Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Energy and Process Engineering

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Performance of Membrane Energy Exchangers in Ventilation

Analyses of Odour Transfer, VOC Transfer, and Sensible and Latent Effectiveness

Master's thesis in Energy and Environmental Engineering
Supervisor: Hans Martin Mathisen
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Preface

This master thesis was written for the Department of Energy and Process Engineering at the Norwegian University of Science and Technology (NTNU) in Trondheim. It was completed during the spring semester of 2023 as part of the TEP4910 course and represents 30 ECTS. Some of the research was conducted during the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* with the subject code TEP4530 written by *Tærum, Mathea L.* and delivered in December 2022. The thesis is connected to the industry-owned research project *Defreeze MEE Now* by Flexit AS, with NTNU and SINTEF as research partners. The membrane energy exchangers evaluated in the thesis were produced and provided by Flexit AS.

I want to thank Professor Hans Martin Mathisen, my supervisor, and senior scientist Peng Liu, my co-supervisor, for their valuable guidance and insightful discussions during my thesis.

I also want to express my gratitude towards laboratory engineer Lars Konrad Sørensen and senior engineer Inge Håvard Rekstad for their valuable assistance. They have been extremely helpful with practical tasks related to the test rig and laboratory experiments and have taught me how to use the laboratory facilities effectively. Without their support, conducting the necessary experiments would not have been possible. I also want to thank Ingeborg Hutcheson Fiskvik and Maria Justo-Alonso for lending me their VOC sensors and assisting with questions regarding the measurements.

Mathea Lie Tærum

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Trondheim, 11.06.2023

Abstract

To ensure energy-efficient operation of buildings and reduce emissions from the operation phase, implementation of heat recovery in ventilation systems is recommended. Membrane energy exchangers offer innovative technology to ventilation systems in energy-efficient buildings as it exploits both heat and moisture recovery to provide acceptable indoor air quality. Important factors in maintaining satisfactory indoor air quality are preventing transfer of odours and volatile organic compounds, which must be addressed for the membrane technology. This study aims to determine the extent of membrane properties' influence on selectivity towards odours and volatile organic compounds and evaluate the performance related to indoor air quality in real-life scenarios.

Three prototypes of membrane energy exchangers (MV-1, MV-2, and MV-3) were evaluated using experimental laboratory methods. Each prototype had different moisture transfer properties and was of the quasi-counter flow type. Odour sensory analyses with panel members were performed to evaluate the odour transfer through the different membranes and the influence of odours on building occupants. Sensors were used for measuring the contaminant crossover of volatile organic compounds, and latent and sensible effectiveness of the membranes were measured under different operating conditions.

Results showed that MV-1, using the membrane with the lowest moisture transfer rate, had the best results regarding odour transfer, with low odour intensity and fewer dissatisfied occupants. This membrane also had the lowest crossover of volatile organic compounds, with 56% less than MV-3 with acetone as source and 4.3% with formaldehyde as source. MV-2 and MV-3, with respectively medium and high moisture transfer rates, showed poorer selectivity to odours and volatile organic compounds but consistent and high results for the effectiveness assessments. MV-1 showed weakness in terms of latent effectiveness as parts of the effectiveness assessment were influenced by unbalanced air flows. However, the valid results indicate 11.9% lower latent effectiveness compared to the highest result from MV-3.

The low latent effectiveness of MV-1 shows the limitations in moisture recovery for membranes with low moisture transfer rates. In contrast, the two membranes with higher moisture transfer rates showed higher effectiveness but lacked selectivity for odours and volatile organic compounds. MV-2 performed worse than MV-3 and is not recommended for use in ventilation based on this study. The decision between a membrane with low moisture transfer rates, like MV-1, and high moisture transfer rates, like MV-3, depends on the specific design requirements. MV-1 is recommended for its significantly better selectivity towards odours and volatile organic compounds, but weaker humidity control must be considered. In cases with minimal risk of exposure to intense odours and volatile organic compounds, MV-3 would be recommended due to its high effectiveness. Overall, the findings emphasize the importance of membrane selection and balanced air flows to ensure optimal indoor air quality. The study highlights the potential membrane energy exchanger optimization has for energy-efficient buildings and comfortable indoor environments.

Sammendrag

For å forsikre energieffektiv drift av bygninger og redusere utslipp fra driftsfasen anbefales bruk av varmegjenvinning i ventilasjonssystemer. Membran energivekslere tilbyr innovativ teknologi til ventilasjonssystemer i energieffektive bygninger og utnytter både varme- og fuktgjenvinning for å oppnå akseptabel inneluftkvalitet. Viktige faktorer for å opprettholde tilfredsstillende inneluftkvalitet er å forhindre overføring av lukt og flyktige organiske forbindelser. Dette er et problem som må adresseres for membranteknologien. Denne rapporten har som mål undersøke i hvilken grad membranegenskaper påvirker selektivitet overfor lukt og flyktige organiske forbindelser, og evaluere ytelsen knyttet til inneluftkvalitet i virkelige scenarier.

Tre membran energivekslere (MV-1, MV-2 og MV-3) ble vurdert ved hjelp av eksperimentelle laboratorie undersøkelser. Hver prototype hadde forskjellige fuktoverførings egenskaper og var en kombinasjon av en motstrøms- og medstrømsveksler. Sensorisk analyse av lukt med panel deltakere ble gjennomført for å undersøke luktoverføringen gjennom de ulike membranene og innflytelsen dette har på bygningens brukere. I tillegg ble sensorer brukt til å måle krysskontaminering av flyktige organiske forbindelser, og latent fuktgjenvinnings effektivitet og følbar temperatur effektivitet ble målt under ulike driftsforhold.

Resultatene viste at MV-1, som brukte membranen med lavest fuktoverføring, hadde de beste resultatene med hensyn til luktoverføring, med lavest luktintensitet og færre misfornøyde panel deltakere. Denne membranen hadde også den laveste krysskontamineringen av flyktige organiske forbindelser, med 56% mindre enn MV-3 med aceton som kilde og 4.3% med formaldehyd som kilde. MV-2 og MV-3, med henholdsvis middels og høy fuktoverføring, viste dårligere selektivitet for lukter og flyktige organiske forbindelser, men jevnt høye resultater for effektivitetsundersøkelsene. MV-1 viste svakhet med hensyn til latent fuktgjenvinnings effektivitet, da deler av effektivitetsundersøkelsen ble påvirket av ubalanserte luftstrømmer. Likevel indikerer de gyldige resultatene en 11.9% lavere latent fuktgjenvinnings effektivitet sammenlignet med det høyeste resultatet fra MV-3.

MV-1 sin lave latente fuktgjenvinnings effektivitet viser begrensninger ved fuktgjenvinning for membraner med lav fuktoverføring. I motsetning viste de to membranene med høyere fuktoverføring høyere effektivitet, men dårligere selektivitet for lukter og flyktige organiske forbindelser. MV-2 presterte dårligere enn MV-3 og anbefales ikke for bruk i ventilasjon basert på denne rapporten. Valget mellom en membran med lav fuktoverføring, som MV-1, og høy fuktoverføring, som MV-3, avhenger av de spesifikke designkravene for installasjonen. MV-1 anbefales på grunn av sin betydelig bedre selektivitet for lukter og flyktige organiske forbindelser, men svakere fukt kontroll må tas i betraktning. I tilfeller med minimal risiko for eksponering for sterke lukter og flyktige organiske forbindelser anbefales MV-3 på grunn av sin høye effektivitet. Samlet sett understreker funnene i rapporten viktigheten av membranvalg og balanserte luftstrømmer for å forsikre optimal inneluftkvalitet. Rapporten fremhever potensialet membran energivekslere har for energieffektive bygninger og komfortable innemiljøer.

List of Abbreviations

AHU	**A**ir **H**andling **U**nit
BCT	**B**ulding **C**limate **T**rancker
EATR	**E**xhaust **A**ir **T**ransfer **R**atio
HVAC	**H**eating, **V**entilation, and **A**ir **C**onditioning
IAQ	**I**ndoor **A**ir **Q**uality
ISO	**I**nternational **O**rganization of **S**tandardization
MEE	**M**embrane **E**nergy **E**xchanger
NIPH	**N**orwegian **I**nstitute of **P**ublic **H**ealth
NTU	**N**umber of **T**ransfer **U**nits
PD	**P**ercentage of **D**issatisfied
RH	**R**elative **H**umidity
TVOC	**T**otal **V**olatile **O**rganic **Compounds**
VOC	**V**olatile **O**rganic **C**omponds

List of Symbols

α	Probability of error	[%]
δ	Thickness	[m]
ϵ	Porosity	[%]
ε_L	Latent effectiveness	[%]
ε_S	Sensible effectiveness	[%]
λ	Thermal conductivity	[W/mK]
μ	True mean value	p.d.u.
ρ	Density	[kg/m^3]
χ	Crossover	[%]
Ψ	Stevens law: Sensory perception intensity	p.d.u.
a	Stevens law: Power exponent	[−]
$\mathrm{C}_{e,in}$	Exhaust inlet contaminant concentration	[μg/m^3]
$\mathrm{C}_{e,out}$	Exhaust outlet contaminant concentration	[μg/m^3]
$\mathrm{C}_{s,in}$	Supply inlet contaminant concentration	[μg/m^3]
$\mathrm{C}_{s,out}$	Supply outlet contaminant concentration	[μg/m^3]
d	Diameter	[m]
D	Diffusivity	[m^2/s]
I	Stevens law: Physical stimulus intensity	p.d.u.
k	Stevens law: Constant	[−]
n	Number of panelists	[−]
n_d	Number of dissatisfied panelists	[−]
Δp	Pressure drop	[Pa]
P	Permeability	[m^2/s]
PD	Percentage of dissatisfied	[%]

q_v	Air flow rate	[L/s]
RH	Relative humidity	[%]
s	Standard deviation	p.d.u.
$T_{e,in}$	Exhaust inlet temperature	[°C]
$T_{e,out}$	Exhaust outlet temperature	[°C]
$T_{s,in}$	Supply inlet temperature	[°C]
$T_{s,out}$	Supply outlet temperature	[°C]
U	Uncertainty	[%]
U_R	Random uncertainty	[%]
U_S	Systematic uncertainty	[%]
$w_{e,in}$	Exhaust inlet humidity	$[kg_{H_2O}/kg_{air}]$
$w_{e,out}$	Exhaust outlet humidity	$[kg_{H_2O}/kg_{air}]$
$w_{s,in}$	Supply inlet humidity	$[kg_{H_2O}/kg_{air}]$
$w_{s,out}$	Supply outlet humidity	$[kg_{H_2O}/kg_{air}]$
$\bar{x}$	Mean	p.d.u.

* p.d.u. = procedure defined unit

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1 Introduction

Global commitment to sustainable development in the building sector is growing, but it needs to increase rapidly in pace and scale to reach the Paris Agreement goal of decarbonization by 2050 [1]. According to the *2022 Global Status Report for Buildings and Construction* issued by the UN Environment Programme, the development is currently off-track to reach a zero-emission, resilient, and efficient sector within the given timeline. The report states that the CO_2 emissions from building operations are the highest ever recorded, with emissions at 10 $GtCO_2$-eq. This number is an increase of 5% from 2020 and 2% higher than pre-pandemic recordings in 2019. The global energy demand from buildings has also increased by 4% since 2020.[2]

The Global Buildings Climate Tracker (BCT) monitors the development in the building and construction sector towards reaching the goal of the Paris Agreement and indicates that the sector is off track to reach decarbonization within 2050. These trends are visualized in figure 1.1, which shows the decarbonization level since the beginning level of the Paris Agreement in 2015. The scale goes from zero to a hundred until it reaches the zero-carbon building stock target. The trends in 2020 are highlighted as these values are highly affected by the COVID pandemic, and it shows a negative trend after the pandemic in 2021. The gap between the direct reference path to the goal and the actual progress is increasing.[2]

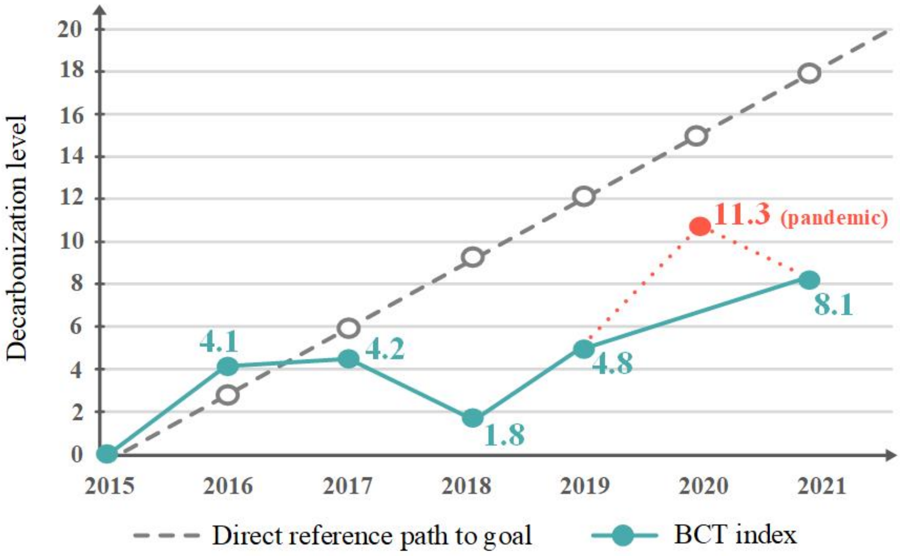

Figure 1.1: Progress of decarbonization of the building and construction sector to reach the target of zero-carbon building stock within 2050.[2]

Although the Global Status Report states increasing emissions, it shows improvements concerning building investment and policy trends. The report shows that the number of countries with mandatory or voluntary regulations for building energy performance is increasing. The number of countries applying building energy codes was 79 in 2021, an increase of 27.4% from 2015. The global investment in energy efficiency related to the building sector is also increasing. Investment in energy efficiency in the building sector was 237 billion USD in 2021, an increase of 51.9% from 2015. These numbers show that there is a growing motivation for commitment to actions for decarbonization and energy efficiency.[2, 3]

As technology advances and building requirements develop, modern buildings are becoming increasingly airtight to improve energy efficiency and ensure thermal comfort. However, research shows that increasing air tightness of buildings can result in higher concentrations of volatile organic compounds (VOC) and CO_2 indoors. Installing proper ventilation systems to maintain good indoor air quality (IAQ) in these tightly sealed buildings is essential.[4]

To reduce energy-related emissions from the operation of buildings and secure energy-efficient solutions, it is recommended to implement heat recovery in all ventilation systems. Heat recovery systems recirculate warm indoor air and transfer heat between the supply and exhaust air streams as fresh air is introduced from the outside.[5] Requirements from TEK17 state that annual temperature efficiency should be at least 80% in a heat recovery ventilator.[6]

A problem with heat recovery in Nordic climates is frost formation in the air flow passage. Frost formation is a common issue for traditional aluminum plate heat exchangers. The formation of frost occurs when dense and warm inside air interacts with the cold surface of the heat exchanger, and it gets humid as the exhaust air condensates in the heat exchanger. The water vapour then freezes to ice if the outside temperature is below freezing point.[7, 8]

Frost formation in the heat exchanger and ventilation system can block the air flow passages, which can result in full or partial blockage. This can increase the system's pressure drop and cause a rise in pressure on the exhaust side. As a result, the air flow rate of the system may decrease due to reduced air flow rate through the exhaust duct. The low air flow rate can consequently increase the need for electric fan power. Additionally, frost formation can decrease the heat transfer rate between the exhaust and supply air streams and cause a draft due to the low temperature of the supply air.[7, 8]

Membrane technology is continuously researched and applied for use in heat recovery. Membrane energy exchangers (MEE) can transfer heat and moisture between the air streams, reducing the risk of frost formation and keeping an acceptable indoor humidity level during the dry winter season. When membranes are chosen for MEEs for use in heating, ventilation, and air conditioning (HVAC) systems, they should transfer only heat and moisture and be resistant to contaminants, odours, and other gases. MEEs should prevent cross-contamination between the supply and exhaust air streams by placing the membrane to separate the air flows.[9]

1.1 Assignment Definition

This thesis is written for the Department of Energy and Process Engineering at the Norwegian University of Science and Technology in Trondheim during the spring semester of 2023. The subject code is TEP4910. The thesis is a continuation of a preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* with the subject code TEP4530 written by *Tærum, Mathea L.* and delivered in December 2022. Some of the research executed in the preliminary project is used to complement the research in this thesis, and some figures and text are directly taken from or based on the study in the preliminary project. Text that is based on the preliminary project is found in parts of the introduction, the theory chapters 2, 3 and 4, and partially in chapter 5 describing the test rig and chapter 6 describing the laboratory experiments and methods. All the figures in the thesis are recreated based on the citations.

The thesis analyzes the odour transfer through and performance of different types of quasi-counter flow MEEs to see how they affect IAQ during different occupant behavior and outdoor conditions. Three MEE prototypes are provided by Flexit AS and tested in the Energy and Indoor Environment laboratory facilities at NTNU. The thesis is connected to the funded research project *Defreeze MEE Now* [10] that looks into the development of new types of frost-free MEEs in Nordic climates. Flexit AS owns the project, while NTNU and SINTEF are research partners.

The main goal of the thesis is to compare different membranes and their effect on IAQ from potential odour transfer, as minimal research has been done in this field of study. The odour evaluation is executed with sensory tests with panel members. To supplement the results, sensors are used to measure VOC transfer between the exhaust and supply air in the laboratory test rig, and sensible and latent effectiveness is measured and calculated at different outdoor air conditions to look further into the performance of the membranes. The data from the laboratory experiments are analyzed, processed, and presented in this study.

The assignment definition is:

Performance of Membrane Energy Exchangers in Ventilation: Analyses of Odour Transfer, VOC Transfer, and Sensible and Latent Effectiveness

The study aims to perform laboratory experiments that give the foundation to answer the research questions below. The main objective is to evaluate the selectivity of the different membranes regarding odour transfer. Additionaly, the crossover of VOC contaminants provides additional information regarding membrane selectivity. The performance of the membranes, their relation to real-life scenarios, and their effect on IAQ are also included in the main objectives.

i. To what extent do the properties of different membranes chosen in membrane energy exchangers influence their selectivity to odour particles and VOC contaminants?

ii. How can the performance of prototype membrane energy exchangers tested in a laboratory relate to real-life scenarios?

iii. How can the performance of membrane energy exchangers affect indoor air quality?

2 Membrane Energy Exchanger (MEE)

The energy needed for cooling and heating buildings can be significantly reduced by recovering heat from the exhaust air. Heat exchangers are used in HVAC systems to transfer heat between the exhaust and supply air streams and are either regenerative or recuperative. The efficiency of a heat exchanger is determined by its type, the size of its surface area, and its heat-transferring properties.[5]

Air-to-air rotary heat exchangers are a commonly used technology in Norway today due to their low frost risk and high temperature efficiency. However, the problem that can occur with air-to-air heat exchangers is that it is a risk of leakage between the air flows. Leakage can lead to contaminant and odour transfer between the supply and exhaust air streams and can be an issue for apartment complexes with a shared air handling unit (AHU). This can result in poor IAQ and dissatisfied occupants. To minimize this risk, a plate heat exchanger can be used instead to reduce air leakage from the rotary heat exchanger.[8, 10–12]

Plate heat exchangers come in several types: e.g. cross flow, counter flow and quasi-counter flow. In the cross flow type, the air flows in perpendicular directions, as shown in figure 2.1. Although cross flow heat exchangers have been dominant on the market for a while due to their easy-to-seal ducts, their efficiency is lower compared to the counter flow heat exchanger.[13, 14]

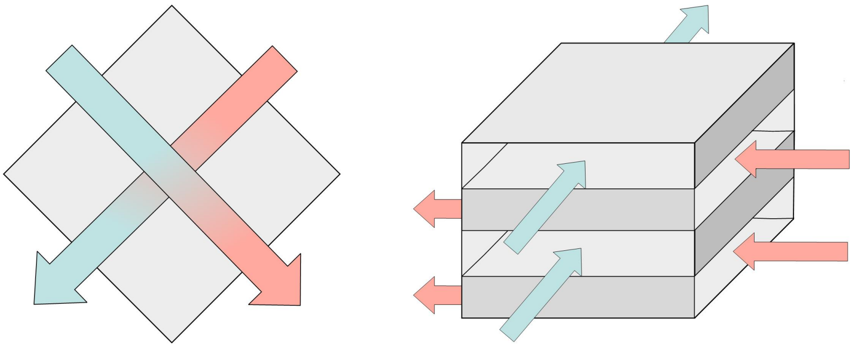

Figure 2.1: Cross flow heat exchanger.[15, 16]

In counter flow heat exchangers, the air flows move in opposite directions, resulting in a larger area of heat transfer and higher efficiency than cross flow heat exchangers. The air movement in counter flow heat exchangers is illustrated in 2.2. This type of heat exchanger can also handle higher flow rates than cross flow. The temperature difference is uniform along the heat transfer area of counter flow heat exchangers, which reduces the thermal stress of the system. The temperature of the cooling outlet can also exceed the temperature of the warm inlet. An issue with the standard counter flow heat exchanger is that obtaining a tight seal between the system's exhaust and supply air ducts can be challenging.[14, 17]

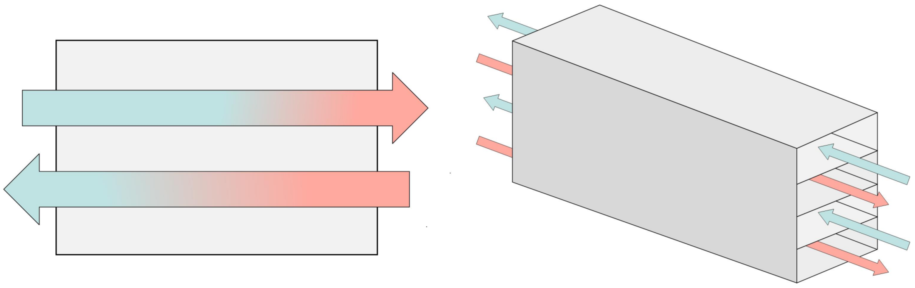

Figure 2.2: Counter flow heat exchanger.[15, 16]

A quasi-counter flow heat exchanger consists of a cross flow heater with a counter flow core, as shown in figure 2.3. This construction takes advantage of the higher efficiency of the counter flow heat exchanger and the simple sealing of the cross flow heat exchanger. This heat exchanger type is better regarding both latent and sensible effectiveness. Quasi-counter flow MEEs are the types researched in this study.[14, 18]

