream	downstream
Greenhouse net	9.0	8.9	7.2	7.1
<u>Aluminium net</u>	<u>8.9</u>	<u>8.4</u>	<u>7.1</u>	<u>6.7</u>
Baseline	8.8	8.7	7.1	7.0

Table 10. Calculated absolute humidity and mixing ratio averages for the second mesh measurement sets.

	Absolute humidity		Mixing ratio	
	g/m^3		*g/kg*	
Pyhäsalmi	upstream	downstream	upstream	downstream
Mist eliminator	14.9	14.8	11.7	11.7
Combination	15.0	14.7	11.8	11.6
Grey mosquito net	14.8	14.6	11.7	11.5
Baseline	14.8	14.8	11.7	11.6
Orivesi	upstream	downstream	upstream	downstream
Mist eliminator	11.8	11.7	9.6	9.5
Combination	11.9	11.6	9.7	9.4
Bidim S02	12.0	11.7	9.8	9.6
Baseline	11.7	11.7	9.6	9.6

The overall performance of the materials was also evaluated with the help of relative ranking of results. The results were ranked based on the measured relative humidity decrease, calculated absolute humidity decrease and measured particle concentration decrease. Unfortunately usefulness of absolute humidity values is a bit questionable as many materials received the same values due to accuracy limitations. Tables 11-12 show the relative ranking of the results. Even if there is fluctuation in the performance of materials in relation to the ranking, superiority of the aluminium net is obvious. Other good performers were combination of mist eliminator and Bidim S02 and fibrous filter fabric Bidim S02 by itself. These were all tried out in operating mines. It must be kept in mind when looking at the humidity decreasing performance of the plant cover net, that it was only tested once, in a standby situation, in which larger droplets offer an easier situation for the net to perform well.

Table 11. Relative ranking of mesh test results by average relative humidity decrease.

Average relative humidity decrease	Average particle concentration decrease	Average decrease of calculated absolute humidity	Material
%	*mg/m^3*	*g/m^3*	
6.70	0.211	0.50	Aluminium net
2.30	0.036	0.30	Filter fabric G3
1.93	0.250	0.15	Grey mosquito net
1.91	0.439	0.20	Bidim S02
1.50	0.080	0.30	Plant cover net
1.22	0.622	0.30	Combination Orivesi
1.20	0.274	0.10	Greenhouse net
1.08	0.099	0.30	Combination Pyhäsalmi
0.79	0.298	0.10	Mist eliminator
0.40	0.070	0.20	White mosquito net

Table 12. Relative ranking of results by average absolute humidity decrease and average particle concentration decrease.

Average decrease of calculated absolute humidity	Material	Average particle concentration decrease	Material
g/m³		*mg/m³*	
0.50	Aluminium net	0.622	Combination Orivesi
0.30	Combination Pyhäsalmi	0.439	Bidim S02
0.30	Plant cover net	0.298	Mist eliminator
0.30	Combination Orivesi	0.274	Greenhouse net
0.30	Filter fabric G3	0.250	Grey mosquito net
0.20	Bidim S02	0.211	Aluminium net
0.20	White mosquito net	0.099	Combination Pyhäsalmi
0.15	Grey mosquito net	0.080	Plant cover net
0.10	Mist eliminator	0.070	White mosquito net
0.10	Greenhouse net	0.036	Filter fabric G3

If costs of the materials are also considered, Bidim S02 was the best of the cheap materials. On the other hand, the superior performance of aluminium net makes it worth the high price. Even if combinations gave quite good fog removal results, the cost of combinations are the highest by far, as more than one layer of material is required. Also, the resistances of the combinations were too high. The measured good humidity decreasing performance of filter fabric G3 is not enough to overcome the high resistance and also otherwise problematic behaviour.

The mesh method results were also evaluated by comparing the best of them to the best performing existing fog removal method based on the field studies, heating. Heating was tested at the Louhi Mine with an airflow of 46.8 m^3/s in the decline. The installed heater capacity, which was capable of decreasing fog thickness, was 94 kW. The measured decrease of relative humidity was 7.1 % on level +130 m close to the heater installation site. In the calculations no heat losses were taken into account and the required heating for warming up the air by 2 ˚C was a bit over 100 kW with two different calculation methods.

To enable easy comparison the calculation method for interior climate design presented with equations 4 and 5 was used. The equivalent theoretical heating capacity required to achieve similar results by heating instead of using the fog mesh was calculated for three mesh systems. The results obtained with three well performing mesh systems, the aluminium net, the fibrous filter fabric Bidim S02, and the combination tested at the Orivesi Mine were used for comparison calculations. The airflows in the decline were 26.7 m^3/s, 30.4 m^3/s, and 51.0 m^3/s, respectively. Heating capacities required to reach similar results to the mesh performances without taking any heat losses into account were 39.7 kW in case of the aluminium net, 21.6 kW in case of the fibrous filter fabric Bidim S02, and 19.7 kW in case of the mist eliminator-fibrous filter fabric combination.

5.5 Error evaluation

The unstable climate of underground mines is a probable cause of error. As the study has been performed in underground mines with changing air velocities, relative humidity, temperature, and particle concentrations, all measured values are susceptible to the error caused by the field research method. Evaluating this error is very difficult. On the other hand, this has been taken into account already in the measurement situation. For example all passing vehicles have been recorded in the result sheets and if air velocity pulses have been noticed, the measurements have been postponed until the pulse has passed the measurement location.

The measurement devices have a limited accuracy, which is prone to show as an error in the results. The accuracies and precision of the devices are discussed in the section with information about the used instrumentation. As the hygrometer assumes standard pressure for dew point values a systematic error realised in these results. However, this error does not affect the observed differences of dew point temperatures and thus does not endanger the authenticity of the conclusions. Even with the water lock the possibility of counting fog droplets as particles exists with DustTrak TSI 8520. Although as fog droplets form around particles acting as nuclei, this should not bring any error to the particle concentration measurement results.

