Design of a HRV (air to air membrane enthalpy exchangers) system

H B. Tlais[11], R C Țarcă[2], D Craciun[2]

[1] PhD School of Engineering Sciences, University of Oradea, 410087, România
[2] Department of Mechatronics, University of Oradea, 410087, Romania

Email: husseintlais1995@gmail.com

Abstract. Using of energy is increasing specially in the last few decades. This increasing have many impacts on the energy sources and environment. Heating, ventilation, and air conditioning systems (HVACs) consume about 50% of building energy use, so governments are working hard in order to develop into sustainable energy. Because of building that are airtight, ventilation is very important in order to improve the indoor air quality and living environment. Designing and installing a heat recovery ventilation system will enter fresh air and improve the indoor air. In this paper we will give the design properties of air-to-air membrane enthalpy exchangers heat exchanger which is the main part of heat recovery ventilator system. In order to improve the performance of that heat exchanger we should take into consideration the properties for membrane distillation include pore size, moisture diffusivity, selectivity, modulus of elasticity, thermal conductivity and tortuosity factor. As a result, developing new membrane designs, utilizing novel flow configurations, designing new channel layouts, and incorporating inserts in the channels are various techniques to enhance the performance of MEEs.

1. Introduction

The fast growth in the world's energy use has raised concerns about supply difficulties, energy depletion, and serious environmental impacts [1]. Climate change and ozone layer depletion are some of the key issues that people have had to deal with [2]. Based on some literature, building energy consumption, including its operation and maintenance, currently accounts for 40% of the total global energy demand [3, 4]. More so, heating, ventilation, and air conditioning systems (HVACs) are estimated to consume 40–60% of a building's energy consumption, a value that varies with the climate [2]. At the same time, this consumption of energy causes a large amount of greenhouse gas emissions, such as the emission of carbon dioxide (CO2). It is estimated that non-stop rises in carbon dioxide emissions will lead to major climate change [5]. Consequently, governments are putting in place policies to develop energy-saving and eco-friendly building technologies [6].
Generality of today's houses are built to be airtight. While this provides a better control over indoor temperature and particulates such as dust and pollen, proper ventilation is often neglected. This leads to a ventilation problem that most of the heating, (HVAC) contractors are needed to solve this problem. Ventilation is necessary for many different reasons such as negative pressure. This problem is in the airtight houses that have negative pressure due to the exhaust systems that suck the air from the house to the outside, that result a negative pressure. In addition to the indoor air pollutants, according to the U.S.

Mechanical ventilation is employed to improve the air quality in rooms, causing a loss of a large amount of heat with the exhaust air. One way to reduce energy consumption is to recover the heat energy contained in the exhaust air stream [10].

Designing and installing a heat recovery ventilation system (HRVS) assumes that fresh air and indoor air are ideally mixed if the flows stated in the guidelines are adopted. What actually takes place is that air is not renewed due to the various air inlets and outlets, increasing the amount of air to reach a minimum IAQ, resulting in an increase in the amount of energy consumed [10]. An additional rise in energy consumption results from the use of very efficient filters that remove dust particles, which are currently the main public problem [14].

The use of energy in old buildings is continues and may also keep rising. For that, it is crucial to restructure these buildings to reduce energy use and CO2 emissions [15]. One option to address this issue is to install hybrid ventilation systems or decentralized facade ventilation [16, 17]. A study by Carlsson et al. [21] came to the conclusion that the combination of modernization consisting in sealing the building envelope and the use of the ventilation with the heat recovery can make up to a 78% reduction in total energy for space heating and up to 83% reduction in greenhouse gas emissions. The objective of this paper is to review the properties of MEE in order to design an efficient MEE that will be introduced in a heat recovery ventilation system.).

2. Literature review

2.1. Ventilation

Ventilation is the mechanism through which clean air is introduced into a controlled space inside a building. In heating ventilation and air conditioning system (HVAC), ventilation is the key issue for providing indoor air quality (IAQ), while it is also responsible for energy consumption in buildings. Thus, improving ventilation systems is crucial not only in energy efficiency but also in increasing IAQ in homes [22], work environments and schools [23]. Ventilation is necessary to maintain minimum health conditions by keeping indoor air clean [24]. There is no doubt that building ventilation directly affects the IAQ, as literature has showed in various studies [25-27]. IAQ is a descriptor of the amount and the types of contaminants in the air [28]. Moreover, according to Ashrae definition, acceptable indoor air is when the concentration of pollutants in the air is not in an identified harmful level and the occupants don't express dissatisfaction.

Ventilation is the act of moving the outdoor air into a building or a room and then distribute it in the area. However, the ventilation process is like the lungs of the building, the main purpose of ventilation is to prepare a healthy air for people breathing. A lacking ventilation rate is related with health problems such as inflammation, communicable respiratory infections, asthma, allergies, and sick building syndrome (SBS) [27]. Thus, ventilation can be done by natural forces such as wind and thermal pressures, by opening window or by an artificial way through mechanical ventilation systems. There are different types of ventilation such as natural ventilation, mechanical ventilation, hybrid ventilation.

