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Modelling and experimental study of protected zone ventilation in industrial working environment

Modellering og eksperimentelt studie av
beskyttet sone ventilasjon i industrielt
arbeidsmiljø

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MASTER THESIS

for

Student Ina Helene Thune

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Modelling and experimental study of protected zone ventilation in industrial working environment

Modellering og eksperimentelt studie av beskyttet sone ventilasjon i industrielt arbeidsmiljø

Background and objective

Mixing ventilation (MV) has been used for more than 100 years, and the disadvantages of using MV systems are still challenging us today, as the supply of fresh air will be mixed up with polluted indoor air. Displacement ventilation (DV) is designed to push pollutants away from the lower part of the room. DV has a high ventilation index, but it is also possible to have stratified exhalations in the occupied zone because of the vertical temperature gradient. Through DV, moreover, the supplied airflow reaching the breathing zone may also transport pollutants from the floor covering or from other pollution sources, which decreases the quality of the inhaled air. In addition, the location of the return openings plays an important role in the distribution of the exhaled contaminant (tracer gas) in the room, which results in the fact that DV may not suitable for heating conditions. Similar to an industrial air curtain, the protected occupied zone ventilation (POV) was subsequently proposed by using a low turbulence plane jet to separate an office environment into a few subzones. Therefore, there is a substantial lack of understanding of the fundamental and critical principle of airflow distribution to create a safe, healthy and productive work environment. The provision of sufficient fresh air from ventilation systems to the areas where workers and products need better local air quality becomes extremely important in the industrial working environment.

The objective of this project is to exam the performance of protected zone ventilation in the industrial working environment of Jøtul company.

The following tasks are to be considered:

1. Literature review of the state of art solutions of the airflow distribution in the industrial working environment, like melting industry.
2. Model the airflow distribution pattern of protected zone ventilation preventing the transport of pollutants from one zone to another zone.
3. Conduct laboratory measurements of the distribution of particulate matter pollutants with the protected zone ventilation method.
4. Conduct a survey/questionnaire about indoor air quality and health of workers at Jøtul.
5. Suggest a cost-effective solution to reduce the exposure of workers to indoor pollutants.

Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

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☒ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☒ Field work

Department of Energy and Process Engineering, 15. January 2017

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Preface

This thesis is part of a Master of Science degree in Energy and Environmental Engineering at the Norwegian University of Science and Technology (NTNU), at the Department of Energy and Process Engineering. This thesis is conducted in cooperation with Jøtul company.

This is a study of indoor air quality and protected zone ventilation of the industry factory Jøtul. The purpose of the thesis is to find a protected zone ventilation solution to minimize the exposure of potentially harmful particles in the air at a working area at Jøtul

Ina Helene Thune

Trondheim, July 9th, 2017

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I would like to thank my supervisor, Guangyu Cao, for guidance and input on fieldwork and experimental work performed in this thesis. I would also like to thank my co-supervisor at Jøtul, Espen Løkkevig, who have helped me set up the field work and for help me better understand the building at Jøtul. Additional thanks goes to Geir Bunæs, Fredrik Ileby and Knut Marthinsen for helping me understand the ventilation system, and Anita Kruse Solbakken and Anne Løkkeberg for helping me find HSE-information in the project work.

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Abstract

In industrial buildings, especially melting and foundry halls, the room air is often filled with smoke and other potentially harmful particles. This is also the case at Jøtul company in Fredrikstad. An indoor climate survey concludes that the workers are dissatisfied with the indoor air quality at the workplace. The industrial environment at a working area called Greplassen at Jøtul is tested, and the environment is simulated in the laboratory at NTNU. With a local environment consisting of a hotplate, a plane jet, a laminar downward airflow and a thermal manikin, the necessary conditions to minimize the exposure to contaminants for the workers by protected occupied zone ventilation is tested experimentally.

The plane jet is used as an air curtain to prevent the contaminants in the upward plume from the hotplate, which simulates the hot stove pieces at Jøtul, from reaching the protected occupied zone. With a constant power supply giving a surface temperature of 170°C, a 'protection velocity' of 2 m/s were needed for the plane jet alone, but the tracer gas measurements showed that a velocity of 1.5 m/s also will give a protection efficiency of around 1. To test the laminar downward airflow (LAF) diffuser ability to supply fresh air to the breathing zone, tracer gas measurements were conducted. A thermal manikin were placed 25 cm underneath the LAF diffuser to create the natural plume from a person, with tracer gas supplied at the manikins feet, as well at by the hotplate. Measurements showed that for a velocity of 0.25 m/s, the tracer gas concentration actually were higher than supply concentration, making the ventilation with this velocity worse than no ventilation at all. For an average velocity of 0.3 m/s for LAF, the tracer gas concentration decreased. Combined with the plane jet with velocity of 2 m/s, the measurement showed that fresh air is supplied to the breathing zone. This is obtained by using a total volume flow rate of 1976 m^3/h, which is well within the measured capacity of the existing ventilation system at Jøtul.

To prevent the air quality of becoming poorer due to a little too low LAF velocities, it is recommended to use a LAF velocity of 0.44 m/s, which gives a total airflow rate of 2822 m^3/h; 288 m_3/h for the plane jet and 2534 m^3/h for the LAF diffuser of 2 m x 0.8 m. This is just within the airflow capasity of 2825 m^3/h measured at Jøtul.

Sammendrag

I industribygg, spesielt i smelteverk, er romluften often full av røyk og andre potensielt skadelige partikler. Dette er også tilfellet på Jøtul fabrikk i Fredrikstad. En inneklimaundersøkelse konkluderer med at arbeiderne er misfornøyde med inneluftkvaliteteten på arbeidsplassen. Det industrielle innemiljøet på et arbeidsområde kalt Greplassen på Jøtul er testet, og miljøet er simulert i laboratoriet på NTNU. Med et lokalt miljø bestående av en kokeplate, en luftjet, en laminær nedadrettet luftstrøm og en termisk oppvarmet dukke, er de nødvendige forholdene for å minimalisere arbeidernes eksponering av forurensning ved hjelp av beskyttet sone ventilasjon testet eksperimentelt.

Luftjeten ble brukt som en luftgardin for å hindre forurensning i den oppadgående varmestrømmen fra kokeplaten, som simulerer de varme ovndelene på Jøtul, fra å nå den beskyttede okkuperte sonen. Med en konstant strømtilførsel som gir en overflatetemperatur på 170°C, trengs en 'beskyttelseshastighet' på 2 m/s for jeten alene, men sporgassmålinger viste at jethastighet på 1.5 m/s også vil gi en beskyttelseseffektivitet på rundt 1.
For å teste den laminære nedadrettede luftstrømmens (LAF) evne til å bringe frisk luft til pustesonen, ble sporgass-målinger utført. En termisk oppvarmet dukke ble plassert 25 cm under den laminære luftstrømmen for å skape en naturlig varmestrøm fra et menneske, og sporgass er tilført ved dukkens føtter, i tillegg til ved kokeplaten. Målinger viste at for en gjennomsnittlig hastighet for LAF på 0.25 m/s, var sporgasskonsentrasjonen høyere enn tilførselkonsentrasjonen, noe som vil si at ventilasjon med denne hastigheten er verre enn å ikke ha noe ventilasjon i det hele tatt. For en gjennomsnittshastighet på 0.3 m/s, begynte sporgasskonsentrasjonen å minke. Kombinert med luftjeten med hastighet på 2 m/s, viste eksperimentene at frisk luft blir tilført i pustesonen. Dette er oppnådd ved å bruke en total luftstrøm på 1976 m^3/h, som er godt innenfor den målte kapasiteten til det eksisterende ventilasjonsanlegget på Jøtul.

For å hindre at luftkvaliteten blir dårligere grunnet litt for lave LAF hastigheter, er det anbefalt å bruke en LAF hastighet på 0.44 m/s, som gir en total luftstrøm på 2822 m^3/h; 288 m^3/h for luftjeten og 2534 m^3/h for LAF med areal 2 m x 0.8 m. Dette er så vidt innenfor den målte luftkapasiteten på 2825 m^3/h på Jøtul.

Contents

List of Figures

List of Tables

Abbreviations

AAD	Advanced air distribution
CO_2	Carbon dioxide
COPD	Chronic Obstructive Pulmonary Disease
CRE	Contaminant removal efficiency
HPZV	Hybrid protected zone ventilation
IAQ	Indoor air quality
LAF	Laminar airflow
N_2O	Nitrous oxide
PE	Protection efficiency
PEE	Personal exposure effectiveness
PEI	Personal exposure index
POV	Protected occupied zone ventilation
PPE	Personal protective equipment
ppm	Parts per million
PV	Personalized ventilation
SBS	Sick building syndrome
SF_6	Sulphur hexafluoride
TVAD	Total volume air distribution
VOC	Volatile Organic Compound

Nomenclature

Latin letters

A_0	m^2	Effective area of diffuser
A	m^2	Free area of diffuser
A_{bs}	m^2	Body surface area
$< C >$	mg/m^3	Average concentration of contaminants in room
C_b	-	Proportion factor for x and y in thermal plume
$c_{breathing}$	mg/m^3	Concentration of contaminants in the breathing zone
C_d	-	Discharge coefficient
$C_e/c_{exhaust}$	mg/m^3	Concentration of contaminants in exhaust air
C_p	J/K	Heat capacity
c_{source}	mg/m^3	Concentration of contaminants from the source
$c_{t\text{-}zone}$	mg/m^3	Concentration of contaminants in the protected zone
d	m	Slot diameter or jet thickness
g	m/s^2	Gravitational force
K	-	Velocity decay constant
K_v	-	Velocity decay constant
n	-	index for centerline velocity decay for plane jet
$PM_{2.5}$	$\mu g/m^3$	Particle matter with aerodynamic diameter <2.5 µm
PM_{10}	$\mu g/m^3$	Particle matter with aerodynamic diameter <10 µm
PM_{100}	$\mu g/m^3$	Particle matter with aerodynamic diameter <100 µm
Q	m^3/s	Airflow rate
$\dot{Q}_k$	kW	Convective heat
U_m	m/s	Maximum velocity at a given distance x from the diffuser
U_0	m/s	Initial outlet velocity from diffuser
V	m^3	Volume
$\dot{V}$	m^3/h	Volume flow rate
x	m	Distance from diffuser
y	m	Vertical distance from the source in thermal plume
y_p	m	Distance from the source to an imaginary point source in plume

Greek letters

σ_1	-	Velocity decay constant
β	1/K	1/T, where T is ambient temperature
ρ	kg/m^3	Density of air
ε^a	%	Air exchange efficiency
${\varepsilon^a}_b$	%	Air exchange efficiency in the breathing zone
ε^c	%	Contaminant removal efficiency
${\varepsilon^c}_b$	%	Contaminant removal efficiency in breathing zone
ε_{exp}	%	Personal exposure index
ε_p	%	Personal exposure effectiveness
τ_n	s	Nominal time constant
$< \bar{\tau} >$	s	Average age of air

1 Introduction

In developed countries, like Norway, people spend 90 % or more of their time indoors (Höppe, 2002). The indoor air quality is thus an important factor for good health and well-being for humans. By working in a contaminated environment, humans become more susceptible to illness and irritation as well as worsening already existing deceases (Folkehelseinstituttet, 2013) (Safety and Health Administration, 2002). This can increase the sick leave as well as decrease the productivity of the workers. An industrial environment is dominated by industrial processes that provide both high levels of heat and pollution. These processes will define the ventilation need, both for supply air and exhaust and local ventilation. Most of today's ventilation is total volume air distribution (TVAD), like mixing or displacement, but as pointed out by Bolashikov et al. (2012) these distributions is not always efficient. To focus on the occupants' conditions, Melikov (2016) suggest a paradigm shift to advanced air distribution (AAD).
This master thesis focuses on the study of protected occupied zone ventilation to minimize the exposure for the worker. This is done by simulating the boundary condition at the factory in the ClimateLab at NTNU, and examine the airflow needed to achieve fresh air in the breathing zone for the worker.

1.1 Background

Jøtul factory in Fredrikstad is an industrial factory for making wood stoves. It is divided into seven sections, see Figure 1. Since Jøtul factory is an industrial building, including melting of iron, the environment is affected by the many heavy contaminant sources. Particulate matter measurement conducted in Thune (2016) suggest that the ventilation system is insufficient, and contaminant levels are quite high throughout the factory, but specially in the melting hall. The values suggest a risk of health consequences over time, and respiratory masks is needed to reduce the risk of health consequences. To improve the air quality in the whole melting hall will be difficult without massive reconstruction of the ventilation system. However, local environment ventilation can be adjusted using the existing construction to protect occupants in working area.

1.2 Objectives

The objective of this master thesis is to examine the performance of protected zone ventilation in the industrial working environment of Jøtul company. The following is the main tasks of the thesis:

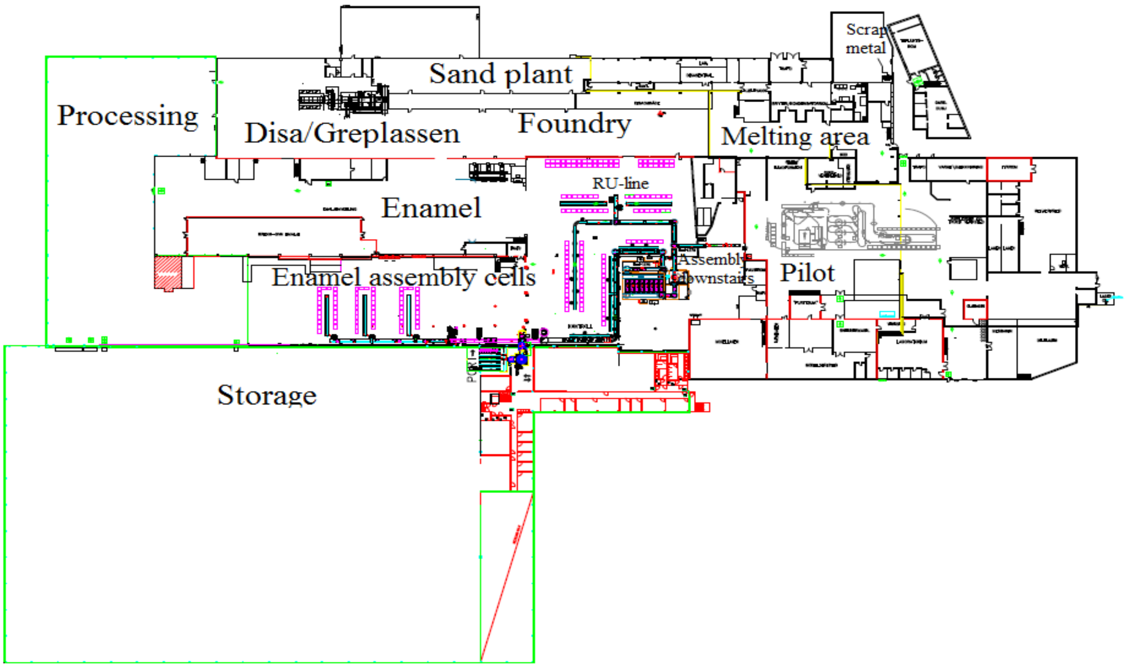


Figure 1: Layout of factory at Jøtul

1. Literature review of the state of the art solutions of the airflow distribution in the industrial working environment, like melting industry.
2. Model the airflow distribution pattern of protected zone ventilation preventing the transport of pollutants from one zone to another zone.
3. Conduct laboratory measurements of the distribution of particulate matter pollutants with the protected zone ventilation method.
4. Conduct a survey/questionnaire about indoor air quality and health of workers at Jøtul.
5. Suggest a cost-effective solution to reduce the exposure of workers to indoor pollutants.

1.3 Limitations

Background measurements were taken at Jøtul to have references when trying to simulate the environment conditions in the ClimateLab at NTNU. To do so, some limitations occurred. The manikin does not move and the effects of the movements of the workers is thus not implemented. The movement and variation of the pieces is not possible, and are replaced in the lab experiments with a hot plate with fixed conditions. It is also difficult to simulate a human being; a thermal manikin was used, but simplifications are used to heat the manikin as well as the lack of breathing mechanism. The creation of a laminar downward airflow also proved to be difficult due to the big surface area and low maximum height of diffuser construction.

1.4 Approach

The means of this master thesis is to find a solution for improving the indoor air quality in the working zone, by protected zone ventilation. For thoracic and respiratory particles, $PM_{2.5}$ and PM_{10}, the highest concentrations where measured in Disa sandblaster. Thus "Greplassen" was chosen as focus area for this thesis. Background measurements were conducted at Jøtul and then the environment were simulated at the ClimateLab at NTNU. A combination of a plane jet and a laminar downward airflow is to be tested. The plane jet should prevent contaminants rising with the thermal plume of stove pieces from reaching the breathing zone of the worker, i.e. create a separate zone. The laminar flow should supply fresh air into the breathing zone of the workers. The 'protection velocity' for the plane jet and the laminar flow is tested separately and then the combination is tested to see the combined effect. Both velocity measurements and tracer gas measurements are conducted in this thesis.

1.5 Literature study

The basic theory on air diffusion devices were found in the book "Ventilation of buildings" (Awbi, 2003), "Ventilasjonsteknikk" (Skåret, 2000) present the basic for thermal plume. Recommended limits for respiratory and thoracic particles concentrations, as well as other substances, are collected from the Norwegian Institute of Public Health (Folkehelseinstituttet, 2013), World Health Organization (2005) and the Norwegian Labour Inspection Authority (Arbeidstilsynet, 2011).

To find state of the art literature, the online bibliographic databases Scopus and Oria (University online library) have been used. Search words used to find relevant research included "contaminant exposure", "health consequences", "protected zone ventilation", "personalized ventilation", "air curtain", "plane jet", "advanced air distribution", "ventilation efficiency", "thermal manikin". Different combinations of the words and filters were used to find the most relevant theory.

Pictures from Jøtul is used with permission from Jøtul.

2 Indoor climate

In an industrial hall, as any other workplace, it is important to create a good indoor environment. The indoor environment consists of (Hanssen, 2007):

- Thermal environment (heat balance for humans, thermal comfort)
- Atmospheric environment (particles and pollutants)
- Acoustic environment (noise, hearing)
- Actinic environment (light and radiation)
- Mechanical environment (ergonomics and accidents)
- Aesthetic environment (pleasing to the senses)
- Psychosocial environment (relationship with co-workers)

The main focus for this specializing project is the atmospheric environment and indoor air quality.

Thermal comfort for a person is subjective, but the operative temperature giving thermal comfort usually is around 21°C depending on the level of clothing and activity. The range of acceptable indoor temperatures for different workplaces in Norway are stated in Arbeidstilsynet (1991). Here it says that for medium heavy work, the temperature can vary from 16–26°C. This means that it should not be colder than 16°C in winter or exceed 26°C in summer. In the summer this is a problem, so the limit is set so that the temperature should not exceed 26°C more than 50 hours in a year. For heavy work the temperature interval is 10–26°C. The relative humidity should be between 20 and 60 %. However, there is no indication that high or low indoor temperature play a major role for life expectancy or sickness (Gunnarsen, 2003). Excessive exposure to heat is called heat stress, while excessive exposure to cold is called cold stress. Gunnarsen (2003) concludes that the productivity can be reduced by 15-30 % due to thermal stress. For a vertical air temperature difference greater than 4 between head and ankle, more than 15% of the occupants will feel a thermal discomfort, which is over the acceptable percentage of dissatisfied (Novakovic et al., 2007).

2.1 Indoor air quality

Indoor air quality (IAQ) is a general denomination for the *cleanliness of indoor air*. It indicates both type and amount of pollutants in the air that may cause health issues and/or discomfort. ASHRAE (2007) define acceptable IAQ as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80 % or more) of the people exposed do not express dissatisfaction." Indoor air quality is of high importance considering humans today, on average, spends 90 % or more of their time indoors (Höppe, 2002). A poor indoor air quality can lead to illness and irritation and other health consequences over time. Health consequences are presented in Chapter 2.1.2.

2.1.1 Air pollutants

Air pollutants can be classified into gaseous pollutants and airborne particles. The latter is defined as solid or liquid particles suspended in the air, also called aerosols.
Gaseous air pollutants is gases in the air and the most common is sulfur dioxide (SO_2), oxides of nitrogen ($NO_x = NO + NO_2$) and ozone (O_3) according to Tiwary and Colls (2009), but also spans CO_2 and Volatile Organic Compounds (VOC), that among others occur from evaporation of solvents in paint. The term VOC includes many different types of chemicals, from hazardous to harmless, health wise. In schools and offices, CO_2 have been the biggest pollutant. That is why air quality in these type of building often are examined by looking at the concentration of CO_2. High levels of CO_2 can cause sick building syndrome (SBS) (Seppänen et al., 1999), which is symptoms linked to spending time in a building. The limit in these kind of rooms is 1000 ppm, but as defined by Arbeidstilsynet (2011), levels of CO_2 up to 5000 ppm (or 9000 mg/m^3) will cause no toxicological, physical or mental problems with stays of eight hours, and therefore this is the boundary value for industries.

Airborne particles are fin, solid or liquid particles suspended in the air, and can be classified by particle size or chemical composition and characteristics. Some particles are denoted by their size because of their ability to penetrate the human body's outer immune system. These are commonly divided into mass fractions. There are three main particle mass fractions; inhalable, thoracic and respiratory fraction. The inhalable mass fraction consists of particles smaller than 100 µm which can be inhaled by nose and mouth, and are normally denoted PM_{100}. The thoracic particles are smaller than 10 µm, denoted PM_{10}, and can pass the larynx. The respiratory fraction is particles less than 2.5 µm and are denoted $PM_{2.5}$. These can reach down to the alveoli. Tjelflaat (2001) define $PM_{2.5}$ as the concentration of the fraction of particles where at least 50 % (by weight) have an aerodynamic diameter less than 2.5 µm. Exposure to coarse particles, $PM_{10\text{-}2.5}$, is as likely to cause illness as fine particles, $PM_{2.5}$, but the fine particles are more strongly associated with mortality (Folkehelseinstituttet, 2015). Arbeidstilsynet (2008) states that "there is as yet no identifiable threshold below which $PM_{2.5}$ would not pose a risk."

Limit values for particulate matter concentration in indoor air is given by several organizations, as seen in Table 1.

	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$
Folkehelseinstituttet (2013), annual mean	8 µg/m^3	20 µg/m^3
Folkehelseinstituttet (2013), 24-hour mean	15 µg/m^3	30 µg/m^3
World Health Organization (2005), annual mean	10 µg/m^3	20 µg/m^3
World Health Organization (2005), 24-hour mean	25 µg/m^3	50 µg/m^3
Arbeidstilsynet (2011), 8-hour working day	5 mg/m^3	10 mg/m^3

Table 1: Limit values for particulate matter concentration given by several institutions

While Folkehelseinstituttet (2013) and World Health Organization (2005) gives the values for levels when occupied through a whole year or 24-hour, Arbeidstilsynet (2011) gives the maximum concentration for respiratory and thoracic particles in a working environment in Norway. If this is exceeded, action must be taken. Even when the values are 25% of the given maximum value, actions should be considered to reduce the risk of health consequences for the worker. When the levels are as high as the maximum limit, the workers should use protection gear in form of respiratory masks, and action have to be made to reduce the exposure. The respiratory masks will filter out parts of the particles and thus reduce the exposure to the worker.

2.1.2 Health consequences

Documented research of how high concentration of airborne particles in the indoor air effect human health are few, but the existing studies indicates that it can lead to (Folkehelseinstituttet, 2015):

- Reduced pulmonary function among susceptible humans
- Increase in cough and bronchitis
- Asthmatic attacks
- Chronic Obstructive Pulmonary Disease (COPD)
- Cardiovascular diseases
- An increase of hospitalization for respiratory and cardiovascular diseases
- An increase of premature death

A report from World Health Organisation (2014) stats that 7 million people (one in eight of total deaths) died as a result of air pollution exposure in 2012. For the indoor air pollution-caused deaths, the percentage distribution between diseases where:

- Stroke - 34 %
- Ischaemic heart disease - 26 %
- COPD - 22 %
- Acute lower respiratory infections in children - 12 %
- Lung cancer - 6 %

In an industrial environment where melted metals are involved, metal in the air is a main concern regarding the human health. In the cast iron, small concentrations of carbon, silicon, phosphorus, manganese and chromium are supplementary to the iron. In addition, traces of other metals are supplied with the scrap metal, like lead. The limit concentration for an 8-hour working day for these metals are represented in Table 2. Even though there are many different metals, previous examinations from Stamina concludes that it is the level of lead that pose the highest risk for the melting workers. From the dust or smoke containing lead, small particles can be dragged into the body by inhaling, and from here reach further into the body. Acute lead

Substance	Limit value [mg/m^3]
Silicon (Si)	10
Phosphorus (P)	0.1
Manganese (Mn)	1
Chromium (Cr)	0.5
Lead (Pb)	0.05
α-quartz, respiratory dust	0.1

Table 2: Limit values for substances in air in a working environment. (Arbeidstilsynet, 2011)

poisoning is rare, and it's more likely the lead poisoning will come slowly as a chronic lead poisoning (Store norske leksikon, 2009). This is caused by long term exposure to lead and symptoms include abdominal pain, anemia and damage of the nervous system. It can also harm the genetic material and pregnant women is thus recommended to stay away from places with lead exposure.

Crystalline silica, more specific α-quartz, can be used in the sand casting in foundries. This substance pose a risk on health for the workers residing in the polluted environment when exceeding the limit value given in Table 2. Crystalline silica is classified as a human lung carcinogen, and crystalline silica dust can cause irritation of the eyes mucous membranes and inhaling it may lead to silicosis, a pulmonary disease. The disease reduce the pulmonary function and makes people more susceptible to lung infections (Safety and Health Administration, 2002).