Installation of a mesh is not without difficulties in an underground mine. In some cases mesh slices did not overlap enough to completely prevent airflow between them. Also the connection of the mesh fabric and the frame was not airtight with every mesh. Only in one case, at the Orivesi Mine with white greenhouse net, this may have caused enough error to show in the results.

In a research project there is always a risk of human error. In this case the project was carried out quite independently by a single researcher, so the probability for this kind of error is higher than in case of a group project, in which the results often go through everybody in the research team.

6 Conclusions

6.1 General

Unofficial information concerning problems caused by fog has been received from many mines. Fog slows down haulage speed affecting production because of the decreased visibility. Poor visibility has been observed to cause at least many close calls in mines and possibly even accidents. Also high particle concentrations in foggy areas are problematic. As fog prevents particle settlement, high concentration is a continuous health hazard in the foggy area.

Further research in this area would be beneficial for the mines struggling with fog problems. This study has been limited to exclude level fogging as well as Aitken nuclei. Particle concentration measurements were limited to the amount of particles acting as fog droplet nuclei in the airflow. No droplet size distribution information was recorded. Droplet size distribution study is the most important direction for future research.

The instrumentation used in the study was chosen based on the best possible performance and accuracy in difficult underground environments with high humidity and susceptibility to damage also taking into account the financial limitations. To achieve more accurate results different measurement devices may be considered. Also, in case of fog removal trials, a visibility sensor may be used for accurate visibility improvement results. Highest accuracies in particle concentration and particle size distribution measurements could most probably be achieved with methods based on gravimetric settlement or hydrodynamic chromatography or with more advanced light scattering and diffraction instruments. Highest accuracy of handheld devices measuring relative humidity and temperatures seems to be ±1 %. The selection is large with multiple manufacturers.

The test methodology was found to be quite good based on the received results, although some measurements were taken only once in each location. A series of measurements, like the second mesh measurement sets, are less prone to error, if they can be arranged without time or other such limitations found in underground mines impeding the research. In a highly automated mine a remotely controlled psychrometric and/or particle concentration measurement system installation collecting and sending data continuously could be considered. This would enable statistical analysis of results. In Finland the availability of these systems is still limited, but, for example, Vaisala Humicap® HMT360 series Humidity and Temperature Transmitters are designed for hazardous and explosive environments (Vaisala, 2007). Particle size and concentration measurement devices for real-time process applications have started to appear on the market during the last couple of years. For example Process Metrix LCC and Wyatt Technology Corporation have such measurement devices available (Process Metrix LCC, 2007, Wyatt Technology Corporation, 2007)

All new method development studies, basic study, and fog removal method comparison tests were performed in the field. More controlled laboratory conditions may increase the knowledge of the fogging phenomenon and help in developing fog removal methods. In this case collaboration of teams with knowledge on mining and meteorology should be considered. The best laboratory for these tests would be one with a cloud chamber. If possible, similar condensation nuclei to the mine environment, like a combination of DPM and dust from a loading area, should be used.

6.2 Interviews

Both local and international interviews provided considerable information. Some methods not mentioned in literature were uncovered and are presented in this thesis. The case studies gave good overview of concepts and methods used in operating modern underground mines.

However, it became obvious that fog and its parameters have not been thoroughly studied in mine environments. The only specific studies concerning fogging are quite old and limited in their contents with respect to theory, conditions and performance. The majority of information available concerning fogging and especially fog removal in mines has been obtained from discussions with mining industry and research personnel instead of from publications. Attention should be paid to this oversight in the mining community to ensure the proper distribution of knowledge through publications and presentations.

6.3 Literature survey

Literature survey uncovered the volatile nature of fog thoroughly. In the underground mining environment, where, for example, diesel equipment, explosives, crushers, and road graders are used, high production of aerosols and particles acting as condensation nuclei ensures favourable conditions for fog formation during operation.

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. 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, as the most promising direction for future research seems to be droplet size distribution study. Measurement devices for reliable recording of fog droplet size distributions are now available (KLD Labs, 2006). Fog removal device combinations also provide a fascinating research subject. Based on testing combinations of devices through field tests their practicality and effectiveness can be defined.

6.4 Basic study

The expected connection between relative humidity and particle concentration was clearly visible from the results. Fog was almost exclusively observed in common with high relative humidity, except when exceptionally high air velocities were also present. However, for the presence of fog, air velocity did not appear to be proportional with any other fog-related parameters. From this it can be concluded that air velocity is not a critical parameter for fogging with normal air velocities in the declines.

In some areas, even where the psychrometric values did not show exactly favourable fogging conditions, some fog was still observed. The measurement results show that the large and giant-sized condensation nuclei tend to stay airborne in the foggy areas. Under these circumstances, it can be concluded that the high particle concentration constantly enhances favourable fog formation conditions sufficiently to prevent the small changes in fog-related parameters that would otherwise stop the process.

About 3 ˚C difference of dew point temperature and air temperature was suggested to be enough to prohibit fog formation based on the measurement results. This temperature – dew point spread gives an idea about the scale of the humidity decrease required in order to achieve fog removal. This information can be used as a guideline in other fog removal surveys. The two ways to achieve a more prominent temperature-dew point spread are reducing moisture content of the air or increasing the air temperature.

6.5 Fog removal method comparison

6.5.1 Increasing air velocity by rerouting

Increasing air velocity by rerouting is highly unlikely to solve fogging problems. This method, suggested in some of the literature was tested in three Finnish mines with similar results. The observed changes were in the location of the fog fronts as well as some fog movement variations. No fog removal was accomplished even with air velocities reaching 2 m/s. Based on the field study results, an air velocity ten times higher than the suggested 0.25 m/s was required for partial dispersal of fog. The costs of the additional fans or changes in existing ventilation systems would tend to make this method unfeasible. Nevertheless, it may warrant consideration in the design of future ventilation systems. However there can be problems like pulsing of the air caused by vehicle movement in the decline with such high air velocities.

