Building and Environment 222 (2022) 109430

Contents lists available at ScienceDirect

Building and Environment

journal homepage: www.elsevier.com/locate/buildenv

Use of membrane energy exchanger in ventilation: Odour sensory measurement

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ARTICLE INFO

Keywords:
Membrane energy exchanger
Odour transfer
Sensory measurement
Indoor air quality

ABSTRACT

Membrane energy exchanger (MEE) for a new generation of energy efficient heating, ventilation and air conditioning (HVAC) systems has attracted wide attention. As MEE has been increasingly employed, extensive studies of heat and moisture transfer features have been carried out. Nevertheless, odour transfer through MEE, which may cause odour nuisance and complaints regarding indoor environment, is seldom studied. For most applications of MEE in ventilation, MEE is presumed to be able to prevent the pollutants transfer including volatile organic compounds (VOCs) and odours, despite a lack of clear scientific evidence. This study measured the potential odour transport through an MEE by using an odour sensation panel. The sensory measurement shows the percentage of dissatisfied could reach 84% for the odour source of waffle mix powder in extract air. In comparison, the percentage of dissatisfied is 5% when there is no odour source. The sensory air acceptability, odour intensity and hedonic tone for the supply air using MEE are assessed by a panel for different odour sources in the extract air. The findings of this study indicate that the odours generated from, such as cooking and cleaning in kitchens and in bathrooms, are likely to be undesirably transferred to the supply air through the tested polypropylene membrane exchanger, which may lead to a poor perception of the indoor environment. It may be particularly important to pay attention to the odour transfer through MEE when the odours originate from a kitchen. More studies for different membranes are recommended in the future.

1. Introduction

Buildings contribute nearly 40% of the total global energy consumption and more than 30% of the CO_2 emissions [1]. HVAC systems consume a significant amount of energy as the demand for indoor thermal comfort and indoor air quality increases. HVAC systems were reported to account for about more than 50% of the total building energy use by analysing a comprehensive database of the building stock [2].

MEEs, which allow both heat and moisture transfer, have been increasingly used for energy-efficient ventilation [3–5]. MEEs demonstrate substantial energy saving potentials in different climates [6–8]. It has been reported that energy for conditioning outdoor air can be saved by 70%–90% using MEE in different climates [9]. By using MEEs in hot and humid climates, MEE presents a unique opportunity to reduce significantly the power requirements for moisture removal by reducing phase change on the cooling coil and has thus been ranked as a superior alternative to traditional HVAC systems with only cooling coil. In cold climates, besides the energy savings associated with heat recovery from warm extract air to cold outdoor air, MEE's moisture transfer function significantly reduces the frosting risk inside the exchanger, which dramatically degrades the heat recovery performance [10–13]. Thus, the preheating energy required to prevent frosting in heat recovery can be lowered. Further, the moisture recovered to the dry outdoor air in cold regions may improve the "too dry" indoor air.

As the progress and advancements of air-to-air MEEs continue, MEE should be expected to become an essential component of the next generation of HVAC systems designed to contribute to zero energy and zero emission buildings [3,5,14,15]. Although MEEs have been progressively employed for energy efficient ventilation in practice, their abilities to prevent cross-contaminants including odour transfer through membranes and exchanger leaks are scarcely examined. Most studies have assumed that the semipermeable membranes of MEEs for ventilation can enable heat and moisture transfer and ideally restrain pollutants and odours transferring to the other side. The mechanism of heat and mass transfer through a membrane is demonstrated in Fig. 1.

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https://doi.org/10.1016/j.buildenv.2022.109430
Received 9 May 2022; Received in revised form 23 June 2022; Accepted 16 July 2022
Available online 2 August 2022

As shown in Fig. 1, the heat and moisture are recovered from warm and humid extract air to cold and dry supply air during winter conditions. The membrane is often assumed to be completely impermeable to airborne pollutants and odours and thus, these are perfectly exhausted outdoors. However, the validity of this assumption is not adequately supported by evidence as pollutants transfer through membranes has been reported [16–18]. Huizing et al. [16] pointed out that current certifications and standards for contaminant crossover are devoted to measuring the exhaust air transfer ratio based on tracer gas tests. They concluded that tracer tests can be used to determine exchanger defects and leakage, but may not account for all sorption and permeation phenomena in polymeric membranes [16]. As a result, the commonly used tracer test method may underestimate or misrepresent pollutants and odour transport in MEEs. The same study also investigated the transport of water vapour, carbon dioxide, oxygen, and VOCs through a number of polymeric membranes. For different tested membranes and chemicals, the contaminant permeance and selectivity vary significantly. Another study [17] tested the permeability of most commonly used hydrophilic and hydrophobic membranes with moisture and five different VOCs (acetic acid, formaldehyde, acetaldehyde, toluene, and ethane). In conclusion, selecting membrane materials for MEE should include a high degree of moisture permeability as well as high VOC selectivity. According to this selection criteria, the polymer membrane polyvinyl alcohol (PVA) is considered the best material, which exhibits high moisture transfer efficiency and prevents VOCs from transferring. Comparatively, polydimethylsiloxane (PDMS) performs the worst for moisture permeation and VOCs prevention, followed by polypropylene (PP) and ethylene cellulose (EC). In light of these findings, the potential pollutants and odours transfer in MEEs should be assessed for the specifically applied membrane type. A general conclusion on pollutants and odour transport through different membranes, which can apply to different membranes, may not exist.

“Odours are mixtures of light and small molecules that, coming in contact with various human sensory systems, also at very low concentrations in the inhaled air, are able to stimulate an anatomical response: the experienced perception is the odour.” [19] Both organic odorants and inorganic molecules contribute to odour levels [20]. VOCs refer to a group of organic chemicals formed by molecules with different functional groups that have different chemical and physical properties. Not all VOCs impinging on the olfactory system produce an odour sensation. On the other hand, inorganic compounds such as H_2S, NH_3, Cl_2 can bind olfactory receptors and affect odour levels due to their low molecular weights [21]. People spend 90% of their time indoors, and homes are the place where we spend the majority of our time [22]. Unpleasant odour may cause complaints of indoor environmental quality and the odour nuisance may bring negative effects ranging from annoyance to documented health effects, leading to a reduced quality of life [23]. An odour-related health concern could be physiological, such as nausea, headaches, drowsiness and irritation, or psychological, such as mood changes or stress [24].