2.1.3 Handling of particle matter in an industrial environment

There are many different ways to handle particle matter depending on the surrounding; room geometry, pollution sources, temperature, humidity etc. An industrial environment is characterized by pollution from for example heating or chemical processes in the working place, and the handling is therefore different from the handling of CO_2 in for example an office. To control the heavy workplace air contamination in the industrial environment, there are seven key steps given by Tjelflaat (2016):

i) Eliminate the process producing the contaminants

   - Substituting to a non-hazardous or less hazardous material.

ii) Isolate the process

- Use of enclosed ventilation, booth to isolate the process or isolating the person.

iii) Minimize exposure

- Minimizing the exposure by ventilation (see Chapter 3, booths, new working procedures and/or working techniques.

iv) Control the contaminant at source

- Minimizing escape of contaminants to the room air by local exhaust ventilation, displacement ventilation in room or keep lids on volatile substances.

v) Monitor exposure to significant hazards

- Monitor both employees' exposure and their health consequences related to the exposure. The testing interval depends on the previous results.

vi) Personal protective equipment (PPE)

- When environment conditions can be hazardous to the worker, personal protection equipment is used. This can include protective shoes, safety glasses and respiratory masks. The equipment need to be maintained and replaced when the function is reduced.

vii) Information to employees

- Inform workers of hazards and what is necessary to control it and their responsibilities.

To eliminate or isolate the process might prove difficult, due to the nature of the process. Then the next step will be to minimize the exposure by ventilation. Such ventilation is presented in Chapter 3.

3 Protection by ventilation

When looking at the environments defined in context with ventilation, there are four main environments:

i) outdoor environment

ii) indoor environment

iii) local environment

iv) micro environment

When defining the purpose of the ventilation, choosing the right focus environment is important to achieve the right result.

3.1 Total volume air distribution

Today most ventilation systems is based on total volume air distribution (TVAD), dominated by mixing and displacement ventilation. These distributions focus on the indoor environment as a whole and an ”average” occupant. The concept of mixing ventilation is that the supplied air at ceiling height should cause mixing that leaves a homogeneous concentration of contaminants in the room, i.e. dilution of the contaminant concentration. Displacement ventilation supply air at floor level at lower temperature than the air temperature and uses the buoyancy forces to transport the contaminated air up to the exhaust at ceiling height. There have been some speculation in the efficiency of these ventilation methods, and Bolashikov et al. (2012) showed that mixing ventilation not always is efficient, depending on the environment conditions. Melikov (2016) points out some general disadvantages of TVAD:

- Air is supplied far from occupant and thus the air may be warm and polluted when it reaches the occupant zone.
- Difficult to control airflow interaction in the room due to changing of strength and distribution of heat loads.
- The airflow is based on average occupants, but humans have large individual differences and the ventilation is only set to give an satisfying environment for 80 % of the occupants.
- Slow responding system to changes in pollution and heat location and load etc.

3.2 Advanced air distribution (AAD)

Due to the above mentioned disadvantages of TVAD, Melikov (2016) propose a paradigm shift to advanced air distribution (AAD), to ensure improvements in the indoor environment. This type of air distribution focuses on supplying air close to the needed area. This means that the AAD works at a local or micro environment. This can in general by divided into personalized and personal ventilation. While the personalized ventilation is building attached, the personal is wearable equipment.

3.2.1 Personalized ventilation

The main concept of personalized ventilation (PV) is to provide fresh (clean and cold) air close to each occupant (Melikov, 2004). There are different types of protection ventilation, but one thing they all have in common is that their main purpose is to reduce the direct exposure of contaminants in the occupant's breathing zone. According to Melikov (2004) personalized ventilation (PV) has two main advantages compared to total volume ventilation (TV):

- Potential to improve the air quality of the inhaled air
- To give each occupant the opportunity to control temperature, local flow rate etc. according to their preferences.

Protected occupied zone ventilation (POV) was developed to protect office workers from epidemic respiratory diseases (Cao et al., 2015), but the same techniques can be used to protect workers in an industrial environment. POV involves separating the room area into subzones by means of air curtains or downward plane jets. The idea is that the plane jet shall prevent the contaminants from the contaminated zone (that is not occupied) to flow into the clean, occupied zone. Thus, it is important to find an effective 'protecting velocity' where the plane jet can separate the zones adequately. The efficiency and ability of protection from the plane jet increases when the plane jet is stronger than the contaminated air flow, but the plane jet may cause a strong mixing flow in the room. The downward plane jet can also be combined with another airflow distribution method. Then Cao et al. (2015) calls it hybrid protected zone ventilation (HPZV). When testing personalized ventilation in combination with mixing ventilation, Melikov et al. (2003) found that the quality of the inhaled air was either higher or equally good as compared to mixing ventilation alone. When combined with displacement ventilation, the inhaled air quality decreased when the flow rates of personalized air was low, which points out the importance of an effective 'protecting velocity'. Melikov et al. (2003) also concluded that a PV system supplying air against the face can improved the ventilation efficiency up to 13-20 times for floor pollution and bioeffluents (organic contaminants). A similar effect is discovered by Licina et al. (2014). Problems with PV and HPZV can be noise, thermal comfort issues and decrease in energy efficiency.

3.2.2 Plane jet

According to Guyonnaud et al. (2000) and Awbi (2003) a free air jet can be divided into four regions; potential core region, characteristic decay region (transition), axisymmetric decay region (developed) and the terminal region. This is illustrated in Figure 2. The potential core spans from the slot exit till 5 to 10 times the slot diameter, *d*, or jet thickness. The length of this region may vary with nozzle shape and turbulence in the air supply. This region is characterized by the constant centerline velocity that is equal to the initial velocity, U_0. In the characteristic decay region, or transition area, the centerline velocity starts to decrease as seen in Equation (1).

$$\frac{U_m}{U_0} \propto \frac{1}{x^n} \tag{1}$$

where x is the distance from the slot opening and n is an index between 0.33 and 1.

The velocity distribution is described by Guyonnaud et al. (2000) as Equation (2).

$$\frac{U(x,y)}{U_0} = \frac{1}{2}[1 + erf(\sigma_1 \frac{y + \frac{e}{2}}{x})] \tag{2}$$

The constant σ_1 is equal to 13.5 (Schlichting, 1968). The characteristic decay region is negligible for circular or square openings.

After around 20 d (diameters) the axisymmetric decay region, or developed region, begins. The flow here is highly turbulent, and the angle of spreading is constant throughout the region. In this region, the centerline velocity is decreasing inversely with the distance x, and is represented as Equation (3).

$$\frac{U_m}{U_0} = \frac{K}{\sqrt{x/h}} \tag{3}$$

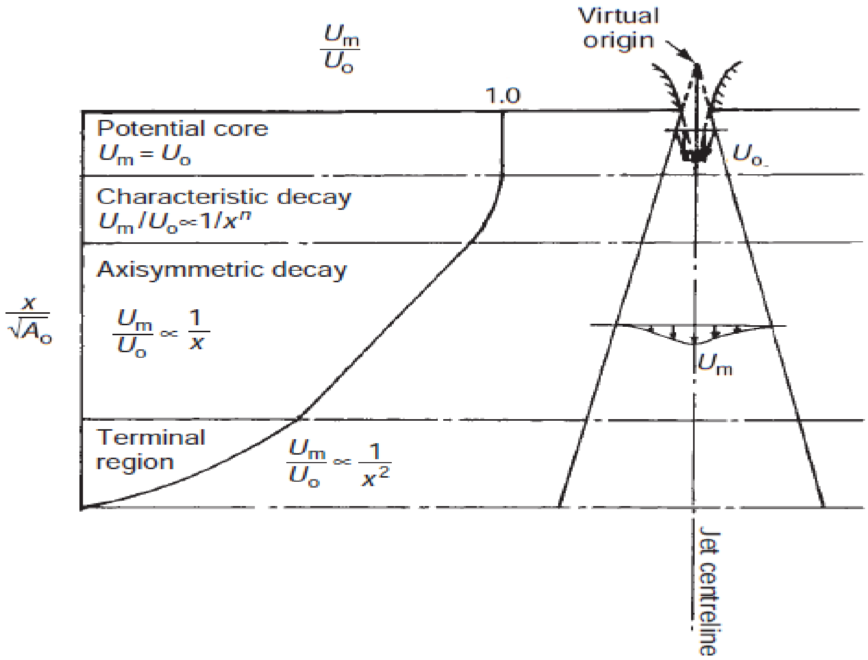


Figure 2: The four regions for a free jet (Awbi, 2003)

where U_m is the local maximum velocity at a distance x from the slot, U_0 is the supply velocity, K is the dimensionless constant of the jet, x is the distance from slot and h is the slot height. Awbi (2003) states that the value for K typically lies between 2.4 (Goertler solution) and 2.67 (Tollmien solution). When modelling the value for worst case scenario is often used.

In the terminal region, the velocity rapidly decrease and the jet is diffusing into the surrounding air. For the centerline velocity, the decay is:

$$\frac{U_m}{U_0} \propto \frac{1}{x^2} \tag{4}$$

3.2.3 Laminar downward flow

Laminar flow occurs when fluid or gas flows in parallel layers in an orderly fashion. For the laminar flow, the Reynolds number is low and the motion of the fluid or gas is smooth and constant. It is been widely used in hospitals the last decades (Perez et al., 2015). To obtain laminar flow, perforated plates can be used. Airflow through perforated plates can be complicated, but Awbi (2003) presented some models for the airflow velocities from a 20

% perforated plate. For the maximum velocity decay in axisymmetric decay (developed) region Equation (5) is valid:

$$\frac{U_m}{U_0} = \frac{K_v}{x/\sqrt{A_0}} \tag{5}$$

where $A_0 = C_d A$, where C_d is the discharge coefficient usually between 0.65 and 0.9 and A is the free area (Awbi, 2003). For a perforated plate with sharp edges, the $C_d = 0.65$ and the free area is gross area times the perforation degree. The value for K_v is given by Awbi (2003) as 4 for 20 % perforation and velocities down to 2.5 m/s. However, for smaller velocities, Fuglseth (2017) found that for distances 1.4 to 1.25 m away from the diffuser, $K_v \approx 0.824x + 0.87$, and for velocities above 0.2 m/s, the average $K_v = 1.44$.

A laminar, uniform flow can be used to counteract convective flows and thus decrease the maximum concentration level in the breathing zone. In such a case, the velocity of the downward flow is very important. If the velocity is low, no effect will occur, if the velocity is almost enough, the downward flow will slow down the upward convective flow and cause an increase in concentration levels, and if the downward airflow velocity is high enough to overpower the thermal plume, this can lead to a 13.5 reduction in the concentration level at the breathing zone (Licina et al., 2014).

3.3 Ventilation Efficiency

Tjelflaat and Sandberg (1996) defines the ventilation in a room as effective when it produces very good air quality in the breathing zone. However, this does not necessarily mean that the ventilation is efficient, since that implies little waste of effort. To measure the ventilation efficiency there are mainly two indices (Mundt et al., 2004):

- *Air exchange efficiency*, ε^{a}, measure of how quickly the room air is replaced.
- *Contaminant removal efficiency*, ε^{c}, measure of how quickly an contaminant is removed from the room.

However, with a change towards AAD and new ventilation methods, new ventilation efficiency indexes are created.

3.3.1 Air exchange efficiency

Air exchange efficiency involves the "age of air" concept. This is based on the simple assumption that the air picks up more contaminants the further it stays in the room, and thus the "age of air" can be determined. The comparison is done against a complete mixing scenario, where all air volume has the same age. This gives the nominal time constant (Tjelflaat and Sandberg, 1996):

$$\tau_n = \frac{V}{Q} \tag{6}$$

where V is the volume of the room and Q is the airflow rate. The air exchange efficiency is defined as ratio between the nominal time constant and the average air change time, measured. It is given in Equation (7)

$$\varepsilon^a = \frac{\tau_n}{2 < \bar{\tau} >} \tag{7}$$

where τ_n is the nominal time constant defined above and $< \bar{\tau} >$ is the average age of air. This equation applies for a complete room and the room-average "age of air" is measured in the extract air duct. The ratio in Equation (7) is 1 for an ideal displacement ventilation, also called piston flow. For full mixing the ε^a = 0.5, while it for displacement flow will be in the region ε^a = 0.5-1.0 (Grieve, 1989). The air exchange efficiency can also be checked for local zones within the room. The index for the breathing zone can be expressed by:

$$\varepsilon_b^a = \frac{\tau_n}{< \bar{\tau} >_b} \tag{8}$$

3.3.2 Contaminants removal effectiveness

The contaminant removal efficiency is based on the contaminant concentrations in the room. The concentration at the exhaust, C_e, is compared to the value measured in the room (Tjelflaat and Sandberg, 1996):

$$\varepsilon^c = \frac{C_e}{< C >} \tag{9}$$

where $< C >$ is the average concentration in the room. When there are contaminant concentrations in the supply, this is subtracted both from the exhaust and room concentration. If there are full mixing, the concentration throughout the room is homogeneous and equal to C_e, which gives an ε^c = 1. Typical values with displacement ventilation is ε^c = 1.5-2.0 for industrial systems and 1.0-1.3 for comfort systems. As for the air exchange efficiency, the contaminant removal efficiency can also be measured for local zones, like the breathing zone:

$$\varepsilon_b^c = \frac{C_e}{< C >_b} \tag{10}$$

The contaminant removal efficiency is used when information about heat and contaminant sources are known, and there are one or few dominant sources.

3.3.3 Personal protection efficiency

Although the contaminant removal efficiency is based on the concentration differences between the exhaust and the relevant zone, this index is based on a full mixing, and thus will not suit the ventilation efficiency for personal protection perfectly.

The efficiency and ability of protection from the plane jet increases when the plane jet is stronger than the contaminated air flow. According to Cao et al. (2014), the protection efficiency (PE) for a plane jet is defined as

$$PE = (1 - \frac{c_{t-zone}}{c_{source}})\ [\%] \tag{11}$$

where $c_{\text{t-zone}}$ is the exhaust concentration in the protected zone, and c_{source} is the exhaust concentration in the polluted zone. For a hybrid protected zone ventilation, the protection efficiency in the breathing zone can be expressed as

$$PE = (1 - \frac{c_{breathing}}{c_{exhaust}})\ [\%] \tag{12}$$

where $c_{\text{breathing}}$ is the concentration in breathing zone and c_{exhaust} is the exhaust concentration.

There are other personalized ventilation indices. This includes the personal exposure effectiveness (PEE), Equation (13), and personal exposure index (PEI), Equation (14).

$$\varepsilon_p = \frac{C_{IO} - C_{IN}}{C_{IO} - C_{PV}} \tag{13}$$

$$\varepsilon_{exp} = \frac{c_R}{c_{exp}} \tag{14}$$

C_{IO} is the inhaled air contaminant concentration without personalized ventilation, C_{IN} is the contaminant concentration in inhaled air, and C_{PV} is the contaminant concentration in the personalized air. The PEE is based on the principle that if only personalized air is inhaled, the effectiveness is 1. For the PEI, c_R is the exhaust concentration and c_{exp} is the exposure concentration. This means that it is high if the occupant is not exposed to contaminants.

3.3.4 Tracer gas measurements

The basic idea behind tracer-gas monitoring is to mark the air with an identifiable substance to be able to track the movement of air. This will help determine the "age of air" and thus the air exchange efficiency. The tracer gas is usually colourless, odorless, inert and not normally present in the environment. Common tracer gases are Nitrous oxide (N_2O), Sulphur hexafluoride (SF_6), and Carbon dioxide (CO_2) when the background concentration is constant (Grieve, 1989).

For tracer gas measurement there are three methods; pulse injection, concentration growth and concentration decay (Grieve, 1989).
The pulse injection method consists of pulses of tracer gas added to the supply air and measuring of concentration in the extract and at a point in the room. This method uses little tracer gas and has a quick response time.
In the concentration growth method, tracer gas is continuously fed into the supply air and the concentration of tracer gas in the room increase. This growth is monitored until the increase flattens out and the tracer gas concentration as approximately constant, as seen in Figure 3.

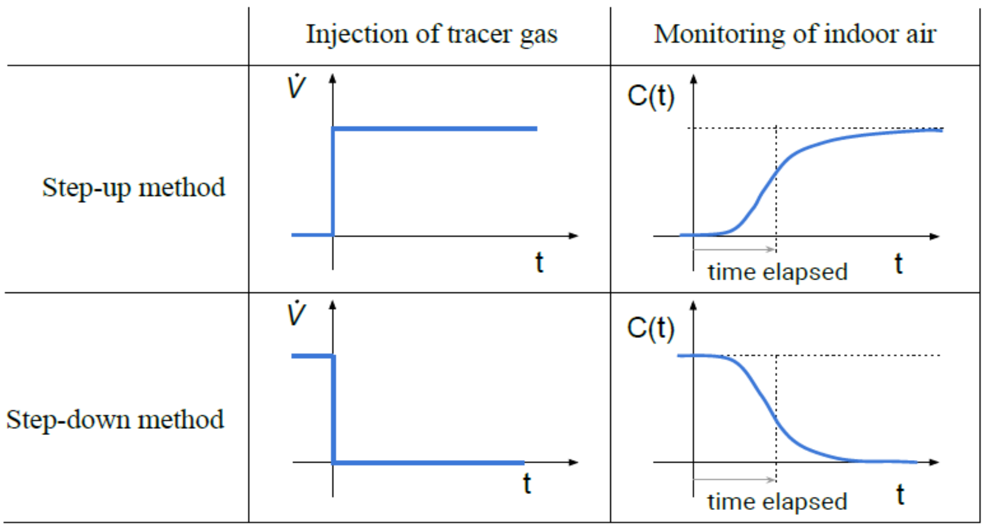


Figure 3: Principle of tracer gas concentration growth and concentration decay. (Søgnen, 2015)

The most common "age of air" method is the tracer gas concentration decay method. The principle of the injection and monitoring is shown in Figure 3. The tracer gas is added into the room until it has been perfectly mixed in the room air. The room air mixing is stopped and the concentration decay is caused by infiltration of unmarked outdoor air.

3.4 Occupants impact on environment

The purpose of ventilation is to protect the occupant, but the occupant's processes also contribute to the pollution and disturbances in the environment. At hospitals and in classrooms, this pollution contribute with a considerable load of the total pollution in the room, while it in an industrial environment will be a small contributor compared to the other processes in the factory. However, in a micro environment, the occupant's impact is a significant factor, even in an industrial environment.

3.4.1 Thermal plumes

Thermal plumes, also called convective plumes, are created by a surface warmer than the room air. Due to convection, heat is transmitted into the air and buoyancy forces makes the air rise. An equation for thermal plume from a point source is given by Skåret (2000) in Equation (15).

$$U_m = \frac{1.63}{{C_b}^{2/3}}(\frac{g\beta}{\rho C_p})^{1/3}(\frac{\dot{Q}_k}{y+y_p})^{1/3} \qquad (15)$$

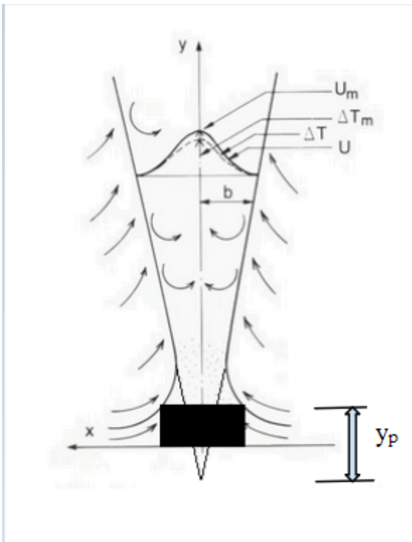


Figure 4: Thermal plume from a point source (inspired by Skåret (2000))

where C_b is the proportion factor for x and y, see Figure 4, and are estimated to 0.235, g is gravitational force, β is $\frac{1}{T}$, where T is the ambient temperature, ρ is the density of the air, C_p is heat capacity, $\dot{Q}_k$ is the convective heat, y is the vertical distance from the source, and y_p is the distance from source to an imaginary point source. The airflow entrain air and the volume increase with height, as seen in Figure 4, with an approximately constant angle. The heat source is usually also a pollution source, and thus the thermal plume often contribute to spreading contaminants in the room.

All occupants are sources for thermal plumes; a plume containing both contaminants released from our bodies as well as heat. A human thermal plume is hard to model due to individual differences, different heat production for different body part and position of the body. Therefore it is hard to find an equation that fits the thermal plume from a human. An approximation can be given by the thermal plume for a point source, Equation (15), while Zukowska et al. (2010) gives integral characteristics for the asymmetric plume.

3.4.2 Thermal manikin

Thermal manikins are used to simulate the performance of a human in experiments. This is a very complex and hard task, due to considerable variation in mean velocity due to human behavior and air stratification (Mierzwinski, 1980)(Zukowska et al., 2010). Tanabe et al. (1994) stats that there are three basic methods for heating up a thermal manikin; heating elements placed at

- the outer surface of the manikin
- the inside surface of the manikin
- the inside space of the manikin

To control the manikin, there are two different methods; to keep the heater temperature constant or to keep supply power constant.

To evaluate the power need for the manikin, the body surface are is needed, which can be calculated by an improved model of Du Bois surface area (Shuter and Aslani, 2000):

$$A_{bs} = 0.00949 m^{0.441} h^{0.655} \tag{16}$$

where A_{bs} is the body surface area in m^2, m is the weight in kg and h is the height in cm.

According to Murakami et al. (2000), the heat loss from a human body is consisting of 29.0 % convection, 38.1 % radiation, 24.2 % evaporation and 8.7 % respiration for a standing person with a metabolic heat production of 1.7 Met. With a manikin without breathing, the heat loss can be divided into convection and radiation with a percentage of the total heat loss 40 % and 60 %, respectively.

Hyldgaard (1998) concluded that the breathing had little effect on the thermal plume above the head of a thermal manikin, sitting or standing.

4 Design, processes and ventilation system at Jøtul

This chapter gives an overview of the building design, processes and the environment at Jøtul factory in Fredrikstad. The information is gathered from observation, the Jøtul database, interaction with workers and measurements performed autumn 2016 (Thune, 2016). The background theory on ventilation system and indoor air quality is discussed in Chapter 2.1 and 3.

The factory at Jøtul is a large factory for making wood stoves. This include the whole process from melting the iron and adding supplements to the packing of the finished wood stoves. The building is 35 000 m^2, with an average height of 7 m, which lead to a total volume of 245 000 m^3. The facility is divided into seven sections; melting hall, sand plant, processing, enamel, assembly, storage and pilot, as shown in Figure 1. An industrial building, especially one including melting of iron and casting, has large pollution sources. The biggest ones is in the melting hall, where iron is melted, transported and cast in casting sand. Throughout the factory there are other pollution sources as lacquering stations, drilling and grinding. The general ventilation system utilizes both displacement, mixing and pressure differences, as well at local exhaust. The supplies and exhausts in the factory are shown in Figure 7. In the melting hall, there are displacement; air is supplied at floor height and is extracted at ceiling height. This relies on buoyancy forces which is natural due to heat loads from melting of iron occurring here. In other areas in the factory both the supply and exhaust is placed close to the ceiling. The original ventilation sys-

Figure 5: Smoke created when melted iron is transported to the foundry

tem were designed to use pressure differences between rooms, to make the air flow from the cleanest zone to the most polluted zone, i.e. from the storage to the melting hall. However, measurements conducted in the factory in the autumn show that the air flows from contaminated zones into cleaner rooms. The factory is equipped with exhaust hoods over the melting ovens and processing stations, but due to unavailability of fixed hoods over for example the transport of melt, the contaminants can't always be handles at the source. This often leads to high levels of contaminants in the indoor air, see Figure 5 and can cause health consequences for the worker.

Location	$\mathbf{PM_{2.5}}$	$\mathbf{PM_{10}}$	$\mathbf{PM_{25}}$
Pilot	323	1107	1404
Melting area	563	6246	10455
Disa foundry	566	4248	6035
Greplassen	1058	7129	9371
Processing	320	1850	2385
Storage	41	392	565
Enamel assembly cells	39	268	379
Enamel	71	492	758
Assembly downstairs	141	427	582

Table 3: Particulate matter measured Thursday 27th October [$\mu g/m^3$]

Measurement of contaminant concentration in the factory was performed autumn 2016, for the project work Thune (2016), see Table 3. These indicates that the ventilation system is not able to handle the high pollution load. Although the levels are within the demand from Arbeidstilsynet (2011) for a working environment, see Chapter 2.1.1, the Folkehelseinstituttet (2015) and other organizations for human health, gives stricter limits, as seen in Table 1. The levels were worst in the melting hall, which is as suspected because the largest pollution sources are located here. Due to these high levels there should be used respiratory masks in this area.

As seen from Table 3, the highest levels for respiratory and thoracic particles are located at "Greplassen". This, as well as the limited working area here, make Greplassen the focus of this thesis. In this area, casting sand is cleaned off the stove pieces in Disa sandblaster. The pieces is transported on a belt out of the machine, and workers sort the different pieces into different containers, see Figure 6. The bits are not fully cooled in the cooling tunnel and the workers therefore have to wear thick gloves when handling the units. Along with the pieces, sand and other contaminants still remaining on the surface will be released into the air. Due to thermal plumes from the hot

Figure 6: Picture of Greplassen taken at Jøtul

pieces, these contaminants can be transported to the breathing zone of the workers, and thus cause a health risk both by small particles passing the larynx and crystalline silica, see Chapter 2.1.2. The temperature at Greplassen can vary from 20°C to 40°C, depending on the season. Since the environment here can be hot and quite heavy, the shift arrangement is so that there are three people per shift, whereas there are two working at a time, one on each side. The third worker has a 15 min break, before it releases the person who have worked the longest.