There are, however, some re-routing applications, which may be worth more study. Both adding fresh air with lower humidity or routing the fogged air through an area causing humidity decrease may have potential as fog removal methods. If foggy air is rerouted through absorbent material or through tunnels with cold walls in which water condenses, this may result in a humidity decrease. As the humidity of the air decreases, likelihood for fogging also decreases. This method is, however, not well tested. Further studies are recommended. Also, addition of fresh air with fewer particles and lower humidity, if possible, may result in reduction of fog thickness. In this case the characteristics of the mixed airflows should be studied in advance to define and avoid reaching the dew point conditions.

6.5.2 Increasing air velocity by an additional fan

Increasing air velocity by an additional fan at the Louhi Mine gave positive results, but only locally, not throughout the decline. Calculations showed that the measured temperature increase and humidity decrease were directly proportional to the heating capacity of the fan. Based on the calculations it can be concluded that the fog removal effect of a fan is due to its effect as a heater because of the warmth radiated by the motor.

In a situation, in which only a slight change in psychrometric parameters is enough to prevent fogging or fogging is a local problem only, this method may be utilized for fog removal. Also in cases with the possibility to bring large amounts of relatively dry or warm fresh air through the fan to the desired location fog removal may be achieved. Overall, it can be concluded that in a long decline with considerable changes of psychrometric properties of air, this method is inclined to fail.

Even if increasing air velocity gave ostensibly good results internationally, the fog removal is not shown to be based on the increased air velocity in any of the cases. Most likely changes in psychrometric parameters were responsible for the fog removal.

6.5.3 Heating

As a method for decreasing relative humidity, installing heaters with the additional fan at the Louhi mine gave fair results. They increased the temperature and decreased relative humidity. A change in these parameters was observed at every measurement point downstream of their location. This was by far the most satisfactory of the tested methods.

Unfortunately the sizing of the heaters was insufficient for complete fog removal in the test case. Formulas used for the capacity sizing were simple and did not take into account every parameter that affects the temperature and humidity throughout a mine like conductivity of the walls and strata temperature. More refined numerical climatic modelling of the complete air route is suggested whenever a detailed quantitative understanding is required.

The international interviews provided a very positive picture of fog removal by heating Four cases in which heating resulted in successful fog removal were discovered. Unfortunately the permission to publish information was only gained for one of these case studies. It would be beneficial for others, if the Canadians, who are experienced in using this method, would publish the information concerning their dimensioning systems and the received results.

6.6 Fog meshes

The relative humidity and particle concentration decreasing effect which was expected from the mesh system was proven to work in practice. Eleven out of twelve tests resulted in a decrease of these values. The tests were performed in two different metal mines, half of the tests in each one, in order to show that the effect is not case sensitive.

The results of the first test were promising. The mesh materials, grey mosquito net, filter fabric G3, white mosquito net, and plant cover mesh reacted differently, but positively for fog removal purposes at the Pyhäsalmi Mine. Also, during the next tests with filter fabric G3, fibrous filter fabric Bidim S02, greenhouse net, and aluminium net at the Orivesi Mine mainly positive results were achieved. The materials with the best fog removal characteristics found were aluminium net, grey mosquito net, and fibrous filter fabric Bidim S02. Both aluminium net and grey mosquito net had a metallic component, and of these materials the relative humidity decreasing effect of the aluminium net was more profound than that of any of the other tested materials. If further fog mesh tests will be carried out, the emphasis should be on materials with high thermal conductivity.

In the second test sets material combinations as well as individual materials were tested in both mines. The only new material introduced was a mist eliminator. This material was developed for fog removal and good results were expected. Unfortunately, the mist eliminator did not meet the expectations, but rather poor relative humidity decreases were measured in the mines.

In these tests the combinations tried out were mist eliminator-fibrous filter fabric Bidim S02 at the Orivesi Mine and mist eliminator-grey mosquito net at the Pyhäsalmi Mine. Grey mosquito net and Bidim S02 were also tested individually.

Two multiple mesh systems gave an improved relative humidity decrease from the mist eliminator. In one of the tests the combined efficiency was well above the individual results, but did not quite reach the sum of the individual efficiencies. In the other, the combination did not perform as well.

The fibrous filter fabric performed better by itself at the Orivesi Mine than when used in the combination with the mist eliminator. Both multiple mesh systems decreased the air velocity notably. Also, air rerouting was observed in the test case at the Orivesi Mine. A combination is thus not necessarily better than a single mesh.

After the measurements the results were analysed by simulations and calculations. With the ventilation network simulation models created earlier for these mines the resistances of the meshes were evaluated.

Resistance and airflow calculations showed more clearly that with the mesh installations air speed decreases and a varying amount of the air moves to another route because of the increased resistance. This was not obvious based on observations only. In some cases the decrease of the airflow in the decline was only a couple of per cent, which can be regarded harmless. On the other hand, especially the combinations caused high resistances with more than 35 % reductions of the airflow in the decline. These reductions seem to depend on the airflow balance in the mine as in two different cases the filter fabric gave very different results concerning the airflow reduction. All resistance values were consistent, but airflow reductions differed depending on the airflow and pressure conditions in the decline. In case of large airflows with high air velocities the effects of the meshes on the airflow were more prominent.

Based on the measurement results moisture content or absolute humidity and air-water mixing ratios were also calculated. Also these showed the superiority of the aluminium mesh in decreasing humidity. Unfortunately the accuracy limitations resulted in receiving a same value for many meshes.

Total performance analysis is presented in Table 13. This final conclusion table shows the materials, decreases of relative and absolute humidity as well as the decrease of particle concentration. It also takes into account the resistances, fog thickness decrease, number of trials, and the costs of the materials.

Table 13. Overall performance ranking of the meshes.