Odours can be quantitatively and qualitatively characterised by sensory or analytical techniques. A sensory technique’s main advantage is the higher sensitivity of the human nose as compared to electronic instruments, while its main disadvantage is that it is relying on the availability of a panel of qualified assessors to ensure reliable and repeatable results [21]. Analytical methodologies do not suffer from human error, but they are less sensitive, not reliable when there are many odorants present at low odour concentrations, and cannot detect the interaction between many odorants [21]. To the best of the authors’ knowledge, odour transfer via MEE in ventilation has not been experimentally measured and analysed despite the fact that MEEs have been increasingly used in practice.

The experimental work presented in this paper provides one of the first investigations into odour transfer through air-to-air MEE in ventilation. The sensory assessment is conducted using untrained panel members for sensing odours in terms of dissatisfaction of the indoor air quality, air acceptability, odour intensity and hedonic tone. Experimental results can be used to contribute to material selection and membrane preparation and the construction of MEE. The outcomes of this study are expected to promote more relevant studies on cross-contamination, including odour transport through MEE and raise awareness of odour transport and thus the potential indoor environmental consequence of using MEE for the stakeholders.

2. Methods

2.1. MEE construction

Depending on the flow arrangements, the MEE can be classified into counterflow, cross-flow, and quasi-counterflow. In theory, counterflow can achieve a recovery efficiency of more than 90%. However, the difficulty connecting the inlets and outlets to ductwork limits its use. Despite its relatively low recovery rate ranging from 50% to 70%, cross-flow MEE is easily connected to ductworks [25]. A quasi-counterflow MEE, which combines the advantages of both flow arrangements mentioned above, has been developed and reported for high efficiency and easy to connect [26,27]. In this study, a quasi-counterflow MEE was constructed and the structure and dimensions of the MEE are illustrated in Fig. 2. The MEE mainly consists of membranes, corrugated aluminium mesh spacers, sealing brackets, and plastic frame. The channels between the parallel membranes are filled with corrugated aluminium mesh, which was used to support the flexible and thin membranes. Sealing brackets and frames are constructed from the plastic by CNC (computer numerical control machinery) and their thickness are 2 mm and 10 mm

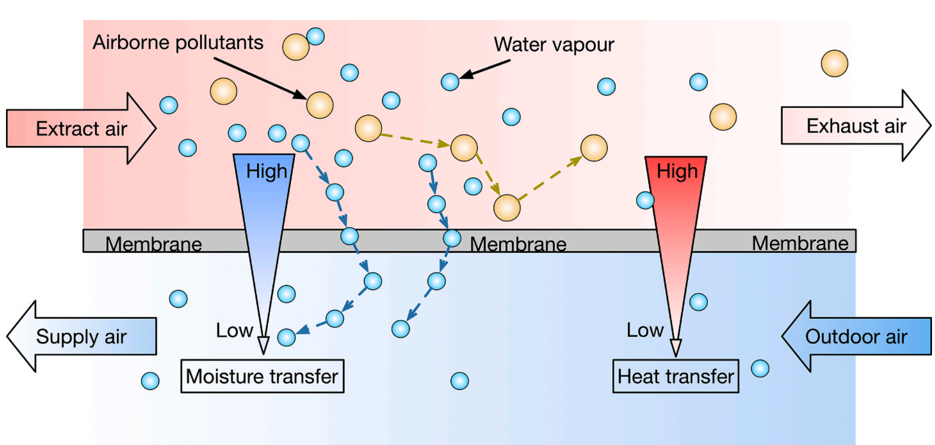

Fig. 1. Heat and mass transfer through a semipermeable membrane in winter condition.

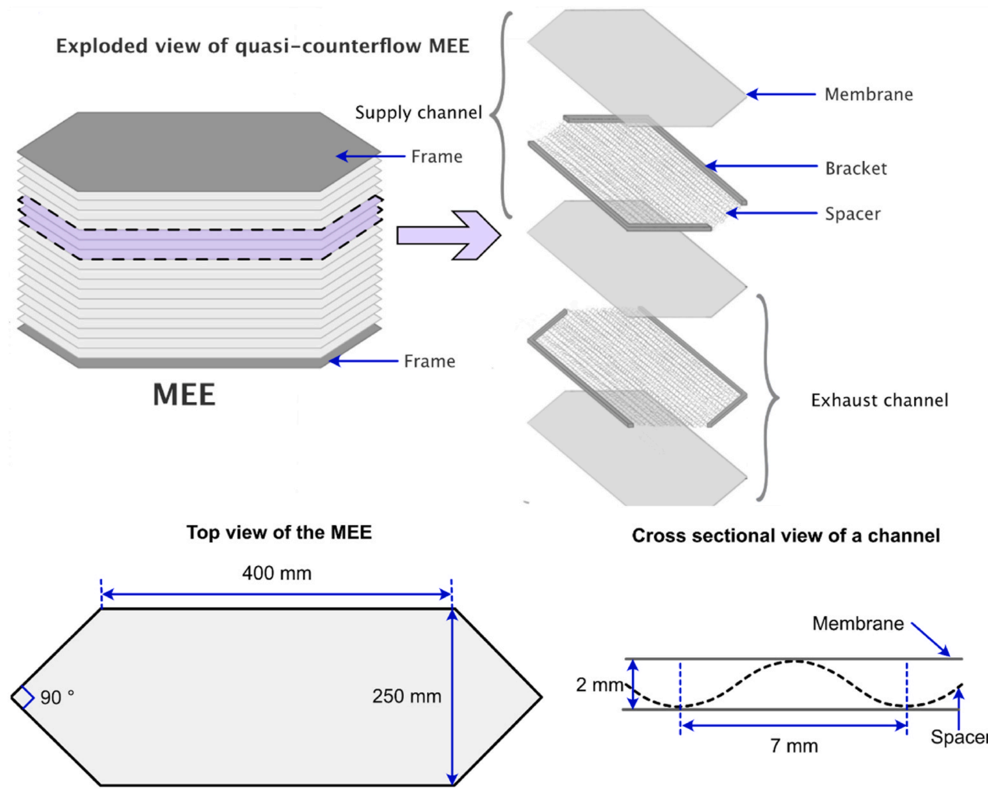

Fig. 2. Exploded view, top view and cross-sectional view of the constructed quasi-counterflow MEE.

respectively. There are nine channels for each exhaust and supply air sides.