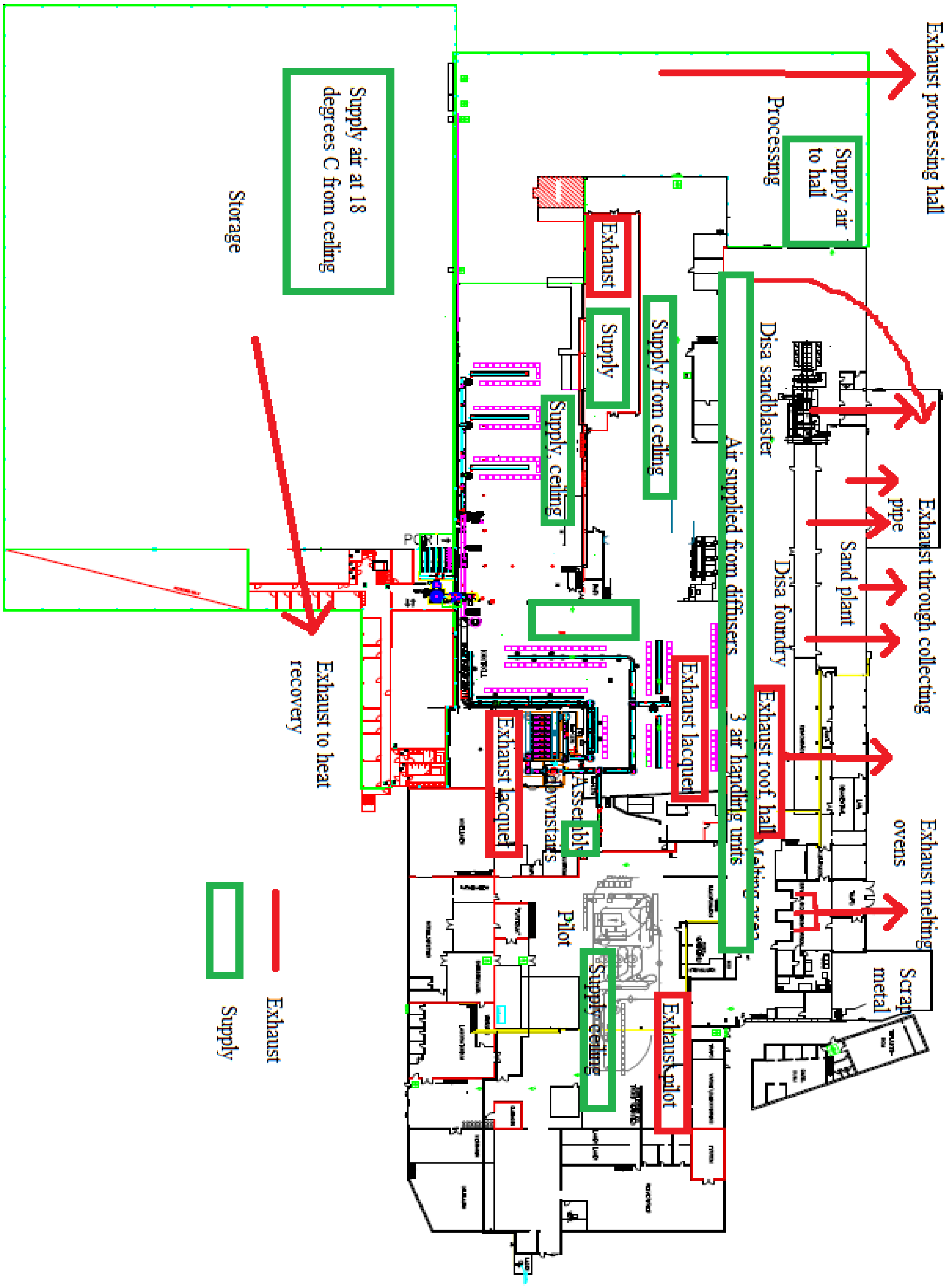


Figure 7: Supply and exhausts at Jøtul

5 Experimental setup and field measurements

In this chapter the method for field measurements and measurement setup for the lab is described. This involved both velocity measurement for the disturbance and particle matter concentrations around the worker. Risk assessment report for the experimental work can be found in Appendix D.

5.1 Field measurements at Jøtul

Background measurements at Jøtul were conducted 28th of February and 1st of March. Velocities, particulate matter concentrations, temperatures and airflow rate in the supply air were measured. For measuring, the following equipment were used: DUSTTREKII Aerosol monitor model 8532 for particulate matter, TSI VelociCalc air velocity meter model 8355 for velocities and airflow rate and Bosch PTD 1 thermal detector to measure surface temperature and room temperature. More information about these instruments are presented in Appendix C.

Figure 8: Greplassen at Jøtul, with dimensions

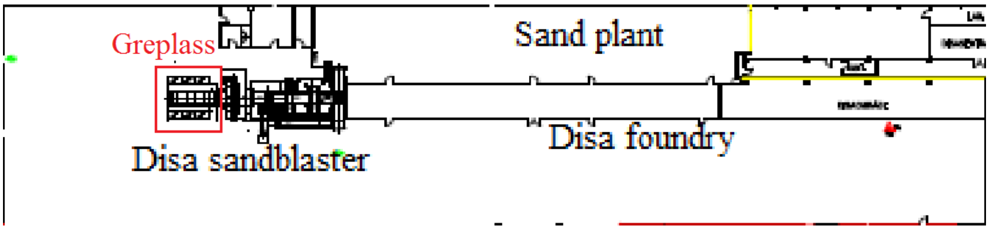


Figure 9: Location of Greplassen in the melting hall

The environment conditions were tested at Greplassen, seen in Figure 8 and Figure 9. The dimensions of the belt are 1.6 m x 4 m x 0.8 m for width, length and height, respectively. While the workers are moving in an area beside the belt which is 4 m long and 0.89 m wide. However, the worker is mainly staying in the middle of the area, with length of 2 m. The velocity and particulate matter concentration were measured simultaneously, with measurement points every 15 cm along the edge of the belt and at the other side of the workers platform. These measurements were conducted for height 1.5 m (Cao et al., 2014) and 1.63 m (Xing et al., 2001), which is the breathing zone of the worker. In addition to this, particulate matter at the melting area and foundry measured to register the improvement in the indoor air quality from measurement done in the autumn. To simulate the thermal plume of the oven pieces, the surface temperature were measured, as well as the room air temperature. For potentially to use the existing ventilation system in an improved solution, the airflow rate to the existing air supply in the area were measured.

5.2 Measurement setup at ClimateLab at NTNU

The measurement conducted at Jøtul in February/March 2017, were implemented in the ClimateLab at EPT, NTNU to simulate the environment at the Jøtul factory, in June 2017. The Climate room is 2.3 m x 4 m x 3.15 m for width, length and height, respectively, see Figure 10. There are mainly four elements in the room; plane jet, low-velocity downward flow, heated manikin and heated plate. Both diffusers are designed for earlier experiments by other students, but the laminar airflow (LAF) diffuser has been modified with a honeycomb.

The extract fans have a capacity of 872 m^3/h each, giving a total extract capacity of 1744 m^3/h. Due to short circuit flow from the plane jet, the extract on the left side in Figure 10, have a tube to extend the extract down to the floor (Fuglseth, 2017).

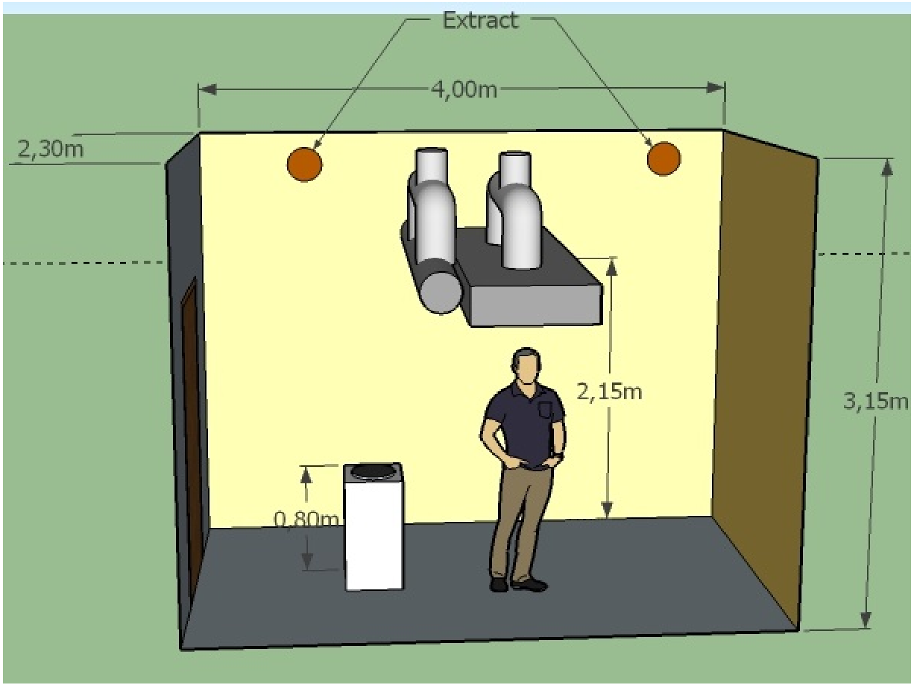


Figure 10: Sketch of ClimateLab at NTNU

5.2.1 Plane jet

The plane jet is built of a Ø250 pipe which is cut in the bottom. The diffuser is 2 m long, the width of the slot is 20 mm, and the slot outlet is 0.1 m, see Figure 11.

To distribute the air, there are two solid plates of wood at the pipe outlets, a perforated plate with 33 % air and a homemade honeycomb made with straws of about 3 mm. The inside of the diffuser is presented in Figure 12. Three solid plates are places on top of the perforated plate. This is done because it initially were too high velocities in the middle and thus this improved the air distribution.

The air to the plane jet is supplied by a central ventilation system. The airflow can be controlled both by the air handling unit, and by a damper in the climate room.

5.2.2 Laminar downward airflow diffuser

The laminar airflow diffuser (LAF) is 2 m long and 0.8 m wide, and were placed close to the plane jet to achieve co-flow situation Fuglseth (2017). This limits the height of the diffuser and thus make it a challenge to achieve

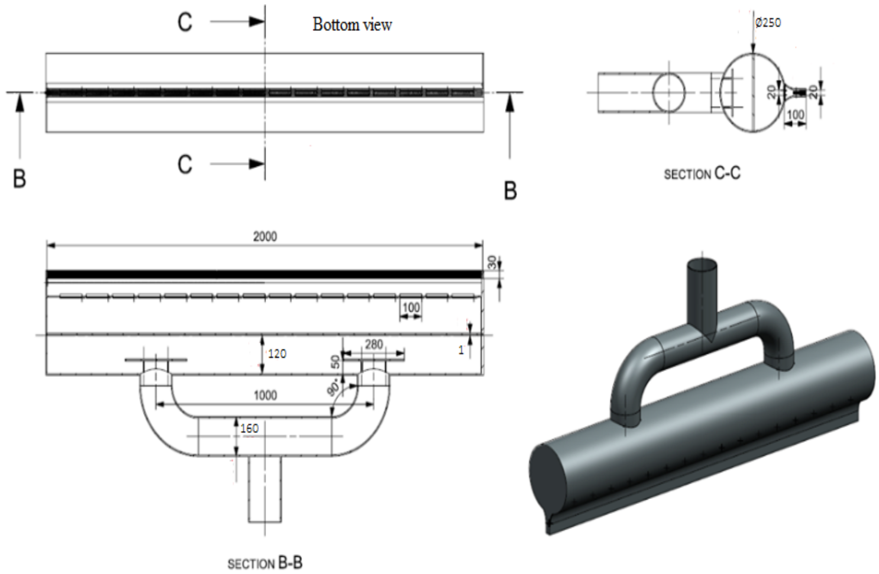


Figure 11: Measurements for the plane jet.

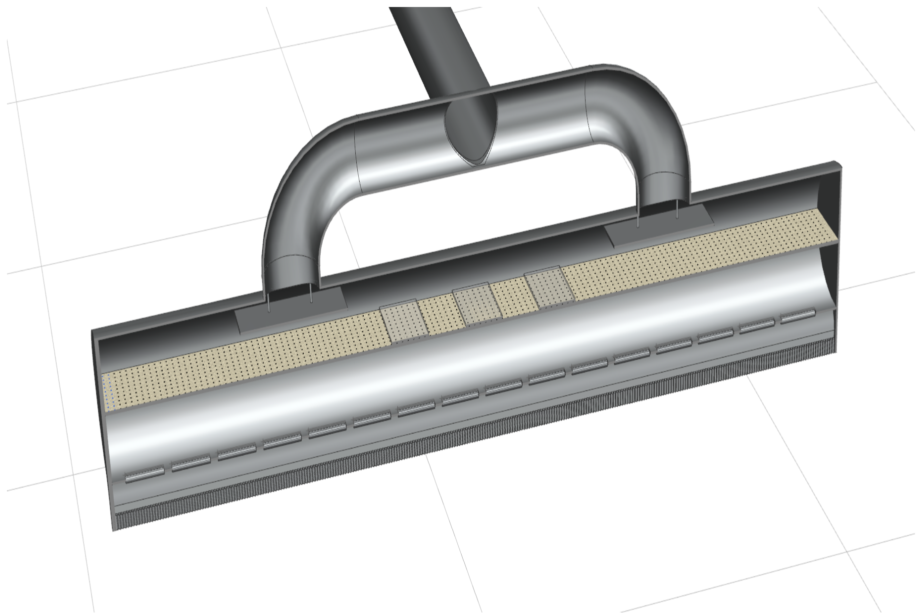


Figure 12: Inside structure of plane jet.

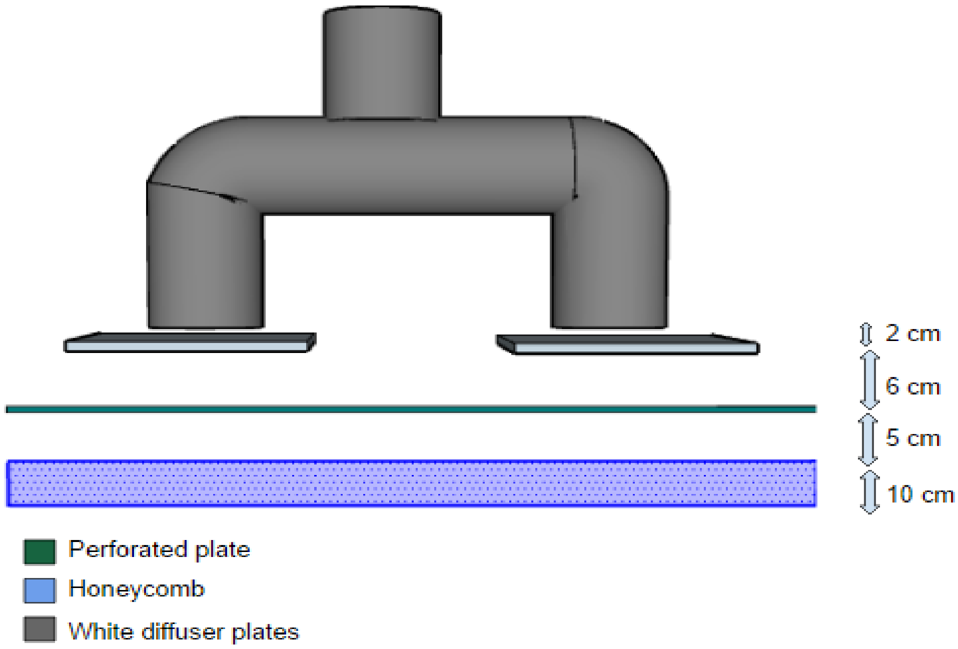


Figure 13: Structure of low-velocity downward flow

good air distribution and even outlet velocities. After testing with perforated plates and other distribution mechanism, the final solution was air distributors, 56 cm x 56 cm, at the pipe outlet to spread the air, then a perforated plate with holes of 3 mm and 33% and at the bottom, a honeycomb to make the flow more uniform, see Figure 13. Since there are only 14 cm from the pipe outlet to the honeycomb, and the surface area of the diffuser is so big, the air will not be evenly distributed. After much experimenting, the decision were made to focus on the distribution for an area 60 cm times 80 cm at the middle. This is the area above the manikin. The head of the manikin is 25 cm from the diffuser.

The air to this unit is supplied by a fan with a capacity of 3720 m^3/h placed in the climate room. This means that the supply air is not taken from the outside, and the control of supply temperature for this unit is therefore limited. The airflow rate is controlled by a manually adjustable valve. The needed valve opening were tested before the experiment and marked to easier adjust in the experiments.

5.2.3 Thermal manikin

To calculate the surface area of the manikin, Equation (16) was used with the height of 190 cm and assumption of 75 kg. This gave a body surface area of 1.98 m^2 for the manikin. The workers at Greplassen at Jøtul are doing medium heavy work and has an activity level of 2 Met. Since 1 Met = 58.15 W/m^2, the worker will have a heat loss of about 230 W (for room temperature of 23°C).

Body part	Needed power [W]	Supplied power [W]
Arm	23	15
Leg	60	60
Torso	51	60 (with head)
Head	13	60 (with torso)

Table 4: Heat loss per body part on manikin

To heat up the manikin, heat is supplied by heating cables inside the manikin, and thus heating up the manikin surface and releasing heat, see Figure 14. There are cables in all body parts. To calculate the needed power to the manikin, and thus type and length of cable, uniform heat production per m^2 were assumed. With the surface area per body part given in Appendix A, the power needed per body part is given in Table 4. Due to restricted lengths of the heating cable, the actual power supplied to each body part were reduces, see Table 4. The temperature is controlled in three places; in one leg, in one arm and in the torso, which is connected to the head. The assumption that the temperature is equal in both legs is utilized. This is also assumed for the arms. The heat distributed to the manikin is controlled by monitoring the inside temperature. In addition, measurement of the surface area were taken to assure a good surface temperature. By heating up the manikin from the inside, the heat is evenly distributed and will give a more natural heat loss. For more details on thermal manikin, see Appendix A. The manikin is placed in the middle underneath the laminar airflow diffuser.

5.2.4 Heated plate

The heated plate simulate the thermal plume from the hot oven pieces at Jøtul. To achieve this a hotplate is used, that is placed at a height 0.8 m above floor and 20 cm away from plane jet origin. This will give a constant heat plume, which is different from at Jøtul where the heat source move and weakens. The constant power supply is chosen to cover the worst case scenario.

Figure 14: Thermal manikin used in the experiments

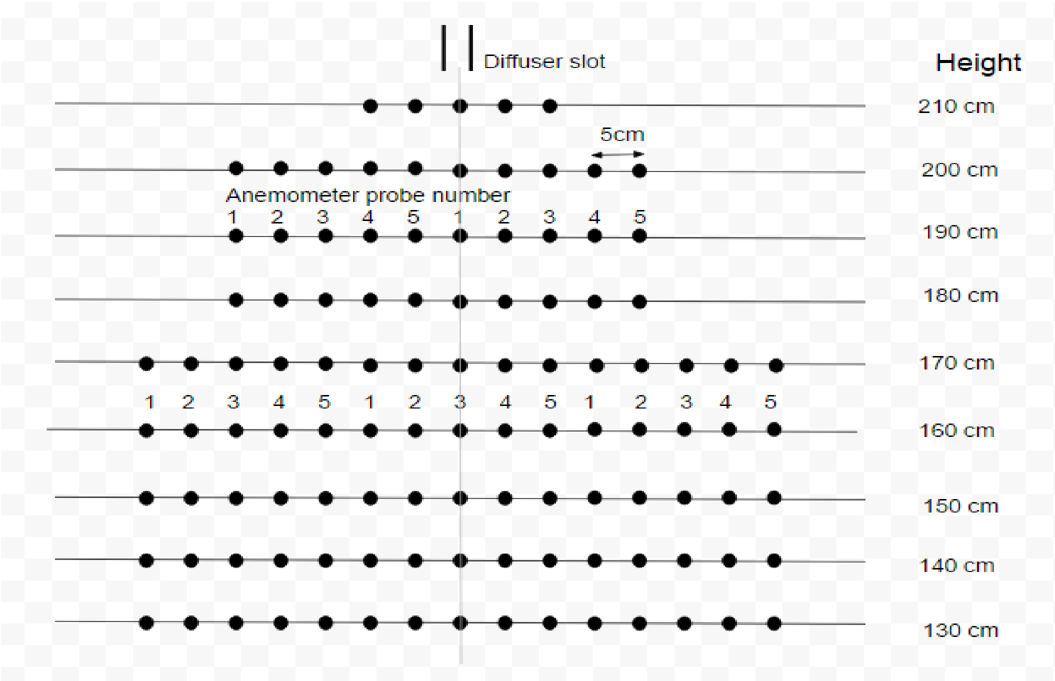


Figure 15: Measurement points used for plane jet experiments

5.2.5 Measurement series

There are mainly two types of measurement series; velocity measurements and tracer gas measurements. Velocity measurements are conducted to find the 'protection velocity' for the plane jet to prevent contaminants from entering the protected occupied zone, and for mapping the velocity distribution of the relevant area for the downward airflow. The tracer gas measurements are conducted to find the contaminant removal efficiency of the protected zone ventilation, and to see how different ratios of U_{jet}/U_{LAF} effect the protection efficiency.

5.2.5.1 Plane jet and heated plate

To determine the 'protection velocity' of the plane jet compared to the thermal plume from the heated plate, velocity measures were taken. For each jet velocity, the distribution of the jet is measured with and without the plate. The initial velocity distribution from the diffuser, U_0, over the 2 m length, was measured before measurements. These were quite similar, and thus the measurements are taken from a point in the middle of the jet, at horizontal planes at different height. The width of the horizontal plane is based on the theoretical angle of a jet, see Chapter 3.2.2. The measurement points are given in Figure 15. Each point is logged every 2 second for 3 minutes. The heated plate is a regular hotplate used for cooking, and it is set to give a surface temperature of approximately 170°C, and is placed 20 cm from the plane jet.

To measure the velocities the Air Distribution Measuring System AirDist-Sys 5000 was used. More information about the equipment is presented in Appendix C.

5.2.6 Tracer gas measurements

To measure the ability to remove air-borne contaminants, tracer gas is released in a continuous and constant flow at two points in the room; at the heated plate 0.8 m above floor and at the feet of the manikin, see Figure 16. The concentration of the tracer gas, N_2O, is measured at five locations in the room. One in the supply air to the laminar airflow diffuser, one at the exhaust and three at the height 170 cm underneath the laminar airflow diffuser. These three are placed at a line in the middle of LAF diffuser, perpendicular to the plane jet; one at the edge toward the jet (x0), one on the edge on the other side (x80) and one on the manikin in the middle. The measurement points is illustrated in Figure 16.

This means that a version of the tracer step-up method is used, and the concentration used in the calculations for protection efficiency is the values measured when a steady-state is achieved. The tracer gas measurements were tested with different airflow rates from the uniform downward flow and plane jet, and with and without the plane jet. The ratios are given in Table 5. The initial outlet velocity distribution is measured in the middle of the LAF diffuser, at 7 lines perpendicular to the plane jet, see Figure 17. The velocities chosen for LAF is based on the results of Licina et al. (2014). The values may be adjusted when seeing the result of the measurements. The measurements are preformed with the heated plate on, and with and without the plane jet to study the influence of the plane jet.

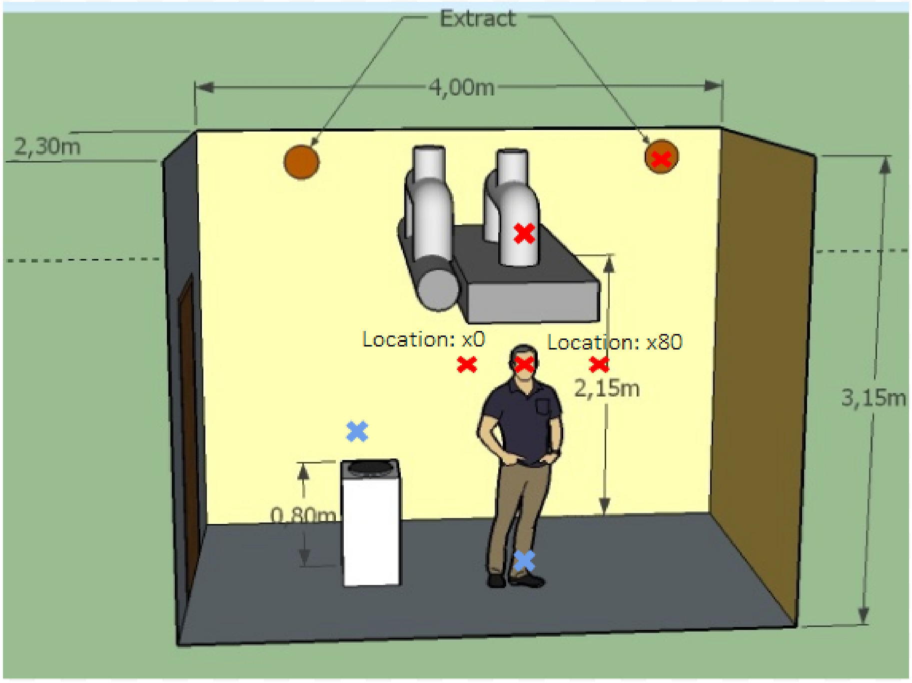


Figure 16: Measurement points (red) and supply (blue) of tracer gas

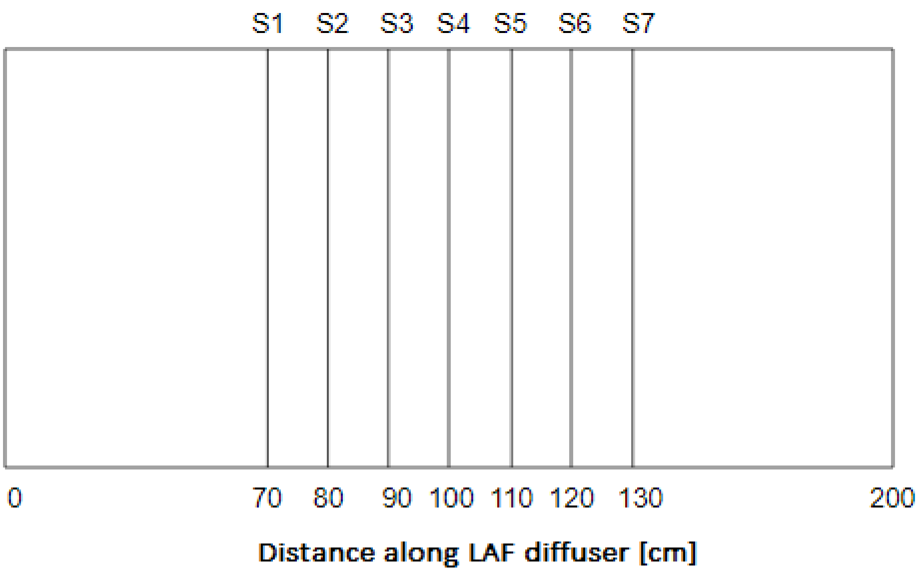


Figure 17: The measurement series taken for the LAF diffuser

U_{LAF} \ U_{jet}	0.15 m/s	0.2 m/s	0.25 m/s	0.3 m/s
0 m/s	1	6	11	16
0.6 m/s	2	7	12	17
1.0 m/s	3	8	13	18
1.5 m/s	4	9	14	19
2.0 m/s	5	10	15	20

Table 5: Numbering for the scenarios in the tracer gas experiments

6 Results

This chapter represents fieldwork, experiment results and the indoor climate survey. The measurements are presented in four different chapters; background measurements at Jøtul, velocity measurements with plane jet and heated plate, tracer gas measurements and indoor climate survey.