Material	Rel. hum.	Par. conc.	Abs. hum.	Resis- tance	Costs	No.	Fog removal	Comments
	%	*mg/m^3*	*g/m^3*	*Ns^2/m^8*	*estimate*			
Aluminium net	6.70	0.211	0.50	0.12	moderate	1	noticeable	metallic
Bidim S02	1.91	0.439	0.20	0.18	very cheap	2	maybe some	
Grey mosquito net	1.93	0.250	0.15	0.10	moderate	2	maybe some	metallic
Combination Orivesi	1.22	0.622	0.30	0.3	expensive	1	noticeable	two layers
Combination Pyhäsalmi	1.08	0.099	0.30	0.59	expensive	1	maybe some	two layers
Plant cover net	1.50	0.080	0.30	0.07	very cheap	1	none	
Mist eliminator	0.79	0.298	0.10	0.22	expensive	2	none	
White mosquito net	0.40	0.070	0.20	0.05	cheap	1	none	
Filter fabric G3	2.30	0.036	0.30	0.29	cheap	2	maybe some	problematic
Greenhouse net	1.20	0.274	0.10	0.03	very cheap	1	increase	unusable

Also equivalent heating capacity required to achieve similar effect with heating as with a mesh was studied. Heating capacity calculations were performed for three mesh systems, the aluminium net, the fibrous filter fabric Bidim S02, and the combination tested at the Orivesi Mine. The theoretical heating capacities with no losses taken into account ranged from about 20 kW with the Orivesi combination to about 40 kW in case of the aluminium net. The highest of these values is only about 40 % of the theoretical heating capacity calculated for the heater tests at the Louhi Mine. Although, the airflow in the decline of the Orivesi Mine at the time of the aluminium net test was less than 60 % of the airflow at the Louhi Mine. It can be concluded that the equivalent heating capacity for the best mesh material was slightly lower in relation to the actual heating test case.

Only one out of twelve tests completed during the study gave a negative result, and only two mesh systems resulted in visible fog thickness decrease. One thing in common for these cases was the decreased dew point by the fog mesh. The aluminium net increased the temperature dew-point spread from about 1 ˚C of a baseline situation to over 2 ˚C. On the other hand, the test with a negative result showed a decrease of temperature-dew point spread. If further study in this field is performed, this influence should be investigated.

As the performance of a fog removal mesh is very dependent on the droplet size, more information concerning this would be beneficial. The knowledge could be helpful in improving existing fog removal methods, in improving mesh method performance, and in developing new methods.

The only study providing droplet size distribution of an underground fog shows the median droplet size to be considerably smaller than those of surface fogs. This hinders the performance of a fog mesh system underground.

It can be concluded that almost every mesh is capable of reducing both relative humidity and particle concentration. The particle concentration decrease is caused by the mesh capturing condensation nuclei with the fog droplets. The effect may be enhanced by a wet mesh.

Mesh systems can decrease fogginess and the likelihood of fog formation. Unfortunately, it is obvious that this effect is not powerful enough for complete fog removal in an underground mine with the tested materials. Further research and development of new materials may change this in the future.

Summary

Fogging in underground mines is a common safety hazard, which is frequently slighted because of the many parameters involved. Information concerning fog problems in mines has rarely been published.

All the common existing and tested fog removal methods have some problems and none of them are suitable for every situation. Developing new methods would be beneficial. Recent research in other fields of science as well as new technological discoveries opens new possibilities to find new avenues of research that could solve the problem.

Interviews, literature study, field tests, and trials to develop new fog removal methods were performed in order to gain more thorough knowledge about underground fogging problems. Demisting and ventilation system changes, methods of fog removal not mentioned in the literature, were discovered by the interviews. From the interviews some fascinating case study information was also obtained. The literature study resulted in many new ideas and in uncovering relevant information from other scientific fields that might benefit the mine ventilation community. Based on this information fog droplet size distribution studies in underground mines are especially recommended.

This study also provided a broad range of field test results from three different underground mines located in a sub-arctic region, in Finland. All these mines, Pyhäsalmi Mine, Orivesi Mine, and Louhi Mine frequently experience fogging in their decline used as a secondary exhaust and travel route.

Basic study results including relative humidity, temperature, dew point, air velocity, and particle concentration are presented and analysed. Methods suitable for the declines of mines located in a sub-arctic evaluated were increasing the air velocity by rerouting, increasing air velocity by additional fans and heating with a fan or heater. These currently employed methods are discussed based upon the field tests and their results.

Increasing air velocity by air rerouting did not give acceptable results. The effect of increasing air velocity by installing an additional fan on fogging was shown to be proportional to the heating effect of the fan. Local fog removal was observed. Heating gave reasonable results decreasing the relative humidity throughout the decline in which it was tested.

Fog mesh for fog removal has been introduced as a potentially new fog removal method. Field tests covering eight mesh materials were tested individually or in as a combination in two mines. Altogether twelve tests were performed and analysed. Eleven out of twelve tests resulted in decrease of relative humidity, which is the main factor regarding fogginess. Also particle concentrations were observed to decrease. The efficiency of the meshes was, however, not good enough for complete fog removal in any of the tests. Even with the best performing mesh, an aluminium net, and a mesh combination of a mist eliminator and fibrous filter fabric Bidim S02 only partial fog removal was observed.

Fog mesh results were analysed further with modelling and calculations. Based on the ventilation simulation models of the mines resistances and airflow reductions caused by the meshes were estimated. The moisture content decrease of air with different meshes was defined by absolute humidity and air-water mixing ratio calculations. Also equivalent theoretical heating capacities required to achieve similar changes to the

psychrometric parameters by heating as observed in the mesh tests were calculated for three well performing mesh systems.

Further study is required with fog mesh systems in order to achieve more complete understanding concerning the functioning of the meshes and to improve the performance. Especially fog droplet size distributions and the tendency of some meshes to influence the dew point temperature as well as temperature-dew point spread could be studied in the future. As best results were achieved with metallic meshes, they should be emphasised in further research.