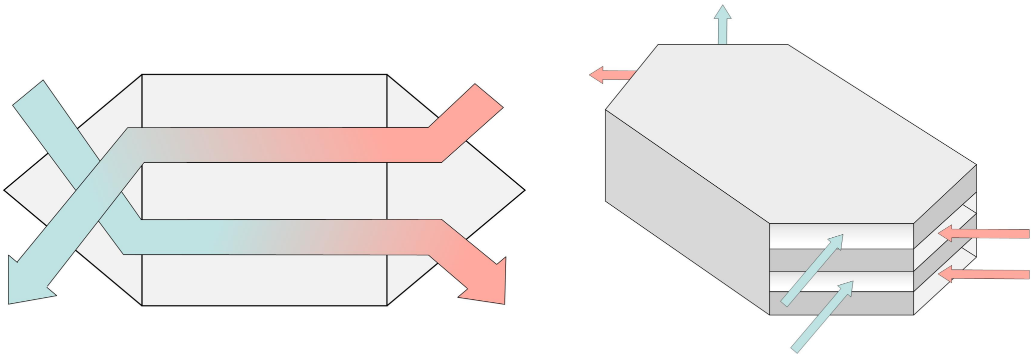

Figure 2.3: Quasi-counter flow heat exchanger.[15, 16]

2.1 Membrane Performance

Membranes are traditionally used for separation in industrial processes, e.g., gas separation and reverse osmosis [19]. Over the last 25 – 30 years, researchers have studies membranes for the energy-saving opportunities it provides to HVAC systems. It is used as an alternative to conventional cooling, heating, and dehumidifying technology. The membranes do not save energy themselves but contribute to improving the processes that do. By using membranes, research by *Woods* (2014) [9] states that HVAC systems can improve the energy recovery processes that exchange moisture between the exhaust and supply air streams, and remove moisture from the air without cooling it to dew-point temperature.[9]

The membrane's role in the MEE is to create a barrier between the two air streams. MEEs can recover heat and moisture between the supply and exhaust air streams with a water-permeable membrane, as illustrated in figure 2.4. The figure shows heat and moisture transfer through the membrane and the impermeability of the airborne pollutants. This makes it possible for the exchanger to utilize the latent and sensible heat in the air more efficiently, which increases the exchanger's and system's total efficiency.[9]

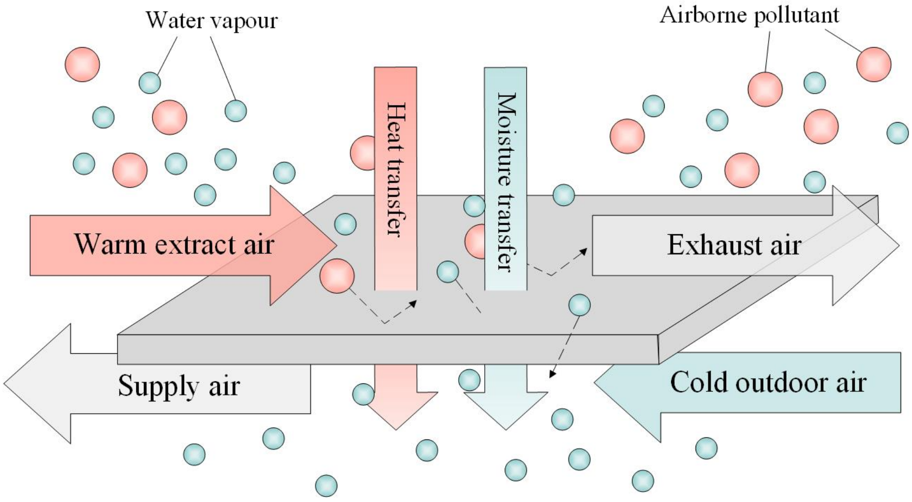

Figure 2.4: Working principle of a MEE with heat and moisture transfer.[5]

When choosing membranes for HVAC systems, it is important to consider their permeable properties. Membranes should have the ability to allow heat and water vapour to pass through, while blocking for odours, contaminants, and other gases. Membranes should prevent cross-contamination as it separates the air flows.[9] Pressure drops over the MEE core and sensible and latent effectiveness are factors used to evaluate membrane performance [14]. These factors are further described in chapter 2.2 and 2.3.

The performance of a membrane depends on various factors, including its thickness, density, thermal conductivity, porosity, and selectivity. For dense membranes, permeability is crucial, while for porous membranes, diffusivity is important. When a membrane has high permeability, less surface area is required for a given process. High selectivity allows water vapour to be removed from an air stream without removing any air. The permeability of membranes can be improved with thinner membranes, higher porosity, and larger pores. However, this might result in less durable membranes and the possibility of pore breakthrough.[9]

2.1.1 Membrane Materials

Membranes are typically defined as dense or porous based on the pore structure of the membrane. The main difference between the two structures is how water vapour moves through them. According to *Woods* (2014) [9], in dense membranes, water vapour is adsorbed on the polymer and moves through the material on a molecular level. In a porous membrane, the water vapour diffuses through the mix of vapour and air within the pore space. Porous membranes are used for liquid/gas contact, while dense membranes are used for gas/gas contact.[9] Figure 2.5 shows the processes through a dense membrane to the left and a porous membrane to the right.

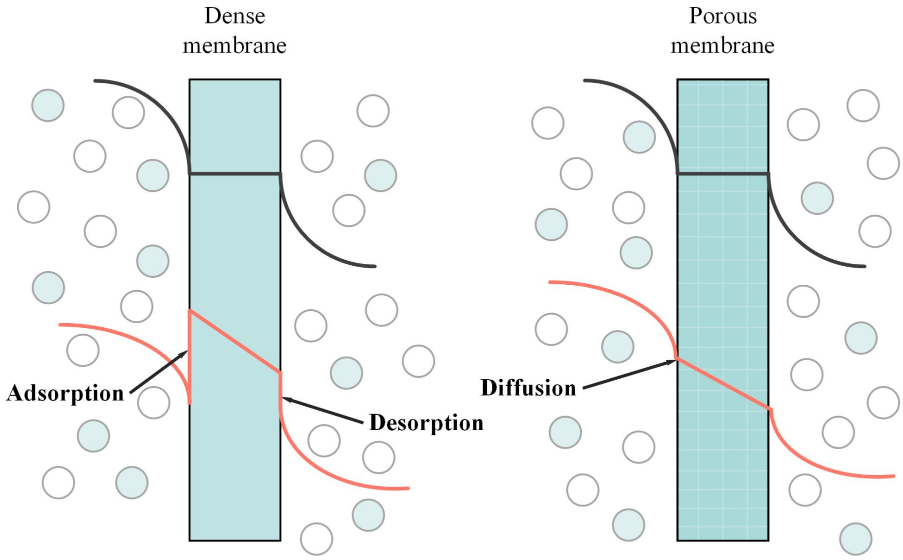

Figure 2.5: Moisture transfer through dense and porous membranes.[9, 20]

Transportation through dense membranes happens by adsorption and desorption because of the small pore size. Molecules adsorb onto the polymer surface, diffuse through the membrane, and then desorb from the opposite polymer surface, as seen in the figure. An example of dense membranes is polyamide membranes. Thin membranes can be used to shorten the length the molecules must travel in the diffusion process. The pores in dense membranes are around 0.1 nm. The permeability of a dense membrane is decided by its diffusivity, which is the rate particles spread through the membrane, and the solubility, which is the amount that will dissolve. The properties of dense membranes make them close to impermeable to odours.[9, 12, 20]

Porous membranes have larger pores and more open volume than dense membranes. The water vapour diffuses through the pore space instead of through the solid polymer, as in the dense membrane. Researchers are developing porous membranes with 0.03 μm to 0.1 μm pore size and 40% to 70% porosity. The porous membrane material is hydrophobic, meaning they are water repellent and the water molecules are more attached to each other than to the solid material. This means that pressure must be applied to the surface tension to transfer moisture through the membrane. This is called diffusion and is illustrated in the figure. The large pores of porous membranes provides a larger contact surface, which increases the heat transfer between the exhaust and supply air streams.[9, 12, 21]

2.1.2 Spacers in MEE

In MEEs, spacers are used as a barrier between the membrane sheets to prevent them from sticking together or collapsing. Membranes shaped as flat sheets are not stable enough to support themselves.[22] The geometrical design of the spacer is essential for the performance of the MEE. A disadvantage of spacers is that it increases the pressure drop. It is therefore important that the spacer is designed well to avoid this and keep the pressure drop at a minimum. The benefits of spacers are that they increase the heat and moisture transfer in the MEE and avoid deflection of the air flow.[9, 23, 24]

2.2 Pressure Drop Through the MEE

Pressure difference is the driving force of MEEs. It is caused by compressors, fans, or pumps, which force the supply and exhaust air streams through the exchanger to transfer energy. The pressure drops occurring in quasi-counter flow exchangers are caused by changes in air flow caused by various factors. There is sudden contraction at inlets and expansion at outlets of the MEE, which is illustrated in figure 2.6. The contraction at the inlet leads to a rapid decrease of the pressure drop before it decreases even further through the exchanger. It increases at the exit as the cross-sectional area increases and there is free expansion, before it stabilizes in the ducts. There are core pressure drops in both the cross and counterpart of the exchanger, and pressure drops due to bends that change the air flow direction.[25, 26]

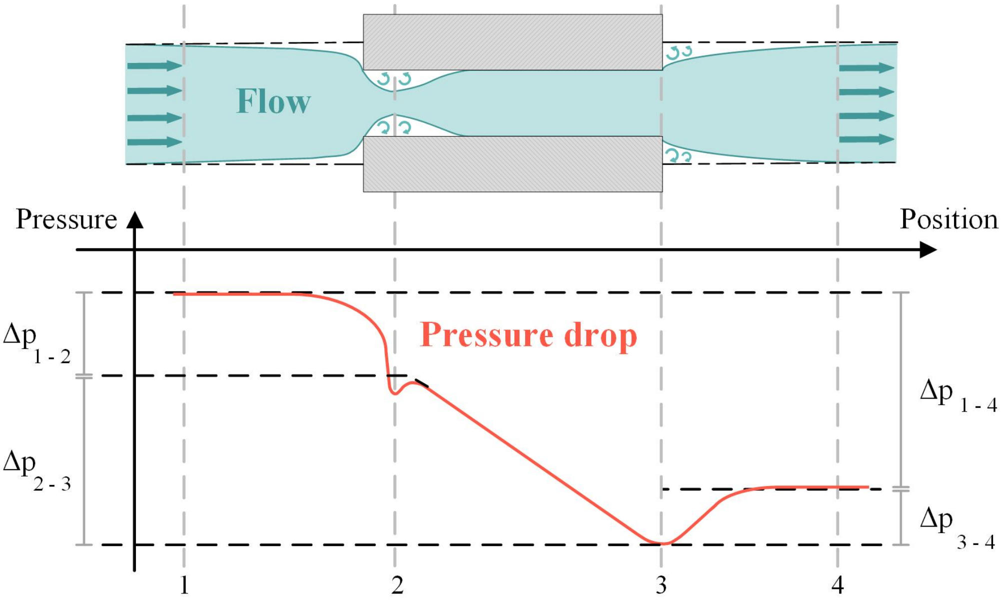

Figure 2.6: Pressure profile through MEE core.[15, 16]

The major losses of the system are the most significant contribution to the total pressure drop. These are the losses due to friction in the cross and counterparts of the exchanger. Minor losses are the air flow interruption caused by components like inlets and outlets, valves, and bends. For MEEs, the minor losses are at the inlet and outlet, and at the two bends each air flow faces in the exchanger core. The total pressure drop over the quasi-counter flow MEE is the sum of the major and minor losses.[16, 25]

2.3 Sensible and Latent Effectiveness

One of the greatest advantages of membranes is their ability to transfer both moisture and heat, which leads to the utilization of both sensible and latent heat of the air, increasing the system's total efficiency.[27] Sensible and latent effectiveness is used to describe the performance of a particular unit or system. Sensible heat is the temperature change independent from phase change. Latent heat is the energy needed for a phase change without temperature variations. The humidity contains latent heat.[28]

According to a research paper by *Zhang* (2010) [14], quasi-counter flow exchangers have 5% higher sensible and latent effectiveness compared to cross flow exchangers. This is due to the efficient heat mass transfer in the counterflow part of the exchanger. Data from research by *Woods*(2014)[9] shows that sensible effectiveness generally is higher than latent effectiveness. *Woods* refers to research by *Zhang* (2008) [29] and *Min et al.* (2009) [30] showing that this is due to the non-negligible moisture resistance of membranes. The moisture resistance of membranes varies with location and local climate. This means that membrane effectiveness can be affected by changes in temperature and relative humidity (RH), affecting the latent effectiveness. The sensible effectiveness can be affected by changes in conductivity. The effectiveness of the membrane is also dependent on air flow rate and membrane area.[9]

There are several ways of calculating membrane effectiveness. A common approach is with the effectiveness-NTU (Number of Transfer Units) method. This is a more detailed method used to analyze the heat and mass transfer in energy exchangers and includes factors like operating conditions, geometry, and design.[31] As the calculations in this thesis are based on measurements done in a laboratory, the measured values can be directly used to calculate the effectiveness. Equation 2.1 below calculates the sensible effectiveness, while equation 2.2 calculates the latent effectiveness. These equations can be used when direct measurements are made and there is a balanced air flow rate in the system.[9, 12]

$$\varepsilon_S = \frac{T_{s,out} - T_{s,in}}{T_{e,in} - T_{s,in}} \tag{2.1}$$

$$\varepsilon_L = \frac{w_{s,out} - w_{s,in}}{w_{e,in} - w_{s,in}} \tag{2.2}$$

In order to calculate the latent effectiveness with the equation above, the humidity ratio (w) must be known. This can be calculated based on measured RH values and temperatures using equation 2.3.[32]

$$w_i = \frac{RH_i \cdot 10^6}{e^{(5294/T_i)} - 1.61 \cdot 10^6 \cdot RH} \tag{2.3}$$

3 Volatile Organic Compounds (VOC)

Volatile organic compounds (VOC) are carbon-based substances in gas form that are emitted from some gases, solids, or liquids that can be present in household products. These products typically contain organic chemicals, like paints and varnishes, cosmetics, cleaning supplies, stored fuels, and numerous others. Products like building materials, furniture, printers, glues, and permanent markers can also emit VOC. Organic compounds can be released from these products when used and, to a certain extent, when stored. The VOC level in the air can also persist long after an activity is completed.[33]

The term volatility refers to how easily a substance vaporizes. If a substance has high volatility and a low boiling point, it is more likely to emit gas into the air. VOC concentration can be measured and consists of different types of gases. Total VOC (TVOC) is often used to describe the total concentration of different organic compounds. The measurements are given as the mass of chemicals per volume of air. Different VOC types are measured with different equipment and techniques, and no measurement technique has the ability to register all present VOC in the air. Because of this, all information about VOC measurement must include how it was measured to provide sufficient practical meaning.[5, 34]

The Norwegian Institute of Public Health (NIPH) is yet to give a numerical recommendation for the concentration of TVOC in indoor air or gases emitted from materials. The reason for this is that the academic basis is insufficient and would lead to an increased amount of measurements where the results, to a minimal degree, can be used in the context of health effects. It is, however, recommended to use human judgment and avoid unnecessary exposure. Particularly toxic VOCs are assessed separately, which will be further addressed in the chapter concerning formaldehyde and acetone.[35]

Exposure to VOC is generally higher indoors than outdoors due to lower air exchange rates in indoor environments and stronger sources.[36]. According to the standard for indoor environmental input parameters for energy performance of buildings, NS-EN 19798-1:2019 [37], buildings should have interior materials with low or very low emitting of pollutants. The following limits for low and very low polluting buildings in table 3.1 are given by the standard. The table shows the limits for TVOC, formaldehyde, and carcinogenic VOC.[37]

Table 3.1: Criterias for low and very low polluting buildings.[37]

	Low pollution	**Very low pollution**	
TVOC	< 1000	< 300	[μg/m^3]
Formaldehyde	< 100	< 30	[μg/m^3]
Carcinogenic VOC	< 5	< 5	[μg/m^3]

VOCs can cause both mild and severe diseases over a short or long period of time. The most significant contributors regarding the impact of VOC are the length of time the person has been exposed to the compounds and the level of exposure. Only some VOCs have known adverse health effects. The impacts of harmful VOCs can be immediate symptoms like headache and irritation in the throat, eyes, and nose, or more severe long-term impacts like lung diseases or cancer. Carcinogenic VOC can cause cancer and is, for instance, found in tobacco smoke. The recommended limit for carcinogenic VOC in buildings is low, as shown in table 3.1.[33, 37]

3.1 VOC Types: Formaldehyde and Acetone

There are numerous types of VOCs. Each VOC has its unique characteristics, with different risks of harmful health effects and varying toxicity levels. This study focuses on two types of VOCs: formaldehyde (CH_2O) and acetone (C_3H_6O).[38]

Formaldehyde

Formaldehyde is a type of VOC primarily known for its pungent odour. It is a colourless gas that is flammable. Experience of discomfort due to odour from formaldehyde ranges between 50 μg/m^3 and 500 μg/m^3, hence the low limits given in table 3.1.[36]

A person experiencing short-term exposure to formaldehyde can have skin, throat, nose, and eye irritation, nausea, coughing, sneezing, teary eyes, breathing difficulties, and general discomfort. Formaldehyde can be found indoors as a VOC source from combustion processes such as cooking, heating, smoking, and candle burning. It also stems from new building materials like e.g. insulation, glue, paints, textiles, and wallpapers. Higher concentration levels of formaldehyde over a longer exposure period can increase the risk of cancer. At regular IAQ, the cancer risk from formaldehyde exposure can be neglected. NIPH recommends a maximum limit of formaldehyde concentration of 100 μg/m^3 up to 30 minutes of exposure.[35, 36, 39]

Acetone

Acetone is a VOC found naturally in the environment or manufactured chemically. It is a clear liquid with a distinct taste and odour. It is a flammable substance that evaporates quickly and dissolves in water. Acetone can be found naturally in volcanic gases, insects, plants, and trees, but is also present in industrial processes and manufactured sources like vehicle exhaust, landfills, and tobacco smoke. Industrial processes release more acetone into the environment than natural processes.[40, 41]

Acetone is used to dissolve other substances, as well as it is used to make plastic, paint, cleaning products, and personal care products. An example of a product that can contain acetone is nail polish remover. Exposure to acetone can cause irritation in the throat, eyes, and nose at moderate exposure. Ingesting or breathing high amounts of acetone over a short period can lead to nausea, headaches, increased pulse, changes in the amount and size of blood cells, and unconsciousness. Furthermore, if acetone is in direct contact with the skin, it can cause the skin to become irritated, dry, and cracked.[41]

3.2 Contaminant Crossover and Leakage

Crossover of contaminants in the heat exchanger refers to the contaminants that are transferred between the exhaust and supply air. The transfer mechanisms can be due to pressure differences between the air streams causing diffusion through the membrane, air leakage between the air flows, or transfer in e.g. rotary wheels. Any of these factors can cause cross-contamination in the exchanger. If there is air leakage in the ventilation system, it can reduce the amount of fresh air delivered, affecting air quality and balance of the two air streams. In addition, air leakage can decrease the effectiveness of energy- and heat exchangers by affecting the pressure levels in the system. Figure 3.1 illustrates the transfer of contaminants from the exhaust air to the supply air through the membrane.[42–44]

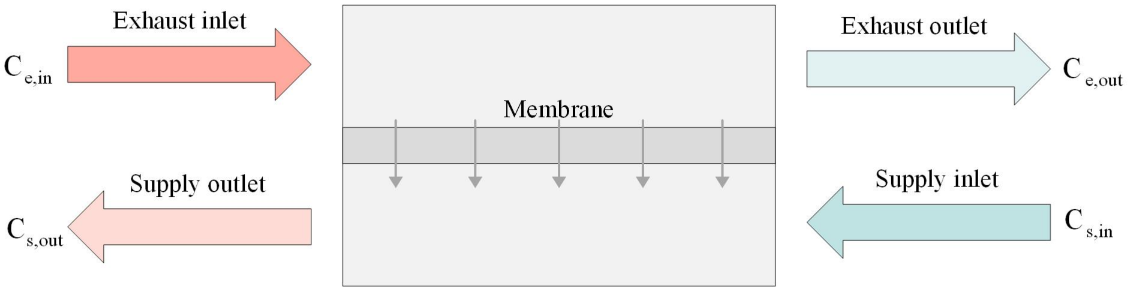

Figure 3.1: Cross-contamination from exhaust to supply air flow.[45, 46]

Exhaust air transfer ratio (EATR) is the share of contaminants that are transferred from the exhaust air to the supply air. EATR can be calculated with equation 3.1 in cases where the air flow is equal on both sides. C$_{s,in}$ and C$_{s,out}$ is the concentration of contaminants at the inlet and outlet of the supply air flow, while C$_{e,in}$ is the concentration of contaminants at the exhaust air inlet. This is also illustrated in figure 3.1.[42, 44, 46]

$$EATR = \frac{C_{s,out} - C_{s,in}}{C_{e,in} - C_{s,in}} \tag{3.1}$$

The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Handbook from 2020 compares EATR for commonly used heat and energy exchangers. MEEs have an EATR between 0% and 5%, while a fixed plate heat exchanger has an EATR between 0% and 2%. There are larger variations for the energy and heat wheel, with an EATR between 0.5% and 10%, showing the higher transfer ratio occurring in rotating parts of exchangers.[46] To evaluate the crossover, χ, of contaminants, equation 3.2 can be used. It looks at the percentage of contaminants transferred from the exhaust air stream to the supply air stream in the MEE.[45]

$$\chi_i = \frac{C_{i,s,out}}{C_{i,e,in}} \cdot 100\% \tag{3.2}$$

4 Indoor Air Quality: Odour

An odour is defined by the International Organization of Standardization (ISO) as a pleasant or unpleasant smell caused by chemical compounds emitting into indoor air[47]. Perception of odours also depends on the room's environmental conditions, which relate to the room temperature, RH, and ventilation conditions. Pollutants from VOCs, which can cause strong odours, are one of the main reasons for complaints on IAQ.[48]

The perception of odours is non-linear and varies based on several factors. Stevens power law relates the stimulus intensity with the sensation magnitude and is given in 4.1. The equation calculates the intensity of sensory perception (Ψ) by including a constant (k), the intensity of the physical stimulus (I), and a power exponent (a). The power exponent depends on the type of stimulation addressed, and for smell, 0.6 is used.[49]

$$\Psi = k \cdot I^a \tag{4.1}$$

Odours can be divided into categories that describe specific odourants shown in the odour wheel in figure 4.1. It shows different smells that can be recognized and put into categories and how they can be perceived in the olfactory organ. Specific categories stem from chemically made products, while others are from natural products. Some odours are more commonly found in everyday life products than others.[50]