6.1 Field measurement results at Jøtul

The measurements performed at Jøtul 28th of February and 1st of March show that the air temperature at Greplassen is 23°C. However, temperatures of up to 40°C are reported in the summer. In addition is the temperature higher above the oven pieces, which can have a surface temperature of 170°C for the larger pieces. Smaller pieces are better cooled down in the cooling tunnel and temperatures of 80°C were measured. The velocity measured along the belt at Greplassen show that the average velocity on the limit between belt and working area is approximately 0.15 m/s, see Figure 18. This is quite low considering the plume from the oven pieces, and may indicate that the thermal plume is weak. However, there are several factors that may justify the possibility of significant plume. The velocity is measured in a horizontal direction, and thus will not capture the full magnitude of the thermal plume. In addition, there were some downward supply air that may have partially counteracted the plume. Due to the disturbance of the supply air, the velocity measurement is not a good representative for the influence of the environment on a new supply system. That is why the surface temperature of the oven pieces are simulated in the laboratory instead. However, these measurement insinuate that the room velocity at Greplassen is a little higher than that in the laboratory at NTNU, and thus indicate that the disturbance at Greplassen is greater than at the laboratory at NTNU. The volume flow rate of the existing pipe supplying Greplassen with air, were measured to 5650 m^3/h. This airflow is divided between the two sides of the belt, and thus the available flow rate for the area tested in the lab, is 2825 m^3/h. However, when measuring the particulate matter concentration in this supplied air, it revealed that this air is polluted, see Figure 19, and thus further contributes to the pollution of the occupied zone. To utilize this existing ventilation system, the air ducts needs to be cleaned.

The particulate matter concentration measured at Greplassen show an huge improvement compared to the concentration taken in the autumn 2016, as seen in Figure 20 and Figure 21. The values measured in the spring vary

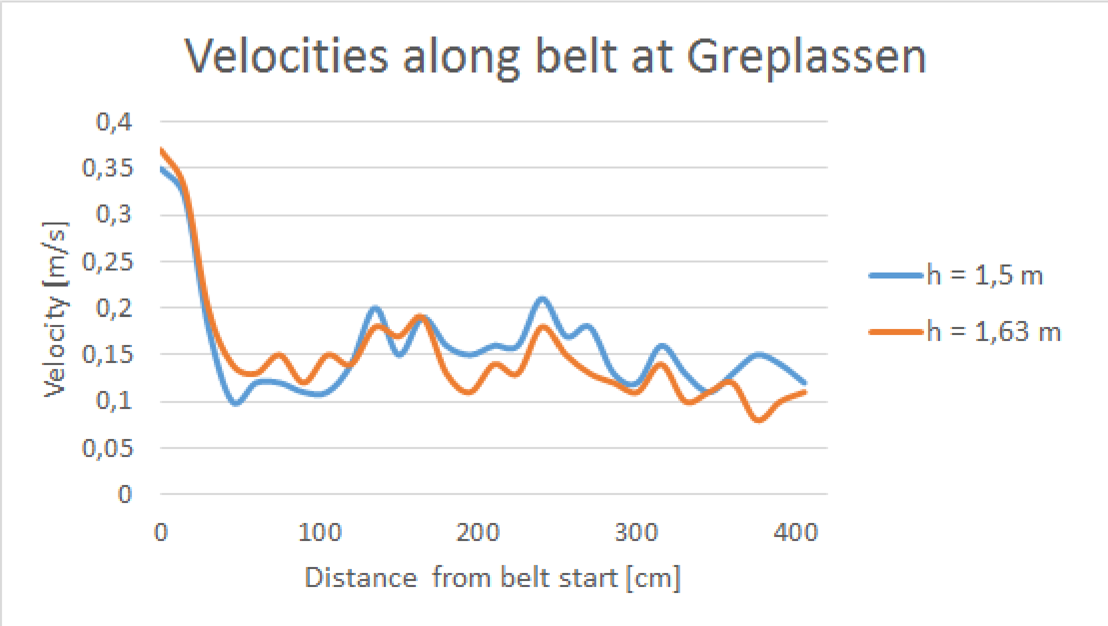


Figure 18: Velocity measured along belt for two heights at Greplassen

around 0.2 mg/m^3 for PM_{10} and somewhat lower for $PM_{2.5}$, which is well within the requirement for a 8-hour working day from Arbeidstilsynet (2011), but higher than the 24-hour mean for both World Health Organization (2005) and Folkehelseinstituttet (2013), as seen in the figures. The P_{10} and $PM_{2.5}$ concentrations are also well underneath the 25% limit of maximum limit for a 8-hour working day and thus no action is needed according to Arbeidstilsynet (2011). However, as presented in Chapter 2.1.1 there is "no threshold below which $PM_{2.5}$ would not pose a risk." Besides, the air at Greplassen contains crystalline silica, type α-quarts, and this share in the air is not measured in this thesis. Since the improvement of ventilation system is done at the exhaust for the smoke from melted iron, it can be these particles that are removed from Greplassen and making crystalline silica a bigger share of the total respiratory particles in the air. As presented in Figure 20, the $PM_{2.5}$ concentration is over the limit for crystalline silica, type α-quartz, respiratory dust, given by Arbeidstilsynet (2011). Tests done by Stamina presented in Thune (2016) reveal that this concentration have been over the limit in 2015. The workers use respiratory protection to reduce the exposure, and in general perceive the particle concentration in the air as too high, see Chapter 6.4. To prevent the need for respiratory masks and improve the perceived air quality, a protected zone ventilation system is recommended.

Something to notice about the concentration measurements at Greplassen

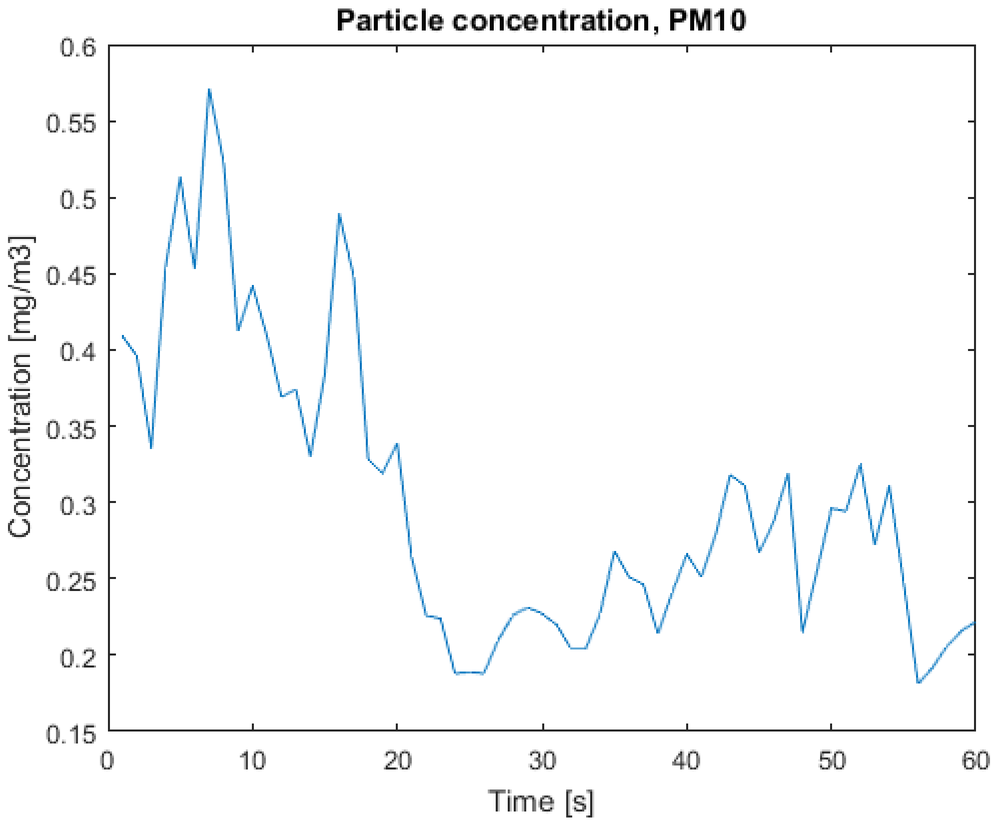


Figure 19: Particulate matter concentration in the supply air to Greplassen

is the peaks that occur on both sides of the worker area; towards the belt and towards the container. This is presented in Figure 22, and is caused by the contaminated thermal plume from the pieces. The concentration on the belt side is higher, and the peaks are more remarkable at the belt side, since the surface temperature decrease the longer it is in the room air, and thus the thermal plumes weakens and the spread of the sand particles decrease.

Due to the decrease in the concentrations measured at Greplassen spring 2017 compared to the measurements from autumn 2016, the concentrations at the melting area and foundry was retested, the locations are marked in Figure 23. The mean result are presented in Table 6. The concentration in the whole melting hall has improved. This support the assumption that it is the smoke particles containing metals that are extracted better and reduce the total PM_{10} concentration. This further indicates that the percentage of crystalline silica of the total particle concentration can be quite high. The

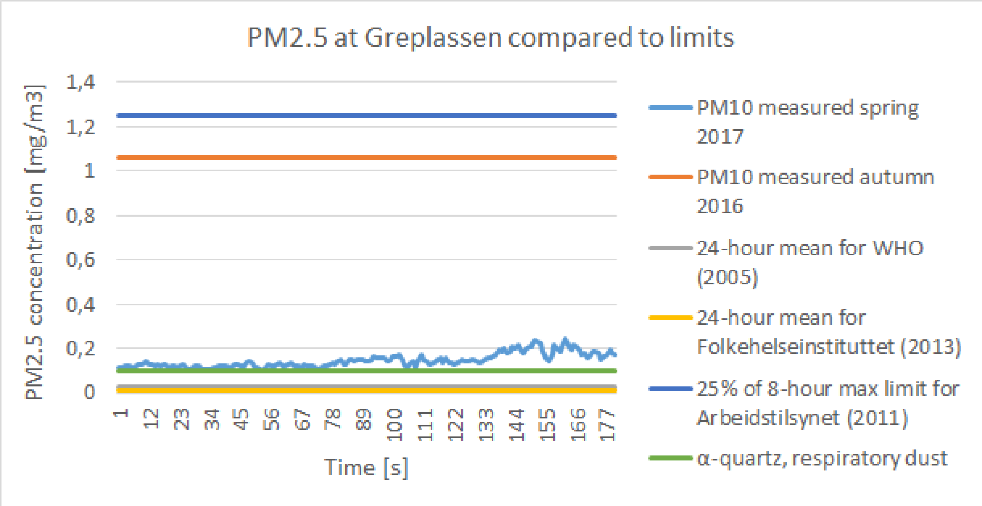


Figure 20: $PM_{2.5}$ concentration at Greplassen compared to limit values

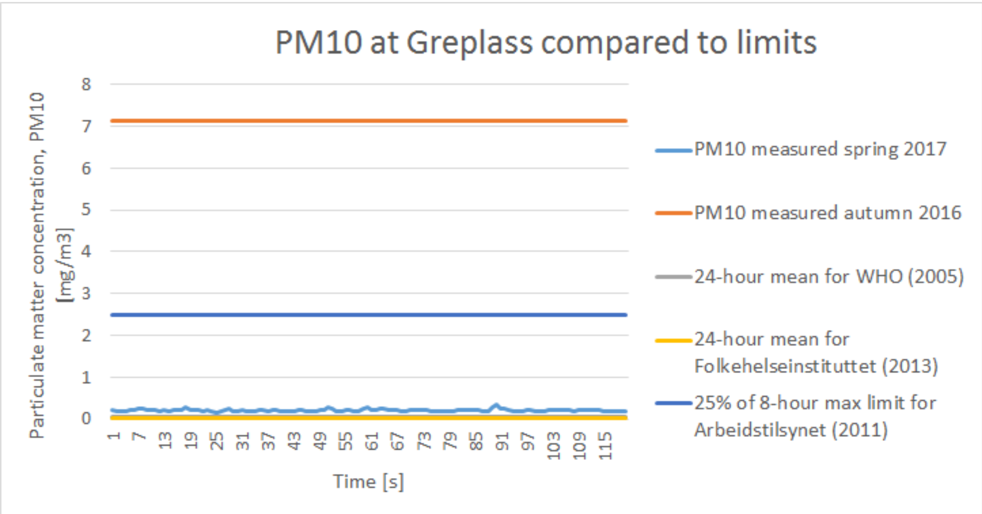


Figure 21: PM_{10} concentration at Greplassen compared to limit values

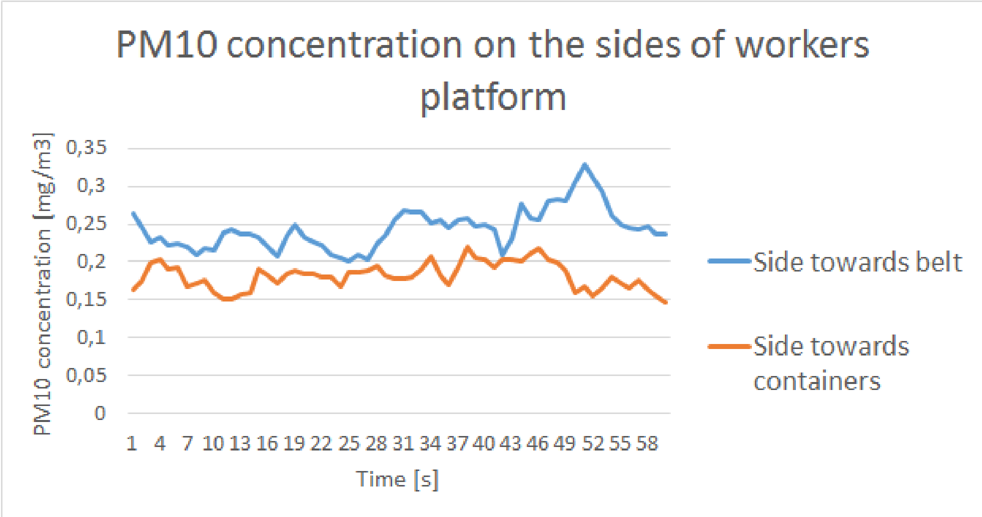


Figure 22: PM_{10} concentration at both sides of the working platform

value of $PM_{2.5}$ is only a little lower than PM_{10} concentration, and since the α-quartz particles are respiratory, this can indicate that this share in the total pollution may be high. However, the concentrations measured at the locations varied much; from 0.9 to 2.5 mg/m^3 for the melting area, 0.3 to 0.7 mg/m^3 for the foundry and from 0.1 to peaks up to 0.5 mg/m^3 for Greplassen.

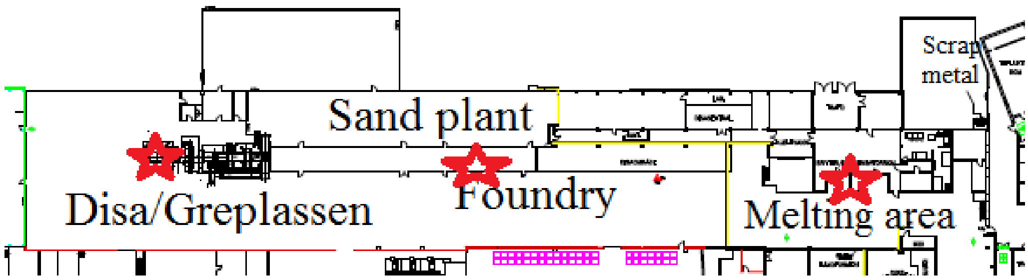


Figure 23: Measuring locations for particulate matter concentration at Jøtul

Location	**PM_{10} concentration [mg/m^3]**
Melting area	1.43
Foundry	0.44
Greplass	0.22

Table 6: Particle concentration in melting hall measured spring 2017

6.2 Velocity measurements at Climate Lab, NTNU

The velocity distribution for the plane jet for $U_0 = 2$ m/s is represented in Figure 24. This velocity is presumed to have the highest degree of accuracy compared to theory since it is the highest in the experiments. By higher momentum in the jet, it is less vulnerable to disturbances in the room.

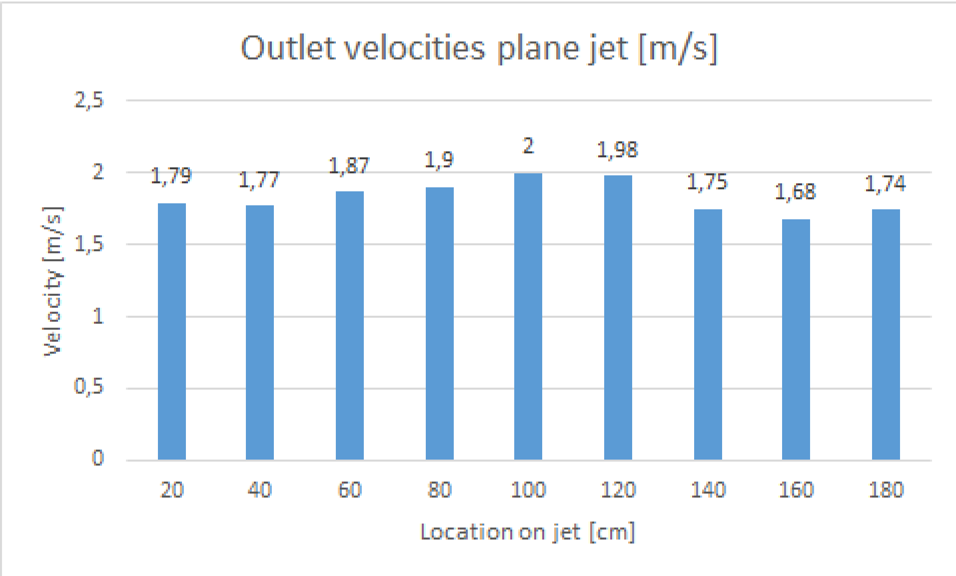


Figure 24: Initial outlet velocities for plane jet

For velocity distribution for LAF, initial velocities were tested for all the velocities used in the tracer gas measurements. The measurement series are illustrated in Figure 17, and the result is showed in Table 7–10. The airflow is not evenly distributed, and this cause an uncertainty in the measurement results.

Distance on short side of LAF [cm]										
	0	**8**	**16**	**24**	**32**	**40**	**48**	**56**	**64**	**72**
S1	0.03	0.00	0.15	0.18	0.18	0.00	0.01	0.10	0.12	0.37
S2	0.16	0.16	0.19	0.19	0.22	0.11	0.14	0.16	0.17	0.12
S3	0.22	0.22	0.22	0.22	0.03	0.21	0.19	0.21	0.22	0.17
S4	0.17	0.16	0.17	0.16	0.03	0.20	0.18	0.21	0.23	0.12
S5	0.14	0.14	0.14	0.14	0.20	0.14	0.14	0.14	0.14	0.20
S6	0.09	0.12	0.14	0.16	0.05	0.08	0.10	0.10	0.11	0.11
S7	0.04	0.00	0.07	0.13	0.02	0.00	0.07	0.09	0.10	0.33

Table 7: Initial outlet velocities [m/s] for LAF at 0.15 m/s

Distance on short side of LAF [cm]										
	0	**8**	**16**	**24**	**32**	**40**	**48**	**56**	**64**	**72**
S1	0.06	0.11	0.22	0.25	0.04	0.07	0.03	0.14	0.19	0.16
S2	0.29	0.25	0.26	0.28	0.05	0.21	0.20	0.22	0.23	0.25
S3	0.28	0.25	0.27	0.33	0.06	0.29	0.28	0.29	0.31	0.22
S4	0.18	0.20	0.20	0.20	0.06	0.27	0.29	0.25	0.32	0.19
S5	0.16	0.22	0.17	0.14	0.25	0.15	0.16	0.18	0.20	0.16
S6	0.08	0.14	0.18	0.21	0.25	0.07	0.14	0.14	0.13	0.23
S7	0.09	0.02	0.11	0.17	0.06	0.03	0.14	0.14	0.15	0.21

Table 8: Initial outlet velocities [m/s] for LAF at 0.2 m/s

Distance on short side of LAF [cm]										
	0	**8**	**16**	**24**	**32**	**40**	**48**	**56**	**64**	**72**
S1	0.09	0.10	0.28	0.36	0.11	0.12	0.12	0.08	0.26	0.29
S2	0.43	0.36	0.36	0.37	0.12	0.26	0.23	0.28	0.29	0.21
S3	0.36	0.33	0.37	0.42	0.23	0.38	0.38	0.37	0.41	0.18
S4	0.22	0.24	0.25	0.22	0.15	0.36	0.33	0.33	0.40	0.20
S5	0.16	0.26	0.18	0.19	0.12	0.16	0.19	0.23	0.24	0.23
S6	0.03	0.13	0.22	0.27	0.17	0.09	0.16	0.17	0.16	0.35
S7	0.12	0.10	0.15	0.19	0.22	0.03	0.19	0.18	0.19	0.27

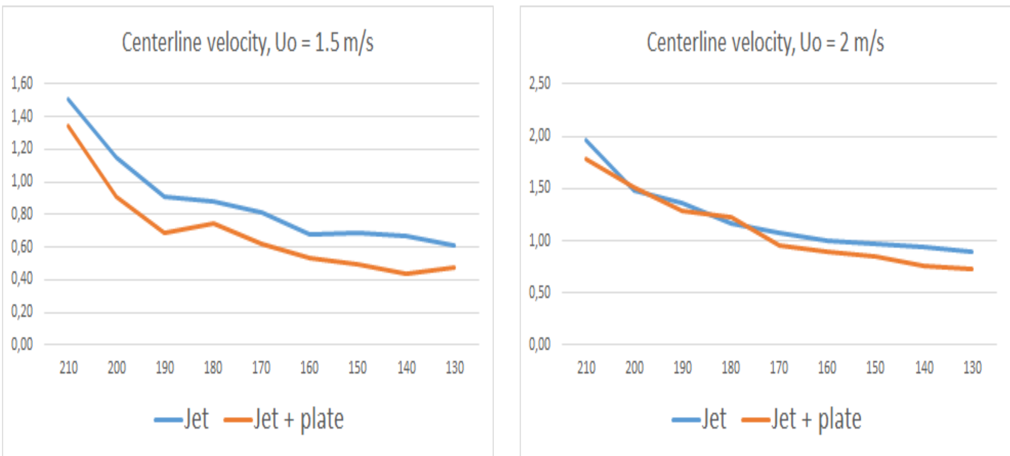
Table 9: Initial outlet velocities [m/s] for LAF at 0.25 m/s

Distance on short side of LAF [cm]										
	0	**8**	**16**	**24**	**32**	**40**	**48**	**56**	**64**	**72**
S1	0.10	0.07	0.28	0.38	0.16	0.18	0.19	0.10	0.25	0.28
S2	0.42	0.36	0.42	0.46	0.10	0.30	0.26	0.31	0.33	0.27
S3	0.34	0.26	0.46	0.55	0.11	0.44	0.46	0.45	0.49	0.23
S4	0.25	0.28	0.28	0.26	0.13	0.43	0.42	0.44	0.50	0.26
S5	0.20	0.31	0.20	0.20	0.20	0.22	0.23	0.25	0.27	0.28
S6	0.05	0.20	0.27	0.33	0.11	0.12	0.20	0.19	0.21	0.40
S7	0.16	0.11	0.19	0.20	0.27	0.08	0.19	0.18	0.21	0.31

Table 10: Initial outlet velocities [m/s] for LAF at 0.3 m/s

6.2.1 Plane jet and heated plate

The necessary 'protection velocity' to prevent the polluted upward flow from the heated plate to penetrate the plane jet were tested. The centerline velocities for the plane jet compared to the velocities with the heated plate are presented in Figure 25. For the initial outlet velocity of 1.5 m/s, the centerline is about 0.2 m/s lower for the scenario with the heated plate than without. For 2 m/s the centerline velocity is approximately equal until 45 cm from the diffuser outlet. This means that the upward plume from the hotplate affect the whole centerline of the jet for U_0 = 1.5 m/s, but doesn't affect the plane jet significantly for height 170 cm and up for U_0 = 2 m/s. This indicates that for U_0 = 2 m/s, the pollution from the plate will not



(a) U_0 = 1.5 m/s

(b) U_0 = 2.0 m/s

Figure 25: Centerline velocity of plane jet with and without hotplate

reach the breathing zone in the protected zone and 'protection velocity' is reached.

The measurements also showed that the centerline offsets to the right, towards the laminar airflow diffuser. This is clearly seen in Figure 26. Already at a height of 170 cm, the centerline have shifted from the origin of the jet. The offset is about 10 cm at the height 130 cm. Since the distance between the plane jet and laminar airflow diffuser is only 6 cm, this offset means that the jet crosses over into the downward laminar airflow area, and affect the boundary conditions for the laminar flow more than expected. This will occur from the height of 170 cm and thus affect the breathing zone of the occupant. But as long as this flow is downward it will not counteract the laminar downward flow and cause a co-flow.