The detailed dimensions and specifications of the MEE used in this study are tabulated in Table 1. The leakage test for the constructed MEE was conducted using the tracer gas method which complies with the testing standard EN308 [28]. The N_2O is used as a tracer, and the leakage consists of internal leakage from the exhaust side to the supply side, as well as external leakage from the test rig to the environment. The tested internal and external leakage rates were measured at 2.1% and 3.6%, respectively.

2.2. Test rig for odour sensation measurement

The test rig consists of the tested quasi-counterflow MEE, ductworks connections, fans, measuring equipment, odour supply and an environmental chamber for odour sensation. The inlets and outlets of the quasi-counterflow MEE are connected to four headers with flanges. The exchanger is insulated by 60 mm thick foam plates for all external surfaces. Fig. 3 shows the laboratory set up at the Norwegian University of Science and Technology for testing the performance of the MEE, including its temperature and moisture efficiency, and odour transfer. The view of the test rig is also presented in Appendix Figure A1.

The odour sources are placed at the exhaust air inlet before the fan for better mixing the odour-containing air with the extract air. The exhaust air in the test rig is connected to the laboratory's extract air ductwork in order to prevent the odour from spreading in the laboratory. Orifice plates in straight sections of the ductwork and manometers were used to measure the supply and exhaust airflow rates based on the standard ISO 5167 [29]. The speeds of the fans in the supply and exhaust sides were adjusted to maintain balanced airflow rates. Temperatures, relative humidity, and static pressure were measured at each header close to the inlets and outlets of the MEE. Four T-type thermocouples, with accuracy of ± 0.1 °C, are placed close to each inlet and outlet of the MEE to measure the air temperature. At an airflow rate of 7.3 L/s, the MEE presented sensible and latent effectiveness of 90% and 76%, respectively.

Table 1
Dimensions of the tested MEE in this study.

Parameter	Value	Unit
Number of membrane layers	9	–
Number of channels for each flow	9	–
Exchanger width	250	mm
Exchanger length (counterflow part)	400	mm
Channel height	2	mm
Corrugation period	7	mm
Width of inlets and outlets	177	mm
Height of inlets and outlets	44	mm

2.3. Polypropylene porous membrane used in the MEE

Membranes applied in MEEs can generally be classified as porous or dense based on their transfer principle [8]. It has been found that the heat conduction resistance through the porous and dense are normally negligible compared to heat convection resistance due to the thin thickness of membranes. However, the impact of moisture transfer resistances through membranes relative to moisture convection is significant and cannot be neglected [8].

A hydrophobic polypropylene (PP) membrane, which is commercially available for MEEs in the market, is used for the constructed quasi-counterflow MEE in this study. Table 2 lists some of the key properties of the studied PP membrane. Hydrophobic PP membranes cannot be wetted by moisture [30].

A scanning electron micrograph (SEM) of the membrane for the tested MEE is shown in Appendix Figure A3. The pore size of the PP membrane ranges from around 10 nm–500 nm. The PP membrane has outstanding thermal and chemical stability [30] and thus is assumed to be not particularly reactive to the environment or during normal use. Complex interactions exist between the membrane and the permeating

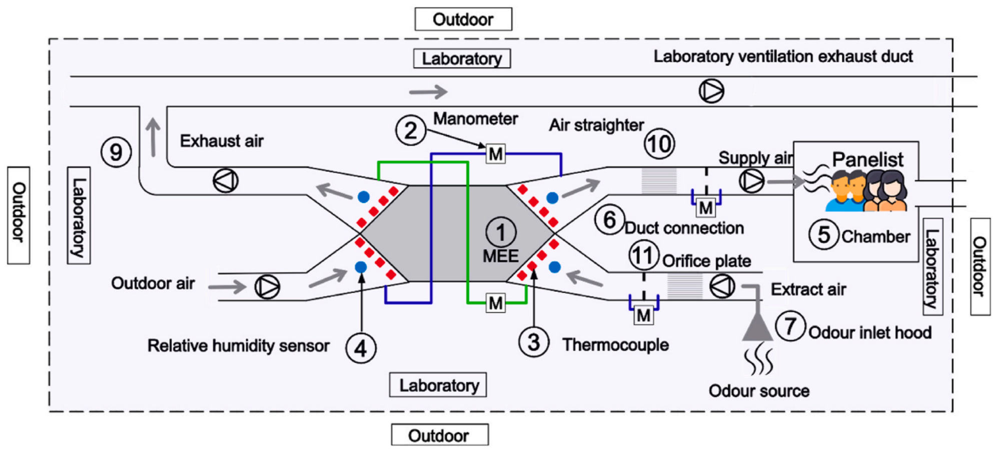

Fig. 3. A schematic view of the test rig showing the quasi-counterflow MEE, ductwork connections, and test sensors. The numbering order corresponds to that shown in Figure A.1.