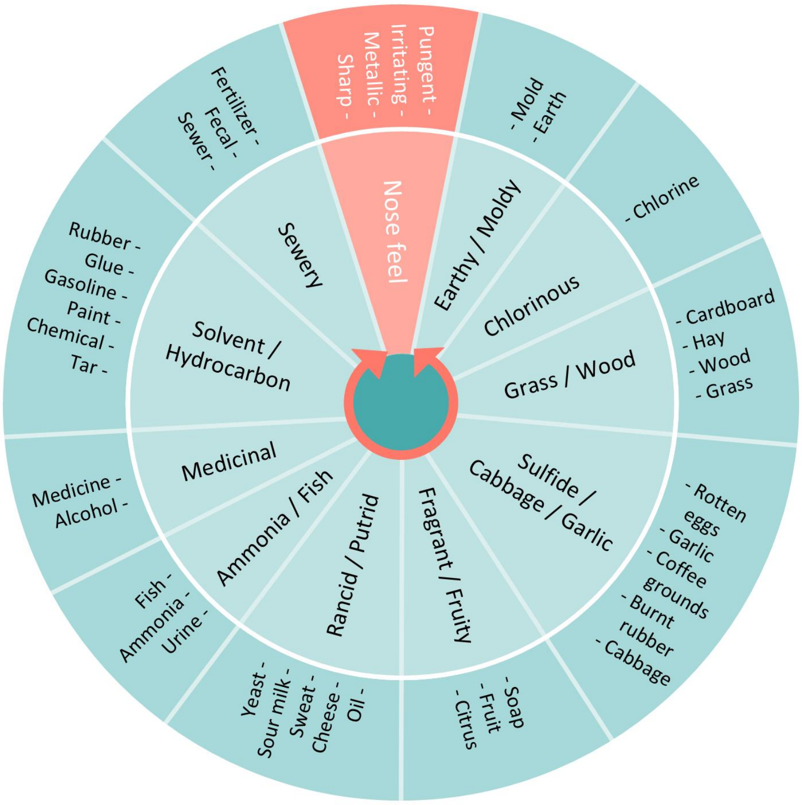

Figure 4.1: Odour category wheel and perception in the nose.[50]

4.1 Technique for Odour Sensory Analysis

ISO 16000-30:2014[51] is a standard that describes the procedure for sensory panel analysis of odour in buildings. The standard explains different methods for assessing odour, depending on whether the panel members are trained or untrained. There are two ways to conduct odour measurement testing: direct testing in real conditions or in a laboratory. Real conditions can be more sensitive to outside disturbances, and there is a risk of the odour being modified. In the laboratory, the odour tests can either be from samples collected in real conditions or directly introducing odour sources to an air system. The sampling procedure can be complex, while the direct use of odour sources at the laboratory is easier to repeat if errors occur during sensory testing. This method sends the concentrated air through a sniffing port, allowing panelists to evaluate the air quality directly.[51]

The sensory panel odour analysis addresses the three assessments presented in this chapter: acceptability, intensity, and hedonic tone. The main test methods to evaluate odour are acceptability and perceived intensity, while the hedonic tone evaluation can complement these assessments. For a trained panel, the evaluation of acceptance and perceived intensity has to be performed independently, while the assessments can be combined if the panel members are untrained. The testing of acceptability, intensity, and hedonic tone is executed with the procedure that the panelist first sniffs the air and then attempts to answer the given questions.[51]

4.1.1 Odour Acceptability and Percentage of Dissatisfied

The acceptability of an odour evaluates the quality of the indoor air and is a parameter for the percentage of dissatisfied occupants. The assessment should include at least 15 untrained panel members, but it will have more accurate results with more participants. Equation 4.2 calculates the predicted percentage dissatisfied (PD) by looking at the share of dissatisfied people compared to the total number of panelists. The total number of people participating in the test is given by n, while n_d is the number of dissatisfied people. The panelists are presented with a yes/no question of whether they find the odour acceptable. According to the standard, the following question should be asked: "*Imagine you are exposed to this odour in your everyday life. Would you consider this odour acceptable?*".[51]

$$PD = \frac{n_d}{n} \cdot 100\% \tag{4.2}$$

Acceptability can also be measured at a scale from *clearly acceptable* at +1 to *clearly unacceptable* at -1, as shown in figure 4.2. The following question should be asked when ranting the acceptability "*Imagine you are exposed to this odour in your everyday life. How would you rate this odour on the following scale?*".[51]

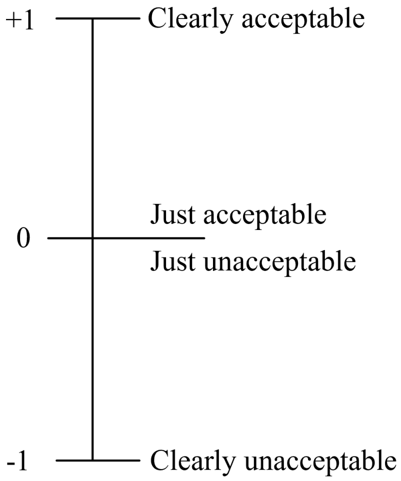

Figure 4.2: Odour acceptability scale from clearly acceptable (+1) to clearly unacceptable (-1).[51]

4.1.2 Odour Intensity

The perceived odour intensity can be measured as the intensity of an odour source on a scale that consists of values from 0, indicating no odour, to 6, indicating extremely strong odour. Only whole numbers should be given as answers, and the question can be presented as in figure 4.3.[51]

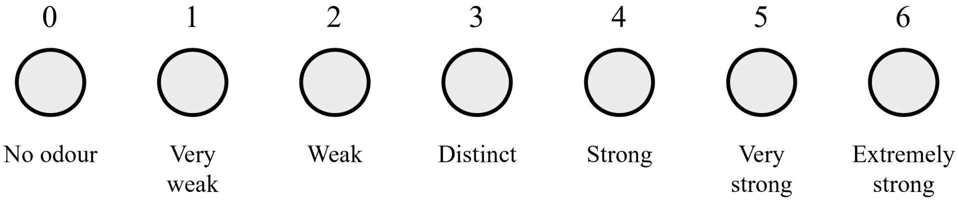

Figure 4.3: Odour intensity scale from no odour (0) to extremely strong odour(6).[51]

4.1.3 Hedonic Tone

A sensory test evaluates hedonics to determine whether the odour is pleasant or unpleasant. It is often used together with the evaluation of perceived odour intensity. The hedonic tone depends on the odour and its mixture, the concentration, and each panelist's experience and relationship with the odour. The hedonic tone is assessed with a scale ranging from -4 to 4, where 0 is neutral. Very pleasant odour is defined as 4, and extremely unpleasant odour is defined as -4, as illustrated on the scale in figure 4.4.[51]

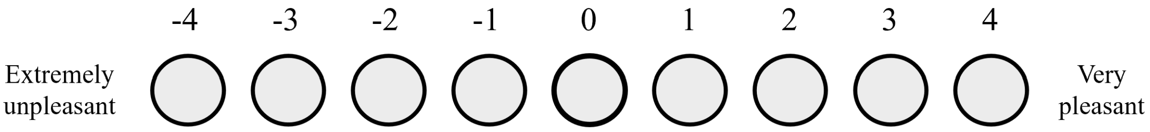

Figure 4.4: Hedonic tone scale from extremely unpleasant (-4) to very pleasant (4).[51]

5 MEE Test Rig and Tested Membrane

The laboratory test rig used for experiments is located in the basement of the Heat Engineering Laboratory at NTNU, Gløshaugen, and is a part of the Indoor Environment Laboratory facilities. Flexit AS has provided three new MEEs for the research in the master thesis. In addition to the new MEEs, an old MEE installed in the test rig for the Ph.D. research of Liu [20] was evaluated for odour transfer by a sensory panel during the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* written by *Tærum, Mathea L.* and delivered in December 2022. This chapter describes the layout and components of the MEE laboratory test rig, sensors and measuring devices installed and used in the laboratory, and the characteristics of the MEEs.

5.1 Laboratory Test Rig

The MEE test rig was initially built and utilized for Peng Liu's Ph.D. thesis in the period between 2012 and 2016 [20]. Since then, the test rig has been used for several master theses and project works. The original construction of the test rig is shown in figure 5.1. This setup is used in the thesis for the experiment of latent and sensible effectiveness and VOC sensor measurements. The environmental chamber is used to regulate the supply air temperatures for the effectiveness assessment.

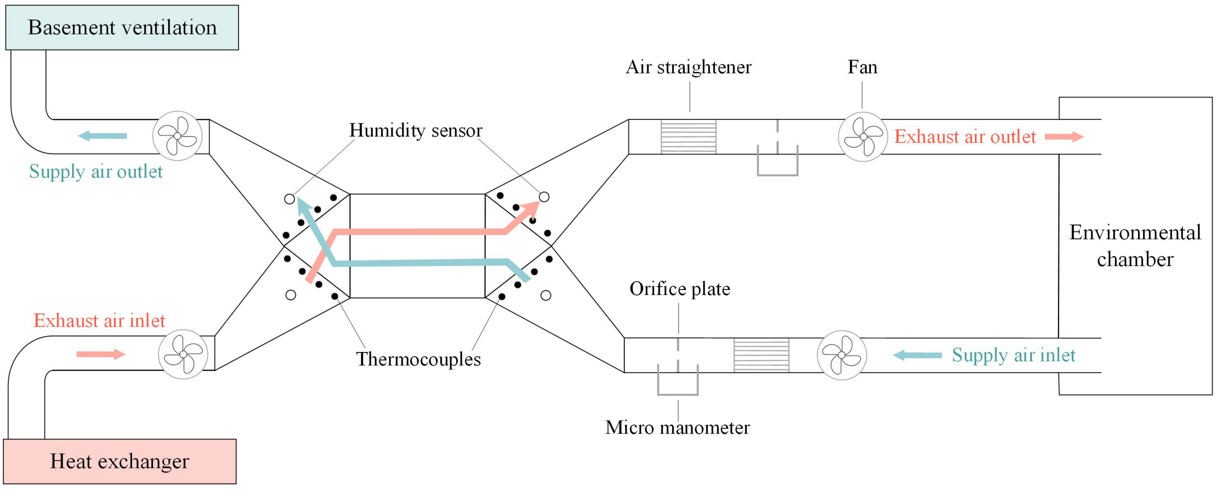

Figure 5.1: Sketch of original MEE test rig. Based on Liu (2016).[20]

The test rig consists of two duct channels, one providing supply air and one with exhaust air. Four fans move air through the system, where two are placed before and after the MEE for each duct channel. These fans balance the air flow rates and distribute air throughout the system. Thermocouples and humidity sensors on the inlets and outlets of the MEE are used to measure air temperatures and RH in the exchanger, respectively. Two micro manometers are used to measure the pressure over the orifice plate and over the supply and exhaust air flows in the exchanger. These measurements are further addressed in chapter 5.2.

Orifice plates are used for measuring pressure drop with pressure transducers and are installed in the straight parts of the duct system, as shown in the sketch of the test rig. One orifice plate is placed in the supply duct and one in the exhaust duct. These plates, with an opening diameter of 45 mm, calculate air flow rates in the two ducts by measuring the pressure drop. Air straighteners are installed in front of the orifice plate in both ducts to shorten the required length of the straight duct. The rectangular elements on the inlet and outlet sides of the MEE are connected to the round ducts with smooth expansion and contraction diffusers.[20]

Odour experiments were previously tested in the laboratory in 2020 for the master thesis of M. Skaten [15]. A sketch of the MEE test rig used for the odour sensory experiment and its components is shown in figure 5.2. To prevent strong odours from being released into the laboratory air when the odour samples are placed under the hood, the exhaust flow is connected to the basement ventilation system. The supply air is extracted from the laboratory room. The connection of the exhaust duct to the fan is severed in order to apply the odour sources to the system. A flexible duct with a hood is attached to the system at the exhaust flow inlet to supply the odour samples to the system.

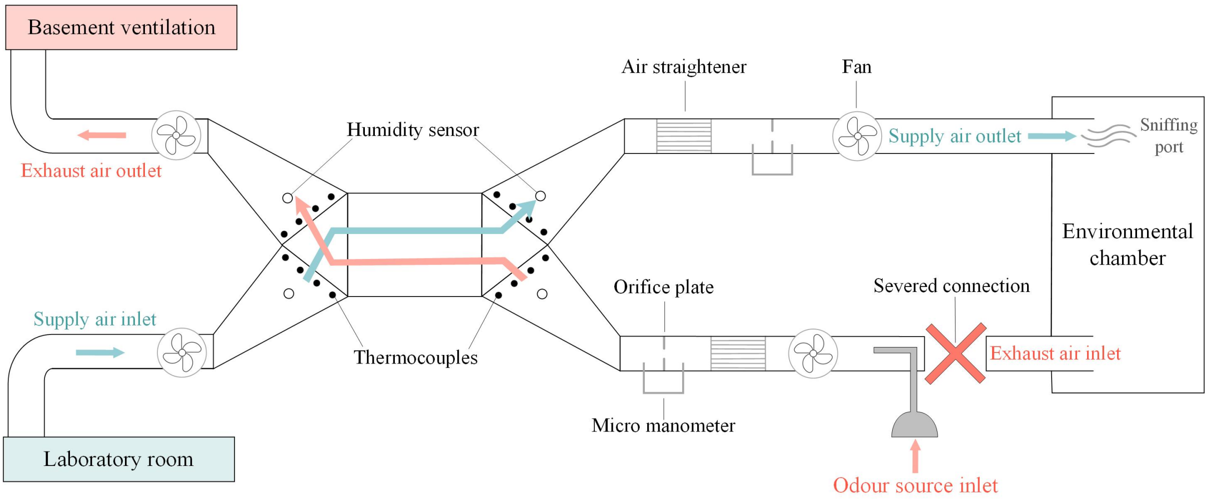

Figure 5.2: Sketch of MEE test rig for odour sensory experiment. Based on Skaten (2021).[15]

5.2 Measuring Devices used in the MEE Test Rig

Crucial factors like temperature, pressure, and RH are measured in the test rig. Temperatures and relative pressure are measured by sensors installed in the rig and are directly connected to LabVIEW, while pressure and pressure drops are measured separately with micro manometers. An overview of the measuring devices installed and used on the test rig with their operating conditions and accuracy is given in table 5.1.

Table 5.1: Operating conditions and accuracy of measuring devices in the MEE test rig.[15, 20]

Measuring device	Operating conditions	Accuracy
DPM TT570 micro manometer	0°C to 50°C	± 1% of reading ± 0.1 Pa
Pettersen T-type thermocouples	-20°C to 20°C	± 0.05°C
Vaisala HMT330 humidity sensor	-20°C to 40°C	± 0.8% of reading ± 1% RH

To measure the air temperatures over the exchanger, four T-type thermocouples are mounted at each inlet and outlet of the MEE, as shown in figure 5.4. These thermocouples are manufactured by *Petterson*, with operating conditions between -20°C and 20°C, and accuracy of ± 0.05°C. Figure 5.3 shows the MEE after it is attached to the rest of the system. RH is measured with one transmitter at each inlet and outlet. The model used is HMT330 by Vaisala. Additionally, two DPM TT570 micro manometers are used to manually measure the pressure drop over the orifice plates and the MEE core on supply and exhaust air flow. The volumetric air flow in the supply and exhaust ducts is calculated based on the pressure measured over the orifice plate.[20]

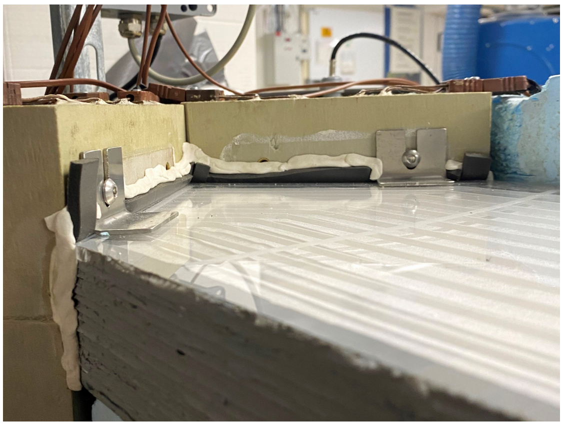

Figure 5.3: Membrane attachment.

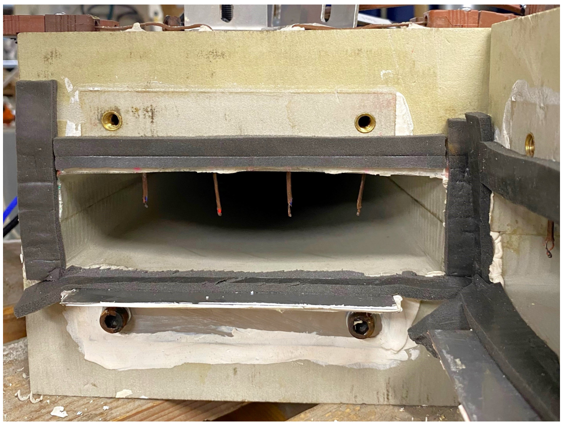

Figure 5.4: Thermocouples.

5.3 Membrane Configuration and Properties

The MEEs provided by Flexit AS are all quasi-counter flow energy exchangers. The quasi-counter flow arrangement combines the advantage of high counter flow effectiveness and easy cross flow sealing. Three new MEEs have been received from Flexit AS for experiments in this study. The new MEEs are assembled by Flexit AS and ready for installation in the test rig. An older MEE built and installed for the Ph.D. of Liu between 2012 and 2016 was constructed in the laboratory. This MEE was tested during the preliminary project for odour transfer with a sensory panel, and the results are given in appendix E.1.

The MEEs provided by Flexit AS consist of seven membrane layers. The air flow is directed by 13 channels located between the membrane layers, as can be seen in figure 5.5 showing one of the membranes.

Figure 5.5: Surface image of MEE provided by Flexit.

The layers of the components in the MEEs are illustrated in a simplified version in figure 5.6. Spacers are used to ensure that the membranes do not stick to one another. The plastic brackets provide space for the air channels in the system and, together with the top and bottom plastic frame, seal the construction together and provide an air-tight exchanger.

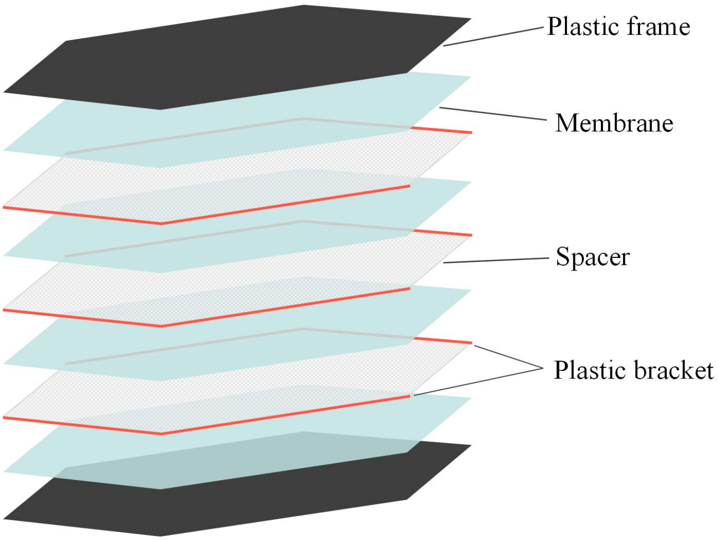

Figure 5.6: Configuration of the MEE in the test rig.[15, 20]

There is limited information on the material and properties of the three MEEs provided by Flexit. The information available for this study is given in table 5.2, including the membrane type used and its moisture transfer resistance, describing whether the moisture transfer rate is low, medium, or high. The moisture transfer properties of the MEEs differ based on the type of membrane used. MV-1 has the lowest moisture transfer, while MV-3 has the highest due to the membrane used.

Table 5.2: Moisture transfer properties for MV-1, MV-2 and MV-3 provided by Flexit AS.

	Membrane type	Moisture transfer resistance	Moisture transfer rate
MV-1	No. 20 (ID RG223)	114.3 s/m	(Low)
MV-2	No. 3 (ID 2325)	58.56 s/m	(Medium)
MV-3	No. 5 (ID RMFDPF 100260010)	20.00 s/m	(High)

The MEE installed in the period between 2012 and 2016 consists of a porous membrane made of polypropylene. It is significantly more information about this membrane than the new MEEs provided by Flexit, as the old MEE was constructed at NTNU laboratories for the Ph.D. work of Liu[20]. The older MEE uses a porous membrane with hydrophobic properties, meaning it repels humidity well. It is uncertain to which degree the membrane has degraded since 2016, as several different tests have been conducted on it. The membrane properties of the older MEE are shown in table 5.3.

Table 5.3: Properties of the polypropylene MEE built for Ph.D. work in 2012-2016.[15, 20]

	Parameter	**Value**
ρ	Density	370 $\mathrm{kg/m^3}$
D	Diffusivity	$2.42 \cdot 10^{-5}$ $\mathrm{m^2/s}$
P	Permeability	$1.6 \cdot 10^{-12}$ $\mathrm{m^2/s}$
ε	Porosity	41%
λ	Thermal conductivity	0.16 W/mK
δ	Thickness	$3.2 \cdot 10^{-5}$ m

6 Laboratory Execution and Methods

This chapter presents the experimental methods used for the laboratory assessments. This includes a detailed description of the preparations that were made beforehand, how the experiments were conducted, and how the results were obtained. Before starting the experiments in the lab, a risk assessment had to be completed and approved. A description of the most important parts of the risk assessment is found in appendix A, while a complete version of the document is delivered separately from the thesis.

Three laboratory experiments were performed on each of the three MEEs. Odour sensory panel testing is the main experiment and is performed to evaluate odour transfer between the exhaust and supply air flows in the system. This odour experiment is performed on the three MEEs, including one sensory test without a membrane for comparison purposes and on the old MEE from the Ph.D. work [20]. The evaluation of the old MEE was performed during the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* written by *Tærum, Mathea L.* and delivered in December 2022. Results from the old MEE are not presented with the results from the new MEEs, but given in appendix E.1. In addition to the odour sensory experiments, VOC sensors were used to measure formaldehyde and acetone transfer, while the final experiment adjusted supply air temperatures to determine the latent and sensible effectiveness of the MEEs.

6.1 Pressure Drop and Volumetric Air Flow

It is decisive to know the system's pressure drop and volumetric air flow while running laboratory experiments. The pressure drop is measured manually with the two DPM TT570 micro manometers over the MEE supply and exhaust sides, and over the two 45 mm orifice plates in the straight duct channels. The power of the four fans is adjusted to get the desired air flow through the ducts while having as low pressure drop as possible. An Excel sheet provided by NTNU based on NS-EN ISO 5167-1 [52] and NS-EN ISO 5167-2 [53] is used to calculate the volumetric air flow rate of the straight ducts using the measured pressure drop over the orifice plates.