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Appendix A

Fogging in underground mines – a poll

Personal information

Name:
Position:
Contact information (optional):

Mine information

Mine name:
Ore type:
Country:
Climate:
Mine depth:
Mining method:

Fogging problems

Please underline relevant options.
Time of occurrence:
Spring *Summer* *Autumn* *Winter*
Area of occurrence:
Workings *Levels* *Decline* *Upcast shafts* *Downcast shafts*
Fog thickness (estimate):
Light *Moderate* *Thick* *Heavy*
Fog type:
Normal *Ice fog*

Visibility at worst (estimate):

Fog removal methods used/in use at the mine:

Fog removal success:

Fog related measurements, when choosing a removal method (if applicable):

Comments on fog removal costs:

Additional information:

The source of the information provided in this form can be referenced in articles and/or the Dissertation (please underline):
Yes *No*

Appendix B

Basic study results

Table B-1. Results of the first basic measurement set at the Pyhäsalmi Mine.

Meas. point	Depth	Particle concentration	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
	m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
1	1425	0.129	0.7	21	71.5	16.2	no
2	1400	0.25	0.4	23.2	47.3	11.4	no
3	1375	1.19	0.9	21.2	52.7	11.7	no
4	1350	0.252	0.6	21.4	58.8	13.6	no
5	1300	1.763	1.1	20.4	64.6	14.1	no
6	1250	0.898	0.2	20.1	68.7	14.7	no
7	1200	0.892	0	22.6	62.6	15.4	no
8	1125	1.454	0.5	21.8	67.7	15.9	no
9	1100	1.802	0.3	21.6	63.8	15.1	no
10	1080	1.53	0.4	21.9	68.7	16.4	no
11	1010	1.241	0.3	20.8	76.7	16.8	no
12	930	1.202	0.4	21.8	76.7	17.4	no
13	850	1.036	0.8	21.7	80.6	18.3	no
14	780	1.06	0.3	21.5	79.9	17.9	fog
15	680	0.848	1	20.5	81.0	17.5	fog
16	600	0.785	0.5	21.3	77.8	17.6	fog
17	425	0.681	0.4	18.8	79.2	15.8	fog
18	360	0.57	0.8	13.1	80.4	10.2	some fog
19	300	0.429	1.3	15.1	75.5	11.4	some fog
20	160	0.183	0	14.8	76.0	11.2	no
21	140	0.129	0.8	13.9	84.1	11.9	no
22	100	0.103	0.9	13.6	80.6	10.9	no

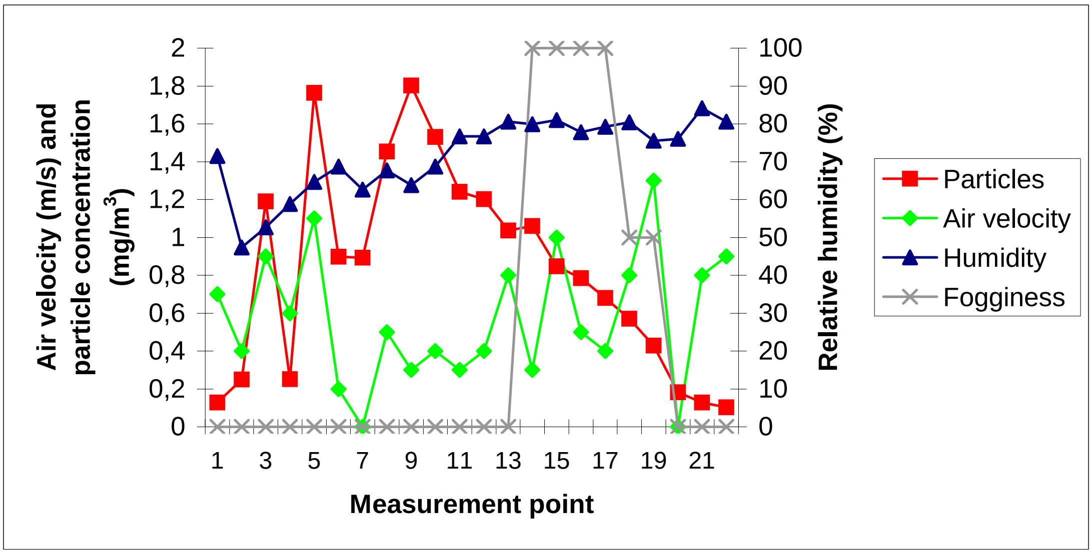

Figure B-1. Results of the first basic measurement set at the Pyhäsalmi Mine.

Table B-2. Results of the second basic measurement set at the Pyhäsalmi Mine.

Meas. point	Depth	Particle concentration	Air velocity	Temperature	Relative humidity	Dew point	Fogginess
	m	*mg/m*^{3}	*m/s*	*˚C*	*%*	*˚C*	*estimate*
1	1425	0.228	0.8	20.5	72.2	15.8	no
2	1405	0.475	0.6	21.7	53.3	15.2	no
3	1375	0.73	1.8	22.1	71	15.2	no
4	1350	0.693	1.3	20.8	74.2	15.9	no
5	1300	0.982	0.1	21.2	70.6	16.8	no
6	1250	1.123	0.9	21.6	74.1	16.3	no
7	1200	0.901	0.9	21.7	79.9	17	no
8	1125	0.877	1.1	20.5	81	17	no
9	1100	1.158	0.4	20.4	81.1	17.3	no
10	1080	1.273	1.1	20.5	81.6	17.3	no
11	1010	1.532	0.8	20.6	74.2	17.5	some fog
12	930	3.027	0.9	22.2	76.0	17.5	some fog
13	850	2.171	1	22.5	85.3	17.8	some fog
14	780	4.547	1.1	20.6	85.0	18	some fog
15	680	4.643	1.4	20.2	85.0	17.8	some fog
16	620	4.603	1.6	19.8	87.3	17.6	fog
17	600	4.65	1.5	19.8	86.3	17.6	fog
18	520	7.755	1.3	17.6	92.8	16.7	fog
19	500	5.018	1.5	18.9	85.5	16.8	fog
20	425	0.246	0.1	17.9	75.9	14.5	no
21	400	0.161	0.3	15.2	82.0	12.6	no
22	360	0.162	0.8	14.2	80.1	11.2	no
23	300	0.196	0.9	14.9	74.7	10.9	no
24	240	0.173	1.2	13.5	85.1	11.1	no
25	160	0.662	0.9	11.5	88.5	10.3	fog
26	150	1.093	1.3	12.3	88.0	10.9	fog
27	140	0.844	1.5	11.3	92.6	10.9	fog
28	130	0.588	1.2	10.8	89.6	9.7	fog
29	75	0.879	1	9.4	91.1	9.1	fog
30	70	0.334	1.5	9.0	89.9	8.9	fog
31	50	0.149	1.7	9.2	85.0	8.7	some fog

Table B-3. Results of the basic measurement set at the Louhi Mine.