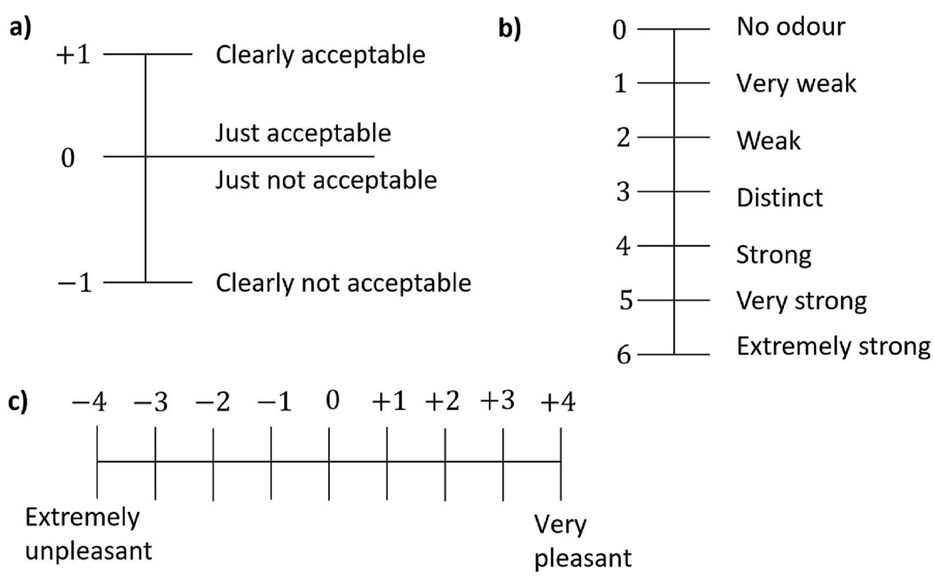

Fig. 4. a) Air acceptability scale, b) Odour intensity scale, c) Hedonic tone scale.

Table 2
Properties of the PP membrane in the tested MEE.

Membrane Properties	Value	Unit
Thermal conductivity	0.16	W/(m•K)
Thickness	0.032	mm
Density	370	kg/m^3
Water vapour permeability	1.6e-12	m^2/s
Porosity	41%	–

species, including odour chemical compounds, air, and water vapour. It should be noted that although some key properties of the membrane tested in the MEE are illustrated, the membrane in the odour transfer test is treated as a “black box” in this study due to some non-disclosed membrane information and the complexity of the interactive effects between odour molecular and membranes. The overall performance of the quasi-counterflow MEE was measured in terms of odour transport through the MEE. The investigation of interactions between membranes, air, moisture and odour chemical compounds is beyond the scope of this study.

2.4. Odour sensation test

The two main methods for assessing odour emissions are chemical analysis and sensory analysis [24]. Chemical analysis is generally used to identify the molecules and concentrations of the chemicals in the air. It is considered a powerful tool for environmental assessment. This approach, however, faces several obstacles, including 1) the method cannot provide sensory properties of the analysed molecules, 2) the detection thresholds from the chemical analysis may be higher than sensory threshold, 3) the mixture effects from odour intensity and odour nature are not considered [24]. On the contrary, sensory analysis with the olfactory system is the undoubtedly most sensitive and broader range odour detector, whose high complexity and efficiency derive from millions of years of evolutionary development [31]. Human nose is recognised as a highly sensitive detector of certain chemicals in extremely low concentrations. Comparatively to chemical analysis, sensory analysis is less expensive and more straightforward. Introducing odour assessment standards has improved the reliability and reproducibility of results from the sensory analysis [32].

Specifically, this study applied the sensory indoor air testing standard of ISO 16000–30:2014 [32]. The selection of panel members complies with the requirement established by ISO 16000–30:2014. To be qualified as a panel member, the person should: 1) be at least 18 years, 2) be motivated and available to complete the experiment, 3) have no health conditions or allergies which could affect the sense of smell, 4) avoid using personal hygiene products containing perfume, 5) ideally not smoke or use tobacco; however, they can participate if they refrain from tobacco 2 h before and during the experiment, 6) Not eat, chew gum or drink anything except water during the last 30 min before the experiments.

According to ISO 16000–30, an untrained panel measuring odour should consist of at least 15 members. The study used 19 members, all of whom met the above criteria for panel members. Their ages ranged from 23 to 26. About two-thirds of the panel members are women and one-third are men, and they are all Norwegian. For the last 30 min before the measurements were carried out, panel members are kept in a well-ventilated and low-stress environment. Various materials inside the test rig and materials in the testing chamber may also have a slight odour due to degassing. Therefore, members of the panel are introduced to the test environment prior to measurements starting. This will enable them to become adapted to the odour (referring to odour adaptation), and they will be expected to distinguish between the background odour and the new odour introduced through the MEE. The air in the climate chamber where the sensory measurements were conducted before the sensory test was used as the reference air in this study. Adaptation to odours is the process by which one becomes accustomed to them. When there are multiple odours present, the adaptation process requires a longer period of time. The adaptation process also varies depending on the odour. The testing chamber for odour sensation was kept a room air temperature at 20 °C and relative humidity of 20%–35%. An introduction to their tasks is also given to the panel during the experiment. Preliminary testing showed that it takes around 15 s from the odour is supplied until it is noticeable at the sniffing port in the chamber. The time from when the odour sample is removed, until there are no more lingering odours, takes around 45 s. Based on the preliminary testing, the panel members are instructed to wait 30 s before they start sniffing after the odour sample is placed under the ventilation hood. After all members of the panel have evaluated the air, the sample is removed, and a timer interval of 1 min is set before the operator proceeds to the next sample. An air quality questionnaire is distributed that provides scales for perceived air quality (PAQ), air acceptability (AA), odour intensity (OI) and hedonic tone (HT). Five different odour sources (as shown in Appendix Figure A2) were placed in the extract air, including two blank samples, are evaluated by the panel. The liquid odour sources, i.e., cleaning product and perfume, were sprayed onto a sponge placed underneath the hood. Other odour sources including paint, waffle mix powder and food waste were placed the underneath the hood. It is prohibited for the panel to discuss their odour sensation with each other as this could influence their individual opinions.

PAQ is based on the human subject's perception of OI, AA and percentage of dissatisfied (PD). The International Organization for Standardization (ISO) has standardised the method in ISO 16000–30:2014 [32]. OI and odour concentration are the most important descriptors of an odour [33].

