Impact of optimized residential ventilation with energy recovery on health and well-being

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ABSTRACT

With rising insulation standards and air tightness in buildings, the use of mechanical ventilation becomes more relevant. In this context, energy recovery offers a significant contribution to the decarbonisation of building operations. Heat recovery systems are widely spread in residential ventilation. Moreover, enthalpy exchangers recovering sensible and latent heat have an increasing share of use in residential ventilation, especially in cold climates, as they not only reduce the energy demand but also increase the indoor air humidity in winter seasons. In moderate climates, the outdoor air provides sufficient moisture content in transitional periods. Hence, enthalpy exchangers have to be bypassed to avoid too high indoor air humidity. Since heat and moisture transfer are conjugated in membrane-based enthalpy exchangers, this leads to a decrease of recovered sensible heat as well. Consequently, the research question arises regarding how efficient moisture transfer in an enthalpy exchanger has to be in order to provide a healthy and comfortable indoor air environment with minimum energy demand.
In this study, we optimize a membrane-based enthalpy exchanger regarding membrane thickness and permeability to improve the overall performance of a residential ventilation unit. Therefore, we develop a simulation setup consisting of a thermal zone model, residential ventilation unit with the enthalpy exchanger model, and the control logic for the system. This simulation setup is combined with a genetic algorithm for optimization. We define a multi-objective optimization problem in order to optimize energy demand and indoor air humidity level.
The study shows that the system's energetic optimum in moderate climates (Cuxhaven) lies at a membrane thickness of 120 µm. Regarding humidity level, thin membranes with 65 µm lead to overall more comfortable humidities. In consequence, enthalpy exchanger with lower latent efficiency lead to not only better overall energetic performance in moderate climates but also more comfortable indoor air conditions. With slightly higher energy demand compared to the energetic optimum, a significant increase regarding comfortable indoor air humidities is achievable.

KEYWORDS

Enthalpy exchanger; optimization; residential ventilation; thermal comfort

1 INTRODUCTION

With rising insulation standards, buildings' air tightness is increasing. In consequence, ventilation becomes more and more relevant not only in non-residential but also in residential buildings. Typical residential ventilation systems inherit an energy recovery system as the key component. The most common form of energy recovery is sensible heat recovery. In the past decades, the usage of enthalpy recovery increased in share, especially in cold climates or warm and humid climates. Membrane-based enthalpy exchangers (MEEs) are one very common form of enthalpy recovery in residential ventilation. The membranes separate the air streams and are able to transfer heat as well as moisture. In this way, they can heat and humidify the fresh air in cold climates or cool and dehumidify the fresh air in warm and humid climates.

Many researchers have investigated membrane-based enthalpy exchangers. These studies can be divided into four different categories: investigations on the performance of MEE under different boundary conditions, investigation on different membrane materials for MEE, enhancement in flow structures of MEE, and general optimization of MEE.

Different studies address the analysis of the impact of volume flow rate, temperature and humidity boundary conditions on the effectiveness of MEE (Zhang et al., 2008; Min and Su, 2011; Nasif and Al-Waked, 2014, 2014; Al-Waked et al., 2015; Koester et al., 2017; Siegele and Ochs, 2019). They all found that sensible and latent effectiveness increase with decreasing volume flow rate. The latent effectiveness depends more on the volume flow rate than the sensible effectiveness. Moreover, the studies show that the influence of outdoor and indoor air states on the MEE's performance is dependent on the membrane material. Some membrane materials show a significant influence of the boundary conditions and others show no significant influence and perform in the same way for different boundary conditions.

This goes along with the second category of investigations regarding the influence of the membrane material. Many researchers have investigated different membrane materials in order to increase sensible and latent heat transfer in MEE (Zhang et al., 2008; Min and Su, 2010; Nasif, 2015; Koester et al., 2017; Baldinelli et al., 2019). They all show that especially the latent effectiveness is sensitive to membrane material.

Other studies address the optimization of the flow structure in MEEs in order to increase the performance of the enthalpy exchanger (Al-Waked et al., 2015; Albdoor et al., 2020a). One way to increase the performance is to increase the share of the counter-flow arrangement in the MEE. Another option is to break the boundary layer with spacers or similar geometric elements. Although these are able to increase the sensible and latent effectiveness, they also increase the pressure drop of the MEE, which leads to a higher electric energy demand for the fans.