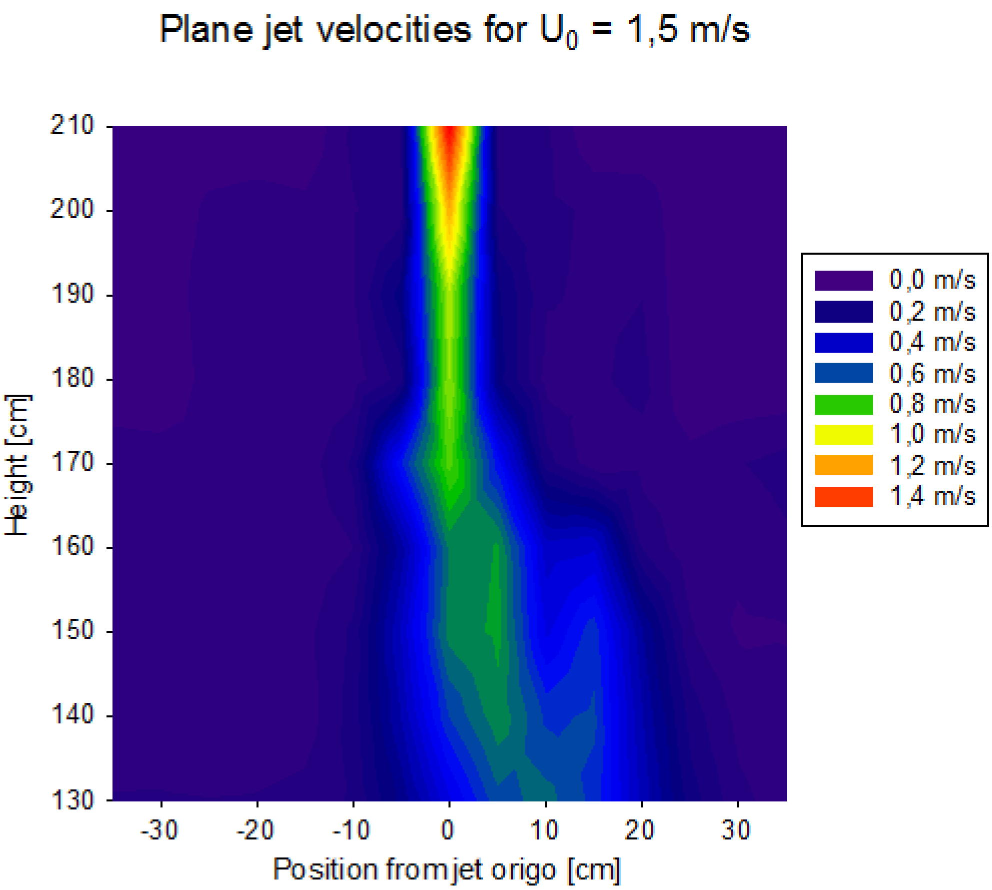


Figure 26: Velocity distribution for the plane jet without the heated plate, $U_0 = 1.5$ m/s

Figure 27 and Figure 26 presents the velocity distribution under the jet with and without the heated plate, respectively. The velocities on the left side of the jet centerline in Figure 27 is upward heated flow from the hot-plate. This is also shown in the increase of temperatures on this side. The temperature in the room in general is 2°C higher when the hotplate is on than without it. When interacting with the downward plane jet, the upward heated plume decrease the downward flow velocity and offsets the centerline of plane jet from the origin position already between 180 and 190 cm above the floor. The velocity measurements were omnidirectional, which mean that direction is unknown, and it does not show if the upward or downward flow is the dominant. However, both the distribution and temperatures indicates

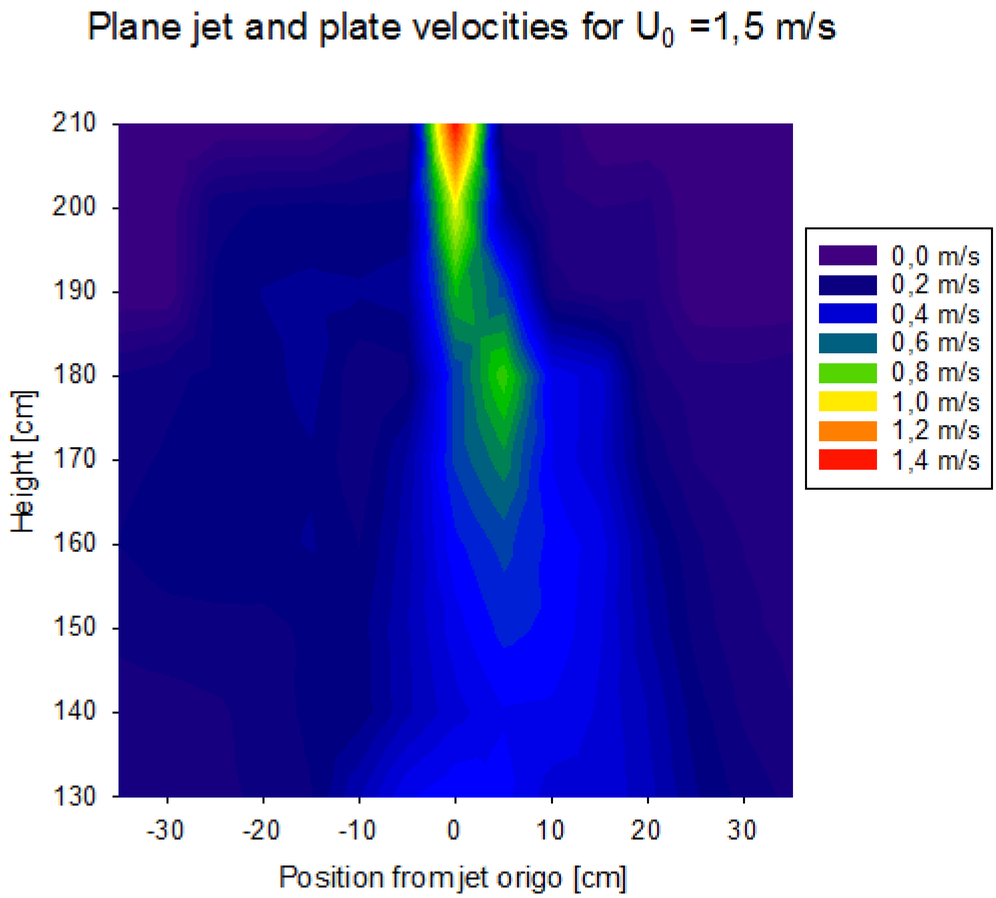


Figure 27: Velocity distribution for the plane jet with the heated plate, U_0 = 1.5 m/s

that the plane jet is stronger than the convective plume from the hotplate also at 130 cm. But the velocity is lower here and centerline offset. This means that any outer disturbances may cause the protection to break. The room air velocity measured at Jøtul may be enough to break through the jet. This can indicate that the air at breathing zone may be polluted from the a heat source on the opposite side of the jet for this velocity.

The velocity distribution for a initial outlet velocity of 2 m/s, with and without a heated plate, is presented in Figure 28 and Figure 29. The offset for this velocity seems less than for $U_0 = 1.5$ m/s, with the offset being approximately 5 cm at the height 130 cm instead of 10 cm. As for the measurement with initial velocity of 1.5 m/s, the left side of the jet is dominated by the upward plume from the hotplate in Figure 29. The difference in Figure 29 compared to Figure 27 is that velocity gap between the upward velocity from plume and downward plane jet is much clearer all the way. There are no visible shift of position for the plane jet either, and this indicates that the plane jet is strong enough to not be affected by the upward plume. This also means that the sensitivity to room air disturbances is reduced. Tolerance for disturbances is important due to movement both of occupants and other environmental changes. Due to the strength of the plane jet, pollution will not penetrate the protected zone.

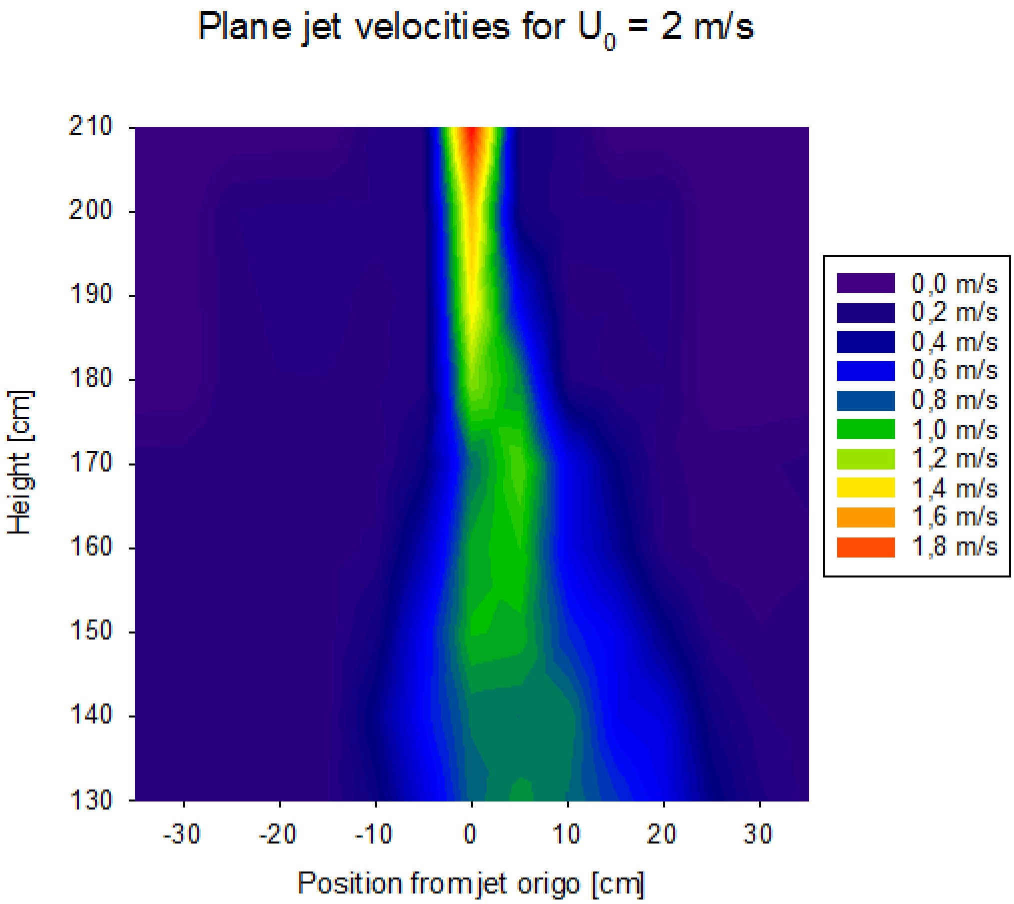


Figure 28: Velocity distribution for the plane jet without the heated plate, $U_0 = 2$ m/s

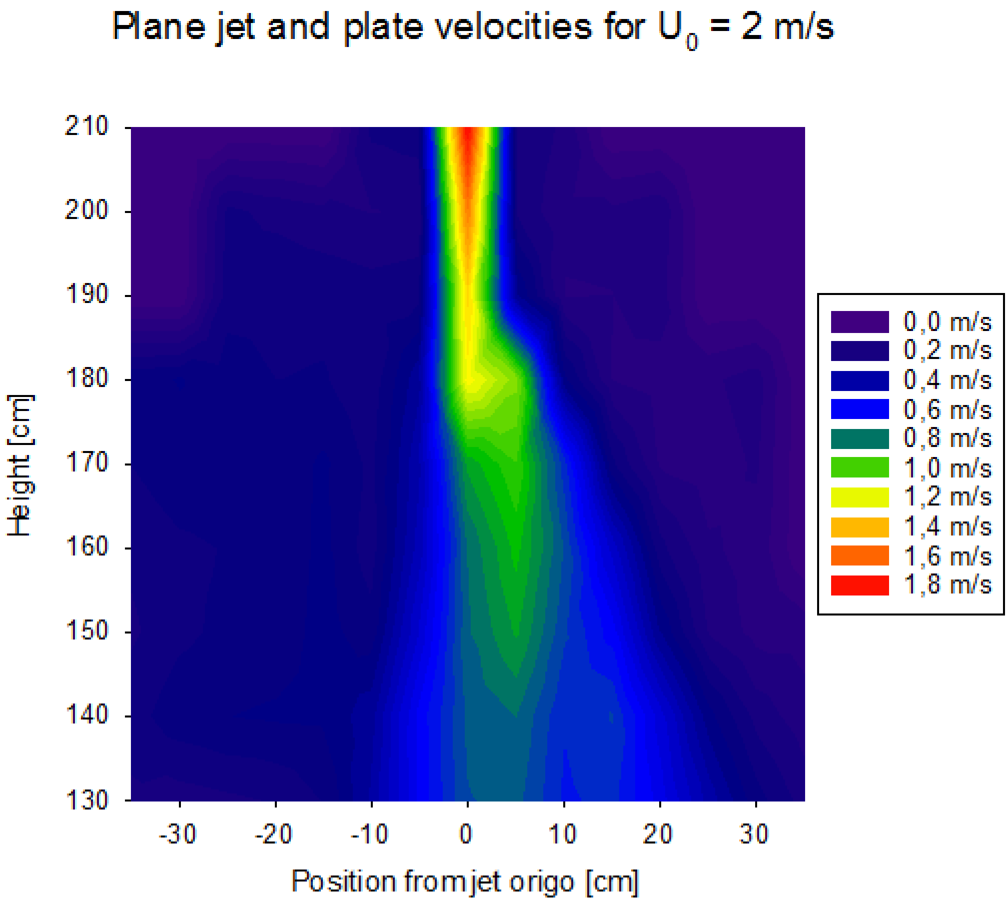


Figure 29: Velocity distribution for the plane jet with the heated plate, U_0 = 2 m/s

6.3 Tracer gas measurements at Climate Lab, NTNU

In the tracer gas measurements the volume flow rate of the two diffusers were measured, and the total volume flow rate of supplied air in each scenario is presented in Table 11.

The tracer gas measurement equipment is presented in Appendix C. The tracer gas supply varies a little due to pressure drops in the pressure regulator, seen in Figure 30. In this measurement the ventilation is off, so the tracer gas concentration increase over time. The figure shows that the tracer gas concentration supply in the measurements is not constant and will vary with peaks whenever gas is released. Thus this needs to be considered when the ventilation efficiency is calculated. This also means that the ratio between the local concentration and exhaust, must be taken for the peak concentrations.

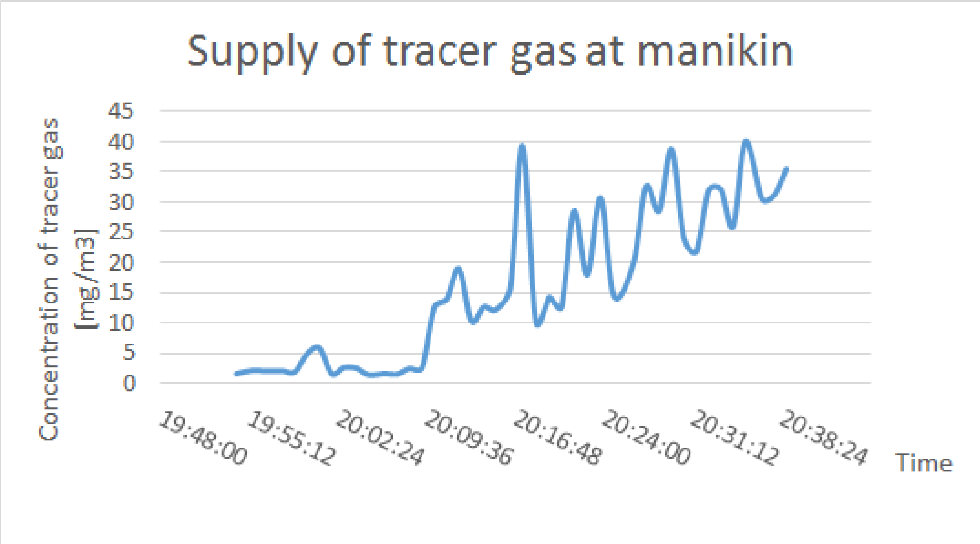


Figure 30: Concentration of tracer gas at manikin without ventilation

U_{jet} \ U_{LAF}	0.15 m/s	0.2 m/s	0.25 m/s	0.3 m/s
0 m/s	720	1191	1409	1688
0.6 m/s	806	1277	1495	1774
1.0 m/s	864	1335	1553	1832
1.5 m/s	936	1407	1625	1904
2.0 m/s	1008	1479	1697	1976

Table 11: Total volume flow [m^3/h] of supplied air for the combination of U_{jet} and U_{LAF} in the experiments

The protection efficiency (PE) for the manikin in all the scenarios in the tracer gas experiment are presented in Table 12. These are calculated by the use of Equation (12) presented in Chapter 3. In these calculations, the supply concentration is subtracted.

Scenario	**Protection efficiency (PE) for x0**	**Protection efficiency (PE) for x80**	**Protection efficiency (PE) for manikin**
6	0.788	0.922	-4.992
7	0.858	0.648	-29.942
8	0.918	-0.070	-38.439
9	1.063	0.684	-31.235
10	1.264	-0.047	-63.520
11	0.270	0.969	-8.618
13	0.557	0.938	-8.138
14	0.984	1.036	-20.349
15	1.029	0.297	-41.805
16	-0.189	0.910	-3.114
18	0.898	1.029	-35.321
19	1.275	0.895	-12.782
20	1.190	0.951	0.902

Table 12: Protection efficiency (PE) for the three location in breathing zone for the scenarios in the tracer gas experiment

As seen in Table 11, the protection efficiency for the location x0 in general is high. However, the efficiency is notably lower for U_{LAF} of 0.25 m/s and 0.3 m/s when U_{jet} = 0 m/s. This is reasonable since there is nothing to prevent the contaminants from the hotplate to reach this point. It also show the LAF velocity of 0.2 and 0.25 m/s, respectively, at this point is not enough to protect the occupants from this pollution source. For all the cases when U_{jet} = 2 m/s, the protection efficiency is over 1, which means that the purpose is reached. Also for the velocity of 1.5 m/s is the protection efficiency high, around 1, and this may indicate that with the co-flow from the LAF, the plane jet only needs a velocity of 1.5 m/s to protect the occupant from this pollution source.
For the location x80, the PE is high, almost 1, for all the scenarios for U_{LAF} = 0.3 m/s. This means that at this velocity, the LAF diffuser can handle the contaminants in this zone. The variation for the lower velocities is due

to the sensitivity to disturbance from the room environment.
For the manikin location, the PE is highly negative, meaning that the manikin concentration is many times the exhaust concentration. However, at the scenario 20, the PE is 0.9, which means that it is almost no contaminants in the breathing zone.

Manikin location

Since one of the tracer gas supplies is placed at the manikin legs, the measured concentration at the manikin breathing zone will tell how well the downward flow counteract the thermal plume, and thus if the air in the breathing zone is fresh. Using Equation (5), with a $K_v \approx 0.75$ for a distance 0.25 m from the diffuser (Fuglseth, 2017), the expected velocity that hits the head at each test velocity is presented in Table 13. The effective area, $A_0 = C_d A = 0.65 * (0.8 * 0.6) m^2 * 0.33 = 0.103$ m^2.

Initial outlet velocity, U_0 [m/s] from LAF	**Calculated velocity at manikin head, U_m [m/s]**
0.15	0.14
0.2	0.19
0.25	0.24
0.3	0.29

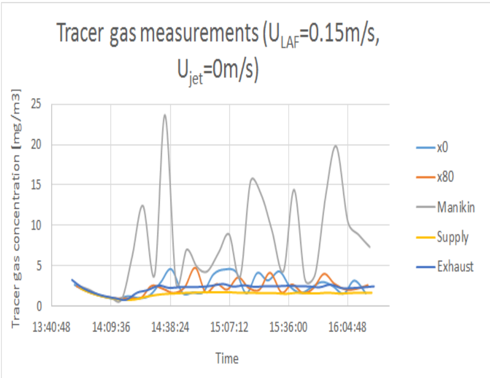
Table 13: Calculated velocity at manikin head using Equation (5)

When looking at the tracer gas measurements for $U_{LAF} = 0.15$ m/s and 0.2 m/s, see Figure 31, the peaks are of approximately 20 mg/m^3, which is the concentration supplied tracer gas concentration. This means that at these outlet velocities, the airflow is too weak to make an impact in the breathing zone.

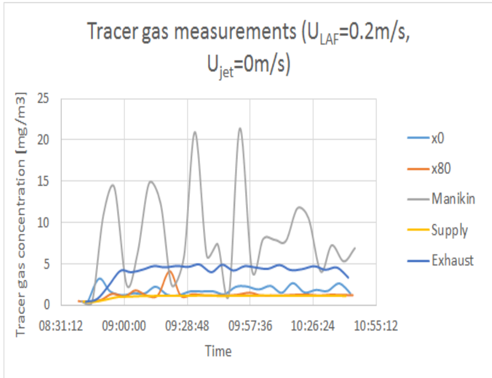
For the initial velocity of 0.25 m/s, concentrations higher than the supplied tracer gas is measured, as seen in Figure 32. This is caused by the downward flow being only slightly weaker than the upward plume, and thus the upward plume velocity is slowed down in this area, and causes the contaminants to accumulate. This is the same pattern Licina et al. (2014) experienced with a sitting manikin.

When $U_{LAF} = 0.3$ m/s, the tracer gas concentration starts to decrease under the supplied concentration at the manikin, but it is not until the U_{jet} = 2 m/s that the concentration at the manikin is underneath the exhaust concentration. This is shown in Figure 33–35.

The manikin concentration is lower when the plane jet is off than when it has a velocity of 1 m/s. This is not as expected, as the concentration



(a) U_{LAF}=0.15 m/s



(b) U_{LAF}=0.2 m/s

Figure 31: Tracer gas concentrations for laminar airflow diffuser without the plane jet

should be the same or higher. This is probably caused by sources of error, for example that the supplied tracer gas concentration were lower, or that the concentration output for the two supply tubes is varying. For Figure 34(b), the high concentration at the start is due to pressure in the pressure regulator by closing valve on the gas tank between measurement series. For a jet velocity of 2 m/s, see Figure **??**, the concentrations is generally low. This means that the tracer gas doesn't reach the measurement location, but also that the tracer gas is diluted into the room, and the concentration at the exhaust is only around 3 mg/m^3.

Location: x0

The location called x0 is the measuring point at the edge of the laminar airflow diffuser, towards the plane jet, at height 170 cm. This means that it will lie within the distribution of airflow from the plane jet. As seen in Figure 33, the location x0 have a quite stable concentration of 5 mg/m^3. When the jet is on, the concentration is visibly lower, as seen in Figure 34. This means that the plane jet has an effect. This is further implied in Figure 35, where the increased velocity of the jet leads to a $\varepsilon^c > 1$ for all locations. However, at most of the measurements in the experiments, the concentration at x0 is around the value for the exhaust. This implies that the air here is as in the rest of the room, and might suggest that the tracer gas supply placed by the hotplate doesn't give a constant flow, and sometimes nothing at all.