6.2 Odour Sensory Analysis

Odour sensory experiments are performed with panel members following the method given in ISO 16000-30:2014 [51]. Preliminary testing of the odour experiment was performed during the preliminary project in advance of the laboratory execution with panelists. This test was executed to understand the intensity of the odour samples and the time intervals. Knowledge about time intervals is essential to know how long it takes for the odour to reach the sniffing port and the time necessary for the odour remains to leave the system. Preliminary testing is essential to have efficient and successful panel testing.

Based on preliminary testing, it was found that it takes between 30 and 60 seconds for different odour sources to become detectable in the sniffing port once placed under the hood. Additionally, it takes between 45 and 60 seconds for the odour to disappear from the system. To ensure accurate results, the time intervals for the sensory panel testing were chosen based on these findings with an added time margin. The selected time intervals for the sensory experiment are listed below:

Time interval for odour to reach sniffing port: 1.5 min

Time interval for odour to leave the system: 1.5 min

The system has a distinct background scent. It remains strong during preliminary testing, even if the system is run for a long time. Feedback from the sensory analysis performed on the old MEE during the preliminary project showed that the background scent affected the evaluation of the odour samples. To differentiate between the background odour and the odour samples, panelists are requested to evaluate the background odour at the beginning of the sensory tests using the same evaluation factors as the odour samples.

6.2.1 Odour Sources

During the panel testing at the lab, the panelists were asked to identify and evaluate air acceptability, odour intensity, and hedonic tone, as explained in chapter 4. Three blank samples without additional odour and six samples of household products were used. The odour samples used were Jif universal spray, salami, perfume, paint sample, waffle, and shower soap. Pictures of the products used as odour samples are found in appendix B. The sample order used in the sensory test execution and the concentrations of the odour samples are shown in table 6.1.

Table 6.1: Odour samples and concentration in tested order.

	Odour sample	**Concentration**
Test 1	Jif universal spray	60 sprays
Test 2	Salami	6 slices
Test 3	Blank sample	-
Test 4	Perfume	30 sprays
Test 5	Paint	500 ml (the whole can)
Test 6	Waffle	2 plates
Test 7	Blank sample	-
Test 8	Shower soap	ca. 35 g (80 cm)
Test 9	Blank sample	-

The intensity of the odour samples is chosen based on experimenting with various intensities in the preliminary testing. The waffle was cooked at home on the same day as the test to avoid the strong odour from cooking waffles filling the entire laboratory area. The waffles were put in plastic bags while still warm and tied it tightly to keep the moisture and odour as strong as possible. The liquid odour products were soaked in sponges before they were placed under the exhaust hood. Cardboard plates were used under all samples to avoid remains getting stuck on the table and interfering with the remaining samples. In preliminary testing, there was minimal odour from the paint sample. To increase the intensity of the paint sample, the can was stirred before it was put under the hood to initiate movement of odour particles.

6.2.2 Description of Sensory Panel Experiment

The sensory odour panel test was performed in environmental room B039 at Heat Engineering Laboratory at NTNU, Gløshaugen. A questionnaire was handed out to each panel member with questions and scales based on ISO 16000-30:2014 [51]. The questionnaire is shown in appendix C. A total of four odour sensory experiments were performed in this study, in addition to the assessment performed on the older MEE during the preliminary project work. Three sensory analyses were carried out for each new MEE, and an additional sensory test was conducted to compare the odour transferred between the air flows with the odour supplied directly into the sniffing port. An overview of the dates the tests were performed and how many panel members participated is shown in table 6.2. All tests took around 50 minutes.

Table 6.2: Overview of the executed odour sensory analyses: Practical factors

Membrane	Date	Nr. of participants		Age range
Old MEE	16.11.2022	22 panel members	(18 F, 4 M)	22–26
MV-1	02.03.2023	25 panel members	(16 F, 9 M)	23–27, 43
MV-2	01.03.2023	20 panel members	(12 F, 8 M)	23–27
MV-3	27.02.2023	23 panel members	(20 F, 3 M)	23–26
No MEE	06.03.2023	20 panel members	(13 F, 7 M)	23–26

Before participating in the tests, the panelists should have been in an environment without significant odours and good air quality. These conditions were challenging to implement during the tests, as no such room was available at the laboratory. The sensory test should also ideally be performed with the panelists standing in the middle of the room [51]. This is not possible in the lab, and the odours are analyzed through a sniffing port connected to the supply duct. The sniffing port is shown in figure 6.1. The air entering the sniffing port has a constant flow, and the flexible duct of the sniffing port is therefore kept as horizontal as possible to avoid unnecessary bends that interfere with the air flow rate. The odourous air is sent into the system through the supply hood connected to the exhaust inlet duct, shown in figure 6.2.

Figure 6.1: Sniffing port.

Figure 6.2: Odour supply hood.

If the panel members are unsure about the answer, they can repeat the sniffing for up to 90 seconds. According to the standard [51] , if the panelist has yet to make up their mind within 90 seconds, there should be a 5 minute break in an odour-neutral room before the assessment is repeated. This is also challenging to execute in the laboratory with untrained panelists, and the panel members were asked to leave the question unanswered if still uncertain after 90 seconds.

In order to accurately assess emissions and odours, it is important to maintain a constant temperature and RH in the room. These conditions should be recorded and monitored throughout the sensory test. The laboratory temperature should not exceed 25°C, and fluctuations of less than ±3°C are acceptable. The conditions of the MEE test rig and the environmental chamber should be logged before and during the sensory test. This logging includes the occupancy and furnishing of the room, temperature and RH, and other climatic conditions.[51] Table 6.3 shows the system's air flow for each sensory test and the ambient conditions in the laboratory during each sensory test.

Table 6.3: Overview of the executed odour sensory analyses: Laboratory conditions

Membrane	Temperature	Relative humidity	Air flow
Old MEE	19.52 °C	25.05 %	6.2 L/s
MV-1	18.95 °C	24.88 %	6.0 L/s
MV-2	18.96 °C	24.84 %	6.2 L/s
MV-3	18.88 °C	24.97 %	6.1 L/s
No MEE	18.91 °C	25.01 %	6.0 L/s

Selection of Sensory Panel Members

The sensory odour analyses in this study use untrained panel members. It is recommended to have 20 to 25 people for testing with untrained panel members, but the minimum to approve the test following the standard is 15. As previously shown in table 6.2, all five tests were within the recommended number of panel members. The recommended number of panelists for a trained panel is less, with 12 to 15 as recommended and eight as the minimum.[51]

In order to qualify as a panel member for sensory testing according to ISO 16000-30:2014 [51], the following criteria must be fulfilled:

- Must be motivated and available to complete the sensory testing
- Must be at least 18 years old
- Must not suffer from allergies or health conditions that affect the sense of smell
- Must not be sick with something affecting the sense of smell at the time of the sensory test (e.g. a cold, the flu or COVID)
- Must not chew gum, eat, or drink anything besides water 30 minutes before, and during, the test
- Must not use tobacco two hours before or during the test
- Must not have bad personal hygiene or use perfumes, deodorant and other cosmetics with strong scents that interfere with the odour samples

The panelists were instructed to avoid eating, drinking, and chewing gum for at least 30 minutes before the test, as required by the standard [51]. They should also not wear products with strong scents of perfume or use tobacco products before and during the test. To ensure impartial results, the panelists were requested not to discuss their impressions of the odours or the answers on the questionnaire with each other during the test.

6.3 VOC Sensor Measurements: Contaminant Transfer

To be able to evaluate contaminant transfer between the exhaust and supply air flows, VOC sensors are used. The sensors were developed by Maria Justo Alonso in conjunction with her Ph.D. research from 2022 [54]. Four sensors are used for the laboratory experiments, where each consists of four sensor modules, as shown in figure 6.3.

Figure 6.3: VOC sensor and connection of sensor modules.

The sensors are connected to a Raspberry Pi that logs the measurements. The sensor modules used are WZ-S which measures formaldehyde, SPS30 which measures PM2.5 and PM10, SCD30 which measures humidity, temperature and CO_2, and SGP30 which measures TVOC. The formaldehyde sensor module is the one used in this study. Two different VOC sources are measured independently: formaldehyde and acetone. Both are measured with the formaldehyde sensor module, as acetone has a strong intensity and can still show accurate trends on the measurements due to cross-sensitivity of the sensors. Table 6.4 shows the technical specifications for the WZ-S formaldehyde sensor module.

Table 6.4: Technical specifications of WZ-S formaldehyde sensor module.[15, 54]

Technical specification	
Detectable gas	CH_2O
Detection range	0–2 ppm
Overload	10 ppm
Resolution	0.001 ppm
Operating temperature	-20°C to 50°C
Operating humidity	10% to 90% RH
Lifetime	5 years

Fellow master's student Ingeborg H. Fiskvik has recently performed calibration on the sensors. It is therefore considered unnecessary to perform a full calibration on the equipment. A preliminary test is instead performed to see how accurate the measurements on each sensor are. The sensors are placed at a table in the environmental chamber and measured for two hours to indicate the measurement variations between each sensor. The sensors with the most similar measurements are used for the experiments. The formaldehyde concentration was measured in the basement with all four sensors, two separate times, for two hours of measurements. An average value was found from these measurements and is used to correct the concentration in the experimental calculations.

During the laboratory experiment, the VOC sources are put into the environmental chamber and enter the MEE through the exhaust air stream. One of the sources used is a particle board that is constructed using resin containing formaldehyde. The particle board is wetted to emit as much formaldehyde as possible before it is put into the environmental chamber. Nail polish remover is also used as it contains acetone, which is a common VOC. A piece of fabric is soaked in nail polish remover and put in the entrance of the exhaust duct. This is expected to be a strong source of VOC in the first minutes but then rapidly decrease in intensity as the vaporization diminishes. The air flow during the testing is the same as during the odour sensory analyses, approximately 6 L/s. No adjustments are made to the temperature or RH in the system during the VOC sensor measurements.

Sensors are placed in the supply outlet duct and the exhaust inlet duct. The size of the sensors is larger than the ducts in the lab, and cardboard boxes are constructed into the test rig for sensor placement. The initial 30 minutes of measuring are disregarded from the results as the sensors need time to warm up for the measurements to stabilize.

The laboratory sensor measurements are divided into two separate tests. The preliminary testing showed that the sensors had difficulty functioning after the insertion of nail polish remover, and the measurements after showed significant errors as the sensors were exposed to too high concentrations. It is also easier to study the details in each graph when the nail polish remover and particle board are performed separately, as the preliminary testing showed significant differences in the concentration. The time course for the sensor measurement with nail polish remover is given below:

30 min: Sensor stabilization time

15 min: No VOC source

15 min: VOC source (nail polish remover)

Before the wetted particle board emitting formaldehyde enters the system, sensor measurements are taken for 30 minutes to differentiate between the formaldehyde source and the concentration in the regular laboratory air. The time course for the sensor measurement with wetted particle board is provided below:

30 min: Sensor stabilization time

30 min: No VOC source

1.5 hours: VOC source (wetted particle board)

6.4 Latent and Sensible Temperature Effectiveness

In order to evaluate the temperature performance of the MEEs, latent and sensible temperature effectiveness were measured and calculated. Measurements were done with the temperature and humidity sensors installed at the outlet and inlet of the exchanger in LabVIEW. Calculations are based on the equations given in chapter 2.3.

During the experiments, the RH is kept at regular room levels and is not adjusted. The temperatures were changed to illustrate outdoor air temperatures, while the indoor air exhaust was set to 21°C. The air flow rate is kept constant at 6.9 L/s. The temperatures and air flow rate are decided based on previous experiments on the test rig for the Ph.D. thesis of Liu [55]. The temperatures chosen are as follows:

Indoor air conditions:	21°C		
Outdoor air conditions:	-6°C	0°C	11°C

To regulate the indoor air temperature, an AHU with a temperature-regulating bath was used. The environmental room B039 was used to adjust the supply air temperatures. It took several hours for the temperatures at the exchanger to stabilize so the measurements could begin. The temperature had to be set to colder in the environmental room for it to be the correct temperature at the measuring points by the exchanger. Once the desired temperature was reached and stabilized, the measurements were recorded for two hours with a 60 second interval. There was a risk of frost formation as the supply air temperature reached minus degrees. Therefore, a flexible inspection camera was used to see if there was frost at the supply outlet side of the MEE.

6.5 Uncertainty Analysis

Uncertainty analyses are performed after the laboratory experiments to better understand the results' accuracy and whether or not the results can be regarded as acceptable. Inaccuracies in the experiments can come from several factors. Lack of attention from the operator of the experiments is defined as gross error and must be eliminated. These errors are attempted eliminated by keeping focus throughout the experiments and sufficient preliminary testing to be prepared for the laboratory experiments. Errors caused by the equipment used are defined as systematic errors and are usually provided by the manufacturer so they can be addressed after measurements are performed. Lastly, there are random errors which are uncertainties from external influences on the experiments or poor resolution of the equipment.[56, 57]

Uncertainty with Single Variable

To calculate the mean value of a selection of measurements, which can further be used to determine the uncertainty, equation 6.1 is used. The mean value is given as $\bar{x}$, n is the number of readings, and above the fraction line is the total sum of the measurements.[57]

$$\bar{x} = \frac{\sum x}{n} \tag{6.1}$$

The mean value is used to determine the standard deviation (s) with equation 6.2, which is used to calculate the random uncertainty (U_R) with equation 6.3. The total uncertainty can then be calculated with equation 6.4, including both the random uncertainty and the systematic uncertainty (U_S) of the equipment.[57]

$$s = \sqrt{\frac{\sum(x-\bar{x})^2}{n-1}} \tag{6.2}$$

$$U_R = \pm\frac{s}{\sqrt{n}} \tag{6.3}$$

$$\Delta U = \pm\sqrt{{U_R}^2 + {U_S}^2} \tag{6.4}$$

Uncertainty with Multiple Variables

For uncertainty assessments with multiple variables, equation 6.5 is used to determine the general uncertainty. The variables used in the equation are measured individually.[57]

$$U_r = \sqrt{\left(\frac{\partial r}{\partial x_1}U_{x_1}\right)^2 + \left(\frac{\partial r}{\partial x_2}U_{x_2}\right)^2 + ... + \left(\frac{\partial r}{\partial x_n}U_{x_n}\right)^2} \tag{6.5}$$

This method is used to calculate the uncertainty for the sensible effectiveness with equation 6.6 and the latent effectiveness with equation 6.7. The moisture content is calculated with equation 2.3 presented in chapter 2.3, while the temperatures are measured directly with the thermocouples in the laboratory test rig. The uncertainties for the measuring points are given with ΔT and Δw. An uncertainty within ±5% is generally acceptable for these calculations.[57]

$$U_{\varepsilon_S} = \sqrt{\left(\frac{T_{s,o}-T_{e,i}}{(T_{e,i}-T_{s,i})^2}\cdot\Delta T_{s,i}\right)^2 + \left(\frac{1}{T_{e,i}-T_{s,i}}\cdot\Delta T_{s,o}\right)^2 + \left(\frac{T_{s,i}-T_{s,o}}{(T_{e,i}-T_{s,i})^2}\cdot\Delta T_{e,i}\right)^2} \tag{6.6}$$

$$U_{\varepsilon_L} = \sqrt{\left(\frac{w_{s,o}-w_{e,i}}{(w_{e,i}-w_{s,i})^2}\cdot\Delta w_{s,i}\right)^2 + \left(\frac{1}{w_{e,i}-w_{s,i}}\cdot\Delta w_{s,o}\right)^2 + \left(\frac{w_{s,i}-w_{s,o}}{(w_{e,i}-w_{s,i})^2}\cdot\Delta w_{e,i}\right)^2} \tag{6.7}$$

Accuracy of Odour Sensory Assessments

The accuracy of odour sensory assessments is expressed with confidence intervals. For odour sensory assessments, a 90% confidence interval of the mean should be used, according to ISO 16000-30:2014 [51]. The principle of a two-tailed confidence interval is illustrated in figure 6.4. The curve illustrates the range of answers from the panelists, where the upper and lower 5%, marked in blue, is excluded, hence two-tailed. 1-α is the statistical certainty of the assessment, where α is the probability of error. A 90% confidence interval means that $t_{1-\alpha/2}$ is $t_{.95}$, which is used for n-1, where n is the number of participants in each experiment. The t-distribution and values used for calculation are found in table D.1 in appendix D.[51]

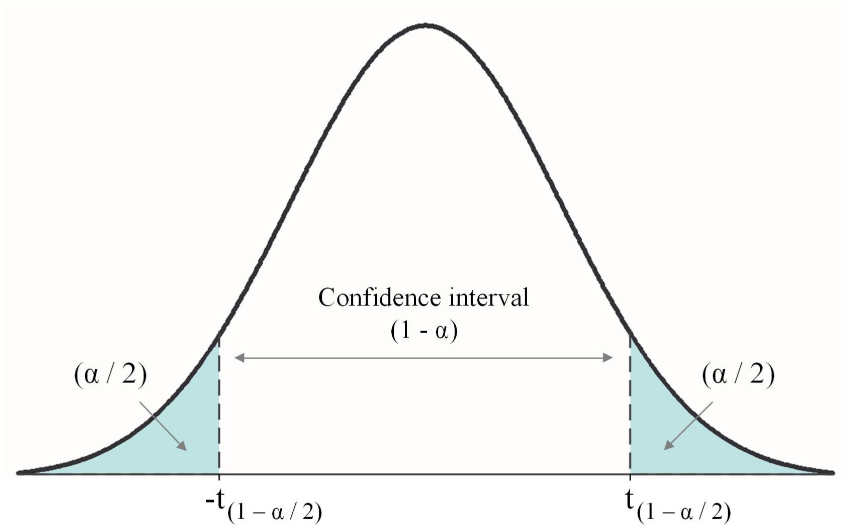

Figure 6.4: Illustration of two-tailed t-distribution for confidence intervals.

The confidence interval of odour assessments is calculated with equation 6.8. The equation shows a two-sided confidence interval for μ, a random interval around the estimated mean, $\bar{x}$. It has a statistical certainty of (1-α) and contains the true mean value, μ. The standard deviation, s, is calculated with equation 6.2, and the estimated mean, $\bar{x}$, is calculated with equation 6.1. ISO 16000-30:2014 [51] provides limits to determine if the different assessments are acceptable. The 90% confidence interval for odour acceptability is accepted if under 0.2, while odour intensity and hedonic tone are accepted under 1. If the confidence interval is not within limits, conducting the experiment again with a larger panel is recommended.

$$P\left(\mu\epsilon\left[\bar{x}\pm\frac{s}{\sqrt{n}}\cdot t_{(1-\frac{\alpha}{2});n-1}\right]\right)=(1-\alpha) \tag{6.8}$$

7 Results with Discussion

This chapter presents the results of the laboratory experiments conducted during the master thesis. The results are presented and consecutively discussed in this chapter before a broader discussion draws parallels between the performance of the membranes from the three experiments and how it relates to real-life scenarios in a summarizing discussion in chapter 8.

The experiments included odour sensory analyses with panelists and measuring the transfer of formaldehyde and acetone from different VOC sources between the supply and exhaust air streams using VOC sensors. Additionally, sensible and latent effectiveness tests with temperature regulations were conducted. Data was collected using LabVIEW, portable measuring devices, and various sensors. The data was analyzed using Excel and presented and discussed in this chapter.

Three MEEs with different moisture transfer properties were tested for all the laboratory experiments to compare the membranes' performance. MV-1 has the membrane with the lowest moisture transfer and is illustrated in blue, MV-2 has a membrane with medium moisture transfer and is illustrated in red, while MV-3 has the highest moisture transfer and is illustrated in grey. Flexit AS provided information about the properties of the three membranes after the laboratory experiments were conducted to prevent subjective influence of the measurements.

7.1 Odour Sensory Analysis

The sensory panel experiments were conducted four times, once for each of the MEEs and once with direct air supply to the panelists without membrane transfer. The nine odour samples were evaluated by a group of untrained panelists, all within the acceptable number of people given in *ISO 16000-30:2014: Sensory testing of indoor air* [51]. The laboratory conditions during the experiments also met the required standards for a sensory odour test. The panelists evaluated the different odour samples using a questionnaire based on the standard provided in appendix C. The questionnaire asked the panelists to evaluate whether the odour was acceptable, its intensity, and how pleasant it was perceived, as well as make guesses about what the odour source could be. Table 7.1 contains a compilation of the guesses from the four odour sensory experiments. Some guesses were correct or in the same odour category, while others were incorrect. The correct guesses are highlighted.

Table 7.1: Guesses from panel members on odour sources. Selection from all four sensory experiments.

	Odour sample	**Panel guesses**
Test 1	Cleaning spray	Soap, bread, rug, **cleaning spray**, citrus, food, apple
Test 2	Salami	Meat, ham, **salami**, old food, chicken, corn, onion, sausage
Test 3	Blank sample	Bread, salami, flower, old furniture, basement, **nothing**
Test 4	Paint	Perfume, flower, berries, cleaning product, mint, nothing
Test 5	Perfume	Cookies, **perfume**, cleaning spray, scented candle, banana
Test 6	Waffle	Bread, cake, cheese, cookies, yeast dough, mold, old biscuit
Test 7	Blank sample	Perfume, dog food, old furniture, sweet, **nothing**
Test 8	Shower soap	**Soap**, berries, candy, **shampoo**, cleaning spray, nothing
Test 9	Blank sample	Perfume, berries, cake, flowers, shampoo, **nothing**

In addition to the evaluation of MV-1, MV-2, MV-3, and no MEE, a sensory odour analysis was performed in the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* written by *Tærum, Mathea L.* and delivered in December 2022. This experiment was performed on the older MEE originally installed in the test rig for the Ph.D. work of Liu [20]. The results from this assessment are given in appendix E.1. For the older MEE, the samples rated with high intensity were often rated low on acceptability and how pleasant they were perceived. These trends suggest that the panelists generally preferred air with low odour intensity. The panel members most commonly accepted odours from the soap and cleaning products category. The shower soap sample was rated the highest in terms of acceptability and pleasantness, and had a low percentage of dissatisfied at 23%. In contrast, the salami sample had the worst outcome of all nine samples tested, with the lowest acceptability and hedonic tone and the highest percentage of dissatisfied at 64%. These results imply that the category containing soap and cleaning products was more accepted than odour from food products.

The panelists were also asked to evaluate the background odour in the duct, in addition to the assessments described in the standard. During the preliminary project work, it was observed that the background odour was very noticeable and difficult to distinguish from the odour samples, and it was therefore decided to perform further evaluation on the background odour. A detailed assessment and visual representation of the evaluation of the background odour is given in appendix E.2. The evaluation showed that the majority of panelists rated the background odour intensity between weak and distinct for all experiments. The hedonic tone rating was slightly unpleasant but leaned towards neutral. In terms of acceptability, the background odour was neither accepted nor unaccepted. Around 50% of the panelists expressed dissatisfaction with the background odour, except for the experiment with membrane MV-3, where only 30% were dissatisfied.