To improve the sensible and latent effectiveness Albdoor et al. used an approach to minimize the entropy generation of MEE with a genetic algorithm (GA) (Albdoor et al., 2020b). They aim to optimize the design of an MEE. They varied mass flow rates through the MEE, length and width of the MEE, channel height, membrane thickness and thermal conductivity and the membrane material's diffusion coefficient. They could find an optimum in design that reduces the entropy generation by 20 – 30 %. Nevertheless, the optimum they found lies at very small mass flow rates. How the optimized MEE performs at nominal mass flow rates needed to ventilate the room properly is not shown in their study.

Zhang used a reliability-based approach to optimize MEE design under uncertain conditions (e.g. production tolerance) (Zhang, 2016). The aim function is the economic return of the MEE. They found that parallel-plate MEE with asymmetric polymer membranes performs best in the investigated data set. Moreover, they could show that the MEE's performance will degrade with uncertain geometric parameters compared to the exact parameters. Their study focusses on warm and humid climates. Therefore, it might not be transferable to other climatic regions.

Men et al. optimized the design of MEE with a particle swarm optimization algorithm (Men et al., 2021). Their multi-objective optimization aims to reduce entropy generation and increase economic return.

All the optimization studies have in common that they try to increase the performance of MEE. Moreover, they only consider the MEE itself for their optimization. The studies lack the investigation of the influence on the holistic system consisting of the ventilation unit and the building. Since all the studies concentrate on warm and humid or cold climates, these approaches might be sufficient. Nevertheless, in moderate climates, outdoor air humidity is sufficient for building ventilation during the spring and autumn season. During these periods, high latent effectiveness can lead to high indoor air humidities. Hence, the research question arises about how efficient the latent effectiveness of MEE has to be in order to perform best in the context of the holistic system. In this paper, we optimize the design of MEE considering the overall energy demand of the building and the indoor air comfort for different climatic regions.

2 METHODOLOGY

To optimize MEE in the context of the holistic system, we build up an optimization framework. This framework consists of a dynamic system model combined with a control algorithm. The system model is linked to a genetic optimization algorithm that varies the MEE's parameters.

2.1 Objectives and parameters used for optimization

We choose two objectives for our optimization. As first objective, we use the total use energy demand of all components. Therefore, the heating power, cooling power and electric power of the fans are integrated during the annual simulation and summed up. The GA aims to minimize the total use energy demand.
The second objective is the violation of comfortable indoor air humidity. The objective uses the two different definitions shown in Table 1. Typical international standards define a range between 30 and 65 % relative humidity for indoor air environments (Designation: Standard). (Sterling et al., 1985) investigated the impact of indoor air humidity on humans and found the range of 40 to 60 % relative humidity as a good compromise between all influences. Therefore, we choose this range as second definition (Designation: Tight). By investigating both definitions, we can analyse how the optimum design of MEE depends on the desired indoor air humidities.

Table 1 Definitions of comfortable indoor air humidity

Designation	Lower limit	Higher limit	Ref.
Standard	30 % relative humidity	65 % relative humidity	(American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2020)
Tight	40 % relative humidity	60 % relative humidity	(Sterling et al., 1985)

As violations of the comfortable indoor air humidity occur dynamically during the annual operation, we define a KPI to quantify the violations. We use the *Integral Absolute Error* ($\mathrm{IAE_{rH}}$) which is well known in the field of control engineering as basis for our KPI. The KPI is shown in Equation (1). Whenever the relative humidity φ in the building overshoots the higher limit $\varphi_{\max}$ or undershoots the lower limit $\varphi_{\min}$, the difference will be integrated over the time the violation occurs.

$$\mathrm{IAE_{rH}} = \int \max(\varphi(t) - \varphi_{\max}, 0) + \max(\varphi_{\min} - \varphi(t), 0)\ dt \tag{1}$$