On the other hand, mechanical ventilation system provides a more reliable, controllable, and comfortable means of ventilation than natural means and consumes energy.

2.2. Heat recovery

Heat recovery is defined as a device working between two air sources at different temperatures, which transfers energy from one side to the other. That is, it works by preheating the arriving air to the interior through recycled waste heat. Currently, heat recovery systems can recover around 60–95% of waste energy, a very promising ration for future application [29]. The main four categories of heat recover system used in residential buildings are rotary wheel, membrane plate, heat pipe, and run-around systems. A typical heat recovery system in residential buildings is usually made of a heat exchanger core, a fresh air inlet and separate contaminated air exhaust outlet, and a fan, as shown in the demonstration (Fig 1) of Mardiana- Idayo et al [30]

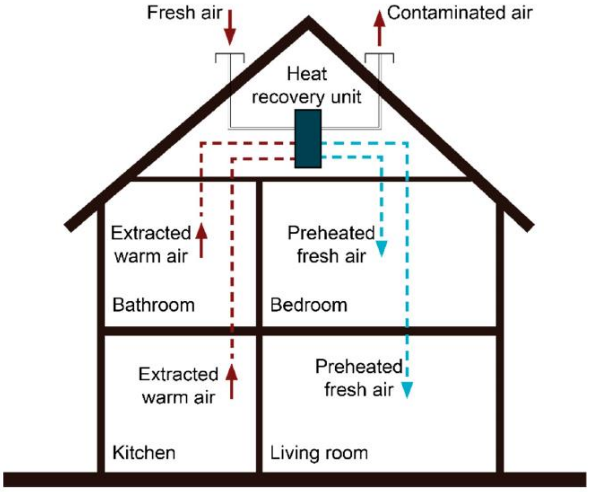

Figure 1 A typical heat recovery system in residential buildings

Heat exchangers are a vital part of the heat recovery systems. The heat exchanger is an energy employment device with a wide usage in power engineering, petroleum refineries, food industries etc. [31-33].

3. Design properties

3.1. Design of HRV system

In order to design a heat exchanger there are many factors that must be taken into consideration to approach the needed results. The physical model of a membrane-based energy recovery ventilator for air conditioning includes supply and exhaust stream channels and a membrane, which is used instead of metal materials in total enthalpy exchangers and air-to-air heat exchangers. The supply and exhaust airstreams flow along the channels and exchange heat and moisture in a counter-current flow arrangement.

3.2. Properties of membranes used in MEEs

The effectiveness of a membrane distillation system relies on the characteristics of the membranes chosen. Essential membrane properties for membrane distillation include pore size, moisture diffusivity, selectivity, modulus of elasticity, thermal conductivity and tortuosity factor as stated in reference [35].

3.3. Pore size

Liu defines pore size as the nominal diameter of membrane pores [35]. This characteristic impacts the membrane's structure and, as a result, the mechanism of moisture transfer through it [37]. Based on pore size, membranes can be divided into two categories: dense and porous. Dense membranes typically have a pore size of approximately 0.1 nm, whereas porous membranes have a pore size of around 0.1 μm [38]. A larger pore size can enhance a membrane's moisture exchange ability, but it also raises the risk of unwanted gases and contaminants passing through. Consequently, MEEs require membranes with appropriate pore sizes to prevent such issues.

3.4. Moisture diffusivity

The most crucial property of the membranes utilized in MEEs is their moisture diffusivity, i.e. permeability. This term refers to the amount of moisture that diffuses through a unit surface area of the membrane per unit time [35]. Membranes with high moisture diffusivity permit water vapour to diffuse more quickly than those with low moisture diffusivity. The moisture diffusion resistance (MDR) is the inverse of the moisture diffusivity and indicates the membrane's ability to resist water vapour permeation. MDR accounts for 65-90% of the total moisture transfer resistance [40].

3.5. Selectivity

The term selectivity refers to a membrane's capacity to transmit water vapour over other air components, as referenced in [35]. A high selectivity value indicates that the membrane primarily permits water vapour transfer while limiting cross-contamination with unwanted gases. Increasing the pore size of the membrane can lead to a reduction in selectivity, as noted in [46]. Since MEEs not only recover energy but also maintain indoor air quality at acceptable levels, it is crucial to employ membranes with high water vapour selectivity in these systems.

3.6. Modulus of elasticity

The modulus of elasticity is a measure of the stress change to the strain change during elastic deformation [47]. In MEE design, the modulus of elasticity of the membrane is a critical parameter to minimize membrane deflection [41]. According to [48], membrane elasticity strongly affects the pressure drop in MEE channels. Differential pressure between adjacent channels can cause membrane deflection, which depends on both the thickness and modulus of elasticity, and high deflection can occur even with moderate pressure differences. Since MEE membranes are typically thin, high elastic modulus membranes are necessary to prevent significant deflection. A higher membrane elastic modulus leads to less flow misdistribution due to membrane deflection, resulting in more uniform convective heat/moisture transfer coefficients and better MEE performance [49].