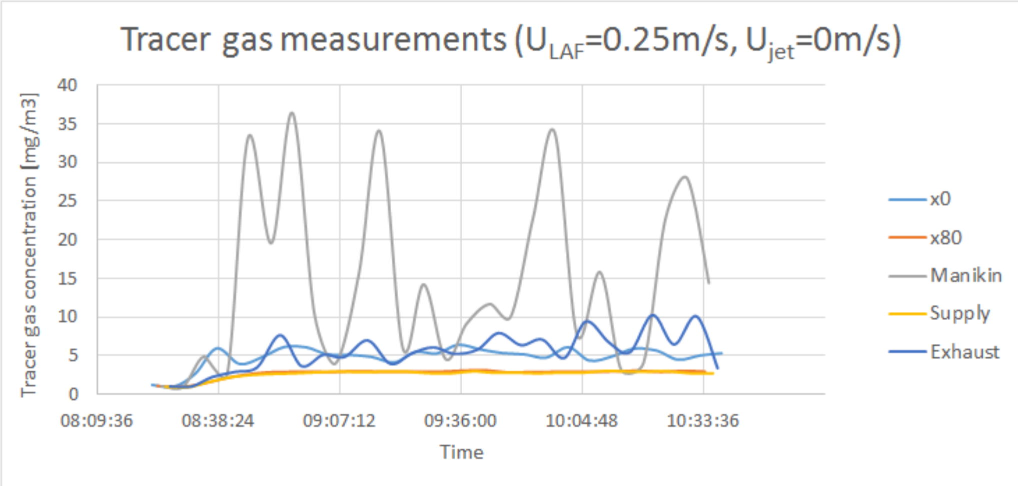


Figure 32: Tracer gas concentration for U_{LAF} = 0.25 m/s without plane jet

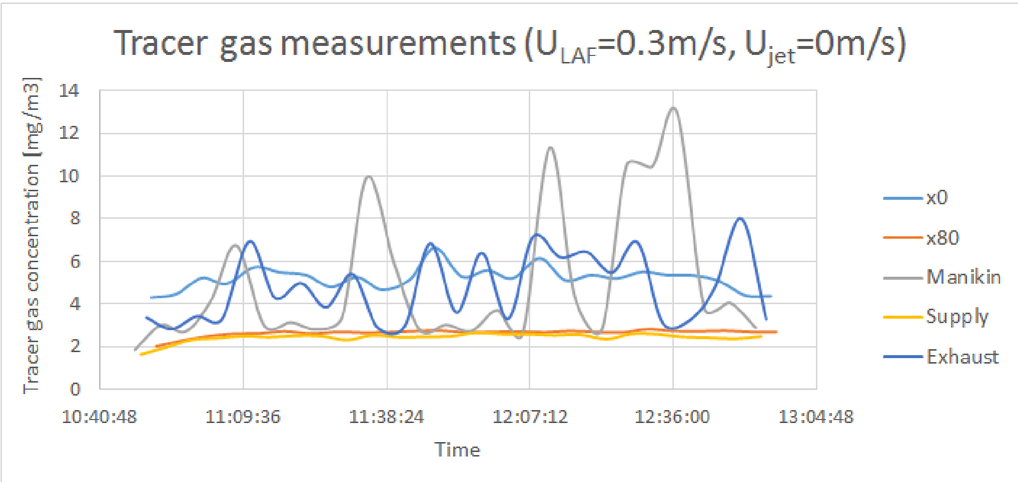
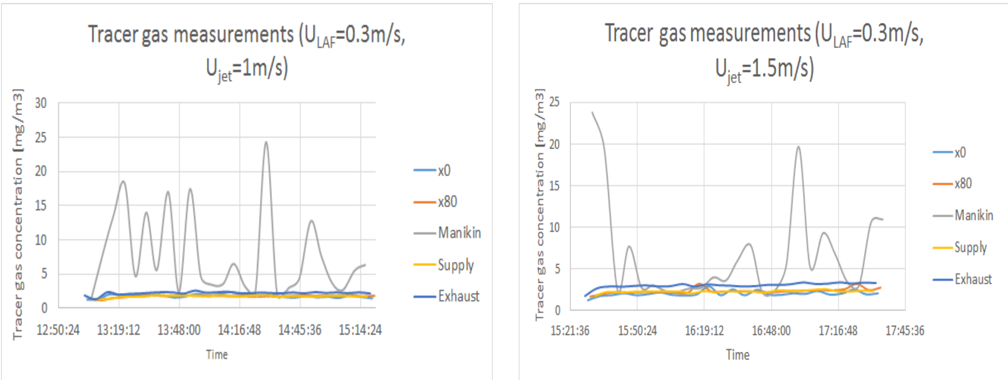


Figure 33: Tracer gas concentration at five locations for U_{LAF}=0.3 m/s and U_{jet}=0 m/s

Location: x80

The location called x80 is the measuring point at the edge of the laminar airflow diffuser, not towards the jet, at height 170 cm. This will lie on the boarder between the protected zone and the room air. It is mostly around the same as the tracer gas concentration in the supply air, but have some peaks at lower velocities for the laminar airflow. These peaks can be seen in context with peak concentrations at the manikin, but is only a fraction of these. Since the tracer gas supply is placed on the front side of the manikin, the



(a) U_{jet}=1 m/s (b) U_{jet}=1.5 m/s

Figure 34: Tracer gas concentrations at five locations for U_{LAF}=0.3 m/s

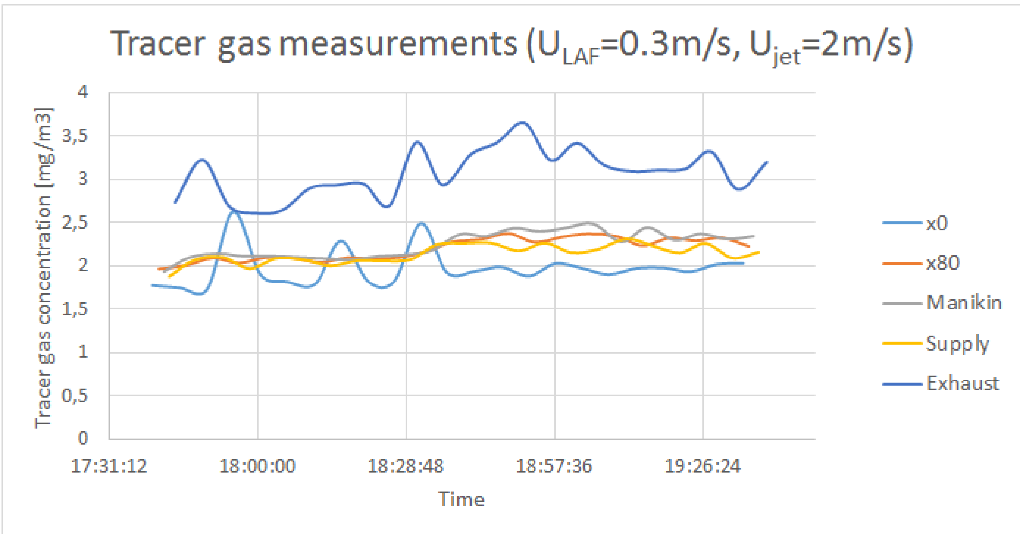


Figure 35: Tracer gas concentration at five locations for U_{LAF}=0.3 m/s and U_{jet}=2 m/s

concentration is therefore often small. The fact that the concentration have peaks for lower velocities can mean that the downward flow only contributes to spread the contaminants in an horizontal direction.

6.3.1 Correction for real situation

From the experiment, the total volume flow needed to obtain protection against contaminant exposure is 1976 m^3/h. This is lower than the existing capacity to the area. However, to fit it to a real life situation some changes needs to be calculated and adjusted for. For a height of 0.5 m between head and outlet, the velocity hitting the head for U_0 = 0.3 m/s is 0.28 m/s when using K_v = 1.44. To have a velocity of 0.29 m/s at this height, the initial outlet velocity need to be 1.31 m/s. However, to be sure that the supply velocity is high enough, a velocity higher than this is recommended, at least when the airflow capacity allows it.

6.4 Indoor climate survey

The indoor climate survey was given to the workers in the melting hall, and 9 workers answered. The questionnaire is given in Appendix E.

When asked how the workers perceive the indoor air quality, the majority were dissatisfied, as shown in Figure 36. Only 11% answered that the air

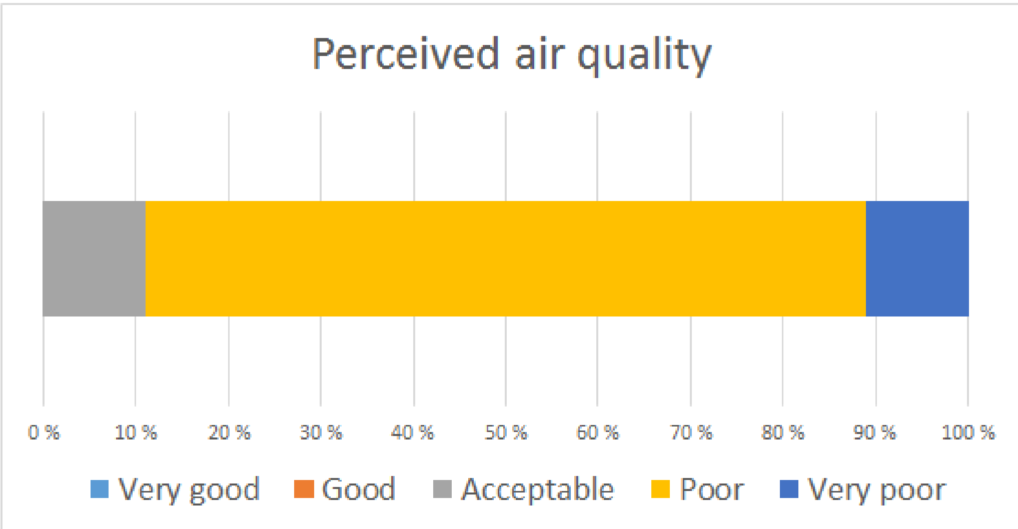


Figure 36: Perceived air quality in the melting hall

quality is acceptable, which is far from the 80% ASHRAE (2007) finds necessary to define it as an acceptable indoor air quality. In fact the perceived indoor air quality is so poor that all the participants perceived the outdoor air as fresher than the air from the ventilation system. This is supported by the concentration levels measured in the supply air at Greplassen that shows this air in fact is polluted. 56% also perceived the air quality to decrease during the day and vary between subzones in the melting hall. Half of the workers believe this to be caused by the ventilation system's inability to remove contaminants created in the hall. Another reason for the poor perceived air quality for 33% of the participants can be that they can't control the air quality. In addition is the air supplied to the needed area limited.

The dissatisfaction with the indoor climate is further presented in Figure 37, which shows perceived discomfort factors over the last three months. The survey reveals that all participants have experienced some discomfort with the indoor air due to temperatures, humidity, draught and/or particles in the air. The most remarkable is that 78% of the workers in the melting

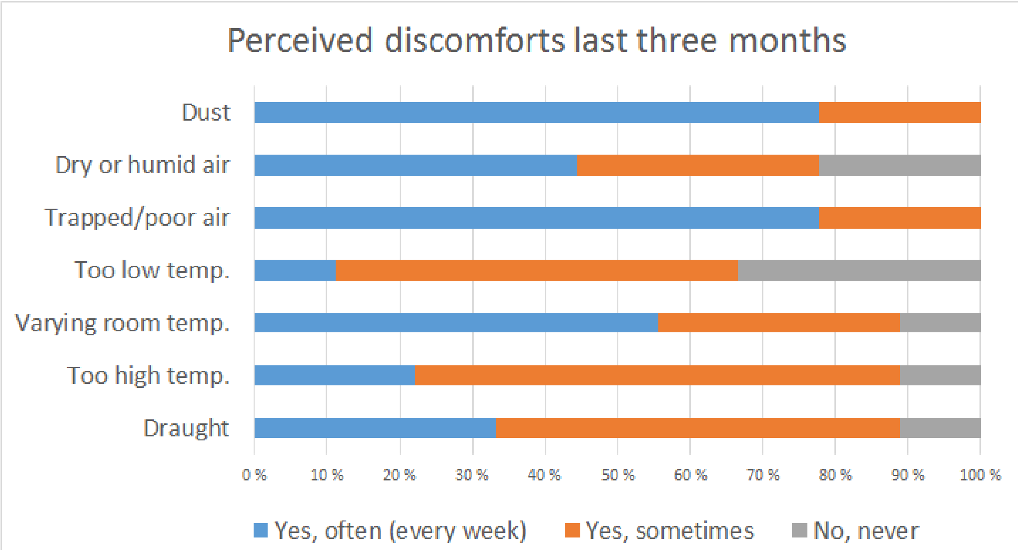


Figure 37: Sources of discomfort in the melting hall for the last three months

hall perceive dust and poor indoor air as something that discomforts them often. The workers also states problems with the humidity of the air, though humidity measurements performed autumn 2016 this was within the acceptable factors of 20%–60%. However, the temperature can come up to 40°C in the summer, and when the temperature increase the humidity can feel more prominent, and thus the air is perceived humid. From Figure 37, it is clear that the temperature also cause dissatisfaction; with workers states that it is too low, to high and varying temperatures. The problem is that the indoor temperature varies with the outdoor temperature; it is too cold in the winter and too warm in the summer, mainly. The dissatisfaction of temperatures during seasons are presented in Figure 38. The dissatisfaction can be caused due to the lack of ways to control the temperature, as 89% says that they have no opportunity to control this.

The symptoms workers have experienced the last three months is presented in Figure 39. This reveals that most of the workers have experienced typical symptoms for poor indoor air, as eye irritation and fatigue. 78% of the participants answered that they thought these discomforts are caused by the indoor climate at the workplace, while the rest said that they didn't

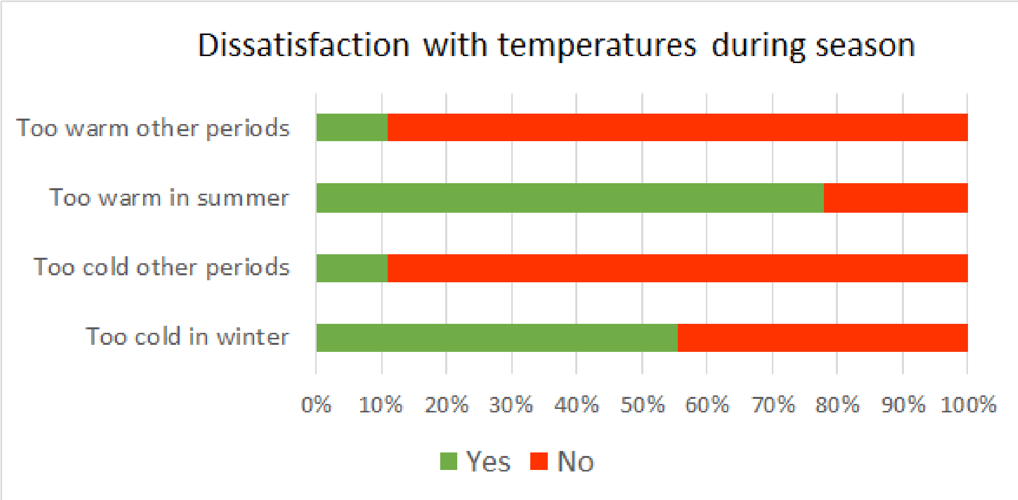


Figure 38: Perceived temperatures during seasons in the melting hall

know if they environment were to blame. However, only one said to have been to the doctor the last twelve months due to symptoms caused by the working environment.

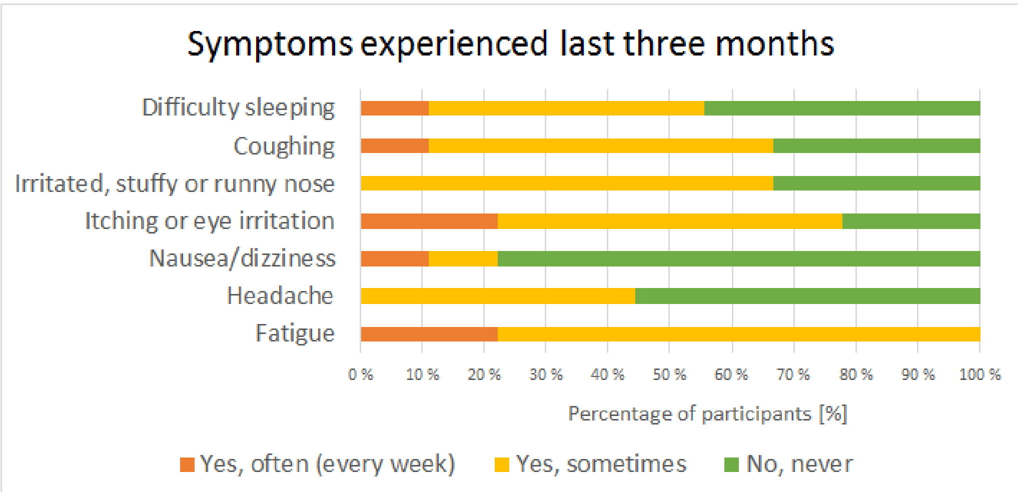


Figure 39: Symptoms experienced by the workers last three months

7 Discussion

The purpose of this thesis is to find a solution for protected occupied zone ventilation that will protect the workers from the contaminants in the indoor air.

Since the manikin were so close to the downward airflow diffuser, the needed initial velocity necessary to counteract the thermal plume in the experiments, will be lower than the actual velocity needed at Jøtul. In a real life situation, the downward flow outlet will be placed higher, and thus the need for a higher velocity may occur. Usually only low velocity is wanted so the occupant don't feel any draught, but at a working environment as Greplassen, the tolerance for air velocities is higher as long as the temperature supplied doesn't give a too high temperature difference.

The tracer gas measurements are influenced by the non-constant supply flow of tracer gas and the non-uniform velocity distribution of the laminar downward airflow. The manikin head is placed at approximately 100 cm of the length of LAF and 40 cm on the width, i.e in the middle of LAF. Since the manikin concentration is measured at the breathing zone, the measurement point is located at about 32 cm, but are affected by the airflow at 40 cm, which will follow the manikin head down and into the breathing zone. For 0.15 m/s and 0.2 m/s the velocity at 32 cm is nearly zero, while it for 0.25 m/s and 0.3 m/s is over 0.10 m/s. The velocity at 32 cm is higher for 0.25 m/s than 0.3 m/s, but for 40 cm it is opposite. The tracer gas measurements suggest that the velocity at 40 cm plays an important role. For the average velocity of 0.3 m/s, the velocity is over 0.4 m/s at 40 cm, and this may indicate that the needed velocity is 0.44 m/s. For this velocity at a height of 25 cm between head and diffuser outlet, the volume flow rate for a laminar airflow diffuser when evenly distributed over an area of 2 m x 0.8 m, will be 2534 m^3/h.

7.1 Limitations and simplifications in laboratory measurements

A simplification in this thesis was to assume that the body surface had uniform temperature or uniform heat production without including the thermoregulatory processes of the body in response to the environment. In addition an error on the temperature sensor for the legs malfunctioned, and the surface temperature became as hot as 41°C. Due to limited time until deadline, the measurements were conducted with this error. This cause a more powerful thermal plume, and it is reasonable to assume that the downward flow velocity needed to counteract the thermal plume in this experiment, will be higher than the case over a person. Furthermore, the manikin was not dressed. The workers at Jøtul are wearing pants, t-shirt, shoes and gloves and maybe sweaters.

Another simplification is done with the stationary station of both the manikin and the heated plate. Both the workers and the oven pieces are in motion at Jøtul; the oven units are moved from the belt to the container on the other side of the working platform by the workers. The constant heat production of the plate is also a simplification, because at the factory it is the hot surfaces that create the thermal plumes. The stove piece temperature decrease and are moved to a different location, and thus won't create a constant plume. Besides, the pieces from Disa are of various shapes and sizes and thus various temperatures. The plate at the experimental measurements are chosen to a worst case scenario to make sure the velocities will be sufficient.

In the laboratory the laminar downward diffuser and plane jet is tested against thermal plume, while the rest of the room is still. This may not be the case at Jøtul. This were attempted tested, but due to the supplied air at Greplassen, these measurements will not give an accurate picture of the room environment velocities around the working area. There might be a 0.15 m/s horizontal airflow that will disturb the jet and laminar downward airflow.

8 Conclusion

Background measurements were performed at Jøtul, simulated and tested with a protected zone ventilation system experimentally in the laboratory at NTNU.

The particulate matter concentration at Greplassen showed a huge improvement from the measurement performed in the autumn 2016. The values for $PM_{2.5}$ and PM_{10} is well within the limits for a 8-hour day given be Arbeidstilsynet (2011), but over the recommended limits for a 24-hour mean given by Folkehelseinstituttet (2013) and World Health Organization (2005). The value can still cause health consequences over time. In addition, there are crystalline silica, type α-quartz, in the air that can cause lung diseases. The concentration of this substance is not measured in this thesis, but should be regularly tested. The indoor climate survey show the dissatisfaction of the indoor air climate, and especially indoor air quality. Both the variation in temperature during the seasons, the lack of control possibilities and the high particle concentration in the air is perceived as dissatisfying by most of the workers.

The needed 'protection velocity' to prevent air from the polluted side with hotplate to cross over to the occupant zone, were measured to be 2 m/s. For initial outlet velocities of 1.5 m/s or less, the downward jet flow is visibly disturbed and offsets towards the occupied zone. This show that it is sensitive to disturbances, and may fail to protect the occupant at Jøtul.

The tracer gas measurements were conducted for different combinations of plane jet velocity and laminar airflow velocity. These measurements revealed that for an average LAF velocity of 0.3 m/s the tracer gas concentration starts to decrease. This measurement series also show that the plane jet had a significant impact, with the velocity of 2 m/s contributing to a very good protection efficiency in the manikin breathing zone. The protection efficiencies also indicate that with the co.flow of the diffusers, a velocity of 1.5 m/s is enough to prevent the pollution from the hotplate to reach the protected zone. However, the results also show that for a velocity of 0.25 m/s, the concentration is higher than the supplied tracer gas concentration. This means that if the downward velocity is just little lower than the plume upward flow velocity, the air in the breathing zone will be worse than without any ventilation at all. Because of the short distance between the manikin head and laminar airflow diffuser, the velocity needed at Jøtul will be higher than the experimental result. Due to this, as well as the result of the poorer air quality with a little too low downward flow, it is recommended to use an average laminar airflow velocity of 0.44 m/s combined with 2 m/s at plane jet. This is also in context with the outlet velocity measured at a point over the manikin head. This will give a flow rate or 2534 m^3/h for the laminar airflow and 288 m^3/h for the plane jet, giving a total volume airflow rate of 2822 m^3/h, supplied air to the local environment. This is within the existing ventilation system capacity of 2825 m^3/h. However, the air supplied by this system today is polluted and before the new protected zone ventilation can be installed, the ventilation ducts needs to be cleaned.

References

AGA (2013). *Sikkerhetsblad - Dinitrogenoksid (Lystgass)*. AGA.

Arbeidstilsynet (1991). Veiledning om klima og luftkvalitet på arbeidsplassen. www.arbeidstilsynet.no/binfil/download2.php?tid=79437. Accessed: 2016-10-14.

Arbeidstilsynet (2008). DIRECTIVE 2008/50/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ambient air quality and cleaner air for Europe. http://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1478160526338&uri=CELEX%3A32008L0050. Accessed: 2016-11-03.

Arbeidstilsynet (2011). Forskrift om tiltaks- og grenseverdier. http://www.arbeidstilsynet.no/binfil/download2.php?tid=237714. Accessed: 2016-09-26.

ASHRAE (2007). Ventilation for Acceptable Indoor Air Quality. http://www.mintie.com/assets/pdf/education/ASHRAE%2062.1-2007.pdf. Accessed: 2016-11-22.

Awbi, H. B. (2003). *Ventilation of buildings*. Taylor & Francis.

Bolashikov, Z. D., Melikov, A. K., Kierat, W., Popiołek, Z., and Brand, M. (2012). Exposure of health care workers and occupants to coughed airborne pathogens in a double-bed hospital patient room with overhead mixing ventilation. *Hvac&R Research*, 18(4):602–615.

Cao, G., Nielsen, P., Jensen, R., Heiselberg, P., Liu, L., and Heikkinen, J. (2015). Protected zone ventilation and reduced personal exposure to airborne cross-infection. *Indoor air*, 25(3):307–319.

Cao, G., Sirén, K., and Kilpeläinen, S. (2014). Modelling and experimental study of performance of the protected occupied zone ventilation. *Energy and Buildings*, 68:515–531.

Folkehelseinstituttet (2013). Luftkvalitetskriterier - Virkninger av luftforurensning på helse. Norm, Najonalt folkehelseinstituttet, Oslo, Norge.

Folkehelseinstituttet (2015). Anbefalte faglige normer for inneklima. Revisjon av kunnskapsgrunnlag og normer – 2015. Norm, Folkehelseinstituttet, Norge.

Fuglseth, J. S. (2017). Characterization of a combined downward jet for protected zone ventilation reducing exposure risk of occupants to indoor pollutants. Master's thesis, NTNU.

Grieve, P. W. (1989). *Measuring ventilation using tracer-gases*. Brüel & Kjær.

Gunnarsen, L. (2003). Thermal climate. In Nilsson, P.-E., editor, *Achieving the desired indoor climate*, chapter 3.1, pages 91–113. Narayana Press, Denmark.

Guyonnaud, L., Solliec, C., Dufresne de Virel, M., and Rey, C. (2000). Design of air curtains used for area confinement in tunnels. *Experiments in Fluids*, 28(4):377–384.

Hanssen, S. (2007). Enøk i bygninger, chapter 4-innemiljø. *Gyldendal Norsk Forlag*, 3:99–133.

Höppe, P. (2002). Different aspects of assessing indoor and outdoor thermal comfort. *Energy and buildings*, 34(6):661–665.

Hyldgaard, C. E. (1998). Thermal plumes above a person. In *International conference on air distribution in rooms*.

Licina, D., Melikov, A. K., Sekhar, C., and Tham, K. W. (2014). Interaction of convective flow generated by human body with room ventilation flow: impact on transport of pollution to the breathing zone. In *13th International Conference on Indoor Air Quality and Climate*.

LumaSense Technologies (2011). *User Manual for Application Software 7620*. LumaSense Technologies.

Melikov, A. K. (2004). Personalized ventilation. *Indoor Air*, 14(s7):157–167.

Melikov, A. K. (2016). Advanced air distribution: Improving health and comfort while reducing energy use. *Indoor air*, 26(1):112–124.

Melikov, A. K., Cermak, R., Kovar, O., and Forejt, L. (2003). Impact of airflow interaction on inhaled air quality and transport of contaminants in rooms with personalized and total volume ventilation.

Mierzwinski, S. (1980). *Air motion and temperature distribution above a human body in result of natural convection*.

Mundt, M., Mathisen, H. M., Moser, M., and Nielsen, P. V. (2004). Ventilation effectiveness.

Murakami, S., Kato, S., and Zeng, J. (2000). Combined simulation of airflow, radiation and moisture transport for heat release from a human body. *Building and environment*, 35(6):489–500.

Novakovic, V., Hanssen, S., Thue, J., Skarstein, Ø., and Gjerstad, F. (2007). Enøk i bygninger-effektiv energibruk. *Oslo: Gyldendal undervisning*, 63.

Perez, J. M., Golombek, S. G., Alpan, G., and Sola, A. (2015). Using a novel laminar flow unit provided effective total body hypothermia for neonatal hypoxic encephalopathy. *Acta Paediatrica*, 104(11):e483–e488.

Safety, O. and Health Administration, O. (2002). Crystalline silica exposure health hazard information. `https://www.osha.gov/OshDoc/data_General_Facts/crystalline-factsheet.pdf`. Accessed: 2016-12-06.

Schlichting, H. (1968). Boundary-layer theory.

Sensor electronic (2010). *Air Distribution Measuring System AirDistSys5000 Operator's manual*. Sensor electronic.

Seppänen, O., Fisk, W., and Mendell, M. (1999). Association of ventilation rates and co2 concentrations with health andother responses in commercial and institutional buildings. *Indoor air*, 9(4):226–252.

Shuter, B. and Aslani, A. (2000). Body surface area: Du bois and du bois revisited. *European journal of applied physiology*, 82(3):250–254.

Skåret, E. (2000). *Ventilasjonsteknisk håndbok*. Norges byggforskningsinstitutt.

Søgnen, O. B. (2015). Indoor climate in a zero energy building. Master's thesis, NTNU.

Store norske leksikon, s. (2009). Blyforgiftning. `https://sml.snl.no/blyforgiftning`. Accessed: 2016-12-06.