AA is evaluated on a scale from clearly acceptable (+1) to clearly unacceptable (−1), shown in Fig. 6 a). Both ISO 16000–30:2014 [32,34] operate with the same scale set-up. Having been presented with the scale, the panel were asked, "Imagine you are exposed to this odour in your everyday life. How would you rate this odour on the following scale?" [32]. A percentage of dissatisfaction also reflects the acceptable level of air quality. However, the acceptability is answered as a yes/no question, not a scale. The panel were asked: "Imagine you are exposed to this odour in your everyday life. Would you consider this odour acceptable?" [32]. The number of dissatisfied people, i.e. the people who answered "No" is represented as n_d in Eq. (1), and n is the total number of members in the panel.

$$PD = \frac{n_d}{n} \times 100\% \quad (1)$$

Gunnarsen and Fanger [34] evaluated odour intensity. The scale on a five-point scale from no odour (0) to overwhelming odour (5), whereas the ISO standard uses a six-category scale. The ISO scale [32] is shown in Fig. 4 b). Hedonic tone refers to how pleasant or unpleasant a smell is to a person. The OI and AA have a direct effect on how pleasant the odour is perceived. The hedonic tone scale is a nine-point scale from the ISO standard [32] for indoor air. The scale ranges from extremely pleasant (+4) to extremely unpleasant (−4), as shown in Fig. 6 c).

3. Results and discussion

Five different odour samples are used for the odour transfer measurement, along with two blank rounds with no odours. Table 3 details the odour samples tested. The right side of the table depicts what the panel members guessed was the source of the odour. Among the samples, only numbers 4, 6 and 7 are correctly guessed by at least one panel. However, the majority of the panel were unable to identify the source of the odour.

The odour samples used in this study are listed in Table 3, and can also be seen in Appendix Figure A2. In this study, a group of five odour sources, which are commonly found in households, are used to represent the odour transport process through the MEE in a ventilation system.

Fig. 5 shows the calculated PD based on the answers provided by the panel. Test 4, which uses waffle mix powder as an odour source in the extract air, has the highest PD value (84.2%) of these seven odour sensory tests. The two tests with the lowest PD are Test 2 (no odour source) and Test 1 (paint as an odour source). The PD for the other blank odour source (Test 5) is also low, but not among the two lowest. A possible explanation could be that Test 5 is performed after Test 4, from which odour may be retained in the air or absorbed in the wall of the chamber where the sensory tests were conducted. A similar PD is obtained in tests 3, 6 and 7 (corresponding to perfume, cleaning sprays, and food waste, respectively). In light of Test 2 (with no odour source present in the extract air) as a reference, the PD results in Fig. 8 provide clear evidence that odours can transfer from the extract air to the supply air through the tested MEE. This finding is consistent with the results of the low selectivity for PP membrane reported in Ref. [18]. The sensory measurements suggest that the MEE may cause odour nuisance when used in ventilation systems. As a result, the membrane selection, construction of MEE, and placement of fans should be carefully considered in order to reduce odour transfer during MEE design and use.

It should be noted that odour transfer is tested on the constructed MEE, not merely at the membrane level. The possible odour transfer can attribute to transfer through membranes and leaks and gaps in the MEE. The latter, however, should be limited since over-pressure is kept from supply to the exhaust air side during these tests and the leakage test with tracer gas indicates the constructed MEE has a high level of internal and external airtightness.

Fig. 6 illustrates the dissatisfaction votes from individual panel members for supply air with various odour sources present in extract air in ventilation incorporating with the tested MEE. It can be seen that the dissatisfaction votes or the ability to perceive an odour considerably

Table 3
Odour samples and guessed odours during the sensory experiment.

Test	Odour	Guessed odours
Test 1	Paint	Perfume, soap
Test 2	No odour source	Perfume, soap, licorice, cleaning product, sweet
Test 3	Cleaning spray	Tobacco, sweet, food waste (milk), egg
Test 4	Waffle	Waffle, potato, cake, egg
Test 5	No odour source	Tobacco, coffee, nail polish remover, sweet
Test 6	Perfume	Apple, perfume, paint, cleaning product, soap, oil
Test 7	Food waste	Tobacco, food waste, sweet

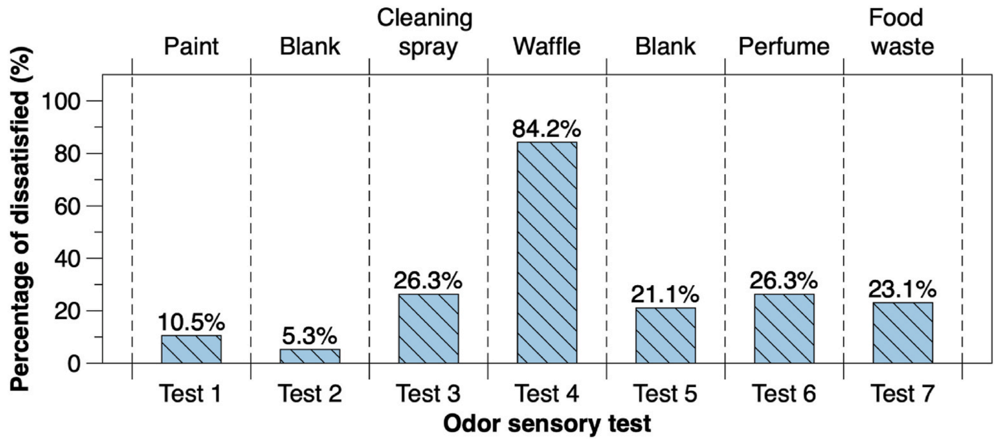

Fig. 5. Percentage of dissatisfied results for the MEE odour transfer using different odour sources in the extract air.