The graphs used to present the results from the questionnaire analyses are box and whisker plots. It is illustrated with a box that represents the central 50% of the answers, excluding the upper and lower 25%. Inside the box, a horizontal line represents the median answer, and an x represents the mean answer. The whiskers show the full range of the answers, from highest to lowest. To distinguish between the four sensory panel experiments, each test is assigned a different colour. The colour blue represents MV-1, red represents MV-2, grey represents MV-3, and green represents the analysis with no MEE.

7.1.1 Percentage of Dissatisfied

The initial question on the questionnaire asked whether the odour was acceptable for everyday exposure. The question was presented as a *yes* or *no* question to calculate the percentage of dissatisfied people. The percentage was determined by comparing the number of panelists who answered *no* to the total number of participants in the experiment, using equation 4.2. The results from the assessment are given in figure 7.1.

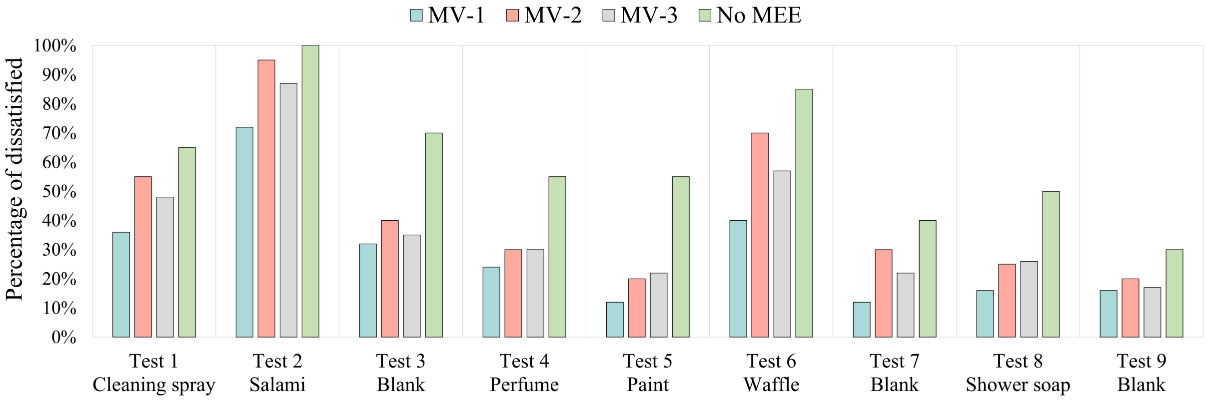

Figure 7.1: Percentage of dissatisfied evaluation for each odour sample.

The graph displays trends regarding the evaluation of the different membranes and variations in how the panelists evaluated the different odour samples. All the odours had some panel members that were dissatisfied, as none of the odours were rated with a percentage of dissatisfied of 0%. Out of all the tests conducted, the one with no MEE in the green bar had the highest percentage of dissatisfied people. On the other hand, the evaluation of MV-1 in the blue bar showed the lowest percentage of dissatisfied people for all odour samples. The red bar displays the results of MV-2, which, on average, had the highest percentage of dissatisfied out of the experiments with MEEs. The exception was the paint sample and the shower soap sample, where MV-3 showed higher percentage of dissatisfied, and the perfume sample, where MV-2 and MV-3 showed the same result.

According to the results, MV-1 had the lowest percentage of dissatisfied occupants. This could indicate that less odour was transferred between the air streams using MV-1 due to its low moisture transfer properties. Interpreting the differences between MV-2 and MV-3 was more challenging. It was less difference between the membrane properties of MV-2 and MV-3, compared with the membrane used in MV-1. MV-3 is the membrane with the highest moisture transfer, but results showed that MV-2 transferred more odour than MV-3. Several panelists rated the blank samples as dissatisfying despite the fact that they should have been considered odourless. The panelists were unaware that some samples were blank and rated them as an odour. Their expectation of an odour made them consider the blank samples dissatisfying. The background odour most likely also affected the blank odours, as the evaluation of background odour showed dissatisfaction for 50% of the panelists.

The samples containing food showed the highest percentage of dissatisfied. These samples contained salami and waffle, where salami showed a higher percentage of dissatisfied than waffle. Additionally, the blank sample after the salami had the highest percentage of dissatisfied ratings among the three odourless samples. The high dissatisfaction of the salami likely affected the following blank sample. It was possible that the odour lingered in the system or in the minds of the panelists, as it clearly left an impression during the experiment.

7.1.2 Odour Acceptability

To evaluate odour acceptability, the same question was used as when determining the percentage of dissatisfied. Odour acceptability was rated on a scale from clearly acceptable (1) to clearly unacceptable (-1). Figure 7.2 presents the answers from the odour acceptability assessments in a box and whisker plot. The different membranes are separated by colour.

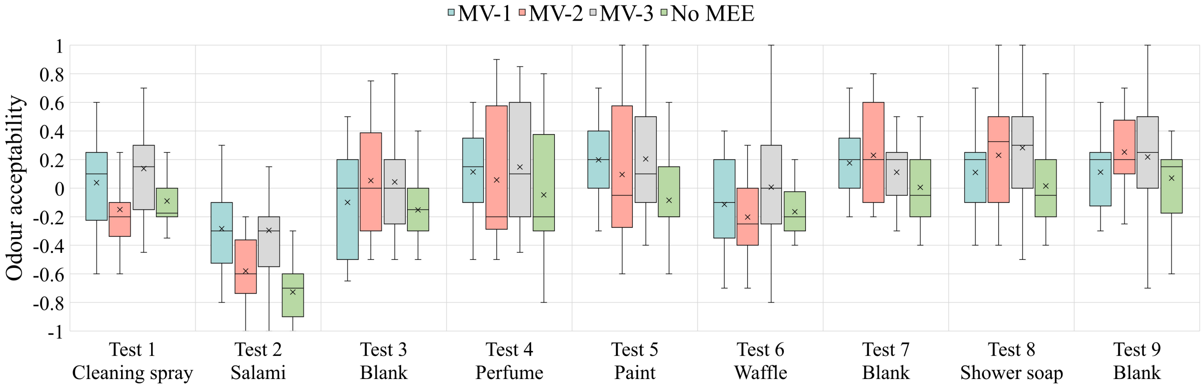

Figure 7.2: Odour acceptability evaluation for each odour sample.

To emphasize the results of the odour acceptability assessment, table 7.2 shows the average values for all tests and their 90% confidence interval. The confidence intervals were calculated with equation 6.8 and values from the t-distribution table in appendix D. As stated in ISO 16000-30:2014 [51], the odour acceptability assessment was considered accurate if the 90% confidence interval of the mean did not exceed 0.2. As seen in the table, all tests were under the acceptable limit.

Table 7.2: Average odour acceptability values including 90% confidence interval.

	MV-1	MV-2	MV-3	No MEE
Test 1	0.04 ± 0.11	-0.15 ± 0.15	0.14 ± 0.12	-0.09 ± 0.10
Test 2	-0.28 ± 0.11	-0.58 ± 0.09	-0.30 ± 0.13	-0.73 ± 0.08
Test 3	-0.10 ± 0.13	0.05 ± 0.15	0.04 ± 0.13	-0.15 ± 0.10
Test 4	0.11 ± 0.10	0.06 ± 0.19	0.15 ± 0.16	-0.05 ± 0.17
Test 5	0.20 ± 0.09	0.10 ± 0.19	0.20 ± 0.13	-0.09 ± 0.11
Test 6	-0.11 ± 0.11	-0.20 ± 0.11	0.01 ± 0.15	-0.17 ± 0.08
Test 7	0.18 ± 0.08	0.23 ± 0.14	0.11 ± 0.08	0.01 ± 0.10
Test 8	0.11 ± 0.09	0.23 ± 0.16	0.28 ± 0.15	0.02 ± 0.13
Test 9	0.11 ± 0.09	0.25 ± 0.11	0.22 ± 0.15	0.07 ± 0.13

None of the MEEs showed the lowest acceptability for all tests, looking at the mean value. However, the experiment with no MEE had the overall lowest acceptability, even though MV-2 was rated lower for the cleaning spray and waffle. Looking at the results from the experiments using MEEs, the lowest rated acceptability was for MV-2 for all the odourous tests, while MV-3 was rated slightly lower than MV-2 for the three blank samples. MV-1 had minimum variations from test to test, and the average values stayed within ±0.2 for all tests except for the salami sample at -0.28. The graphs show that the test containing salami was by far the lowest accepted odour of the nine tests. However, the salami sample was rated higher with the MV-1 membrane than the others, as they all rated salami closer to unacceptable.

MV-1 had the membrane with the lowest moisture transfer, which explains why it typically received ratings closer to zero in most tests. There should have been considerably less odour transfer through this membrane, hence weaker odour at the sniffing port. It is natural to assume that a weak odour was rated close to neutral and a more pungent odour closer to acceptable or unacceptable based on how pleasant it is perceived.

When comparing the acceptability assessment with the percentage of dissatisfied, the three odour samples rated highest for percentage of dissatisfied was also the odour samples rated closest to unacceptable. These samples were cleaning spray, salami, and waffle. Out of all the samples, salami had the highest percentage of dissatisfied participants and was also rated closest to unacceptable in all four experiments.

7.1.3 Odour Intensity

The evaluation of the intensity of the odour was rated on a scale from no odour (0) to extremely strong odour (6). The results from the four sensory panel tests are illustrated in the box and whisker graph in figure 7.3.

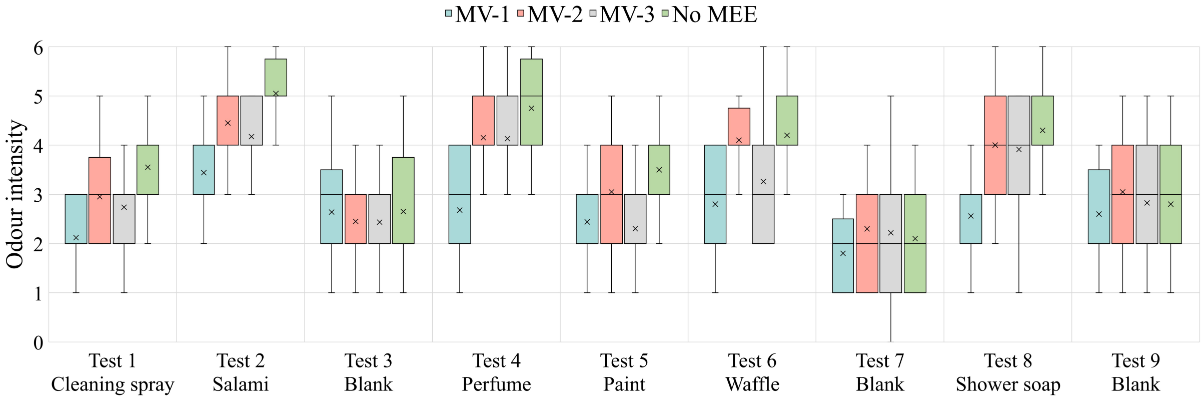

Figure 7.3: Odour intensity evaluation for each odour sample.

The mean intensity values are shown with an x in the figure and in table 7.3. Additionally, the values listed in the table contain the 90% confidence interval of the mean for all tests. This interval was calculated using equation 6.8 and values from the t-distribution table found in appendix D. All results from the odour sensory assessments were within the acceptable confidence interval of 1 for odour intensity given in ISO 16000-30:2014 [51], as seen in the table.

Table 7.3: Average odour intensity values including 90% confidence interval.

	MV-1	MV-2	MV-3	No MEE
Test 1	2.12 ± 0.23	2.95 ± 0.35	2.74 ± 0.34	3.55 ± 0.35
Test 2	3.44 ± 0.36	4.45 ± 0.37	4.17 ± 0.26	5.05 ± 0.27
Test 3	2.64 ± 0.39	2.45 ± 0.45	2.43 ± 0.33	2.65 ± 0.45
Test 4	2.68 ± 0.37	4.15 ± 0.32	4.13 ± 0.40	4.75 ± 0.36
Test 5	2.44 ± 0.32	3.05 ± 0.42	2.30 ± 0.37	3.50 ± 0.46
Test 6	2.80 ± 0.32	4.10 ± 0.40	3.26 ± 0.39	4.20 ± 0.35
Test 7	1.80 ± 0.29	2.30 ± 0.43	2.22 ± 0.47	2.10 ± 0.38
Test 8	2.56 ± 0.35	4.00 ± 0.45	3.91 ± 0.40	4.30 ± 0.34
Test 9	2.60 ± 0.33	3.05 ± 0.42	2.83 ± 0.44	2.80 ± 0.51

The average values in the graph and table show that the sample using no MEE had the highest intensity for all sources that contained a household product, while it was similar to the assessments with the three MEEs for the blank samples. For the two final blank samples, both MV-2 and MV-3 were rated with higher intensity than no MEE, while no MEE was rated slightly higher than the three membranes for the first blank sample. MV-1 had the lowest intensity evaluation of all the samples except for the first blank sample. MV-2 had a higher intensity rating compared to MV-3 for all tests. Test 2, containing salami, was rated with the highest intensity for all four assessments. Perfume, waffle, and shower soap were also rated high on intensity, while the three blank samples, paint, and cleaning spray were rated with lower intensity.

Based on the evaluation of odour intensity, it can be assumed that the moisture transfer properties of the membranes are connected with the odour transfer. MV-1 had the lowest moisture transfer and was also rated with the lowest odour intensity. The test with no MEE supplied the odour directly into the sniffing port, which resulted in high intensity. Although MV-3 had the highest moisture transfer and should have had the highest intensity of odours, MV-2 was rated with higher intensity for all samples. This contradicts the connection between moisture transfer properties and odour transfer.

By comparing the intensity of odours with the percentage of dissatisfied and acceptability evaluations, it can clearly be seen that the two most unacceptable samples with the most dissatisfied panel members also had the highest odour intensity. These were the samples of salami and waffle. Perfume and shower soap were also rated with high intensity, but were perceived as acceptable by most people compared to odours from the food samples.

7.1.4 Hedonic Tone

The hedonic tone was evaluated on a scale from very pleasant (4) to extremely unpleasant (-4), with zero being neutral. Figure 7.4 shows the results from the hedonic tone evaluation from the four sensory experiments in a box and whiskers plot. The box shows the central half of the answers, excluding the upper and lower quarter, and the whiskers show the range of the answers from all the panelists.

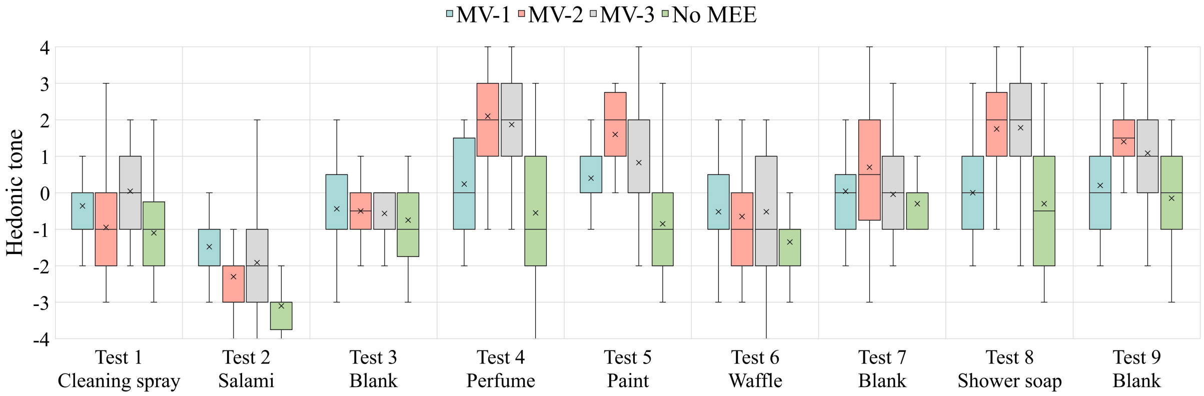

Figure 7.4: Hedonic tone evaluation for each odour sample.

The mean values of each assessment are illustrated with an x in the figure, but to clearer compare the results, table 7.4 shows the average values of all the odour sensory assessments, including their 90% confidence interval. Similarly to the odour intensity, the 90% confidence interval of the hedonic tone should not exceed 1, as given in ISO 16000-30:2014 [51]. As seen in the table, this was accomplished for all tests. Equation 6.8 was used to calculate the confidence interval, and values from the t-distribution table in appendix D were used.

Table 7.4: Average hedonic tone values including 90% confidence interval.

	MV-1	**MV-2**	**MV-3**	**No MEE**
Test 1	-0.36 ± 0.35	-0.95 ± 0.52	0.04 ± 0.45	-1.10 ± 0.48
Test 2	-1.48 ± 0.37	-2.30 ± 0.59	-1.91 ± 0.57	-3.10 ± 0.25
Test 3	-0.44 ± 0.45	-0.50 ± 0.61	-0.57 ± 0.48	-0.75 ± 0.42
Test 4	0.24 ± 0.45	2.10 ± 0.51	1.87 ± 0.47	-0.55 ± 0.78
Test 5	0.40 ± 0.33	1.60 ± 0.43	0.83 ± 0.55	-0.85 ± 0.61
Test 6	-0.52 ± 0.43	-0.65 ± 0.58	-0.52 ± 0.60	-1.35 ± 0.39
Test 7	0.04 ± 0.36	0.70 ± 0.67	-0.04 ± 0.50	-0.30 ± 0.26
Test 8	0.00 ± 0.40	1.75 ± 0.51	1.78 ± 0.52	-0.30 ± 0.75
Test 9	0.20 ± 0.46	1.40 ± 0.43	1.09 ± 0.57	-0.15 ± 0.45

The graph and table show that MV-1 was rated closest to neutral, at zero, for all samples. The experiment without a membrane was below zero for all nine tests, and was ranked as the most unpleasant. MV-3 was generally rated closer to neutral than MV-2. The salami sample was rated as most unpleasant, while the perfume and shower soap were rated closest to pleasant.

MV-1 was evaluated as neutral on the hedonic tone scale. This indicates that there was less odour transferred between the air streams with this membrane, resulting in a neutral pleasantness level with lower odour intensity. During the no MEE evaluation, the panelists rated the supplied odours with a strong intensity as unpleasant, stating that it is unacceptable with high-intensity odours in a ventilation system.

When comparing hedonic tone to the previously shown odour assessment categories, it showed clear connections. The three samples with the lowest acceptability were also rated as the most unpleasant in the hedonic tone assessment. The samples with the highest odour intensity rating were also rated highest and lowest on acceptability and hedonic tone. For the salami, perfume, waffle, and shower soap samples that were rated with high intensity, salami was rated with the lowest acceptability and as most unpleasant, similar to the waffle sample that was below neutral for both assessments. Perfume and shower soap were rated above neutral for acceptability and rated high on pleasantness. These results imply that the soap and perfume products were often accepted and rated as pleasant, even with high intensity. In contrast, odours from food products were neither pleasant nor accepted. The odours with high intensity were easier to distinguish if they were pleasant or not, hence if they were rated acceptable or unacceptable.

7.1.5 Summarizing Remarks: Odour Sensory Analyses

All four odour sensory assessments showed that the perception of odour varied for the panel members between each sample and especially between the different experiments. This trend was expected since the olfactory system does not function in a linear manner. This is due to varying levels of stimulus intensity and the sensation of magnitude, based on Stevens power law [49].

Clear trends indicate dissatisfaction regarding odours from food samples compared to soap and products containing perfume. For the samples rated with high odour intensity, the food samples showed low acceptability and low pleasantness. In contrast, the soap and perfume-containing products were rated with higher acceptability and pleasantness on the hedonic tone scale. The same trends could be taken from the experiment on the older MEE during the preliminary project. The results showed that the panelists preferred low odour intensity in the air and had higher acceptability for soap and cleaning products compared to food sources.

The panelists rated the three blank samples with the mindset that there was an odour they were evaluating. They were unaware that there were any blank samples and thought they would be presented with nine household products, not six. The blank samples were evaluated in the middle range of the four different assessments, similar to the household products with lower intensity. Hence, it was neither the highest nor lowest rated. In terms of intensity, the samples were rated in the lower range, alongside cleaning spray and paint, which had the lowest intensity of the household products.

All three blank samples were sent into the system after a household product. The previous sample's intensity and evaluation may have influenced the panelists' perception of the blank samples since they were still fresh in mind. It was also possible that the odour from the household product lingered in the system, even though this was attempted to be avoided with the time intervals set during preliminary testing. Test 3, the first blank sample, came after the salami sample which was the sample rated as the most intense, unpleasant, and least accepted. It could be seen in the evaluation of the first blank sample that it had a higher percentage of dissatisfied than three of the household products and the other two blank samples. It was rated as the least pleasant sample out of the three blank samples with slightly lower acceptability. The final blank test came after the shower soap sample, rated with high intensity, acceptability, and pleasantness. This blank sample showed similar trends to the shower soap, with the highest intensity, acceptability, and pleasantness.

There were no clear trends regarding the blank samples for the different membrane types. MV-1 should have more neutral results than the other MEEs, as results showed that this membrane transferred less odours than the others. There was no significant difference between the blank sample results for the three membranes. They were rated somewhat similarly for intensity and acceptability and with more variations for the hedonic tone. It could be challenging for the panelists to separate between the nine tests for MV-1 as the intensity was lower, and it was harder to distinguish between the different samples. The panelists might have searched harder for something to separate the answers, which might have affected the evaluation.

The influence of the background odour was challenging to determine. As previously stated, the background odour evaluation in appendix E.2 showed that around half of the panelists were dissatisfied, it was neither accepted nor unaccepted, and it was rated as vaguely unpleasant with an intensity between weak and distinct. Before the test, the panel members should have a clear understanding of the background odour. They were instructed to evaluate it and spend time to get familiar with it and asked to rule out this scent from the rest of the assessments. Some panelists could be capable of this, while others could find it challenging. This could significantly impact the results of the tests, especially for the blank samples where the background odour is the only scent present.

7.2 VOC Sensor Measurements

The VOC sensors measured contaminant transfer from the exhaust to the supply air stream from two different sources: nail polish remover and wetted particle board. Two laboratory experiments were conducted, and the results were presented separately for each source to easier distinguish between them. Concentration levels were plotted for both cases at the exhaust inlet and supply outlet, and the VOC crossover and EATR were calculated. The VOC sensor measurements were completed at 6.0 L/s, the same air flow rate as the odour transfer experiments. Two different VOC types were used in the experiments: formaldehyde and acetone. The sensor measured formaldehyde, but due to cross-sensitivity and high intensity of acetone, the measurements could also be used for the acetone assessment.