Meas. point	Depth	Particle concentration	Air Velocity	Temperature	Relative humidity	Dew point	Fogginess
	m	*mg/m³*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
1	230	0.035	0.0	12.7	65.4	6.3	no
2	222	0.327	0.1	12.9	65.3	6.4	no
3	206	0.454	0.1	11.2	72.5	6.3	no
4	185	0.430	0.5	11.2	76.8	7.4	no
5	175	0.336	1.1	9.8	80.2	6.4	some fog
6	155	0.541	1.1	8.8	83.8	6.4	fog
7	130	0.282	1.4	9.3	82.6	6.5	fog
8	110	0.691	1.5	9.3	83.4	6.5	fog
9	70	0.857	1.3	8.7	85.6	6.2	fog
10	40	0.912	1.7	8.8	85.9	6.5	fog
11	15	0.557	1.5	8.9	84.7	6.6	some fog

Table B-4. Results of the basic measurement set at the Orivesi Mine.

Meas. point	Depth	Particle concentration	Velocity	Temperature	Relative humidity	Dew point	Fogginess
	m	*mg/m3*	*m/s*	*˚C*	*%*	*˚C*	*estimate*
1	700	0.082	1.0	23.2	51.8	13.0	no
2	665	0.609	1.1	23.4	58.1	14.8	no
3	610	1.739	0.8	19.5	78.6	16.3	no
4	550	1.521	0.9	19.0	79.8	15.8	no
5	490	1.529	1.8	17.6	88.2	16.3	no
6	430	1.101	2.9	17.4	89.4	16.1	no
7	375	1.054	2.6	17.0	90.6	16.1	no
8	310	1.057	2.0	16.5	92.4	16.0	fog
9	276	1.145	1.9	16.2	92.3	15.7	fog
10	235	0.924	1.4	15.8	93.5	15.4	thick fog
11	202	2.633	1.7	15.6	92.8	15.0	thick fog
12	164	2.792	1.3	15.4	92.0	14.9	thick fog
13	132	2.623	1.2	15.1	92.1	14.5	fog
14	97	1.901	1.1	14.8	92.0	14.2	fog
15	66	1.863	0.9	14.3	92.7	14.0	some fog
16	35	2.791	0.7	14.2	92.2	13.6	some fog

Appendix C

Results of the first mesh test sets

Table C-1. Results of the first mesh test day at the Orivesi Mine.

Filter fabric G3

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Moderate fog upstream, less downstream, fabric soaked through, no water streams
Upstr.	0.012	1.2	10.3	89.1	9	
Downstr.	0.01	1.1	10.5	87.5	9.2	

Fibrous filter fabric Bidim S02

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Thick fog upstream, moderate downstream, fabric very wet, many water streams
Upstr.	0.193	1.1	10.2	90.4	9.1	
Downstr.	0.004	1.3	10.6	87.4	9.3	

Baseline

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Moderate fog in both measurement points
Upstr.	0.011	1.4	10.4	89.7	8.8	
Downstr.	0.01	1.8	10.3	89.4	8.8	

Table C-2. Results of the second mesh test day at the Orivesi Mine.

White plastic greenhouse net

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Gathers fog on both sides, water gets attached to the mesh, no water streams
Upstr.	0.549	1.2	10.2	94.3	9.8	
Downstr.	0.275	1.4	10.2	93.1	9.7	

Paint-coated aluminium net

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Moderate fog upstream, light downstream, very wet net, many water streams
Upstr.	0.222	1.1	10.3	92.4	9.1	
Downstr.	0.011	1.1	10.6	85.7	8.4	

Baseline

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Moderate fog in both measurement points
Upstr.	0.753	1.3	10.4	91.2	9.1	
Downstr.	0.778	1.2	10.1	92	9.4	

Table C-3. Results of the mesh tests at the Pyhäsalmi Mine.

	Particle concentration	Air velocity	Temp-erature	Relative humidity	Dew point	Notes
Gray mosquito net, plastic covered metal						
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Light fog, extremely wet mesh, many water streams
Downstr.	1.15	1.2	18.4	92.2	17.5	
Upstr.	0.9	1	18.9	90.2	17.6	
Filter fabric G3						
	Particle concentration	**Air velocity**	**Temp-erature**	**Relative humidity**	**Dew point**	**Notes**
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Very light fog, fabric wet, no water streams
Downstr.	0.31	0.7	19.5	88.5	17.7	
Upstr.	0.24	0.5	19.5	85.5	17.5	
White mosquito net, plastic						
	Particle concentration	**Air velocity**	**Temp-erature**	**Relative humidity**	**Dew point**	**Notes**
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Light fog, almost dry mesh, no water streams
Downstr.	0.61	0.9	19	91.8	17.9	
Upstr.	0.54	0.85	18.8	91.4	17.6	
Green plant cover mesh, woven plastic band						
	Particle concentration	**Air velocity**	**Temp-erature**	**Relative humidity**	**Dew point**	**Notes**
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Light fog, wet mesh, no water streams
Downstr.	0.71	1	18.8	92	17.7	
Upstr.	0.63	0.8	18.8	90.5	17.5	
Baseline						
	Particle concentration	**Air velocity**	**Temp-erature**	**Relative humidity**	**Dew point**	**Notes**
	mg/m³	*m/s*	*˚C*	*%*	*˚C*	Light fog in both measurement points
Downstr.	0.83	0.85	18.8	92.3	17.9	
Upstr.	0.93	1	18.6	92.9	17.8	

Appendix D

Results of the second mesh test sets

Table D-1. Measurement results of the mesh tests at the Pyhäsalmi Mine.