To reach the optimum system performance regarding the two objectives, we choose two different design parameters – membrane thickness and membrane permeability - for the MEE as they mainly influence mass transfer only. Figure 1 shows the impact of the membrane thickness and membrane permeability on the MEE's sensible and latent effectiveness. As can be seen, the latent effectiveness is sensitive to both parameters. On the contrary, both parameters have only a small impact on sensible effectiveness. For this reason, it is possible to design the MEE's latent effectiveness without influencing the sensible effectiveness. Therefore, all results of this study can be attributed to effects caused by latent effectiveness. After a market survey on typical membrane properties, we set the range of membrane thickness to 20 - 200 µm. According to Albdoor et al., typical polymer membranes' permeability varies between 1E-13 and 1E-10 mol/(m s Pa) (Albdoor et al., 2022). Paper membranes usually have higher permeabilities. Hence, we choose a range between 1E-13 and 3E-10 mol/(m s Pa).

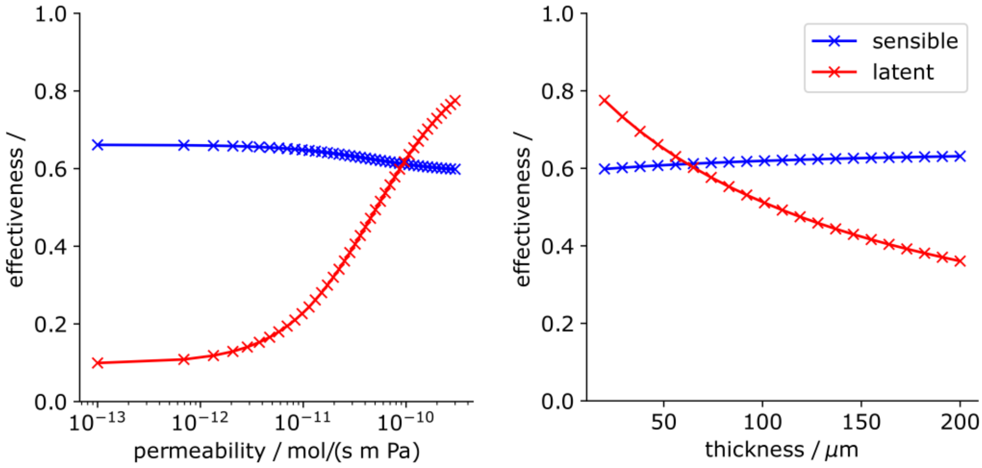

Figure 1 Influence of membrane thickness and permeability on MEE's effectiveness

2.2 Simulation model

The core of the optimization setup is a dynamic simulation model shown in Figure 2. The model consists of a thermal zone model (Lauster and Constantin, 2017) and a residential ventilation unit model. The ventilation unit model consists of a preheater model, an MEE-model and two fan models. The preheater is used to avoid frost formation in the MEE. The MEE-model (Kremer et al., 2019) consists of parallel membranes and can be varied using geometric parameters like membrane thickness, permeability of the membrane, length and width of the MEE, channel height and the number of parallel membranes.