7.2.1 VOC Source: Acetone

The measurements of nail polish remover as a VOC source aimed to see the effect of a highly evaporable liquid and how high VOC concentration in the air flow affected the transfer in the MEEs. The VOC source found in nail polish remover is acetone. The concentration of VOC in the supply outlet and the exhaust inlet from the measurements on all three MEEs are shown in figure 7.5. The concentration in the supply outlet is shown in the dotted line, while the exhaust inlet is in the solid line. MV-1 is illustrated in blue, MV-2 in red, and MV-3 in grey. As the concentration in the first period of the measurements was constant, it has been cropped out of the graph to better visualize the period where the nail polish remover was in the system. The insertion of the nail polish remover into the exhaust inlet duct opening can be seen in the graph. The concentration up until 5 minutes were without the VOC source, while the concentration after 5 minutes shows when the source was inserted.

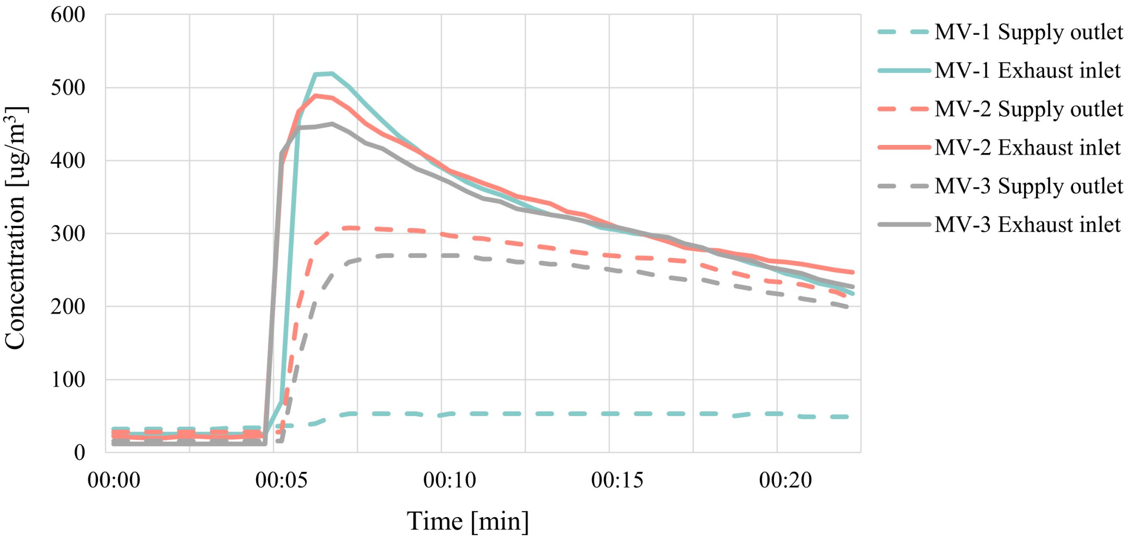

Figure 7.5: Concentration of VOC from nail polish remover in supply outlet and exhaust inlet.

The concentration in the exhaust inlet in all three experiments showed similar trends, as the concentration rapidly increased as the nail polish remover was inserted. In theory, the concentration should be similar in the exhaust duct for all three experiments, as the air flow was the same and the same amount of nail polish remover was inserted into the system. However, practical reasons in the laboratory and daily variations in concentration and measurements could cause differences in the concentration levels for the three MEEs.

The concentration at the exhaust inlet before the nail polish remover was inserted was 25 $\mu g/m^3$ for MV-1 in blue, 21 $\mu g/m^3$ for MV-2 in red, and 12 $\mu g/m^3$ for MV-3 in grey. The same ranking also followed after the insertion, as MV-1 had the highest peak of concentration, followed by MV-2, then MV-3.

The measurements at the supply outlet gave information about the concentration of acetone that had been transferred between the air streams. The concentration was significantly higher using MV-2 and MV-3, compared to MV-1. This shows the effect of the low moisture transfer properties of MV-1 as the concentration in the supply outlet stays low for the duration of the experiment.

The crossover from the exhaust inlet air stream to the supply outlet for the nail polish remover was calculated with equation 3.2 and shown in figure 7.6. Similar to the concentration graph, it can be seen in the graph when the nail polish remover was inserted. The crossover had a drop at around 5 minutes when the nail polish remover was inserted before it rose again. The drop was due to the delay for the concentration to reach the VOC sensor placed in the supply outlet. In this period, the exhaust inlet concentration was much higher for some measuring intervals. After the concentration stabilized in both ducts, the graph also stabilized. During the first five minutes, before the nail polish remover was inserted, there was a higher concentration in the supply outlet than in the exhaust inlet, leading to a crossover above 100%, as seen in the figure.

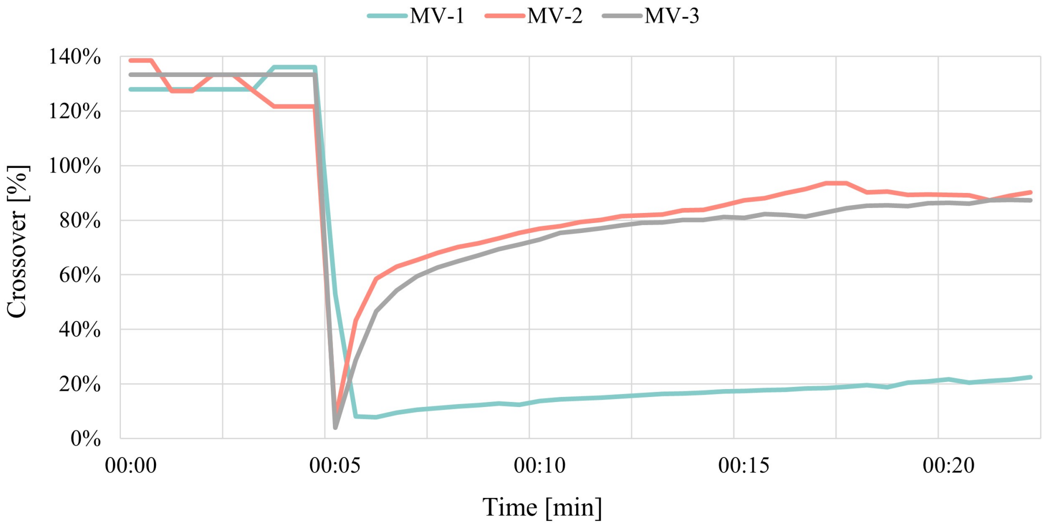

Figure 7.6: VOC crossover from nail polish remover between exhaust inlet and supply outlet.

The crossover followed the trends of the concentration graph. MV-2 and MV-3 had the highest crossover rates, with MV-2 having an average of 5% higher than MV-3. Both MV-2 and MV-3 have higher moisture transfer properties than MV-1, which could explain the higher crossover through their membranes. As expected, MV-1 had the lowest crossover, with levels ranging from 10% to 20% after the nail polish remover was introduced. Compared to the other two MEEs, MV-1 had 62% lower crossover than MV-2 and 56% lower than MV-3.

The EATR takes into account the correction of the supply inlet concentration for both air streams, unlike the crossover graph, which only looks at the direct crossover between the exhaust inlet and supply outlet. Equation 3.1 is used to calculate the EATR. Table 7.5 shows the EATR at the beginning when the nail polish remover was inserted and at the end of the measurements. The increase from start to end is given for all three MEEs.

Table 7.5: Increase of EATR from nail polish remover insertion until end of experiment.

	EATR start [%]	EATR end [%]	Increase [%]
MV-1	5.84	15.2	9.36
MV-2	7.54	87.4	79.9
MV-3	1.25	83.0	81.8

The increase in EATR for all three MEEs from the start at nail polish remover insertion to the end of the measurements increased from MV-1 to MV-3. MV-1 had a considerably lower increase than MV-2 and MV-3, with only 9.36%, compared to respectively 79.9% and 81.8%. This indicates that MV-2 and MV-3 had a much higher transfer from exhaust air to supply air. Additionally, MV-3 had a slightly higher increase than MV-2, which may be due to the membrane used in MV-3 having higher moisture transfer properties.

7.2.2 VOC Source: Formaldehyde

The second VOC source tested in the laboratory experiments was a wetted particle board that emitted formaldehyde. The measurements with the wetted particle board aimed to see how the concentration in the exhaust inlet and supply outlet, as well as the crossover between them, were impacted by a milder VOC source compared to acetone found in nail polish remover. The formaldehyde concentration measured for each MEE is shown in three separate graphs in figure 7.7. The graph furthest to the left shows the concentration from the experiment with MV-1 in blue, the middle graph shows MV-2 in red, and the graph to the left shows MV-3 in grey. The supply outlet is illustrated with a darker shade than the exhaust inlet. The dotted vertical lines show when the particle board was wetted and started emitting formaldehyde.

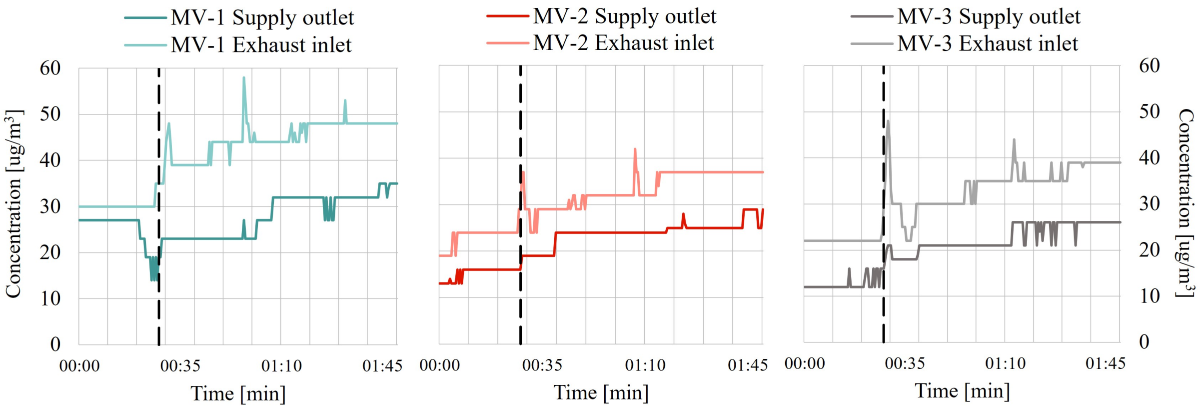

Figure 7.7: Concentration of VOC from wetted particle board in supply outlet and exhaust inlet.

The formaldehyde concentration from the wetted particle board was significantly lower than the concentrations achieved with the nail polish remover. However, there was an increase in the supply outlet concentration for all the MEEs after the insertion of the wetted particle board. The graphs show that the concentration level also varied more between the three MEEs, even though the experiments were executed with the same test rig settings and the same particle board was used. The particle board was wetted to the same degree in each experiment, but the variations could be due to other practical factors like the movement of the air in the environmental room, sensor variations, or other differences that could affect the different concentration levels. The particle board was placed in the same spot for each experiment.

To better see the difference between the concentration in the two air streams, the crossover was calculated based on equation 3.2. The crossover of formaldehyde from the wetted particle board is illustrated in figure 7.8. The dotted vertical line shows the insertion of the wetted particle board.

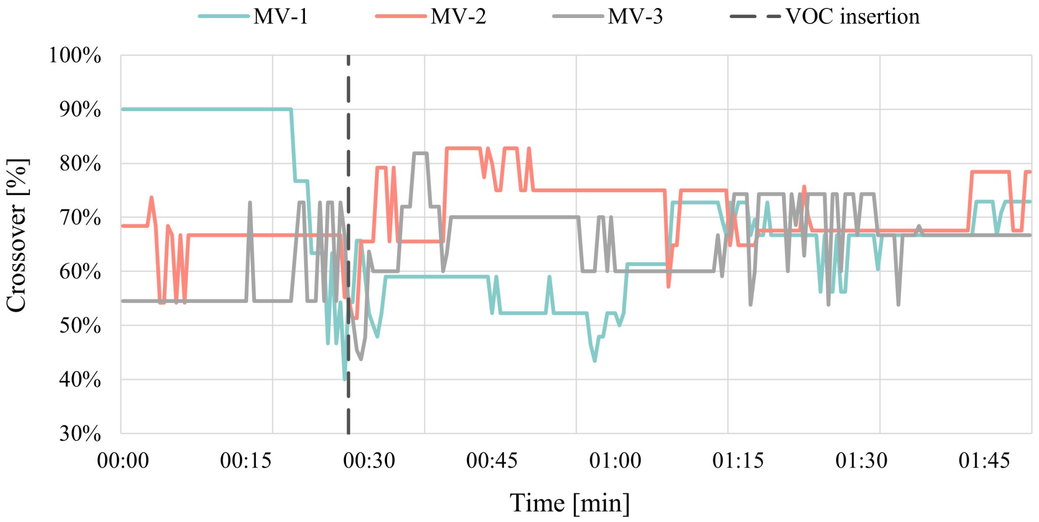

Figure 7.8: VOC crossover from wetted particle board between exhaust inlet and supply outlet.

The particle board showed a more similar crossover between the three MEEs, compared to the results from the nail polish remover assessment. The average crossover before and after insertion of the particle board was respectively 82.5% and 62.5% for MV-1, 65.8% and 72.0% for MV-2, and 56.8% and 66.8% for MV-3. MV-1 had a higher crossover before the insertion than at the end of the measurements due to the high concentration at the supply outlet in normal conditions compared with the exhaust inlet. The crossover decreased as the concentration at the exhaust increased when the particle board was wetted. The sensor in the exhaust duct showed a higher increase of formaldehyde than in the supply duct, as indicated by the concentration graph in figure 7.7. As a result, the crossover for MV-1 was reduced. When looking at the results from the nail polish remover assessment for the same MEE, it is evident that the transfer through MV-1 is minimal. The average crossover before and after insertion increased by 10% for MV-3, meaning a significant part of the formaldehyde was transferred using this membrane. It can also be seen in the graph that there was an increase in the crossover level for MV-3 after the particle board was inserted. MV-2 showed similar trends as MV-3, with an increase of 6% in crossover after insertion.

When looking at the EATR, both the supply outlet and exhaust inlet concentration were corrected using a measured and approximated concentration in the supply inlet. The increase from insertion to end of the experiment of the EATR for the wetted particle board is given in table 7.6. The EATR for the three MEE experiments was calculated with equation 3.1.

Table 7.6: Increase of EATR from wetted particle board insertion until end of experiment.

	EATR start [%]	**EATR end [%]**	**Increase [%]**
MV-1	39.5	49.6	10.1
MV-2	45.3	58.2	12.9
MV-3	25.4	41.8	16.4

The increase in EATR for all three MEEs from the start of insertion to the end increased from MV-1 to MV-3. Although the EATR values were higher for MV-1 than MV-3, the increase for MV-1 was less than for MV-3. This difference could be due to the higher concentration of measurements in the MV-1 experiment. Varying moisture transfer properties of the different membranes could have contributed to the increase in EATR from MV-1 to MV-3. MV-1 transferred less moisture, while MV-3 transferred the most, which could be related to the possibility of transferring VOC contaminants.

7.2.3 Summarizing Remarks: VOC Sensor Measurement

There were variations in the concentrations at the exhaust inlet for both VOC sources. Ideally, the concentration should be the same for all MEEs since the same amount of nail polish remover and the same particle board with the same degree of wetting was used. However, uncertainties in laboratory factors can sometimes be challenging to adjust. The nail polish remover was put into the opening of the exhaust inlet duct, while the wetted particle board was placed in the environmental room. The environmental room is spacious, and there are various factors that could impact the measurements. The equipment used did not provide digital tracking during the experiments, which made it difficult to control and adjust the measurements to ensure similar concentrations for all tests. The differences in concentration should, in theory, only be seen with the supply outlet sensor.

The uncertainty of the measurements with the VOC sensors varies with the results presented. The VOC sensor measurements have higher uncertainties at lower concentrations, which means that the uncertainty plays a minor role in the nail polish remover assessment because of high VOC concentrations. In contrast, the uncertainty of the sensors plays a more significant role in the particle board experiment as these concentrations are lower and show more variations. Both VOC sources are measured using formaldehyde sensors. The formaldehyde sensors react to the acetone source because of cross-sensitivity, as acetone has high concentrations. This may result in slight variations in the exact concentration, but the overall trends are still accurate.

EATR was calculated by correcting with the supply inlet formaldehyde concentration. The supply inlet concentration was only measured in the preliminary work, as more equipment was needed to do measurements in all three ducts simultaneously during the experiment. Measurements were done with four sensors on two different days, and an average concentration was calculated based on these measurements. Although there may have been natural variations, the same supply inlet concentration was used to correct EATR for all experiments.

There were significant differences in the concentration levels observed in the two experiments. Table 3.1 provided the criteria for formaldehyde and TVOC concentration in low and very low polluting buildings [37]. Formaldehyde limits are below 100 $\mu g/m^3$ for low polluting buildings and below 30 $\mu g/m^3$ for very low polluting buildings. The experiment with wetted particle board was below 100 $\mu g/m^3$ but varied from 20 to 60 $\mu g/m^3$, indicating that these concentrations fit for a low polluting builing. The nail polish remover sample reached concentration levels of 400 to 500 $\mu g/m^3$. It is important to note that these limits were given for entire buildings, while the experiment was conducted in a single room.

7.3 Sensible and Latent Effectiveness

The membranes' performance was evaluated in the laboratory by conducting experiments to determine the sensible and latent effectiveness at different supply air temperatures. Data from the temperature and humidity sensors in the test rig were recorded in LabVIEW and used for calculations and illustrations. The supply temperatures evaluated were -6°C, 0°C, and 11°C. The temperatures were adjusted using the environmental room, and all tests were conducted with an air flow rate of 6.9 L/s. The air flow rate and temperatures were chosen based on the Ph.D. work of Liu [20] on the same test rig.

At each supply air temperature, measurements were performed for two hours for all three MEEs. Average values of the measurements were calculated and used in equations 2.1, 2.2, and 2.3 for calculating the sensible and latent effectiveness. The results are illustrated in figure 7.9.

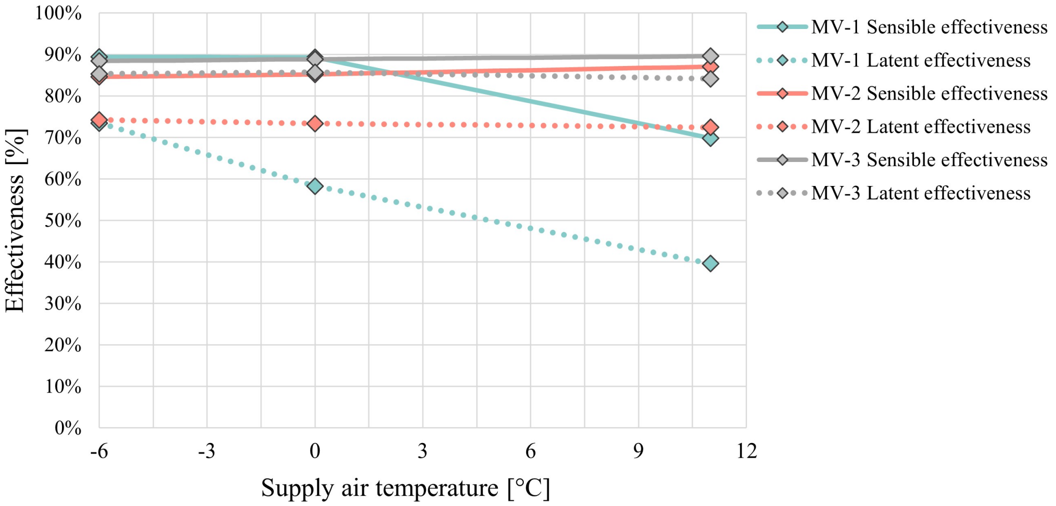

Figure 7.9: Sensible and latent effectiveness at various supply air temperatures.

The graph shows that the latent effectiveness was lower than the sensible effectiveness for all the assessments, as expected based on theory showing that latent effectiveness is lower than sensible due to the moisture resistance in the membranes [9]. To better compare the results, table 7.7 presents the values together with the uncertainty of the sensible and latent effectiveness, calculated from equation 6.6 and 6.7 using experimental measurements. Most uncertainties fell within the acceptable range of 5%, while some were slightly above. The uncertainties above 5% were all connected to the latent effectiveness, which overall had higher uncertainties than the sensible effectiveness. This difference may be attributed to the lower accuracy of the humidity sensors compared to the thermocouples, as shown in table 5.1 in chapter 5.2.

Table 7.7: Values for sensible and latent effectiveness with uncertainties.

			-6°C	**0°C**	**11°C**
MV-1	Sensible effectiveness	[%]	89.4 ± 3.3	89.2 ± 1.5	69.8 ± 1.9
	Latent effectiveness	[%]	73.4 ± 6.6	58.3 ± 2.0	39.6 ± 4.4
MV-2	Sensible effectiveness	[%]	84.6 ± 2.0	85.2 ± 4.6	87.0 ± 1.5
	Latent effectiveness	[%]	74.2 ± 4.1	73.3 ± 5.4	72.4 ± 7.3
MV-3	Sensible effectiveness	[%]	88.4 ± 1.5	88.8 ± 2.1	89.5 ± 2.9
	Latent effectiveness	[%]	85.3 ± 5.7	85.7 ± 3.1	84.1 ± 4.4

The graph and table also show that MV-3, the membrane with the highest moisture transfer, consistently had high sensible and latent effectiveness and minimal variations for the different supply air temperatures. MV-2 also had minimal variations for the three chosen supply air temperatures but lower effectiveness than MV-3. The difference between MV-2 and MV-3 varied between 2.83% and 4.51% for sensible effectiveness, and 13.9% and 15.6% for latent effectiveness. The effectiveness of MV-3 was higher than that of MV-2, particularly when it came to latent effectiveness. MV-2 has lower moisture transfer properties than MV-3, resulting in slightly lower latent effectiveness. These results indicate a correlation between high moisture transfer properties and high latent effectiveness.

MV-1, the membrane with the lowest moisture transfer, showed large fluctuations for the different supply air temperatures. The latent effectiveness for MV-1 was the lowest of the three membranes for all temperatures and decreased by 59.8% from -6°C to 11°C. The sensible effectiveness for MV-1 was high for -6°C and 0°C, but decreased by 24.6% for the experiment with 11°C. The most significant error was the drop of the sensible effectiveness, as sensible effectiveness should be independent of the outdoor temperature, hence constant for both -6°C, 0°C, and 11°C. The drop was also unexpectedly large for the latent effectiveness, but it is more normal with natural variations in the latent effectiveness than for the sensible.