Particle concentration (*mg/m³*)								
	Mist eliminator		**Combination**		**Mosquito net**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	0.331	0.303	0.481	0.447	0.059	0.079	0.078	0.139
	0.446	0.288	0.407	0.515	0.12	0.187	0.184	0.373
	0.499	0.391	0.603	0.459	0.237	0.139	0.958	0.737
	0.495	0.331	0.538	0.317	0.251	0.156	0.45	0.614
	0.562	0.411	0.598	0.394	0.2	0.184	0.726	0.584
Average	0.4666	0.3448	0.5254	0.4264	0.1734	0.149	0.4792	0.4894
Variance	0.0074	0.0029	0.0069	0.0056	0.0067	0.0019	0.1348	0.0555
Std. dev	0.0863	0.0540	0.0828	0.0748	0.0817	0.0439	0.3671	0.2356
Air velocity (*m/s*)								
	Mist eliminator		**Combination**		**Mosquito net**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	2.3	2	2.3	1.7	2.4	2.2	2.4	2.6
	2.3	2.1	2.2	1.6	2.5	2.1	2.5	2.6
	2.3	2	2.4	1.8	2.4	2.1	2.4	2.5
	2.4	2	2.3	1.8	2.3	2.1	2.4	2.5
	2.4	1.9	2.3	1.7	2.3	2.1	2.5	2.4
Average	2.34	2	2.3	1.72	2.38	2.12	2.44	2.52
Variance	0.003	0.005	0.005	0.007	0.007	0.002	0.003	0.007
Std. dev	0.055	0.071	0.071	0.084	0.084	0.045	0.055	0.084
Temperature (*˚C*)								
	Mist eliminator		**Combination**		**Mosquito net**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	18.6	18.8	18.9	18.7	18.6	18.9	19.1	18.9
	18.8	18.9	18.9	18.7	18.6	18.7	18.6	18.9
	18.6	18.7	18.6	18.6	18.5	18.6	18.9	18.6
	18.8	18.6	18.6	18.7	18.7	18.7	18.6	18.6
	18.7	18.7	18.6	18.7	18.7	18.6	18.6	18.6
Average	18.7	18.74	18.72	18.68	18.62	18.7	18.76	18.72
Variance	0.01	0.013	0.027	0.002	0.007	0.015	0.053	0.027
Std. dev	0.1	0.114	0.164	0.045	0.084	0.122	0.230	0.164
Relative humidity (*%*)								
	Mist eliminator		**Combination**		**Mosquito net**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	91.7	91	91.7	90.7	92.3	90.8	89.6	89.9
	92.2	91.4	92.6	91.4	92.3	90.4	90.1	90.9
	93.3	92.5	93.3	92.2	93	91.1	92.6	92.6
	93.5	92.8	93.8	92.9	93.6	91.4	93.2	93.1
	93.3	92.4	93.4	92.2	93.3	91.5	93.7	93.5
Average	92.8	92.02	92.96	91.88	92.9	91.04	91.84	92
Variance	0.64	0.602	0.683	0.717	0.345	0.203	3.483	2.36

Std. dev	0.8	0.776	0.826	0.847	0.587	0.451	1.866	1.536
Dew point (*˚C*)								
	Mist eliminator		**Combination**		**Mosquito net**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	17.7	17.7	17.7	17.6	17.7	17.6	17.6	17.7
	17.7	17.7	17.8	17.7	17.7	17.6	17.6	17.6
	18.1	17.6	17.8	17.7	17.8	17.6	17.8	17.7
	17.7	17.7	17.8	18	17.9	17.7	17.8	17.7
	17.7	17.8	17.8	17.7	17.8	17.6	17.8	17.7
Average	17.78	17.7	17.78	17.74	17.78	17.62	17.72	17.68
Variance	0.032	0.005	0.002	0.023	0.007	0.002	0.012	0.002
Std. dev	0.179	0.071	0.045	0.152	0.084	0.045	0.110	0.045

Table D-2. Measurement results of the mesh tests at the Orivesi Mine.

Particle concentration (*mg/m³*)								
	Mist eliminator		**Combination**		**Bidim S02**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	0.446	0.245	0.856	0.156	1.52	0.605	0.063	0.074
	0.571	0.234	0.815	0.369	1.195	0.639	0.074	0.114
	0.819	0.209	1.238	0.607	1.273	0.767	0.089	0.066
	0.859	0.209	1.063	0.243	1.4	0.672	0.213	0.24
	0.766	0.198	0.745	0.233	1.234	0.49	0.293	0.341
Average	0.6922	0.219	0.9434	0.3216	1.3244	0.6346	0.1464	0.167
Variance	0.0312	0.0004	0.0411	0.0313	0.0179	0.0102	0.0104	0.0143
Std. dev	0.1765	0.0196	0.2028	0.1769	0.1337	0.1009	0.1018	0.1196
Air velocity (*m/s*)								
	Mist eliminator		**Combination**		**Bidim S02**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	1.6	1.4	1.4	1.1	1.6	1.5	2.1	2.1
	1.8	1.6	1.4	1.1	1.6	1.5	2.1	2.1
	1.8	1.6	1.3	1.2	1.7	1.4	2.1	2
	1.7	1.5	1.5	1.2	1.6	1.4	2	2
	1.7	1.5	1.4	1.3	1.6	1.4	2.1	2.1
Average	1.72	1.52	1.4	1.18	1.62	1.44	2.08	2.06
Variance	0.007	0.007	0.005	0.007	0.002	0.003	0.002	0.003
Std. dev	0.084	0.084	0.071	0.084	0.045	0.055	0.045	0.055
Temperature (*˚C*)								
	Mist eliminator		**Combination**		**Bidim S02**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	14.8	14.8	14.8	14.4	14.8	14.6	14.8	14.7
	14.7	14.6	14.8	14.6	14.7	14.4	14.8	14.8
	14.7	14.7	14.8	14.4	14.7	14.6	14.8	14.9
	14.7	14.7	14.7	14.5	14.6	14.6	14.8	14.8
	14.8	14.6	14.8	14.6	14.7	14.6	14.8	14.8
Average	14.74	14.68	14.78	14.5	14.7	14.56	14.8	14.8
Variance	0.003	0.007	0.002	0.01	0.005	0.008	0	0.005
Std. dev	0.055	0.084	0.045	0.100	0.071	0.089	0.000	0.071