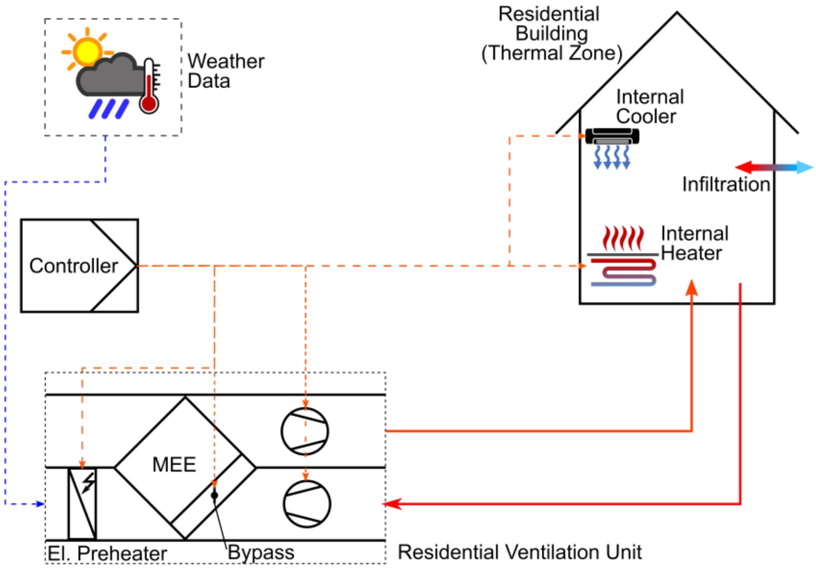

Figure 2 Structure of simulation setup used for optimization

The thermal zone model represents the building structure. The building structure is parametrized using the Tool TEASER (Remmen et al., 2018). The tool delivers typical elements according to the year of construction and translates the building structure into a thermal network (resistance-capacity-model). In this study, we choose 2015 as the year of construction.
We consider an infiltration of 0.06/h in the thermal zone model but assume no window ventilation in addition to the mechanical ventilation. The thermal zone model inherits an idealized heating and cooling model to control indoor air temperature. The ideal cooler does

not consider any condensate formation and therefore provides sensible cooling only. Internal loads such as persons, machines and light are modelled according to (Schweizer Ingenieur- und Architektenverein, 2024) considering latent heat production of persons and other sources (e.g. plants and shower).
All in all, the building energy system modelled inherits the functionality of energy recovery, heating, and cooling. No active humidification or dehumidification is applied. Therefore, indoor air temperature is fully controllable, but indoor air humidity control is limited to energy recovery. As no dehumidification is applied, the absolute indoor air humidity is always equal to or higher than the absolute outdoor air humidity due to internal gains.

2.3 System control

We develop a controller for the residential ventilation unit to control the fans and the bypass over the MEE to avoid too high indoor air temperatures and humidities. Moreover, the controller sets the cooling and heating power for the internal devices. The set point temperature for heating and cooling is derived from the German standard DIN EN 16798-1 (German Institute for Standardization, 2022). Figure 3 shows the limits for comfortable room temperature as defined by DIN EN 16798-1. We use the lower limit for a comfortable room temperature as the set point for heating and the higher limit as the set point for cooling. Since no dehumidification is considered in the simulation model, the humidity will not decrease in the building model. Hence, we use the higher limit of comfortable indoor air humidity to control the bypass over the MEE. If the indoor air humidity exceeds the limit, the bypass will open, reducing the latent and sensible heat recovered. We use two different ranges for the definition of comfortable indoor air humidity presented in Table 1.

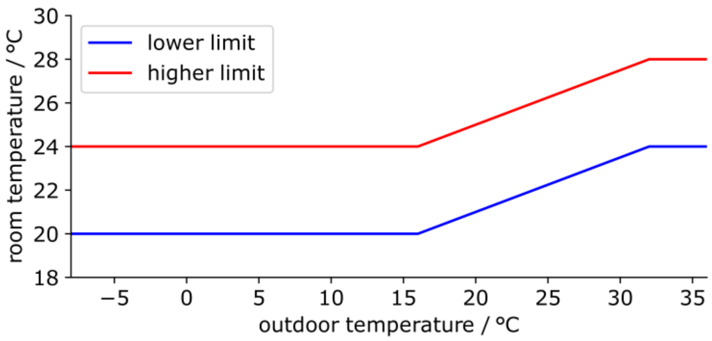

Figure 3 Limits for comfortable room temperature according to (German Institute for Standardization, 2022)

2.4 Optimization setup

Using the Dymola-API of the Python package ebcpy (Wüllhorst et al., 2022), the simulation model is linked to the optimization algorithm programmed in Python. We use a GA provided by the optimization package PyGAD (Gad, 2021) for the optimization. The parameters used for the GA are listed in Table 2. For detailed information on the parameters and their influence on the optimization, please refer to (Gad, 2021). For each parameter variation of the MEE, an annual simulation is carried out and the results are provided to the optimization algorithm. In the first step, the algorithm sets up an initial population consisting of pairs for membrane thickness and permeability values. For each pair, the simulation is carried out. The algorithm uses the results to create the next generation of parameter pairs. This process is iterated until the defined number of generations (see Table 2) is reached.