Tanabe, S., Arens, E. A., Bauman, F., Zhang, H., and Madsen, T. (1994). Evaluating thermal environments by using a thermal manikin with controlled skin surface temperature. *Ashrae Transactions*, 100.

Thune, I. H. (2016). Airflow distribution and indoor air quality of industrial micro environment. *Specializing project*, NTNU.

Tiwary, A. and Colls, J. (2009). *Air pollution: measurement, modelling & mitigation*. CRC Press.

Tjelflaat, P. and Sandberg, M. (1996). Assessment of ventilation- and energy-efficiency in design for large enclosures.

Tjelflaat, P. O. (2001). Air distribution methods and dimensioning. In Goodfellow, H. D., editor, *Industrial Ventilation Design Guidebook*, chapter 8.2, pages 604–611. Academic press.

Tjelflaat, P. O. (2016). Industrial ventilation - key principles. University Lecture.

TSI Incorporated (2017). *DUSTTRAK^{TM}II AEROSOL MONITOR MODEL 8530/8531/8532/8530EP Operation and service manual*. TSI Incorporated.

World Health Organisation, W. (2014). 7 million premature deaths annually linked to air pollution. `http://www.who.int/mediacentre/news/releases/2014/air-pollution/en/`. Accessed: 2016-11-25.

World Health Organization, W. (2005). Who air quality guidelines for particulate matter, ozone, nitrogen dioxide and sulfur dioxide. `http://apps.who.int/iris/bitstream/10665/69477/1/WHO_SDE_PHE_OEH_06.02_eng.pdf`. Accessed: 2016-12-12.

Xing, H., Hatton, A., and Awbi, H. (2001). A study of the air quality in the breathing zone in a room with displacement ventilation. *Building and environment*, 36(7):809–820.

Zukowska, D., Popiolek, Z., and Melikov, A. (2010). Determination of the integral characteristics of an asymmetrical thermal plume from air speed/velocity and temperature measurements. *Experimental Thermal and Fluid Science*, 34(8):1205–1216.

A Appendix A: Thermal manikin

Based on Tanabe et al. (1994) and the height of the manikin, the surface body area of each body part is:

Name of body part	Area [m^2]
Left foot	0.05
Right foot	0.05
Left leg	0.15
Right leg	0.15
Left thigh	0.23
Right Thigh	0.23
Crotch	0.18
Head	0.11
Left hand	0.045
Right hand	0.045
Left arm	0.07
Right arm	0.07
Left shoulder	0.08
Right shoulder	0.08
Chest	0.22
Back	0.22
Total	1.98

Table 14: Surface area of each body part of the manikin

The manikin is regulated by three temperature sensor within the manikin; one in the arm, one in the leg and one in the torso. These sensors gives feedback to a temperature regulator as is used for floor heating. The regulator box is shown in Figure 40.

This gives the possibility to set a wanted temperature inside the manikin. The sensor for the arm will regulate the power supply to both arms, as the one in the leg will control both legs. When the measured temperature is underneath the set temperature, the regulator apply power to the heating cables. The cables are placed to lay within the whole length of each body part, and gives 60 W to each leg and to the torso with head, and 15 W to each arm. When the wanted temperature is reached, the power supply stop, until the temperature is 1°C lower than the wanted temperature. This way the temperature will vary somewhat over a time period. Due to the limited spacing within some body parts, the sensor is close to the cable and thus the wanted sensor temperature needs to be found by testing. To find the wanted

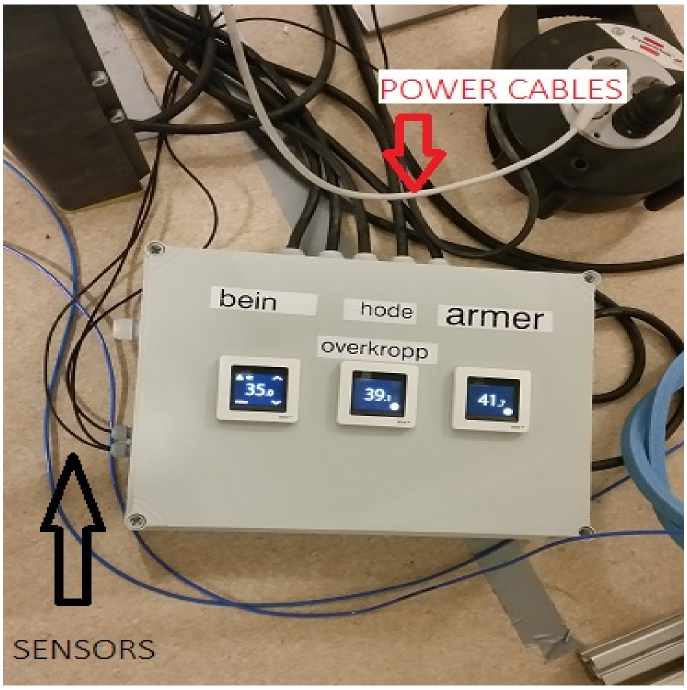


Figure 40: Temperature regulator for the thermal manikin

set temperature, the surface temperature of the manikin was tested. That revealed that the body parts needed different set temperatures and that with these the surface temperature varied mainly between 32 to 35°C, which is an acceptable range for surface temperature of skin.

B Appendix B: Pictures from lab

The fan supplying air to the LAF diffuser and combines pipe for the exhaust on the outside of the room, is showed in Figure 41

Figure 41: The supply fan for LAF diffuser and exhaust pipe on outside of experimental room

When tracer gas measurements were performed, the experimental room setup is presented in Figure 42.

Figure 42: The lab setup during tracer gas measurements

C Appendix C: Description of equipment

In this chapter the details of the measurement equipment it described.

C.1 Air velocity and airflow measurements

For the velocity measurements performed at Jøtul, TSI VelociCalc air velocity meter model 8355 were used, see Figure 43. It has a accuracy of ±0.01m/s for velocities 0.15-2.5 m/s.

For plane jet measurements in the climate lab at NTNU, Air Distribution Measuring System AirDistSys 5000 were used. Five anemometer probes (SensoAnemo5100LSF), which are unidirectional with spherical sensor, measure the air velocity. They are designed for low velocities and have high sensitivity. In addition to velocity, the anemometer probes measure standard deviation of air velocity, temperature, draught rate and turbulence intensity. The setup contains a barometer which automatically corrects according to pressure changes. The transmitter sends the signal to a receiver that is connected to a computer with the corresponding software, see Figure 44. The software program record and analyze data.

Technical data for SenseAnemo5100LSF is presented in Table 15.

C.2 Particulate matter measurements

For particulate matter measurements at Jøtul, DUSTTREKII Aerosol monitor model 8532 were used. It is a handheld device for aerosol mass reading that uses 90°light scattering to measure the concentration. Different mass fractions can be measured by the use of separate filters; PM_1, $PM_{2.5}$, PM_4 and PM_{10}. Specifications are given in Table 16.

Type	**Range**
Diameter of speed sensor	2 mm
Velocity range	0.05... 5 m/s
Accuracy of velocity measurement	± 0.02 m/s ± 1.5% of readings
Directional error above 2 m/s	± 2.5%

Table 15: Technical data for velocity measurement for SenseAnemo5100LSF (Sensor electronic, 2010)

Figure 43: TSI VelociCalc air velocity meter model 8355

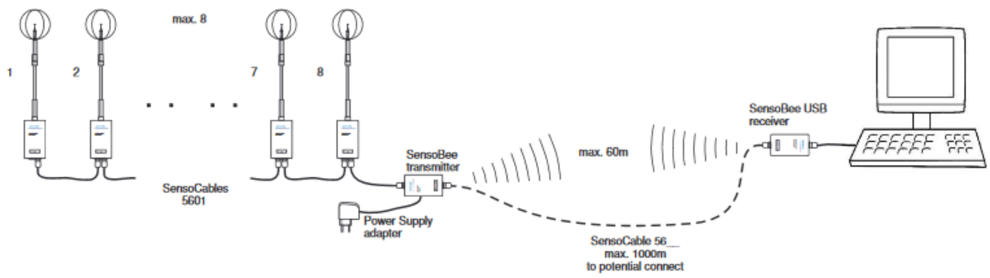


Figure 44: Setup of AirDistSys5000. Picture from Sensor electronic (2010)

Range	0.001 to 150 mg/m^3
Resolution	± 0.1% of reading or 0.001 mg/m^3, whichever is greater
Particle size range	0.1 to 10 µm
Flow rate	3.0 L/min set at factory, 1.4 to 3.0 L/min adjustable
Flow accuracy	± 5% factory setpoint, internal flow controlled

Table 16: Specifications for DUSTTREKII Aerosol monitor model 8532 (TSI Incorporated, 2017)

C.3 Temperature measurements

The Bosch PTD 1 thermal detector uses infrared laser to measure surface temperature, room temperature and humidity in the room. The accuracy of the measurements are ± 1°C for temperature from 10-30°C.

C.4 Tracer gas measurement

The tracer gas measurements were conducted using Brüel & Kjær's sampler and monitor system. It consists of *Multipoint Sampler and Doser Type 1303*, *Multi-gas Monitor Type 1302* (seen in Figure 45) and *LumaSense Technologies Application Software Type 7620* to control the system.

(a) Multipoint Sampler and Doser Type 1303

(b) Multi-gas Monitor Type 1302

Figure 45: Brüel & Kjær's sampler and monitor equipment

The 1303 has six channels for dosing and six channels for sampling. The tracer gas for sampling is collected in plastic tubes up to 50 m long, one channel at the time. The interval for each sample is 1 min. The sampled air is sent to the 1302 for analyzing. This machine can analyze six different gases, see Table 17. The software 7620 activates the wanted gas filters and sample channels. The location for each sample channel can named in the program, and is logged in a database. The results of the analysis can be viewed both numerically and graphically as well as comments can be added. For more information about setup and databases, see LumaSense Technologies (2011).

For this master thesis only the sampler is used, and the gas monitored is N_2O. The tracer gas measurements done by supplying tracer gas from a pressurized cylinder into the room and then monitor the concentrations using Brüel & Kjær, as illustrated in Figure 46.

In Figure 46 the marked points are as follows:

1. Gas bottle with nitrous oxide.

Chemical name	Chemical formula	Molar weight [g/mol]
Sulfur hexafluoride	SF_6	146.05
Carbon dioxide	CO_2	44.01
Carbon monoxide	CO	28.01
Dinitrogen oxide	N_2O	44.01
Toluene	C_7H_8	92.14
Water vapour	H_2O	18.02

Table 17: Gases multi-gas monitor type 1302 can analyze (LumaSense Technologies, 2011)

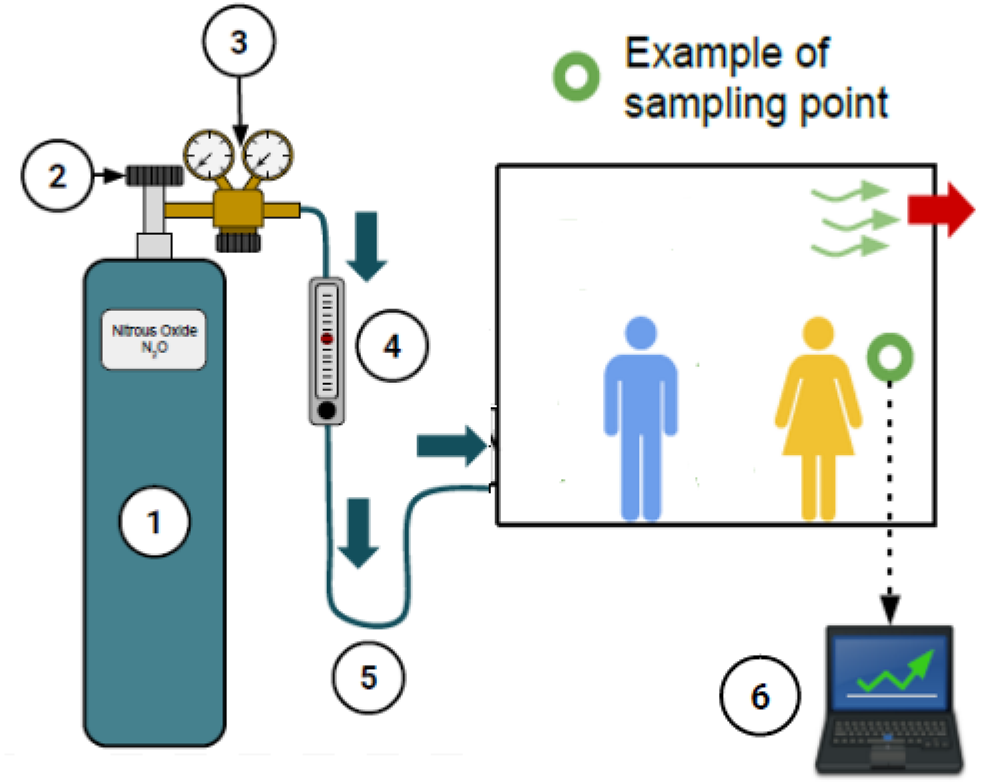


Figure 46: Illustration of the tracer gas measurement setup. Based on Figure by Søgnen (2015)

2. Main closing valve.
3. Pressure regulator and pressure control valve to control the gas output.
4. Rotameter giving the volume flow of gas.

5. Plastic tube delivering the gas into the room.

6. Sampling of concentration for several measurement points and analyzing the results.

The properties of the tracer gas is presented in Table 18. The gas is colorless, non-flammable, smells slightly sweet and not toxic in room temperature. At high concentration, the gas is asphyxiant which means that it reduces or replaces the oxygen in the air and makes it harder to breathe AGA (2013). N_2O is used in surgery and dentistry for anaesthetic and analgesic purposes.

Chemical name	Nitrous oxide
Chemical formula	N_2O
Physical state at 20°C and 1 atm	Gas
Color	Colorless
Smell	Slightly sweet-scented
Molar weight	44 g/mol
Melting point	-90.81°C
Boiling point	-88.5°C
Critical temperature	36.4°C
Relative density, gas (air=1)	1.5
Relative density, liquid (water=1)	1.2
Density	1.98 kg/m^3
Conversion (ppm to mg/m^3)	1 ppm = 1.8 mg/m^3
Toxicity	No known toxicity

Table 18: Tracer gas properties. (AGA, 2013)

D Appendix D: Risk assessment

NTNU SINTEF

Risk Assessment Report

Diffuser experiment with air curtain and co-flow

Prosjektnavn	Modelling and experimental study of protected zone ventilation in industrial working environment
Apparatur	Klimarom VA-lab
Enhet	NTNU
Apparaturansvarlig	Guangyu Cao
Prosjektleder	Guangyu Cao
HMS-koordinator	Morten Grønli
HMS-ansvarlig (linjeleder)	Olav Bolland
Plassering	Klimarom, Varmetekniske labratorier
Romnummer	C247C, 2.etg i klimalab, Varmetekniske labratorier
Risikovurdering utført av	Inge Håvard Rekstad

Approval:

Apparatur kort (UNIT CARD) valid for:	3 måneder
Forsøk pågår kort (EXPERIMENT IN PROGRESS) valid for:	3 måneder

Rolle	Navn	Dato	Signatur
Prosjektleder	Guangyu Cao	**8.5.2017**	Guangyu Cao
HMS koordinator	Morten Grønli		
HMS ansvarlig (linjeleder)	Olav Bolland		

TABLE OF CONTENTS

1 INTRODUCTION

This experiments purpose is to investigate the performance of a combined downward jet and uniform flow for protected zone ventilation. The influence of the airflow velocities on the handling of the pollution sources will be looked at; how well they protect the occupant. The experiment will be conducted in the middle of the small office in the Klimalab.

The experiment will be conducted in several steps:

- **Presetting** of the air curtain nozzle and "laminar air flow diffuser" by measuring the velocity at the outlet to be sure there is an even outflow and that their respective air speeds are at the right ratio to one another. Adjust the fan and valve to get the desired value for the flow velocity. **Calibrating** the anemometers.
- **Measuring** velocities over plumes and from jet to determine the needed airflow to separate zones.
- **Measure** the ventilation efficiency by tracer gas experiments.

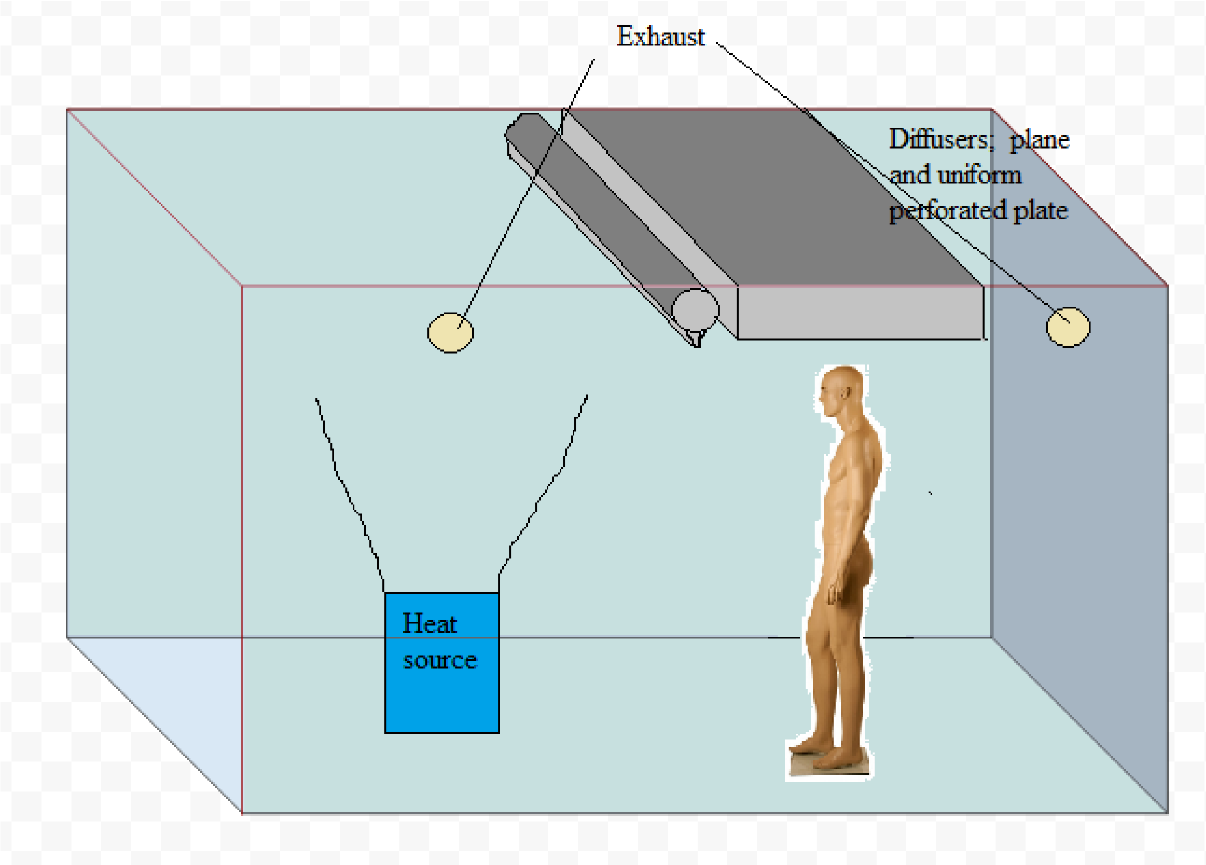
2 ORGANISATION

Rolle	
Prosjektleder	Guangyu Cao
Apparaturansvarlig	Guangyu Cao
Romansvarlig	Lars Konrad Sørensen
HMS koordinator	Morten Grønli
HMS ansvarlig (linjeleder):	Olav Bolland

3 RISK MANAGEMENT IN THE PROJECT

Hovedaktiviteter risikostyring	Nødvendige tiltak, dokumentasjon	DATE
Prosjekt initiering	Prosjekt initiering mal	
Veiledningsmøte Guidance Meeting	Skjema for Veiledningsmøte med pre-risikovurdering	
Innledende risikovurdering Initial Assessment	Fareidentifikasjon – HAZID Skjema grovanalyse	
Vurdering av teknisk sikkerhet Evaluation of technical security	Prosess-HAZOP Tekniske dokumentasjoner	
Vurdering av operasjonell sikkerhet Evaluation of operational safety	Prosedyre-HAZOP Opplæringsplan for operatører	
Sluttvurdering, kvalitetssikring Final assessment, quality assurance	Uavhengig kontroll Utstedelse av apparaturkort Utstedelse av forsøk pågår kort	

4 DESCRIPTIONS OF EXPERIMENTAL SETUP



Location of the room is the little room inside the KlimaLab at VAT laboratories, 2nd floor.

The experimental setup will be like the figure above. There will be measurements of the velocities from the diffusers, temperature in the room and the concentration in exhaust and breathing zone of manikin. Velocity measurements will be done by the use of omnidirectional anemometers. Air will enter the room by the plane diffuser and/or a uniform perforated plate diffuser, and get extracted by the exhaust fans on the back wall. The manikin will be fitted with heat cables on the inside to better simulate a real human. The heat cables can be controlled with dimmers. The cables are using 230V current. A switch on the door to the little room will shut off the current when someone enters the room.

A gas sampler and analyser monitor the tracer gas concentrations. The tracer gas used for experiments are nitrous oxide (N_2O).

Instrumentation to be used:

- Thermometer
- Anemometers
- Diffusers
- Fan controlling the volume flow out of the diffuser
- Exhaust fan x2
- Heated manikin; heating cable within the manikin, approx. 230 W
    - Manikin cable control unit with switch and fuse

- Smoke machine for flow visualization
- Tracer gas sampler – Brüel & Kjær – Type 1303
- Tracer gas monitor - Brüel & Kjær – Type 1302

5 EVACUATION FROM THE EXPERIMENTAL AREA

Evacuate at signal from the alarm system or local gas alarms with its own local alert with sound and light outside the room in question, see 6.2

Evacuation from the rigging area takes place through the marked emergency exits to the assembly point, (corner of Old Chemistry Kjelhuset or parking 1a-b.)

Action on rig before evacuation:
In case of evacuation, the fans and the thermal manikin should be shut down and unplugged. The measurements stop.

6 WARNING

6.1 Before experiments

Send an e-mail with information about the planned experiment to:
iept-experiments@ivt.ntnu.no

The e-mail must include the following information:
- Name of responsible person:
- Experimental setup/rig:
- Start Experiments: (date and time)
- Stop Experiments: (date and time)

You must get the approval back from the laboratory management before start up. All running experiments are notified in the activity calendar for the lab to be sure they are coordinated with other activity.

6.2 Abnormal situation

FIRE
If you are NOT able to extinguish the fire, activate the nearest fire alarm and evacuate area. Be then available for fire brigade and building caretaker to detect fire place.
If possible, notify:

NTNU	SINTEF
Morten Grønli, Mob: 918 97 515	Harald Mæhlum, Mob: 930 14 986
Olav Bolland: Mob: 918 97 209	Petter Røkke, Mob: 901 20 221
NTNU – SINTEF Beredskapstelefon	800 80 388

GAS ALARM
If a gas alarm occurs, close gas bottles immediately and ventilate the area. If the level of the gas concentration does not decrease within a reasonable time, activate the fire alarm and

evacuate the lab. Designated personnel or fire department checks the leak to determine whether it is possible to seal the leak and ventilate the area in a responsible manner.

Alert Order is in the above paragraph.

PERSONAL INJURY

- First aid kit in the fire / first aid stations
- Shout for help
- Start life-saving first aid
- **CALL 113** if there is any doubt whether there is a serious injury

OTHER ABNORMAL SITUATIONS

NTNU:
You will find the reporting form for non-conformance on:
https://innsida.ntnu.no/wiki/-/wiki/Norsk/Melde+avvik

SINTEF:
Synergi

7 ASSESSMENT OF TECHNICAL SAFETY

7.1 HAZOP

See Chapter 13 "Guide to the report template".
The experiment set up is divided into the following nodes:

Node 1	Test rig in Klimalab
Node 2	

Attachments, Form: Hazop_mal
Conclusion: (Safety taken care of)

7.2 Flammable, reactive and pressurized substances and gas

Are any flammable, reactive and pressurized substances and gases in use?

NO	

Attachments: EX zones?
Conclusion:

7.3 Pressurized equipment

Is any pressurized equipment in use?

NO	

Attachments: Certificate for pressurized equipment (see Attachment to Risk Assessment)
Conclusion:

7.4 Effects on the environment (emissions, noise, temperature, vibration, smell)

Will the experiments generate emission of smoke, gas, odour or unusual waste?
Is there a need for a discharge permit, extraordinary measures?

NO	

Attachments:
Conclusion:

7.5 Radiation

See Chapter 13 "Guide to the report template".

NO	

Attachments:
Conclusion:

7.6 Chemicals

Will any chemicals or other harmful substances be used in the experiments? Describe how the chemicals should be handled (stored, disposed, etc.) Evaluate the risk according to safety datasheets, MSDS. Is there a need for protective actions given in the operational procedure?

NO	

Attachments: MSDS
Conclusion:

7.7 Electricity safety (deviations from the norms/standards)

NO	

Attachments:
Conclusion: The use of electrical equipment in this experiment complies with the standards and regulations in terms of touch danger.

8 ASSESSMENT OF OPERATIONAL SAFETY

Ensure that the procedures cover all identified risk factors that must be taken care of. Ensure that the operators and technical performance have sufficient expertise.

8.1 Procedure HAZOP

See Chapter 13 "Guide to the report template".
The method is a procedure to identify causes and sources of danger to operational problems.

Attachments:: HAZOP_MAL_Prosedyre
Conclusion: Simple misunderstanding will not lead to dangerous situations. Form not filled.

8.2 Operation procedure and emergency shutdown procedure

See Chapter 13 "Guide to the report template".
The operating procedure is a checklist that must be filled out for each experiment.
Emergency procedure should attempt to set the experiment set up in a harmless state by unforeseen events.