Relative humidity (%)								
	Mist eliminator		**Combination**		**Bidim S02**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	92.3	91.9	93.4	92.2	94.3	93.8	91.1	91.1
	93.5	92.8	94.3	92.7	94.5	93.8	91.3	91.4
	93.6	92.8	94	92.8	94.7	93.9	91.7	92
	93.9	92.6	94	93	94.7	93.6	92.4	92.1
	93.7	92.9	94.2	93.1	94.9	93.9	92.5	92.2
Average	93.4	92.6	93.98	92.76	94.62	93.8	91.8	91.76
Variance	0.4	0.165	0.122	0.123	0.052	0.015	0.4	0.233
Std. dev	0.632	0.406	0.349	0.351	0.228	0.122	0.632	0.483
Dew point (˚C)								
	Mist eliminator		**Combination**		**Bidim S02**		**Baseline**	
	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.	Upstr.	Downstr.
	14.4	14.2	14.5	14.1	14.5	14.4	14	14
	14.4	14.1	14.5	14.1	14.5	14.2	14.3	14.1
	14.5	14.4	14.6	14.1	14.5	14.4	14.3	14.3
	14.6	14.2	14.5	14.1	14.4	14.4	14.4	14.2
	14.6	14.2	14.5	14.1	14.5	14.4	14.3	14.4
Average	14.5	14.22	14.52	14.1	14.48	14.36	14.26	14.2
Variance	0.01	0.012	0.002	0	0.002	0.008	0.023	0.025
Std. dev	0.1	0.110	0.045	0	0.045	0.089	0.152	0.158

Appendix E

Mollier diagram

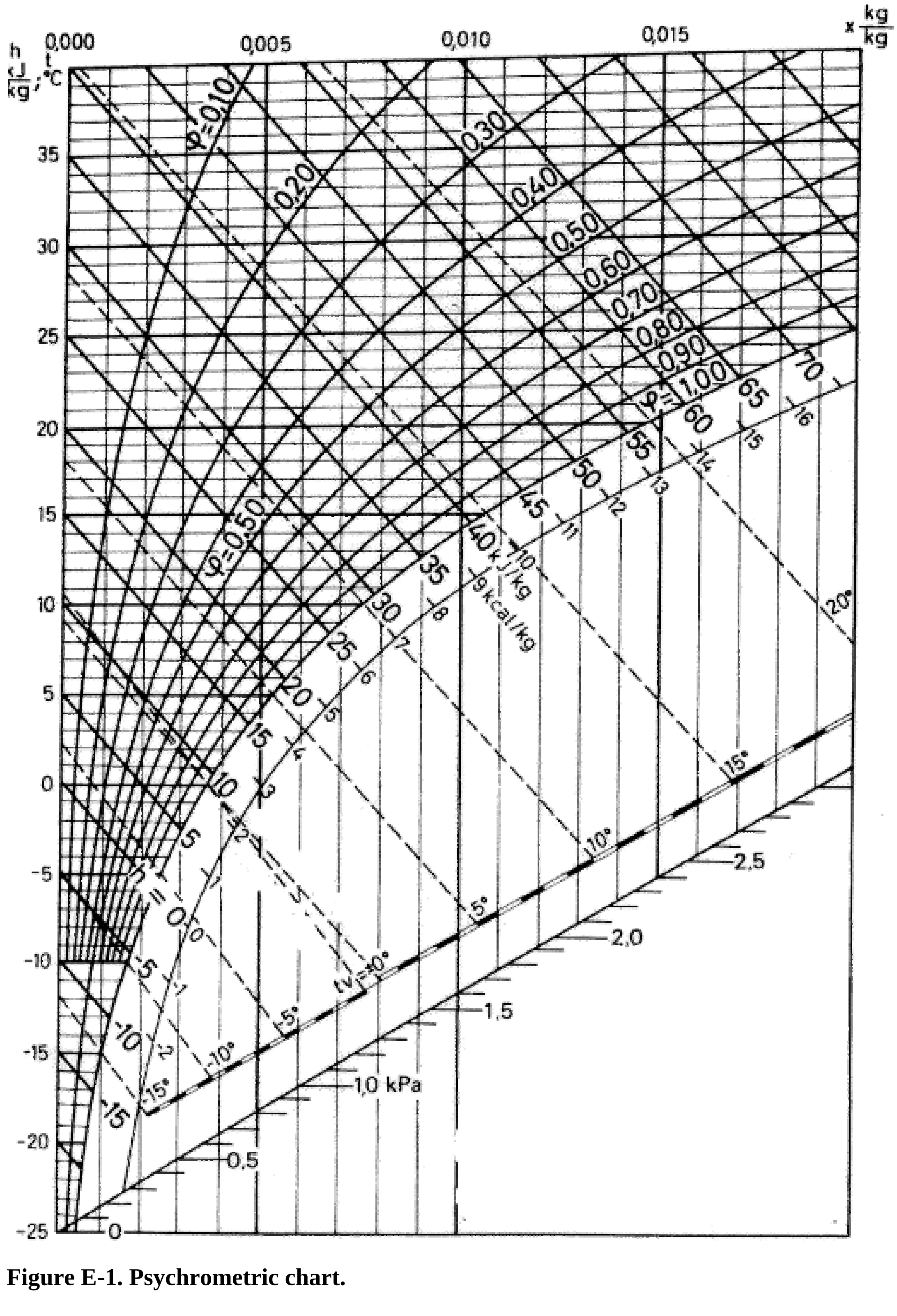

Figure E-1. Psychrometric chart.

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