Table 2: Parameters used for the genetic algorithm

Parameter	Value
Number of generations	20
Solutions per generation	10
Number of genes	2 (membrane thickness and permeability)
Value range for genes	[20 ... 200 µm]; [1E-15 … 3E-10 mol/(m s Pa)]
Parent selection type	steady-state-selection
Crossover type	uniform
Crossover probability	0.8
Mutation type	adaptive
Mutation probability	0.7; 0.4 (thickness; permeability)

2.5 Investigated climatic conditions

We carry out the optimization for three different locations in Europe – Sodankyla, Munich and Cuxhaven. Sodankyla, a city in Lapland (Finland), can be classified as cold and dry climate with a temperature median of 1.4 °C and a humidity median of 3.37 g/kg. The German city of Munich has a moderate continental climate (median temperature: 8.9 °C, median humidity: 5.27 g/kg). Cuxhaven on the contrary is a moderate and more humid climate (median temperature: 9.8 °C, median humidity: 6.01 g/kg) since it is a city located near the German coast. Figure 4 shows the density functions of temperature and humidity for the three locations. The x-axes show the temperature and absolute humidity respectively. The y-axes show the density of how often an interval occurs during the year. We use intervals of 1 K and 1 g/kg to calculate the densities. In Sodankyla, temperatures below 0 °C occur more often than in the German cities. Additionally, low absolute humidities occur more frequently. In Cuxhaven, temperatures between 5 and 20 °C occur more often than in Munich, whereas in Munich higher temperatures between 20 and 30 °C occur more often. Regarding humidity, both German cities have a similar density function, but absolute humidities between 5 and 10 g/kg occur more often in Cuxhaven. This interval is relevant for the operation of the MEE. Since these absolute humidities are sufficient for an indoor air environment, no humidification is needed during the times, outdoor air humidity lies in between the interval. In consequence, MEE cannot provide any benefit regarding comfort. Especially for outdoor air with absolute humidities between 8 and 10 g/kg, the risk of reaching too humid indoor air if operating an MEE is high. Therefore, the difference in optimization results between Munich and Cuxhaven will be interesting to investigate.

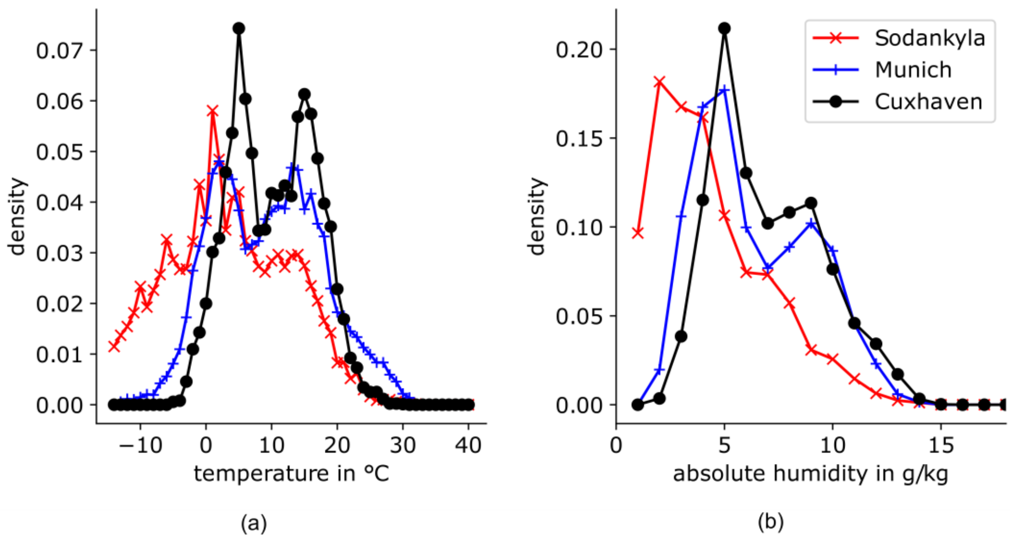

Figure 4 Density functions of temperature (a) and humidity (b) at the three investigated locations

3 OPTIMIZATION RESULTS

Figure 5 shows the results for all annual simulations carried out by the optimization for both objectives and the *Standard* comfort limits for Munich. The x-axis indicates the comfort violation as defined by Equation (1). The y-axis represents the holistic system's total use energy demand. Presented are all solutions, including the non-optimal intermediate solutions (red +). The theoretical optimum shows the best solution for the energy demand and the comfort violation, respectively. Obviously, both objectives cannot be satisfied at the same time. All solutions lying on the dotted line will be optimal design solutions depending on how both objectives are weighted. The best fit indicates the solution with the smallest distance to the theoretical optimum if both objectives are weighted equally. Since the MEE's design influences the energy demand of the residential system less than the IAE_{rH}, the best fit is found in the region with higher energy demand but a low IAE_{rH}.