Attachments: Procedure for running experiments
Emergency shutdown procedure: In case of emergency, fans should be switched off and manikin turned off if possible before leaving the rig.

8.3 Training of operators

The operator should know how to use the anemometers, how to adjust the watt level on the thermal manikin and how to operate both exhaust fans and supply fan. Training should be completed before the actual measurements begin. The operator should also be responsible and tidy, so that no accidents occur. In case of evacuation, the operator should turn off the manikin and the fans and leave the building.

8.4 Technical modifications

- *Technical modifications made by the operator (e.g.Replacement of components, equal to equal)*
- *Technical modifications that must be made by Technical staff (for example, modification of pressure equipment).*
- *What technical modifications give a need for a new risk assessment(by changing the risk picture)?*

8.5 Personal protective equipment

- *Use gloves when there is opportunity for contact with hot/cold surfaces.*

8.6 General Safety

An operator should always be present to follow the measurements. However, there is no risk involved when leaving the rig for a few moments. Door to the room must always be closed during measurements. No entry allowed at that point.

8.7 Safety equipment

Not required

8.8 Special predations

9 QUANTIFYING OF RISK - RISK MATRIX

See Chapter 13 "Guide to the report template".

The risk matrix will provide visualization and an overview of activity risks so that management and users get the most complete picture of risk factors.

IDnr	Aktivitet-hendelse	Frekv-Sans	Kons	RV
	Rotating exhaust fans, danger of contact	1	C	C1
	Contact burn on the smoke machine	1	C	C1

Conclusion: The *Participants has to make a comprehensive assessment to determine whether the remaining risks of the activity/process is acceptable.*

10 REGULATIONS AND GUIDELINES

Se http://www.arbeidstilsynet.no/regelverk/index.html

- Lov om tilsyn med elektriske anlegg og elektrisk utstyr (1929)
- Arbeidsmiljøloven
- Forskrift om systematisk helse-, miljø- og sikkerhetsarbeid (HMS Internkontrollforskrift)
- Forskrift om sikkerhet ved arbeid og drift av elektriske anlegg (FSE 2006)
- Forskrift om elektriske forsyningsanlegg (FEF 2006)
- Forskrift om utstyr og sikkerhetssystem til bruk i eksplosjonsfarlig område NEK 420
- Forskrift om håndtering av brannfarlig, reaksjonsfarlig og trykksatt stoff samt utstyr og anlegg som benyttes ved håndteringen
- Forskrift om Håndtering av eksplosjonsfarlig stoff
- Forskrift om bruk av arbeidsutstyr.
- Forskrift om Arbeidsplasser og arbeidslokaler
- Forskrift om Bruk av personlig verneutstyr på arbeidsplassen
- Forskrift om Helse og sikkerhet i eksplosjonsfarlige atmosfærer
- Forskrift om Høytrykksspyling
- Forskrift om Maskiner
- Forskrift om Sikkerhetsskilting og signalgivning på arbeidsplassen
- Forskrift om Stillaser, stiger og arbeid på tak m.m.
- Forskrift om Sveising, termisk skjæring, termisk sprøyting, kullbuemeisling, lodding og sliping (varmt arbeid)
- Forskrift om Tekniske innretninger
- Forskrift om Tungt og ensformig arbeid
- Forskrift om Vern mot eksponering for kjemikalier på arbeidsplassen (Kjemikalieforskriften)
- Forskrift om Vern mot kunstig optisk stråling på arbeidsplassen
- Forskrift om Vern mot mekaniske vibrasjoner
- Forskrift om Vern mot støy på arbeidsplassen

Veiledninger fra arbeidstilsynet
se: http://www.arbeidstilsynet.no/regelverk/veiledninger.html

11 DOCUMENTATION

- Tegninger, foto, beskrivelser av forsøksoppsetningen
- Hazop_mal
- Sertifikat for trykkpåkjent utstyr
- Håndtering avfall i NTNU
- Sikker bruk av LASERE, retningslinje
- HAZOP_MAL_Prosedyre
- Forsøksprosedyre
- Opplæringsplan for operatører
- Skjema for sikker jobb analyse, (SJA)
- Apparaturkortet
- Forsøk pågår kort

12 GUIDANCE TO RISK ASSESSMENT TEMPLATE

Chapter 7 Assessment of technical safety.

Ensure that the design of the experiment set up is optimized in terms of technical safety.
Identifying risk factors related to the selected design, and possibly to initiate re-design to ensure that risk is eliminated as much as possible through technical security.
This should describe what the experimental setup actually are able to manage and acceptance for emission.

7.1 HAZOP

The experimental set up is divided into nodes (eg motor unit, pump unit, cooling unit.). By using guidewords to identify causes, consequences and safeguards, recommendations and conclusions are made according to if necessary safety is obtained. When actions are performed the HAZOP is completed.
(e.g. "No flow", cause: the pipe is deformed, consequence: pump runs hot, precaution: measurement of flow with a link to the emergency or if the consequence is not critical used manual monitoring and are written into the operational procedure.)

7.2 Flammable, reactive and pressurized substances and gas.

According to the Regulations for handling of flammable, reactive and pressurized substances and equipment and facilities used for this:

Flammable material: Solid, liquid or gaseous substance, preparation, and substance with occurrence or combination of these conditions, by its flash point, contact with other substances, pressure, temperature or other chemical properties represent a danger of fire.
Reactive substances: Solid, liquid, or gaseous substances, preparations and substances that occur in combinations of these conditions, which on contact with water, by its pressure, temperature or chemical conditions, represents a potentially dangerous reaction, explosion or release of hazardous gas, steam, dust or fog.
Pressurized : Other solid, liquid or gaseous substance or mixes having fire or hazardous material response, when under pressure, and thus may represent a risk of uncontrolled emissions

Further criteria for the classification of flammable, reactive and pressurized substances are set out in Annex 1 of the Guide to the Regulations "Flammable, reactive and pressurized substances"
http://www.dsb.no/Global/Publikasjoner/2009/Veiledning/Generell%20veiledning.pdf
http://www.dsb.no/Global/Publikasjoner/2010/Tema/Temaveiledning_bruk_av_farlig_stoff_Del_1.pdf

Experiment setup area should be reviewed with respect to the assessment of Ex zone
- Zone 0: Always explosive atmosphere, such as inside the tank with gas, flammable liquid.
- Zone 1: Primary zone, sometimes explosive atmosphere such as a complete drain point
- Zone 2: secondary discharge could cause an explosive atmosphere by accident, such as flanges, valves and connection points

7.4 Effects on the environment

With pollution means: bringing solids, liquid or gas to air, water or ground, noise and vibrations, influence of temperature that may cause damage or inconvenience effect to the environment.

Regulations: http://www.lovdata.no/all/hl-19810313-006.html#6

NTNU guidance to handling of waste:http://www.ntnu.no/hms/retningslinjer/HMSR18B.pdf

7.5 Radiation

Definition of radiation

Ionizing radiation: Electromagnetic radiation (in radiation issues with wavelength <100 nm) or rapid atomic particles (e.g. alpha and beta particles) with the ability to stream ionized atoms or molecules.
Non ionizing radiation: Electromagnetic radiation (wavelength >100 nm), og ultrasound[1] with small or no capability to ionize.
Radiation sources: All ionizing and powerful non-ionizing radiation sources.
Ionizing radiation sources: Sources giving ionizing radiation e.g. all types of radiation sources, x-ray, and electron microscopes.
Powerful non ionizing radiation sources: Sources giving powerful non ionizing radiation which can harm health and/or environment, e.g. class 3B and 4. MR[2] systems, UVC[3] sources, powerful IR sources[4].
[1]Ultrasound is an acoustic radiation ("sound") over the audible frequency range (> 20 kHz). In radiation protection regulations are referred to ultrasound with electromagnetic non-ionizing radiation. [2]MR (e.g. NMR) - nuclear magnetic resonance method that is used to "depict" inner structures of different materials. [3]UVC is electromagnetic radiation in the wavelength range 100-280 nm. [4]IR is electromagnetic radiation in the wavelength range 700 nm - 1 mm.

For each laser there should be an information binder (HMSRV3404B) which shall include:

- General information
- Name of the instrument manager, deputy, and local radiation protection coordinator
- Key data on the apparatus
- Instrument-specific documentation
- References to (or copies of) data sheets, radiation protection regulations, etc.
- Assessments of risk factors
- Instructions for users
- Instructions for practical use, startup, operation, shutdown, safety precautions, logging, locking, or use of radiation sensor, etc.
- Emergency procedures
- See NTNU for laser: http://www.ntnu.no/hms/retningslinjer/HMSR34B.pdf

7.6 The use and handling of chemicals.

In the meaning chemicals, a element that can pose a danger to employee safety and health

See: http://www.lovdata.no/cgi-wift/ldles?doc=/sf/sf/sf-20010430-0443.html

Safety datasheet is to be kept in the HSE binder for the experiment set up and registered in the database for chemicals.

Chapter 8 Assessment of operational procedures.

Ensures that established procedures meet all identified risk factors that must be taken care of through operational barriers and that the operators and technical performance have sufficient expertise.

8.1 Procedure Hazop

Procedural HAZOP is a systematic review of the current procedure, using the fixed HAZOP methodology and defined guidewords. The procedure is broken into individual operations (nodes) and analyzed using guidewords to identify possible nonconformity, confusion or sources of inadequate performance and failure.

8.2 Procedure for running experiments and emergency shutdown.

Have to be prepared for all experiment setups.

The operating procedure has to describe stepwise preparation, startup, during and ending conditions of an experiment. The procedure should describe the assumptions and conditions for starting, operating parameters with the deviation allowed before aborting the experiment and the condition of the rig to be abandoned.

Emergency procedure describes how an emergency shutdown have to be done, (conducted by the uninitiated),

what happens when emergency shutdown, is activated. (electricity / gas supply) and

which events will activate the emergency shutdown (fire, leakage).

Chapter 9 Quantifying of RISK

Quantifying of the residue hazards, Risk matrix

To illustrate the overall risk, compared to the risk assessment, each activity is plotted with values for the probability and consequence into the matrix. Use task IDnr.

Example: If activity IDnr. 1 has been given a probability 3 and D for consequence the risk value become D3, red. This is done for all activities giving them risk values.

In the matrix are different degrees of risk highlighted in red, yellow or green. When an activity ends up on a red risk (= unacceptable risk), risk reducing action has to be taken

CONSEQUENSES	Catastrophic	E1	E2	E3	E4	E5
	Major	D1	D2	D3	D4	D5
	Moderate	C1	C2	C3	C4	C5
	Minor	B1	B2	B3	B4	B5
	Insignificant	A1	A2	A3	A4	A5
		Rare	Unlikely	Possible	Likely	Almost
		PROBABILITY				

Table 8. Risk's Matrix

Table 9. The principle of the acceptance criterion. Explanation of the colors used in the matrix

COLOUR		DESCRIPTION
Red		Unacceptable risk Action has to be taken to reduce risk
Yellow		Assessment area. Actions has to be considered
Green		Acceptable risk. Action can be taken based on other criteria

Attachment to Risk Assessment report

Diffuser experiment with air curtain and co-flow

Prosjektnavn	Modelling and experimental study of protected zone ventilation in industrial working environment
Apparatur	Klimarom VA-lab
Enhet	NTNU
Apparaturansvarlig	Guangyu Cao
Prosjektleder	Guangyu Cao
HMS-koordinator	Morten Grønli
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Risikovurdering utført av	Inge Håvard Rekstad

TABLE OF CONTENTS

ATTACHMENT A: PROCESS AND INSTRUMENTATION DIAGRAM

ATTACHMENT B: HAZOP TEMPLATE

Project: Modelling and experimental study of protected zone ventilation in industrial working environment **Node: 1**						**Page**	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
Not likely	No flow	Pipe is blocked/bent	Fan wear. Will create under pressure in working part of pipe	Use flow meter by fan and at outlet. Make sure the flow levels are approximately the same	Check the duct set up before turning on the fan. Check flow meters	Turn off the fan again and follow the recommendations	
Not likely	Reverse flow	Fan runs the wrong way	Faulty measurements during experiment	Check that the flow from the fan is correct	Adjust the fan speed and direction of rotation to the desired setting	Turn off the fan again and follow the recommendations	
Low risk	More flow	Fans runs too fast	Faulty measurements during experiment		Adjust the fan speed to the correct speed	Adjust the fan speed to the correct speed	
Low risk	Less flow	Fans runs too slow	Faulty measurements during experiment		Adjust the fan speed to the correct speed	Adjust the fan speed to the correct speed	
Low risk	Higher or lower temperature in thermal manikin	Wrong current level for heat cables	Thermal manikin hotter than desired may cause fire or burns in extreme cases	Make sure the electrical equipment is set up correctly, following the equipment's quidelines	Follow the equipment's guidelines. Make sure the manikin's material can stand high temperature	Adjust input watt level to adjust temperature of heat cables	

NTNU SINTEF

Project: Modelling and experimental study of protected zone ventilation in industrial working environment **Node: 1**						**Page**	
Ref	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
1	More flow	Leakage	Danger of suffocation	Correct operation			

ATTACHMENT C: TEST CERTIFICATE FOR LOCAL PRESSURE TESTING

Trykkpåkjent utstyr:	
Benyttes i rigg:	
Design trykk for utstyr (bara):	
Maksimum tillatt trykk (bara): (i.e. burst pressure om kjent)	
Maksimum driftstrykk i denne rigg:	

Prøvetrykket skal fastlegges i følge standarden og med hensyn til maksimum tillatt trykk.

Prøvetrykk (bara):			
X maksimum driftstrykk: I følge standard			
Test medium:			
Temperatur (°C)			
Start tid:		Trykk (bara):	
Slutt tid:		Trykk (bara):	
Maksimum driftstrykk i denne rigg:			

Eventuelle repetisjoner fra atm. trykk til maksimum prøvetrykk:…………….

Test trykket, dato for testing og maksimum tillatt driftstrykk skal markers på (skilt eller innslått)

Sted og dato   Signatur

NTNU SINTEF

ATTACHMENT D: HAZOP PROCEDURE (TEMPLATE)

Project: **Node: 1**						**Page**	
Ref#	**Guideword**	**Causes**	**Consequences**	**Safeguards**	**Recommendations**	**Action**	**Date/Sign**
	Not clear procedure	Procedure is to ambitious, or confusingly					
	Step in the wrong place	The procedure can lead to actions done in the wrong pattern or sequence					
	Wrong actions	Procedure improperly specified					
	Incorrect information	Information provided in advance of the specified action is wrong					
	Step missing	Missing step, or step requires too much of operator					
	Step unsucessful	Step has a high probability of failure					
	Influence and effects from other	Procedure's performance can be affected by other sources					

ATTACHMENT E: PROCEDURE FOR RUNNING EXPERIMENTS

Prosjekt Energilabprosjekt: EKB-Lab: Diffuser co-flow (Ina Helene Thune) *Modelling and experimental study of protected zone ventilation in industrial working environment*	**Dato**	**Signatur**
Apparatur Diffuser experiment with air curtain and LAF co-flow		
Prosjektleder Guangyu Cao	**8.5.2017**	

	Conditions for the experiment:	**Completed**
	Experiments should be run in normal working hours, 08:00-16:00 during winter time and 08.00-15.00 during summer time. Experiments outside normal working hours shall be approved.	
	One person must always be present while running experiments, and should be approved as an experimental leader.	
	An early warning is given according to the lab rules, and accepted by authorized personnel.	
	Be sure that everyone taking part of the experiment is wearing the necessary protecting equipment and is aware of the shut down procedure and escape routes.	
	Preparations	**Carried out**
	Post the "Experiment in progress" sign.	
	Hang up black blanket (to be able to see smoke profile)	
	Turn on the fan to supply air through the diffuser nozzle, and check outlet velocity at 10 different locations that the flow has an even velocity	
	Measure initial air temperature in the room. Check at 3-4 different heights to be sure there is little thermal stratification	
	During the experiment	
	Measure velocity at all relevant locations	
	Measure pollution concentration in breathing zone	
	Control of tracer gas dosage	
	End of experiment	
	Shutting the supply of tracer gas	
	Turn off fans and heat source	
	Remove all obstructions/barriers/signs around the experiment.	
	Tidy up and return all tools and equipment.	
	Tidy and cleanup work areas.	

	Return equipment and systems back to their normal operation settings (fire alarm)	
	To reflect on before the next experiment and experience useful for others	
	Was the experiment completed as planned and on scheduled in professional terms?	
	Was the competence which was needed for security and completion of the experiment available to you?	
	Do you have any information/ knowledge from the experiment that you should document and share with fellow colleagues?	

Operator(s):

Navn	Dato	Signatur

ATTACHMENT F: TRAINING OF OPERATORS

Prosjekt Modelling and experimental study of protected zone ventilation in industrial working environment	**Dato**	**Signatur**
Apparatur Klimarom		
Prosjektleder Guangyu Cao	**8.5.2017**	Guangyu Cao

	Knowledge about EPT LAB in general	
	Lab • Access • routines and rules • working hour	
	Knowledge about the evacuation procedures.	
	Activity calendar for the Lab	
	Early warning, **iept-experiments@ivt.ntnu.no**	
	Knowledge about the experiments	
	Procedures for the experiments	
	Emergency shutdown.	
	Nearest fire and first aid station.	

I hereby declare that I have read and understood the regulatory requirements has received appropriate training to run this experiment and are aware of my personal responsibility by working in EPT laboratories.

Operator(s):

Navn	Dato	Signatur
Ina Helene Thune	8.5.2017	

ATTACHMENT G: FORM FOR SAFE JOB ANALYSIS

SJA name:		
Date:		Location:
Mark for completed checklist:		

Participators:		
SJA-responsible:		

Specification of work (What and how?):
Risks associated with the work:
Safeguards: (plan for actions, see next page):
Conclusions/comments:

Recommended/approved	**Date/Signature:**	**Recommended/approved**	**Date/Signature:**
SJA-responsible:		HSE responsible:	
Responsible for work:		Other, (position):	

HSE aspect	Yes	No	NA	Comments / actions	Resp.
Documentation, experience, qualifications					
Known operation or work?					
Knowledge of experiences / incidents from similar operations?					
Necessary personnel?					
Communication and coordinating					
Potential conflicts with other operations?					
Handling of an eventually incident (alarm, evacuation)?					
Need for extra assistance / watch?					
Working area					
Unusual working position					
Work in tanks, manhole?					
Work in ditch, shaft or pit?					
Clean and tidy?					
Protective equipment beyond the personal?					
Weather, wind, visibility, lighting, ventilation?					
Usage of scaffolding/lifts/belts/ straps, anti-falling device?					
Work at hights?					
Ionizing radiation?					
Influence of escape routes?					
Chemical hazards					
Usage of hazardous/toxic/corrosive chemicals?					
Usage of flammable or explosive chemicals?					
Risk assessment of usage?					
Biological materials/substances?					
Dust/asbestos/dust from insulation?					
Mechanical hazards					
Stability/strength/tension?					
Crush/clamp/cut/hit?					
Dust/pressure/temperature?					
Handling of waste disposal?					
Need of special tools?					
Electrical hazards					
Current/Voltage/over 1000V?					
Current surge, short circuit?					
Loss of current supply?					
Area					
Need for inspection?					
Marking/system of signs/rope off?					
Environmental consequences?					
Key physical security systems					
Work on or demounting of safety systems?					
Other					

APPARATURKORT / UNITCARD

Dette kortet SKAL henges godt synlig på apparaturen!
This card MUST be posted on a visible place on the unit!

Apparatur (Unit) Diffuser experiment with air curtain, uniform downward flow and manikin	
Prosjektleder (Project Leader) Guangyu Cao	**Telefon mobil/privat** (Phone no. mobile/private) +4791897689
Apparaturansvarlig (Unit Responsible) Guangyu Cao	**Telefon mobil/privat** (Phone no. mobile/private) +4791897689
Sikkerhetsrisikoer (Safety hazards) N_2O gas leakage. Do not touch the manikin while it is plugged in.	
Sikkerhetsregler (Safety rules) Fans and manikin should be switched off when not in use. Do not interfere with the gas without the consent of Unit Responsible.	
Nødstopp prosedyre (Emergency shutdown) Switch off fans and unplug manikin. Shut the tracer gas supply by closing valve on tank.	

Her finner du (Here you will find):

Prosedyrer (Procedures)	In the room
Bruksanvisning (Users manual)	In the room

Nærmeste (Nearest)

Brannslukningsapparat (fire extinguisher)	1.floor VVSLab(syd)
Førstehjelpsskap (first aid cabinet)	1.floor VVSLab(syd)

NTNU **Institutt for energi og prosessteknikk**	**SINTEF Energi** **Avdeling energiprosesser**
Dato	**Dato**
Signert	**Signert**

FORSØK PÅGÅR /EXPERIMENT IN PROGRESS

Dette kortet SKAL henges opp før forsøk kan starte!
This card MUST be posted on the unit before the experiment startup!

Apparatur (Unit)	
Diffuser experiment with air curtain, uniform downward flow and manikin	
Prosjektleder (Project Leader) Guangyu Cao	**Telefon mobil/privat** (Phone no. mobile/private) +4791897689
Apparaturansvarlig (Unit Responsible) Guangyu Cao	**Telefon mobil/privat** (Phone no. mobile/private) +4791897689
Godkjente operatører (Approved Operators) Ina Helene Thune	**Telefon mobil/privat** (Phone no. mobile/private) +4799434023
Prosjekt (Project) Energilabprosjekt: EKB-Lab: Diffuser co-flow (Ina Helene Thune) *Modelling and experimental study of protected zone ventilation in industrial working environment*	
Forsøkstid / Experimental time (start - stop) **03.05.17 – 01.07.17**	
Kort beskrivelse av forsøket og relaterte farer (Short description of the experiment and related hazards**)** Measuring velocity from diffusers and in the critical area between the plumes and downward flow. Measuring the pollutant concentration in the breathing zone of manikin. The door should be closed during measurement. No touching manikin while it is plugged in.	

NTNU
Institutt for energi og prosessteknikk

Dato

Signert

SINTEF Energi
Avdeling energiprosesser

Dato

Signert

E Appendix E: Indoor air questionnaire

Spørreskjema

Inneklima og arbeidsmiljø

Dette spørreskjemaet omhandler inneklimaet på din arbeidsplass og mulige symptomer som du kanskje opplever.

BAKGRUNNSINFORMASJON

- Kjønn
  - Mann
  - Kvinne
- Alder
  - 20-30
  - 31-40
  - 41-50
  - 51-60
  - >60
- Avdeling
  - FYLL INN
- Type arbeidsplass
  - Smelta
  - Støperi
  - Greplass
  - Annet
- Hvor lenge har du jobbet i denne bygningen?
  - FYLL INN
- Gjennomsnitt antall timer tilbrakt i lokalet
  - 15-35 t/uke
  - Mer enn 35 t/uke
- Overtidsarbeid
  - Sjelden
  - Mindre enn 20 t/mnd
  - Mer enn 20 t/mnd
- Røyker du?
  - Ja
  - Nei
- Bruker du kontaktlinser?
  - Ja
  - Nei
- Har du noe problemer med allergiske reaksjoner i øyne og nese?
- Blir du lett irritert i øyne eller luftveier av tobakkrøyk, sterke lukter eller eksos?
- Blir du ofte forkjølet eller får ofte andre infeksjonssykdommer

Hvert spørsmål besvares med

- Ja
- Nei

- Andre kommentarer (FYLL INN)

ARBEIDSMILJØ

- Har du vært **plaget** i løpet av de **siste tre månedene** av noen av følgende faktorer på arbeidplassen sin?
    - Trekk
    - For høy temperatur
    - Varierende romtemperatur
    - For lav romtemperatur
    - Innestengt/dårlig luft
    - Tørr eller fuktig luft?
    - Ubehagelig lukt?
    - Støv og skitt

NÅVÆRENDE SYMPTOMER

- I løpet av de siste tre månedene, har du opplevd noen av følgende symptomer?
    - Tretthet/slapphet
    - Hodepine
    - Kvalme/svimmelhet
    - Kløe, svie eller irritasjon i øyne
    - Irritert, tett eller rennende nese
    - Hoste
    - Vanskeligheter med å sove

Hvert spørsmål besvares med

- Ja, ofte (hver uke)
- Ja, noen ganger
- Nei, aldri

- Hvis du har opplevd plager, tror du det skyldes inneklimaet på arbeidsplassen? I så fall hvilke?
    - Ja
    - Nei
    - Jeg vet ikke
    - FYLL INN
- Har du vært sykemeldt i løpet av de siste 12 månedene på grunn av symptomer du mener skyldes arbeidsmiljøet?
    - Ja
    - Nei
- Har du vært til legen i løpet av de siste 12 månedene på grunn av symptomer du mener skyldes arbeidsmiljøet?
    - Ja
    - Nei
- Problemer med romtemperaturen?
    - For kaldt om vinteren
    - For kaldt til andre tider
    - For varmt om sommeren
    - For varmt til andre tider

- Annet

- Hvordan kontrollerer du temperaturen ved din arbeidsplass?
    - Kontrollerer det gjennom oppvarmingssystem
    - Ved å åpne et vindu eller lignende
    - Jeg kan ikke kontrollere noe som helst

LUFTKVALITET

- Hva synes du om luftkvaliteten på arbeidsplassen
    - Veldig god
    - God
    - Akseptabel
    - Dårlig
    - Veldig dårlig
- Problemer med luftkvaliteten
    - Verre tidlig om morgenen
    - Verre om ettermiddagen
    - Forskjellig fra sted til sted
    - Ikke bra nok mulighet for fjerning av røyk og andre partikler
- Hvordan kontrollerer du luftkvaliteten?
    - Ved å åpne vinduer eller andre åpninger
    - Ved å justere ventilasjonen (bryter)
    - Jeg kan ikke kontrollere noe
    - Jeg har ikke behov for å kontrollere luftkvaliteten
- Anser du utelufta som mer eller mindre «frisk» enn lufta fra ventilasjonssystemet?
    - Utelufta er friskere
    - Utelufta er mindre frisk
    - Omtrent like frisk