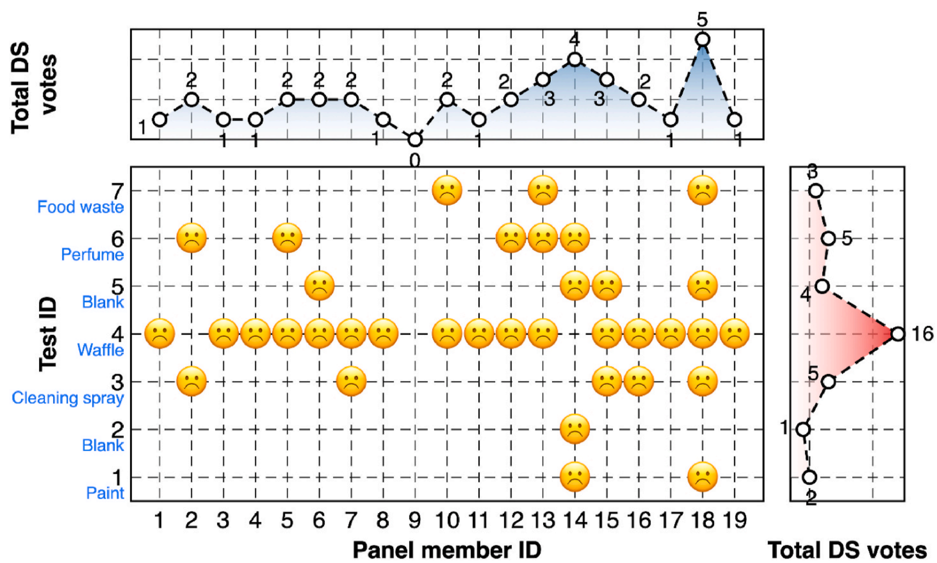

Fig. 6. Dissatisfaction votes from the individual panel member.

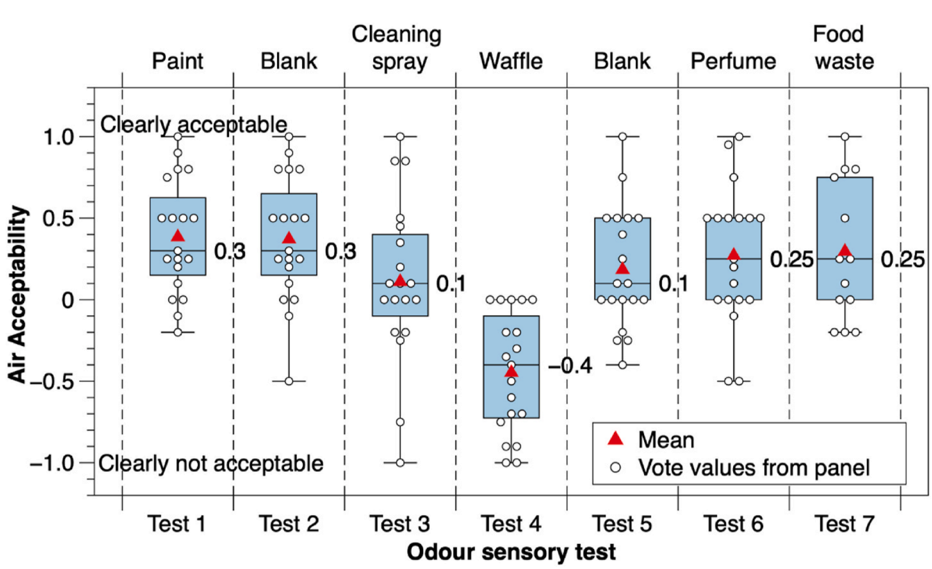

Fig. 7. Air acceptability results for different odour sources in extract air for the tested MEE. In the "box", the horizontal line represents the median value. The red triangle inside the "box" is the mean value. The lower and upper horizontal lines of the "box" represent 25% and 75% percentile, respectively. At the top and bottom, horizontal lines display the maximum and minimum values. The same denotation of the "box" plot applies to Fig. 8 and 9. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

vary among individuals. Panel members have distinct tolerances on whether they are satisfied with the supply air using the tested MEE in ventilation. The panel member number 9 voted no dissatisfaction, whereas the panel member number 18 voted five times for dissatisfaction for seven odour sources tests (including two blank odours). A person's age, gender, smoking habits, and nasal allergies contribute to their differences in odour sensation measurement. In this regard, a panel with a large number of members should be applied for the odour sensation test to reduce the uncertainty caused by individual differences.

The odour emissions from the different odour sources in this work are assumed to be time-invariant and the panel were exposed to constant levels of the odour concentrations during the odour sensation measurements. Their emission intensities and concentrations in the extract air in the measurements are designed with an attempt to be comparable to the realistic conditions in residential buildings. Nevertheless, it may not be fully practical to reflect the actual emissions and concentrations since odour emissions are difficult to control and there are large variations in odour emissions in practice. In addition, the PP membrane may have different affinities and permeabilities to different odour compounds, which results in different odour transfer rates through the MEE.

The results of sensory measurements for AA, OI, and HT are presented in Figs. 7–9, respectively. On a scale of −1 to +1, as shown in Fig. 7, Test 4 has the lowest AA score, with two panel members answering "clearly not acceptable" and no panel member voting higher than zero. In Test 3 (cleaning spray as an odour source), there are the most variations, which represents a wide range of opinions on the air acceptability. It appears that Tests 1 (paint as an odour source) and 2 (no odour source present) have the highest acceptability, and the votes for Test 1 are more convergent.

For the OI, a panel member who perceives no odour will rate it a zero, while someone who perceives an extremely strong odour will rate it as a six. As can be seen in Fig. 8, the OI for Test 4 is the highest, which aligns with the results in Fig. 9. In Test 1 (paint as the source of odour) and in Test 7 (food waste as the source of odour), the panel members are more in agreement. Votes are widely scattered for the test 6 which uses perfume as the odour source in the extract air. For this test, four members of the panel did not detect any odour, while two members detected a "very strong" odour.

There are various methods for sensory evaluations of indoor air quality, but two have been extensively used: sensory assessments of OI and AA. There is no consensus in the literature regarding which methods are suitable for practical applications. This study applied both methods to assess the sensory measurements for odour transfer through MEE in ventilation, which has been recommended using both assessment methods by Ref. [35].

HT is defined as the trait underlying one's characteristic ability to feel the pleasure of an odour. Fig. 9 shows the results of the HT vote from the panel. As expected, out of the tested odour sources present in the extract air, paint, cleaning spray, waffle mix, perfume, food waste, and blank odour, perfume was perceived as the most pleasant. The opinions on the pleasant and unpleasant levels are less convergent in Test 4 with waffle mix as the odour source in the extract air.