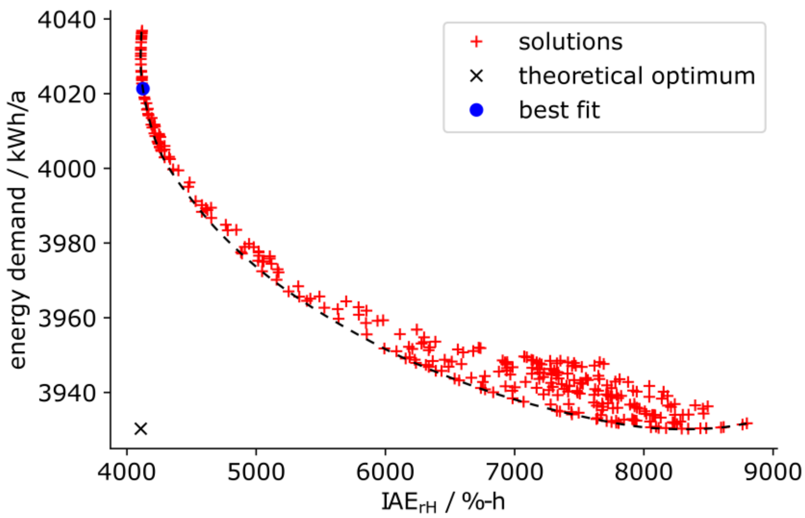

Figure 5 Pareto diagram of optimization results for Munich

Table 3 lists the found optimum design parameters for each objective and for the best fit for all investigated locations and the *Standard* comfort limits. The energy demand and the IAE_{rH} differ significantly between the three locations. While Cuxhaven (moderate climate) has the lowest energy demand and reaches the most comfortable indoor air humidities, the energy demand in Munich is slightly higher and the IAE_{rH} is higher. Moreover, the difference in IAE_{rH} between energetic optimum and comfort optimum increases. This trend is also visible for Sodankyla, the coldest and driest location in this study. Here, energy demand is more than twice as high as in Munich and Cuxhaven. The IAE_{rH} is even six to seven times higher compared to the other two locations.

The results indicate that the optimization algorithm chooses minimum membrane thickness and higher permeabilities in cold and dry climates to minimise the IAE_{rH}. This leads to an MEE with high latent effectiveness (see Figure 1). The gap between the energetic optimum and the IAE_{rH} optimum is getting higher in cold and dry climates. If the latent effectiveness is high (IAE_{rH} optimum) the risk of too humid indoor air during summer and autumn increases causing the bypass over the MEE to open. In consequence, both sensible and latent heat recovery are reduced. Especially during autumn, the outdoor air temperatures are lower. With reduced sensible heat recovery, the internal heater has to provide the energy to keep indoor air temperatures at a comfortable level. Additionally, the MEE could reduce the cooling energy demand during summer seasons when indoor air temperatures are lower than outdoor air temperatures. Reduced energy recovery will therefore lead to higher cooling demands. In consequence, the optimization algorithm chooses thicker membranes and lower permeabilities to minimise energy demand. It has to be highlighted that the difference in energy demand for the energetic optimum and the IAE_{rH} optimum is small (0.5 – 2.5 %). For this reason, the best fit lies at a membrane thickness and permeability near the IAE_{rH} optimum. The results for a cold and dry location like Sodankyla indicate that active humidification should be considered also for residential ventilation to achieve more comfortable indoor air humidities.