There are multiple factors that could contribute to the decrease in the effectiveness of MV-1 at 11°C. There was always the possibility of both technical and human errors during measurements. The drop could come from instrument failure or inaccuracies in the experimental settings. There was also limited information given on the type of membranes used in the MEEs and their properties other than the moisture transfer. It is, therefore, difficult to state if the moisture transfer or membrane resistance was sensitive to changes in supply air temperature. Effectiveness is dependent on the air flow rate in the system. Unbalanced air flow can be distinguished by looking at the temperature and moisture transfer in the exhaust and supply ducts to determine if there are any variations. For a balanced air flow, the temperature and moisture differences should be similar in both ducts. The data from the measurements showed that the average temperature difference between the exhaust and supply was 1.9°C, while the moisture content difference was 0.03 $\text{kg}_{H_2O}/\text{kg}_{air}$. These variations indicate that the drop in effectiveness was most likely due to unbalanced air flow for the supply and exhaust sides during the experiment.

During the effectiveness measurements conducted at -6°C, there was a risk of frost forming in the exhaust outlet opening of the MEEs. The environmental chamber was used to adjust the supply air temperatures for the effectiveness tests, and the test rig was built as illustrated in figure 5.1 in chapter 5, with the exhaust outlet flowing into the environmental room. An endoscope camera was used to attempt to visualize if there was frost at the exhaust outlet, but the camera did not provide credible results and could not tell if frost was formed. However, variations in the volumetric air flow rate were observed during testing. The volumetric air flow rate was measured over the orifice plate in the exhaust duct from the beginning of the measurements to the end after two hours. The decrease was 7% for MV-1, 3% for MV-2, and 12% for MV-3. Despite this, when looking at the effectiveness at -6°C in figure 7.9, there was no indication of frost formation.

8 Summarizing Discussion

The experiments were performed to address the performance of the three membrane types and compare the characteristics of the membranes and how they were evaluated in the different experiments. In this section, parallels are drawn between the three laboratory experiments. The results are put into realistic scenarios to clearly understand the impact MEEs have on IAQ and to establish the relevance of the prototype tests in the laboratory concerning their applicability to real-life scenarios. By evaluating the membrane characteristics from the three experiments, a better insight into the selectivity towards odour particles and VOC contaminants is provided, as well as the effect of varying effectiveness. By exploring the research questions below, the study contributes to understanding the role of MEEs in ventilation systems and their impact on IAQ.

i. To what extent do the properties of different membranes chosen in membrane energy exchangers influence their selectivity to odour particles and VOC contaminants?

ii. How can the performance of prototype membrane energy exchangers tested in a laboratory relate to real-life scenarios?

iii. How can the performance of membrane energy exchangers affect indoor air quality?

These research objectives address the significance of different membrane properties regarding selectivity towards VOC contaminants and odour particles. Additionally, they contribute to evaluating the practicality of the results by looking at the correlation between laboratory results and real-life scenarios. How IAQ is affected by various MEE performances is also addressed.

After evaluating the three laboratory experiments, it can be seen that MV-1 stands out in all the assessments, while MV-2 and MV-3 show more similar results. MV-1 has lower latent effectiveness than the other MEEs despite its low moisture transfer properties but showed less transfer of odours and VOCs. These results indicate significant variations in the selectivity of contaminants for the different membrane moisture transfer rates researched in this study. Answering the first research question, considerably less VOC contaminants and odour particles were transferred between the air streams with the lower moisture transfer rate than the two higher, MV-2 and MV-3. When comparing MV-2 and MV-3, they showed similar trends in the results. However, MV-3 had better effectiveness, lower crossover of VOC, and was slightly better regarding odour transfer, even though there were more variations between the two MEEs in the odour assessments. It can therefore be estimated that MV-3 is a better choice than MV-2.

Looking at MV-1 and MV-3, the results show considerable differences. MV-1 was superior regarding odour and VOC transfer, while MV-3 showed stable and good results regarding sensible and latent effectiveness. However, the effectiveness assessment of MV-1 was affected by unbalanced air flows for the 11°C evaluation and possibly the 0°C evaluation. For -6°C, where the effectiveness measurements for MV-1 can be assumed valid, the sensible effectiveness for the two MEEs is the same, while the latent is 11.9% higher for MV-3. These results indicate lower latent effectiveness for membranes with low moisture transfer properties and vice versa. The unbalanced air flow of MV-1 at 11°C influenced the results to a large degree, emphasizing the importance of technical precision and optimally functioning systems, as imbalances have a significant effect on performance.

Regarding the sensory odour assessments, high concentrations of odour samples were directly supplied to the ventilation system. Answering the second research question, this can sometimes apply to realistic scenarios but, in other cases, be too intense. In general, kitchen areas and rooms where food is prepared tend to have stronger odours compared to other areas in houses or apartments. It is, therefore, a higher risk of odour transfer in ventilation systems connected to the kitchen. Other occupancy areas could have weaker odour sources, usually related to the soap, perfume and cleaning products evaluated in the sensory experiments. These type of odours are rated as more acceptable and pleasant than food sources. The odour intensity of MV-3 was generally rated higher than that of MV-1. However, in some cases, it could still be considered acceptable when rated similarly to MV-1, or sometimes slightly higher or lower. MV-3 was also rated more pleasant in some cases than MV-1. However, the ratings might have been based on whether the panelists liked the scent or not, rather than whether they would find it pleasant in a ventilation system.

The results provided different consequences for the three membranes on different factors. Referring to the second and third research questions, poor selectivity to odour particles and VOC contaminants, like MV-2 and MV-3, can cause bad IAQ. High odour transfer causes discomfort for the occupants, while VOC contaminants can cause physical complications and, in the worst case, serious illness over time. If there is a risk of strong odours in the living areas, it is important to use a MEE with low moisture transfer rates to prevent cross-contamination. This is especially important if the ventilation system is connected to the kitchen or kitchen fan. Using MEEs with low moisture transfer rates can help avoid VOC contamination from areas such as basements or storage rooms that have known VOC sources.

Addressing the third research question, low sensible effectiveness means more energy is required to heat the living space to the desired temperature because less heat is recovered. This could be the case for MV-2, which has the lowest sensible effectiveness of the three MEEs. The low latent effectiveness of MV-1 means this membrane recovers a low amount of moisture in the system. The consequence this has on IAQ varies a lot with the location of the building and seasonal factors. Climate plays a significant role in determining the desired level of moisture transfer in a ventilation system. In areas with a typical Nordic climate, the air tends to be drier than in locations further south. This could result in low RH indoors, particularly in new, energy-efficient buildings, which may require additional air humidification equipment. In newer buildings equipped with ventilation systems, dry air can be a problem, especially in the winter season. Ventilation systems with a focus on heat recovery can, in some cases, remove moisture from the indoor air, resulting in poor IAQ. Locations further south generally have higher moisture content inside throughout the year, and there will not be the same need for moisture recovery.

8.1 Sources of Uncertainty

All three laboratory experiments used a laboratory test rig to evaluate different performance indicators for the MEEs. Several sources of uncertainties for these types of laboratory tests could affect the results. The most significant errors are connected to technical issues on the test rig and human inaccuracies regarding the control of laboratory operations. The control of the experiments could vary with precision, cause variations between the laboratory experiments for the different MEEs, and affect the results.

Potential technical issues on the test rig could influence the quality of the different experiments. The test rig has been in use for several laboratory experiments over the past ten years, with several layout changes and different people monitoring and equipping it. There could be unregistered damage to the system or technical issues due to degradation. It is not possible to control every part of the system to see if there are any damages as most parts of the system are bolted together with metal parts. The preliminary testing, however, aimed to ensure that the test rig functioned properly and the manometers helped adjust the fans to the right power.

Another factor that could affect the results is the air tightness of the connection between the test rig and the MEEs. The MEEs were switched several times to be able to conduct all the experiments on all the MEEs. Because it was necessary to change so often, the most robust materials could not be used to connect the membrane to the test rig, as there could be a risk that the membranes would be broken when they were swapped. Therefore, a softer and more flexible material was used instead, in addition to insulation, to seal all the edges so air would not leak out.

There was an additional source of uncertainty for the odour sensory assessments. Untrained panelists were used for all the experiments. The panel members could be affected by their daily shape and mood, but these factors should be neglectable as the number of panelists was within the recommended for the ISO standard [51]. Another potential issue was that during the sensory testing, the pressure varied from when the hood was placed over the odour sample to when it was in open air. It created a vacuum that affected the pressure, but it was unavoidable in order to complete the experiments. It was a recurring issue for all tests, which makes the comparison valid.

9 Conclusion

Implementation of MEEs in ventilation systems has great potential to improve energy-saving processes as it recovers both heat and moisture from the exhaust air. However, it is crucial to address the impact of these systems on IAQ, preventing cross-contamination and ensuring resistance to odours and contaminants. MEEs offer enhanced control over humidity levels to maintain acceptable IAQ, especially during dry Nordic winters. This study examined three prototypes with different membranes and varying moisture transfer properties to evaluate the performance of MEEs. The study focused on evaluating odour transfer, VOC contaminant crossover, and sensible and latent effectiveness.

Experimental findings showed that MV-1, with the lowest moisture transfer, demonstrated the best results regarding odour transfer and VOC crossover. MV-1 had low odour intensity, less share of dissatisfaction, and VOC crossover 56% lower for acetone and 4.3% for formaldehyde, compared with MV-3. These results indicate how essential the resistance to moisture transfer is on a membrane's selectivity towards odour particles and VOC contaminants. Membranes with higher moisture transfer rates, such as MV-2 and MV-3, showed higher transfer of odour particles and VOC contaminants. However, MV-3, the membrane with the highest moisture transfer rate, showed higher and more consistent sensible and latent effectiveness in comparison with MV-1. The effectiveness assessment of MV-1 was affected by unbalanced air flows. When MV-1 was adequately balanced, there were minimal variations in sensible effectiveness compared to MV-3, but 11.9% lower latent effectiveness. These findings emphasize the importance of a well-functioning system, highlighting how imbalances and variations of different moisture transfer properties could affect the performance of MEEs.

Membranes with poor selectivity to odour particles and VOC contaminants due to high moisture transfer rates, such as MV-2 and MV-3, can contribute to poor IAQ. Poor selectivity could lead to discomfort for occupants and potential health issues associated with exposure to VOCs. The MV-1 membrane demonstrated better results regarding odour transfer and VOC crossover, emphasizing the significance of moisture transfer resistance in improving IAQ. Results obtained from this study found that panelists had varying perceptions of odours for the different experiments. Odours from food sources were rated as less acceptable and less pleasant compared to sources containing products with soap and perfumes.

Several factors must be considered when deciding which membrane is best to install. Properties affecting the membrane performance, like the moisture transfer resistance, further affect the share of recovered moisture affecting the latent effectiveness and the selectivity to odours and VOCs. The consequences of less moisture recovery vary depending on the building's location and seasonal factors, which could lead to dry indoor air in, e.g., the Nordic winter season. These factors are essential to consider based on specific requirements for each particular installation when selecting a membrane for a MEE ventilation system. MV-2, with the medium moisture transfer rate, showed lower effectiveness than MV-3, with a higher degree of VOC crossover and a slightly higher intensity of odour transfer. Therefore, this prototype is not recommended for use in energy-efficient ventilation based on the evaluation in this study.

The low latent effectiveness of MV-1 implies a reduced capacity to recover moisture in the ventilation system, compared to MV-3, with both high sensible and latent effectiveness. However, MV-1 showed much larger selectivity to odours and VOCs than MV-3. The significance of odour and VOC transfer must be considered for each installation. In this study, high concentrations of odours were used. For each particular installation, it is essential to consider the intensity of the odour it will encounter and the probability of VOCs exceeding concentration limits. Based on this, MV-1 is recommended in most cases as its selectivity to odours and VOCs was within acceptable limits. However, in buildings with minimal risk of substantial odour and VOC exposure, MV-3 is a good choice because of its high effectiveness.

The study shows the diversity of membranes that can be used for ventilation installations, as the properties can vary depending on what is required for each design. The findings highlight the importance of membrane selection and proper air flow management in ventilation systems to ensure optimal IAQ. Consideration of odour and VOC exposure and local climate conditions are vital for designing energy-effective ventilation systems with comfortable indoor environments. By addressing all these factors, there is great potential for enhanced IAQ, energy efficiency, and comfort of building occupants through the optimization of MEEs.

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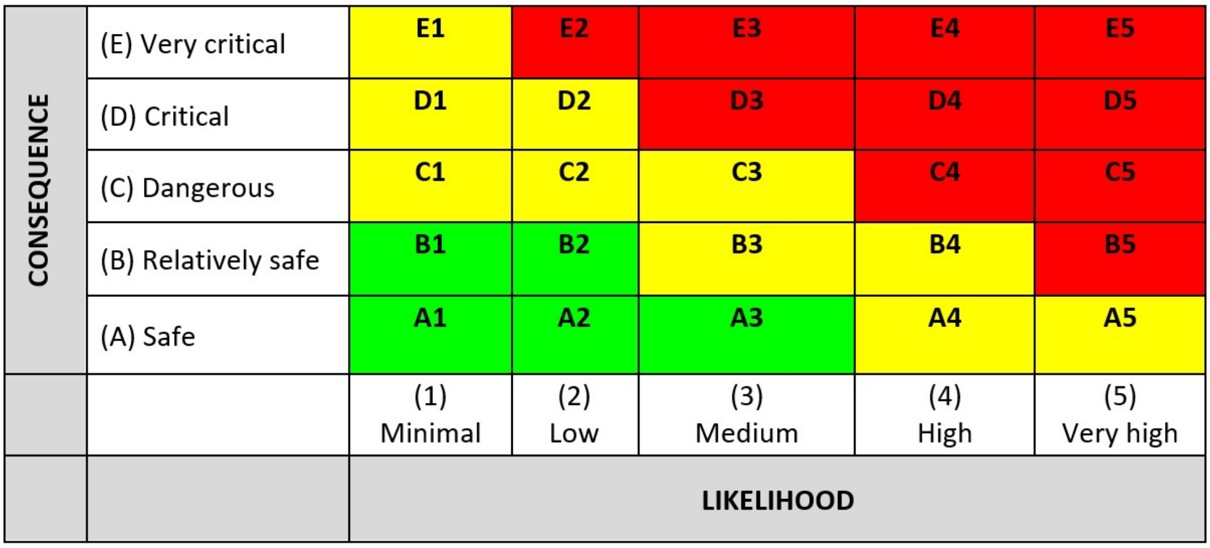
A Risk Assessment

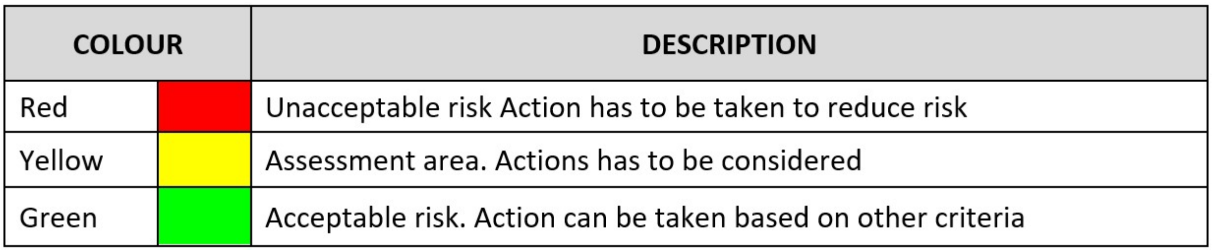
Before being allowed access to the laboratory to perform the experiments, a risk assessment had to be completed and approved. The entire risk assessment document is delivered together with the master thesis but in a separate document. This chapter in the appendix briefly describes the most important parts of the risk assessment.

The risk matrix is considered the most essential element of the risk assessment. Figure A.1 shows the risk matrix and the distribution between likelihood and consequence. The meaning of the colours in the risk matrix is described in figure A.2. The red colour of the risk matrix indicates that it is unacceptable, and action must be taken to reduce it. For the yellow colour, a consideration must be made in each individual case if action is necessary. The green colour indicates that the risk is acceptable and there is no need for action.



CONSEQUENCE	(E) Very critical	E1	E2	E3	E4	E5
	(D) Critical	D1	D2	D3	D4	D5
	(C) Dangerous	C1	C2	C3	C4	C5
	(B) Relatively safe	B1	B2	B3	B4	B5
	(A) Safe	A1	A2	A3	A4	A5
		(1) Minimal	(2) Low	(3) Medium	(4) High	(5) Very high
		LIKELIHOOD				

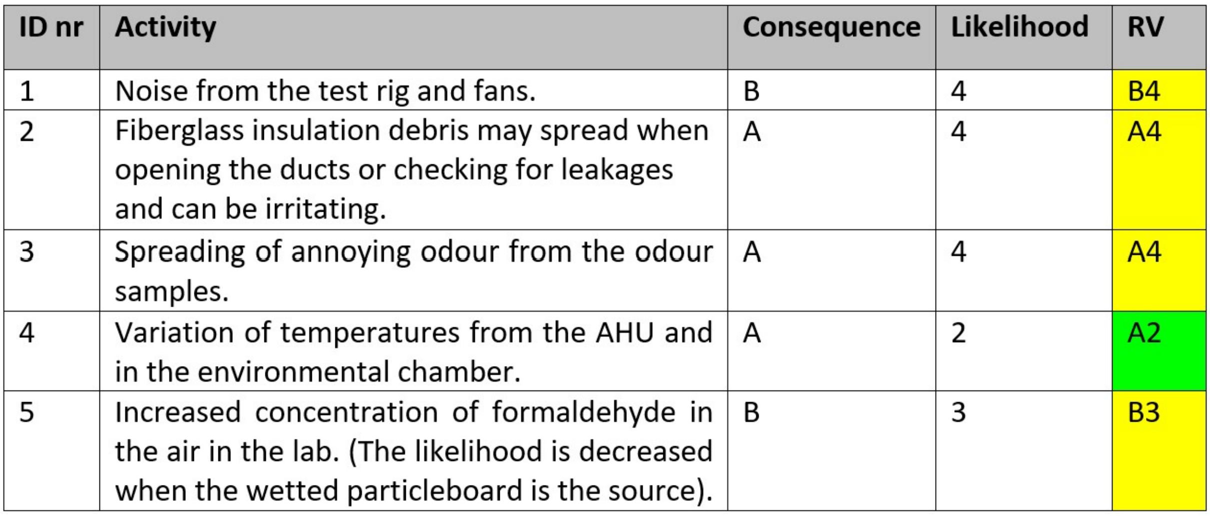
Figure A.1: Risk matrix with consequence and likelihood.



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

Figure A.2: Explanation of the colours used in the risk matrix.

The risks considered for the experiments in this study are given in figure A.3. There is a risk of odour spreading from the samples into the laboratory area for the sensory odour tests. This risk is likely to happen, but the consequence is minimal. It is therefore rated A4. For the effectiveness experiments, temperatures are regulated in both the environmental chamber and the AHU. The likelihood of this affecting the laboratory is minimal, and the consequence is also minimal, and it is therefore rated A2. For the VOC sensor measurements, there is a risk of formaldehyde or acetone causing higher concentrations of VOC in the laboratory. There is a medium likelihood of this happening, but the consequence would still be relatively safe, and it is therefore rated B3. None of the experiments provide unacceptable risk according to the risk matrix.



ID nr	Activity	Consequence	Likelihood	RV
1	Noise from the test rig and fans.	B	4	B4
2	Fiberglass insulation debris may spread when opening the ducts or checking for leakages and can be irritating.	A	4	A4
3	Spreading of annoying odour from the odour samples.	A	4	A4
4	Variation of temperatures from the AHU and in the environmental chamber.	A	2	A2
5	Increased concentration of formaldehyde in the air in the lab. (The likelihood is decreased when the wetted particleboard is the source).	B	3	B3

Figure A.3: Risk evaluation for the laboratory experiments in this study.

B Odour Samples

The products used as odour samples are shown in the figures below. In addition to these, three blank samples were used for the odour sensory experiments.

Figure B.1: Jif cleaning spray

Figure B.2: Salami

Figure B.3: Paint

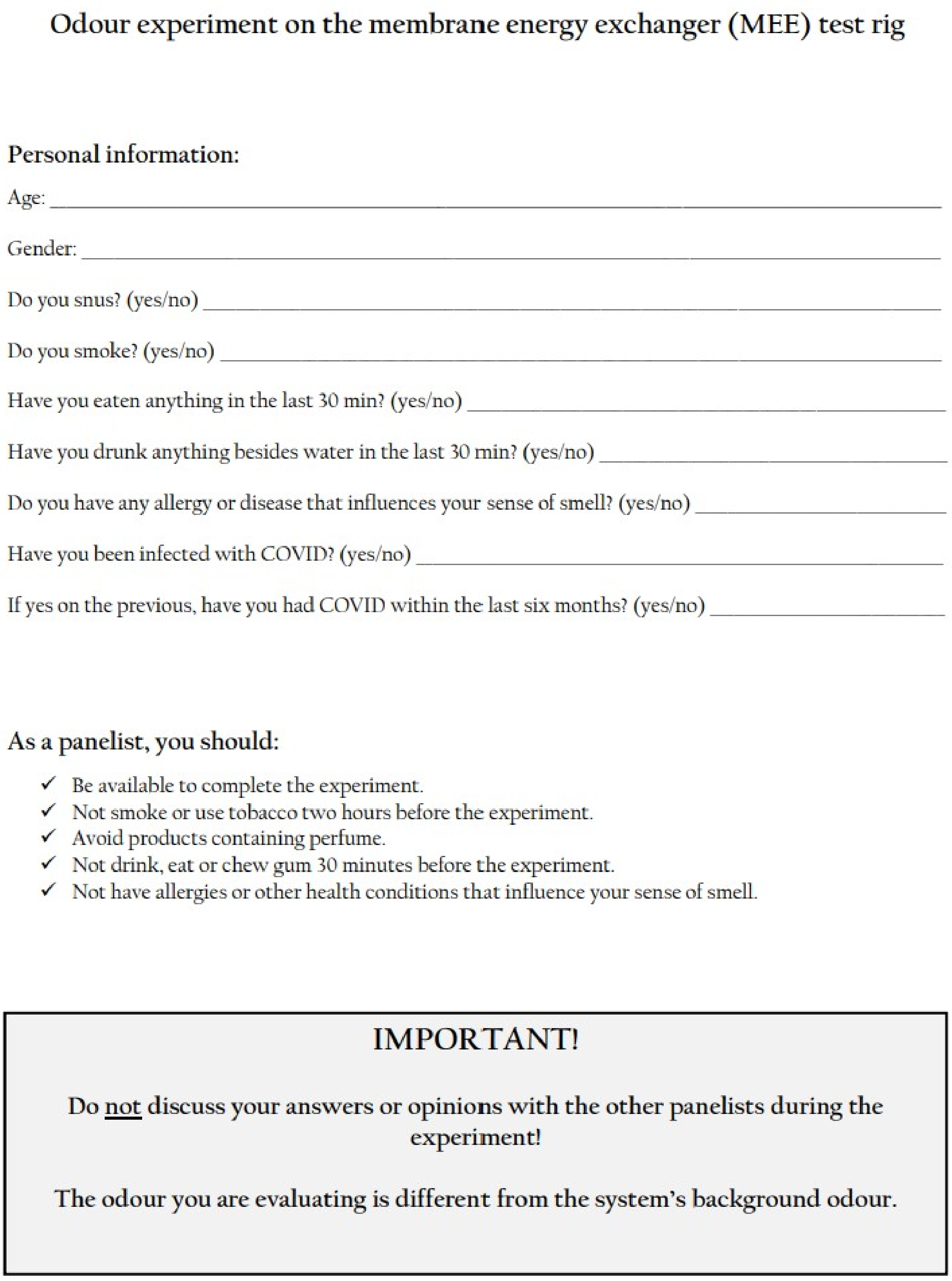
Figure B.4: Perfume

Figure B.5: Waffle

Figure B.6: Shower soap

C Questionnaire

The following four pages include the questionnaire used during the sensory test at the lab. Before the experiments started, it was handed out and explained to the untrained panel members. The questions and scales included are based on *ISO 16000-30: Sensory testing of indoor air*[51].