Additionally, the correlation coefficients between DS and AA, DS and OI, DS and HT are −0.97, 0.98 and 0.73, respectively using the Pearson correlation method [36]. The correlation coefficient can range in value from −1 to +1. The higher absolute value of the coefficient indicates, the stronger relationship between the variables. A value of 0 indicates that the variables do not correlate. This result implies the DS outcomes can be mainly explained by AA and OI and less influenced by HT. However, further studies are required to validate the causalities between these different factors. From Fig. 10, it can be found that the three evaluation scales (AA, OI, and HT) of the odours are strongly correlated. For instance, the AA results have been found to be highly negatively correlated with OI and the Pearson correlation coefficient is −0.93. A similar finding on the correlation for these three evaluation scales for measurements of perceived air quality has been reported by Ref. [37].

4. Limitations of this work

The odour transfer through the MEE in this study was performed under room air temperature. The varying outdoor air temperature may influence the odour transfer and needs to be further studied. When the MEE is used in winter for cold climates, condensation may form on the membrane surface. Some odours may be absorbed into the condensation water and transfers through the membrane together with the condensation water to the supply air side. In this study, the operating condition with condensation is not considered. Two blank tests between the other five odour sensory tests were designed to compare odour sensation tests with the presence of odour sources. There is a noticeable difference between the results of these two blank tests. The second blank may be influenced by the previous strong odour of the waffle mix powder. However, it can also be related to other possible factors such as individual bias or psychological reasons. To further investigate the reason, in future work, future work should provide more time or cleaning to remove previous odours.

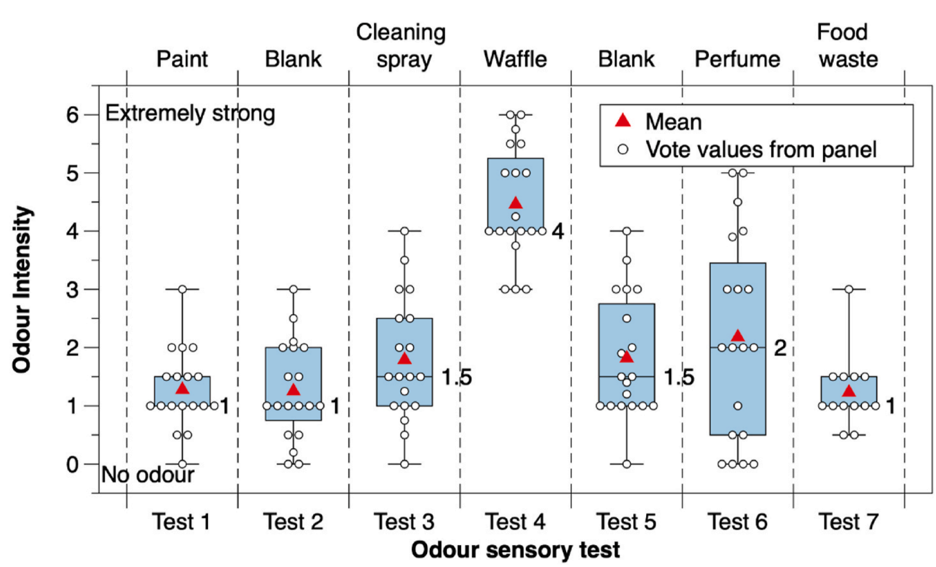

Fig. 8. Odour intensity results for different odour sources in extract air for the tested MEE.

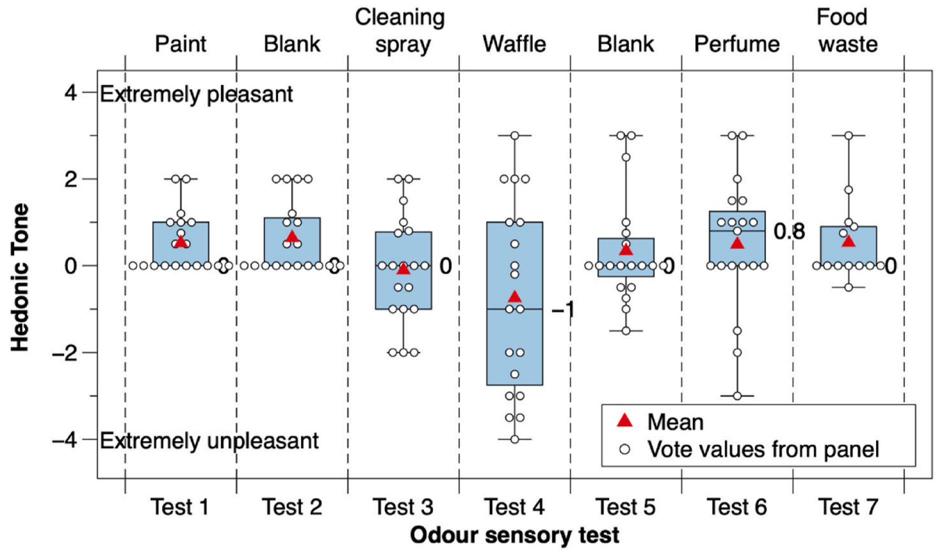

Fig. 9. Hedonic tone results for different odour sources in extract air for the tested MEE.

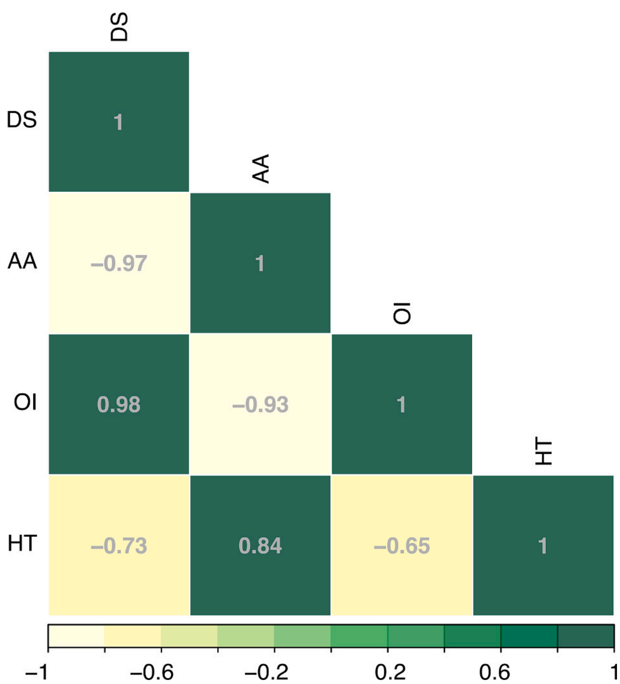

Fig. 10. Pearson correlation coefficients between DS, AA, OI, and HT.