Table 3 Optimal solutions for *Standard* comfort limits

Location	Optimum	Membrane thickness / µm	Permeability / mol/(m s Pa)	Total use energy demand / kWh/a	IAE_{rH} / %-h
	Energetic	155	$1{,}67 \cdot 10^{-10}$	3 930	8 343
Munich	IAE_{rH}	20	$2{,}65 \cdot 10^{-10}$	4 030	4 107
	Best fit	20	$2{,}27 \cdot 10^{-10}$	4 021	4 124
	Energetic	120	$1{,}67 \cdot 10^{-10}$	3 243	3 753
Cuxhaven	IAE_{rH}	75	$2{,}09 \cdot 10^{-10}$	3 257	3 608
	Best fit	65	$1{,}67 \cdot 10^{-10}$	3 253	3 610
	Energetic	150	$1{,}67 \cdot 10^{-10}$	10 049	49 934
Sodankyla	IAE_{rH}	20	$3{,}00 \cdot 10^{-10}$	10 220	26 117
	Best fit	20	$3{,}00 \cdot 10^{-10}$	10 220	26 117

Table 4 shows the optimum design parameters for the *Tight* comfort limits for all locations. The results show that the energy demand slightly increases if the relative indoor air humidity needs to be kept between 40 and 60 %. A more frequent bypass opening over the MEE causes this. If the bypass opens more often, the internal heater has to provide the necessary heating power more often. The IAE_{rH} optimum is found for thinner and more permeable membranes compared to the *Standard* comfort limits. Especially for the location Cuxhaven, this becomes clear. In consequence, the best fit also changes to thinner and more permeable membranes. The results show a significant increase in the IAE_{rH} compared to the *Standard* limits. This is plausible and expectable as no active humidification is considered for the system.
Overall, the optimization results show that in moderate and cold climates the energetic optimum of the holistic system of a ventilated residential building is found for thicker and less permeable membranes. However, thinner and more permeable membranes need to be used for MEE to achieve more comfortable indoor air humidity. The energetic impact of MEE design is smaller than the impact on indoor air humidity. With slightly higher energy demand, significant improvement of indoor air humidity can be achieved. Especially in colder and dryer regions, MEE should be designed with thinner and more permeable membranes.

Table 4 Optimal solutions for *Tight* comfort limits

Location	Optimum	Membrane thickness / µm	Permeability / mol/(m s Pa)	Total use energy demand / kWh/a	IAE_{rH} / %-h
	Energetic	35	$3{,}58 \cdot 10^{-12}$	3 935	43 534
Munich	IAE_{rH}	20	$3{,}00 \cdot 10^{-10}$	4 037	23 213
	Best fit	20	$2{,}99 \cdot 10^{-10}$	4 037	23 216
	Energetic	35	$7{,}93 \cdot 10^{-12}$	3 277	26 311
Cuxhaven	IAE_{rH}	20	$2{,}08 \cdot 10^{-10}$	3 312	18 568
	Best fit	20	$1{,}70 \cdot 10^{-10}$	3 307	18 580
	Energetic	30	$6{,}25 \cdot 10^{-12}$	10 058	114 344
Sodankyla	IAE_{rH}	20	$3{,}00 \cdot 10^{-10}$	10 231	70 894
	Best fit	20	$3{,}00 \cdot 10^{-10}$	10 231	70 894

4 CONCLUSIONS

We have presented a method to optimise the design of MEE in the context of a holistic system and applied the method to a residential building with a typical ventilation unit consisting of a pre-heater and an MEE.
The optimization results show that thicker and less permeable membranes can be used in MEE in order to reach the minimum energy demand for the holistic system. On the contrary, thinner and more permeable membranes lead to fewer violations of comfortable indoor air humidity. The influence of the MEE's design on the energy demand is not significant for the investigated use case of a residential building. With lower insulation standards or active humidification, it might increase. In consequence, the best fit to the theoretical optimum with equal weights on energy demand and comfort violation is located near the minimum comfort violation.
Further investigations could address different building types, including humidification and dehumidification and investigate locations with warm and humid climate conditions. Moreover, other geometric parameters of the MEE, like transfer area or channel height, could be investigated. Transforming the continuous variation of the permeability to discrete values of existing membrane materials is part of further work. Our KPI definition for comfortable humidity addresses only linear dependency on the humidity difference and time. For example, the risk of mould growth depends strongly on the duration of excessive humidity in the room as well as on the value of the relative humidity. Hence, the KPI definition does not provide information on the influence on human beings. This should be addressed in further studies.

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