Odour experiment on the membrane energy exchanger (MEE) test rig

Personal information:

Age: ____

Gender: ____

Do you snus? (yes/no) ________________________________

Do you smoke? (yes/no) ________________________________

Have you eaten anything in the last 30 min? (yes/no) ____________________

Have you drunk anything besides water in the last 30 min? (yes/no) ______________

Do you have any allergy or disease that influences your sense of smell? (yes/no) __________

Have you been infected with COVID? (yes/no) ______________________

If yes on the previous, have you had COVID within the last six months? (yes/no) __________

As a panelist, you should:

- ✓ Be available to complete the experiment.
- ✓ Not smoke or use tobacco two hours before the experiment.
- ✓ Avoid products containing perfume.
- ✓ Not drink, eat or chew gum 30 minutes before the experiment.
- ✓ Not have allergies or other health conditions that influence your sense of smell.

IMPORTANT!

Do not discuss your answers or opinions with the other panelists during the experiment!

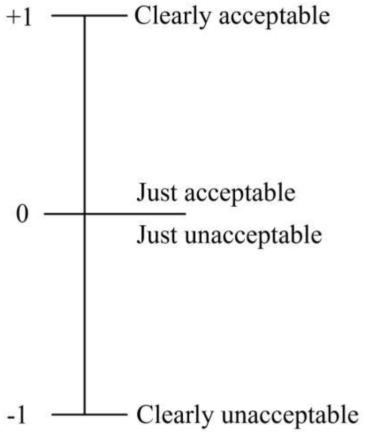
The odour you are evaluating is different from the system's background odour.

Odour acceptability

I. Imagine you are exposed to this odour in your everyday life. Would you consider this odour acceptable?

	Background scent	Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9
Yes/No										

II. Imagine you are exposed to this odour in your everyday life. How would you rate this odour on the following scale?



Background scent	Test 1	Test 2	Test 3	Test 4
+1 0 -1	+1 0 -1	+1 0 -1	+1 0 -1	+1 0 -1

Test 5	Test 6	Test 7	Test 8	Test 9
+1 0 -1	+1 0 -1	+1 0 -1	+1 0 -1	+1 0 -1

Odour intensity

Rate the intensity of the odour on the following scale:

Background scent	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 1	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 2	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 3	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 4	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 5	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 6	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 7	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 8	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong
Test 9	0 ○ No odour	1 ○ Very weak	2 ○ Weak	3 ○ Distinct	4 ○ Strong	5 ○ Very strong	6 ○ Extremely strong

Hedonic tone

Rate how pleasant/unpleasant you found the odour on the following scale:

Background scent	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 1	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 2	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 3	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 4	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 5	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 6	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 7	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 8	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant
Test 9	Extremely unpleasant	-4 ○	-3 ○	-2 ○	-1 ○	0 ○	1 ○	2 ○	3 ○	4 ○	Very pleasant

Odour source

The odours you have been exposed to are all common household odours. Make a guess below on what you think the odour source is:

Test 1	Test 2	Test 3	Test 4	Test 5	Test 6	Test 7	Test 8	Test 9

D Uncertainty of Odour Sensory Analyses

The uncertainties for the odour assessments are calculated with equation D.1.

$$P\left(\mu\epsilon\left[\bar{x} \pm \frac{s}{\sqrt{n}} \cdot t_{(1-\frac{\alpha}{2});n-1}\right]\right) = (1-\alpha) \tag{D.1}$$

To use this equation, table D.1 is used for finding the t-distribution for the four odour sensory assessments. According to ISO 16000-30:2014 [51], a 90% confidence interval is used when finding the accuracy of a sensory odour test. The values used from the table are given in the $t_{.95}$ column, as this is the upper and lower 5%. The number of panelists is n, while the degree of freedom is *n-1*.[58]

The experiment for MV-1 had 25 panelists and use 1.711 to calculate the accuracy, MV-2 and no MEE had 20 panelists and use 1.729 to calculate the accuracy, and MV-3 had 23 panelists and use 1.717 to calculate the accuracy. The values used are highlighted with bold text in the table.

Table D.1: T-distribution for different confidence intervals and degrees of freedom.[58]

n-1	$t_{.80}$	$t_{.85}$	$t_{.90}$	$t_{.95}$	$t_{.975}$	$t_{.999}$
15	0.866	1.074	1.341	1.753	2.131	2.602
16	0.865	1.071	1.337	1.746	2.120	2.583
17	0.863	1.069	1.333	1.740	2.110	2.567
18	0.862	1.067	1.330	1.734	2.101	2.552
19	0.861	1.066	1.328	**1.729**	2.093	2.539
20	0.860	1.064	1.325	1.725	2.086	2.528
21	0.859	1.063	1.323	1.721	2.080	2.518
22	0.858	1.061	1.321	**1.717**	2.074	2.508
23	0.858	1.060	1.319	1.714	2.069	2.500
24	0.857	1.059	1.318	**1.711**	2.064	2.492
25	0.856	1.058	1.316	1.708	2.060	2.485

E Odour analysis

In addition to the odour sensory analyses presented in the results chapter, two additional assessments have been performed. During the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* written by *Tærum, Mathea L.* and delivered in December 2022, an odour panel analysis was performed on the MEE installed for the Ph.D. work of Liu [20]. This assessment is given in chapter E.1. The preliminary project also showed that the panel members were strongly bothered by the background scent in the system. It was therefore decided to perform an evaluation of the background odour in the system prior to each of the four sensory analyses presented in the results chapter. This assessment is given in chapter E.2.

E.1 Odour Analysis from Preliminary Project

The results in this chapter are all from the preliminary project *Use of Membrane Energy Exchanger in Ventilation: Odour Sensory Measurement* written by *Tærum, Mathea L.* and delivered in December 2022. The discussion of the results is also based on or directly copied from the preliminary project. Similarly to the master thesis, the odour sensory test for the older membrane evaluates the percentage of dissatisfied, odour acceptability, odour intensity, and hedonic tone with the same scales and questionnaire as in the master thesis. Box and whisker plots are also used for this assessment.

The percentage of dissatisfied for the older MEE is shown in figure E.1. The results show that test 2 with the salami odour sample has the highest percentage of dissatisfied. The lowest were test 1, test 8, and test 9, respectively, cleaning spray, shower soap, and a blank sample.

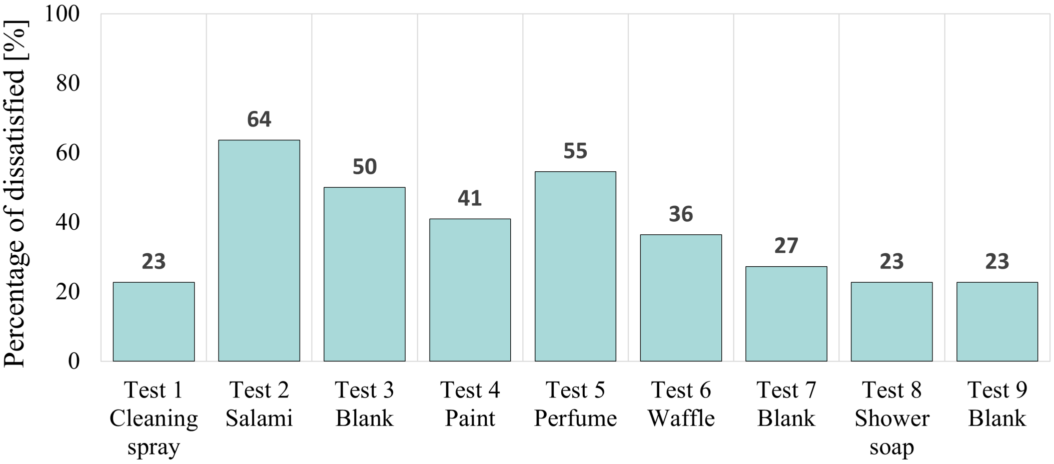


Figure E.1: Percentage of dissatisfied for the nine odour samples for the older MEE.

The evaluation of odour acceptability for the older MEE is illustrated in figure E.2 with mean values and the range of answers. All tests show a wide range from highest to lowest evaluated acceptability. All mean values are above zero except for the evaluation of test 2, which is the salami sample, with an acceptability of -0.14. The highest acceptability is for the shower soap in test 8, followed by the blank sample of test 9 and the cleaning spray in test 1.

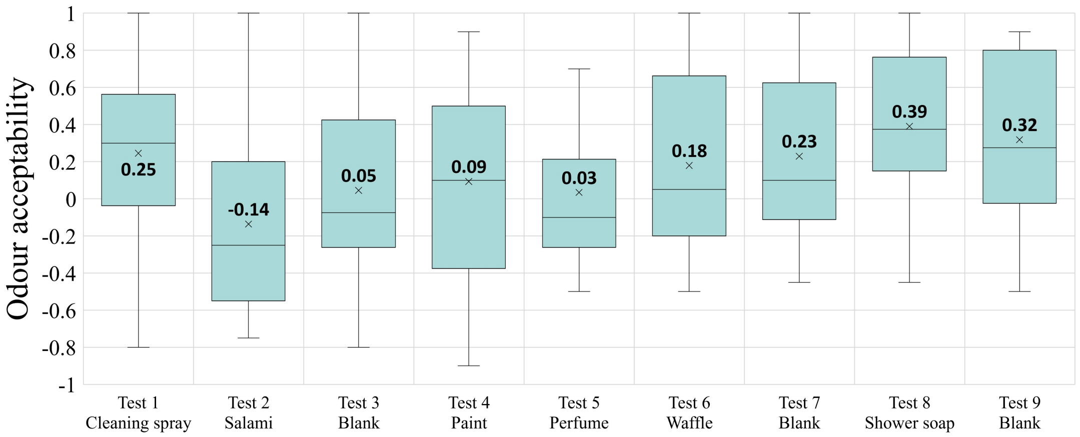


Figure E.2: Odour acceptability for the nine odour samples for the older MEE.

The odour intensity for the nine odour samples in the assessment using the older MEE is shown in figure E.3. All samples except one are evaluated between 2 and 3, which is between weak and distinct intensity. The highest evaluated sample is the paint sample at 3.3, which is between distinct and strong intensity.

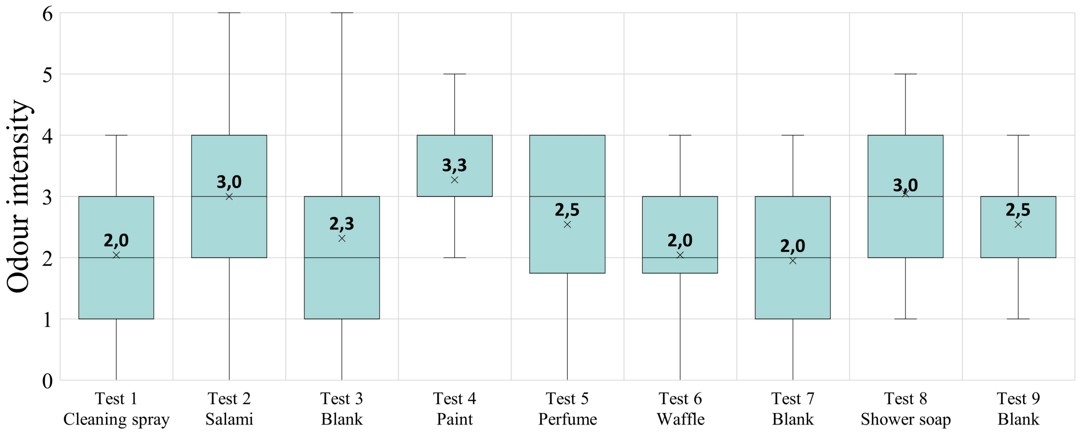


Figure E.3: Odour intensity for the nine odour samples for the older MEE.

Figure E.4 shows the evaluation of hedonic tone for the sensory analysis with the older MEE. The most unpleasant sample is salami, with a hedonic tone of -1.18. All samples except test 8 and test 9 are rated with an average value below zero. Shower soap, which is test 8, has the highest average hedonic tone with 0.86, while test 9, a blank sample, has an average value of 0.36.

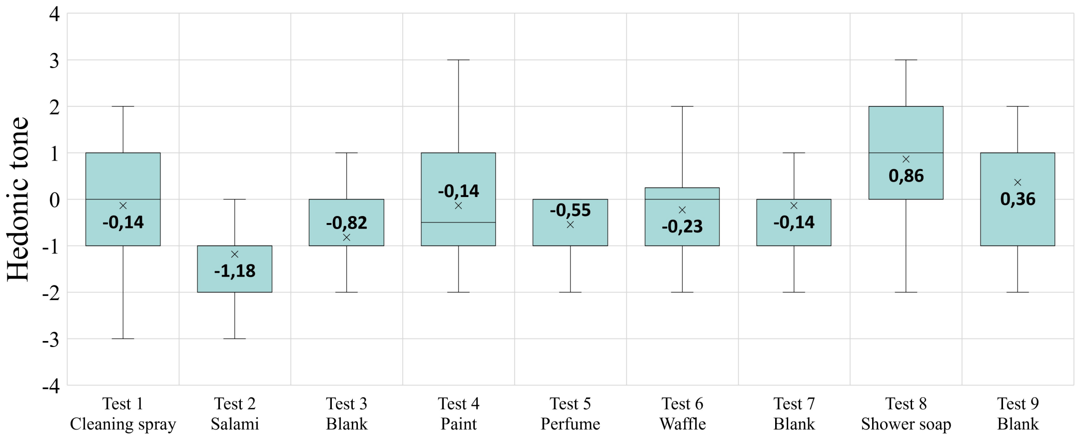


Figure E.4: Hedonic tone for the nine odour samples for the older MEE.

E.2 Odour Analysis of Background Scent

The background odour was evaluated at the beginning of all four tests: MV-1, MV-2, MV-3, and no MEE. The evaluation of background odour is not affected by the different membranes, as the evaluation assesses the scent already in the system. The variations are, therefore, most likely due to daily variations and the mood of the panelists.

Figure E.5 shows the percentage of dissatisfied for the four experiments. The answers vary from the lowest, with 30% dissatisfied panel members for MV-3, to the highest, with 56% for MV-1. The answers provide an average percentage of dissatisfied of 46.5% for the background odour.

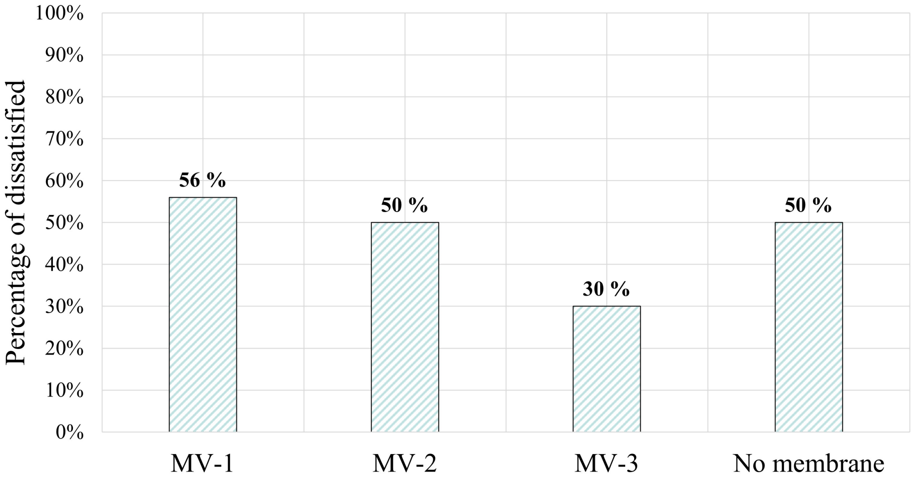


Figure E.5: Percentage of dissatisfied for the background odour.

The evaluation of odour acceptability of the background odour is shown in figure E.6. The mean values vary from -0.08 for MV-2 to 0.00 for MV-3, with the mean average value being -0.04. This indicates an acceptability that is per definition *just unacceptable*. The range of answers shows large variations, with the highest being 0.7 and the lowest -0.8. All the panel members perceive the background odour differently, and some find it more acceptable or unacceptable than others.

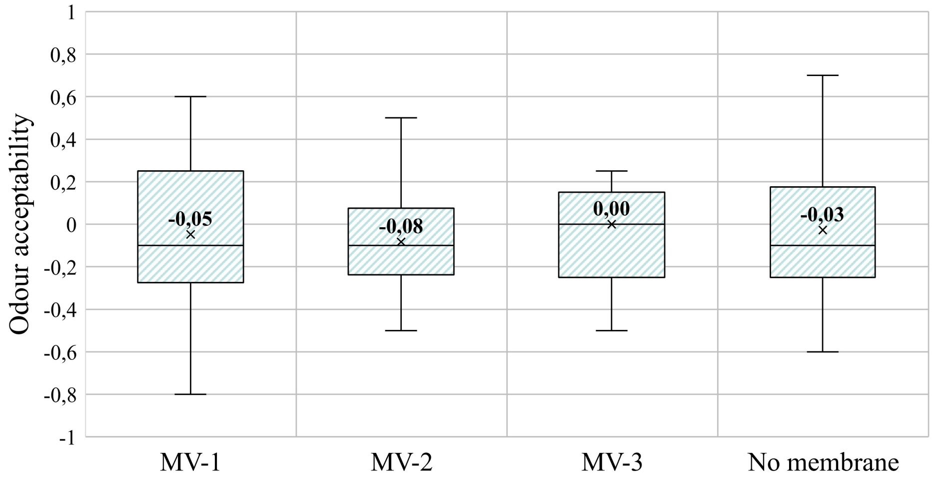


Figure E.6: Odour acceptability for the background odour.

Figure E.7 shows the odour intensity for the four evaluations of the background odour. The central half of the answers are between weak (2) and distinct (3) for three of the tests, while it is between distinct and very weak (1) for the last test. The average mean value is 2.47, between weak and distinct. The evaluation connected to the MV-1, MV-2, and MV-3 tests shows similar results with the same central half, and the same range of answers between 1 and 4, while there is a larger range of answers for the test with no membrane.

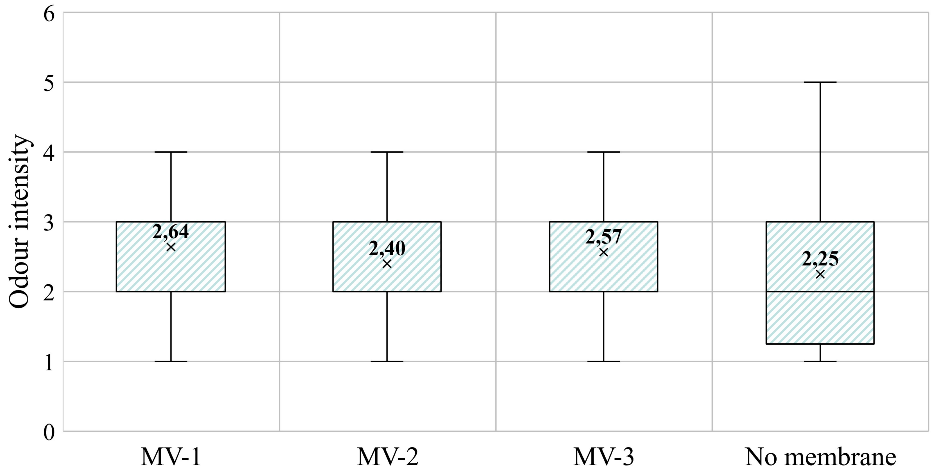


Figure E.7: Odour intensity for the background odour.

The evaluation of hedonic tone for the background odour is shown in figure E.8. All four tests have a mean value below neutral, on the unpleasant side of the scale. The average mean value for hedonic tone from all four evaluations is -0.88. The central half of the answers are between 0 and -2 for all the tests. These results show that the background odour is perceived as unpleasant.

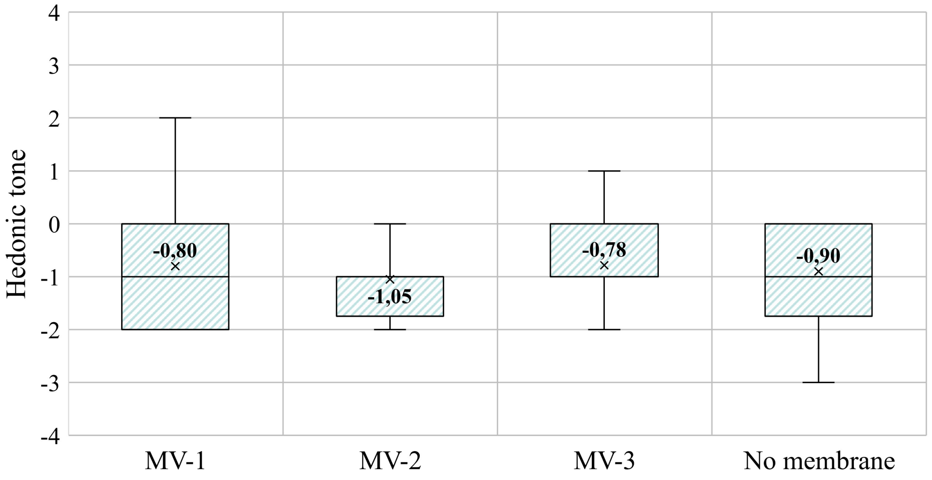


Figure E.8: Hedonic tone for the background odour.

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