5. Conclusions

This study examines odour transfer through a quasi-counterflow MEE in ventilation with a porous PP membrane. The quasi-counterflow MEE was tested and can provide high sensible and latent effectiveness (90% and 76%, respectively, at a tested airflow rate of 7.3 L/s). By using the tracer gas method, internal and external leakages were measured as 2.1% and 3.6%, respectively, for the constructed MEE and ductwork connection to the ambient. The MEE is tested for odour transfer by placing in the extract air a variety of odour sources, including paint, cleaning spray, waffle mix, perfume, food waste, and two blank odours. A 19-member untrained panel assessed the supply air through the constructed quasi-counterflow MEE. Sensory measurements were performed in the chamber to evaluate four factors: dissatisfaction percentage, acceptability of the air, odour intensity, and hedonic tone. The results demonstrate that some odours transferred through MEE are clearly detectable by the panel, such as the waffle mix. In this study, the tested MEE was found to cause odour nuisance by transporting odours into the indoor environment, which led to poor IAQ. This study indicates that the frequently used tracer gas methods may not accurately reflect the movement of odours through MEE in ventilation systems since the tracer method can underestimate or misrepresent odour transport. In addition to heat and moisture transfer ability, MEE should be assessed for its selectivity to odours and VOCs. There may be particular importance to paying attention to the odour transport risk through MEEs when the odour originates from kitchen, which is indicated in the sensory test results of waffle odour transfer. It is recommended that future studies include sensory measurements for other types of membranes used in MEE.

CRediT authorship contribution statement

Peng Liu: Writing – review & editing, Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Hans Martin Mathisen:** Writing – review & editing, Supervision, Project administration, Conceptualization. **Mariell Skaten:** Writing – review & editing, Investigation, Data curation, Methodology. **Maria Justo Alonso:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgement

This research was funded by the Research Council of Norway (NFR) and Flexit AS through the Defreeze MEE Now project (NFR grant number: 296489). The authors would like to acknowledge the involved technician and the laboratory of Department of Energy and Process Engineering at the Norwegian University of Science and Technology. We thank Dr. Yihan Cao for providing advice on statistical analysis.

Appendix

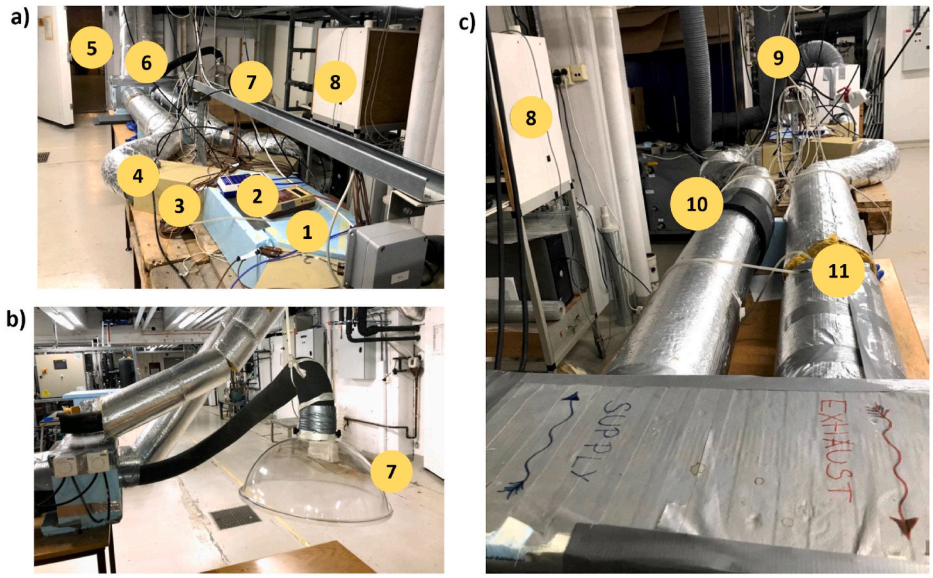

Fig. A.1. The rig for measuring odour transfer and the chamber for measuring odour sensation. Numbers correspond to different components of the MEE test rig, where: 1 - MEE core; 2 - Micro-manometers; 3 - Thermocouples; 4 – Relative humidity sensor; 5 - Environmental chamber for panel sensation; 6 - Ventilation channel connections; 7 - Odour inlet hood; 8 - Computer with LabVIEW; 9 - Ductwork to the basement exhaust; 10 - Air straightener; 11 -Orifice plate with tubes connecting to a manometer..

Fig. A.2. Odour samples a) Paint, b) Cleaning spray, c) Waffle mix, d) Perfume, e) Food waste.

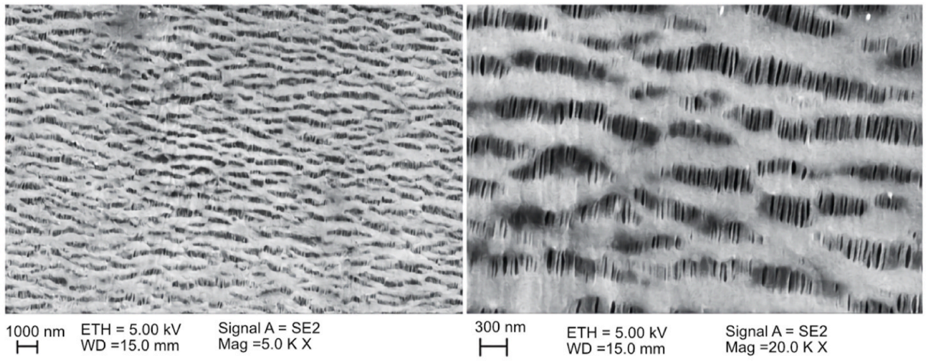

Fig. A.3. Scanning electron micrograph (SEM) images of the PP membrane used in the tested MEE.

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