3.7. Membrane surface wettability

The measurement of water contact angle (WCA) is used to evaluate the surface wettability of a membrane. The primary function of membranes in MEEs is to separate air streams and facilitate the transfer of heat and moisture between them. The wetting behaviour of the membrane can affect the diffusion of water vapour through it. Generally, hydrophilic membranes are preferred for MEEs because they exhibit high water vapour permeability [50]. Membranes with hydrophilic properties contain chemical groups that attract water molecules [51]. Hydrophilicity can be achieved by using hydrophilic membranes such as Nafion, regenerated cellulose, and polyether sulfone (PES) [52]. Alternatively, hydrophobic membranes can be treated chemically, through processes such as fluorination, sulfonating, and block co-polymer formation [50], or physically, by coating the membrane surface or blending materials into the membrane matrix [52]. Physical treatment is preferred over chemical treatment as it is environmentally friendly, controllable, and generally less expensive.

3.8. Thermal conductivity

The ability of a membrane to conductively transfer heat is reflected by its thermal conductivity. Typically, membranes used in MEEs have low thermal conductivity ranging from 0.12 to 0.33 W/m.K [53, 54]].

The tortuosity factor, which is the ratio of the length of the pathway through which water vapour diffuses in a porous membrane to the length of a straight pathway, determines the membrane's water vapour flux. A lower tortuosity factor leads to a higher water vapour flux. The pore geometry influences the value of the tortuosity factor, and there are various possibilities for the pore geometry of porous membranes. However, the value of the tortuosity factor is often assumed to be 2.0 [55].

3.9. Tortuosity factor

The tortuosity factor represents the ratio of the length of the path that water vapour diffuses through the porous membrane to the straight pathway's length [37]. If the tortuosity factor is lower, then the water vapour flux will be higher. The pore geometry determines the tortuosity factor, and there are various pore geometry possibilities for porous membranes. Nonetheless, the tortuosity factor value is often assumed to be 2.0 [55, 56].

3.10. Membrane materials

The choice of membrane materials has a significant impact on the performance of MEEs. In order to select the appropriate materials for a specific application, several parameters that directly or indirectly affect performance should be considered. These parameters include moisture diffusivity, water vapor selectivity, and mechanical properties [41]. A comparative study conducted by Liu et al.[57] investigated potential membrane materials for MEEs. The study found that structural properties such as pore size, porosity, and thickness were the most critical factors in membrane selection. Other factors, such as membrane hardness, durability, and cost, should also be taken into account. According to [57] several materials could be used in MEEs. However, paper and polymer are the two most commonly used materials for membrane fabrication in practice.

4. Conclusion

In our study, we provide a comprehensive review of air-to-air membrane enthalpy exchangers (MEEs), covering various aspects such as membrane properties and materials. First, findings point that membrane properties play a crucial role in the membrane selection process. The MDR contributes significantly to the overall moisture transfer resistance, which can significantly impact the moisture permeation properties of the membrane and consequently affect the MEE's performance. As well, polymeric membranes are commonly used in MEEs due to their favourable moisture permeation properties and cost-effectiveness. The performance of MEEs can be influenced by operating parameters, flow patterns, membrane types, and operating modes.

Various techniques have been explored to enhance the performance of MEEs, such as developing new membrane designs, utilizing novel flow configurations, designing new channel layouts, and incorporating inserts in the channels. The interplay of these techniques can significantly influence the overall MEE performance. Among these techniques, the counter flow configuration has demonstrated the best performance, albeit being challenging to construct due to the inlet and outlet ducts being on the same side.

5. Acknowledgment

The research has been funded by the University of Oradea, within the Grants Competition "Scientific Research of Excellence Related to Priority Areas with Capitalization through Technology Transfer: INO - TRANSFER - UO", Project No. 326/21.12.2021.

References

[1] Xu, Q., S. Riffat, and S. Zhang, *Review of heat recovery technologies for building applications.* Energies, 2019. **12**(7): p. 1285.

[2] Pérez-Lombard, L., J. Ortiz, and C. Pout, *A review on buildings energy consumption information.* Energy and buildings, 2008. **40**(3): p. 394-398.

[3] Tommerup, H. and S. Svendsen, *Energy savings in Danish residential building stock.* Energy and buildings, 2006. **38**(6): p. 618-626.

[4] Omer, A.M., *Energy, environment and sustainable development.* Renewable and sustainable energy reviews, 2008. **12**(9): p.

[5] Cox, P.M., et al., *Acceleration of global warming due to carbon-cycle feedbacks in a coupled climate model.* Nature, 2000. **408**(6809): p. 184-187.

[6] Zhao, D.-X., et al., *Social problems of green buildings: From the humanistic needs to social acceptance.* Renewable and Sustainable Energy Reviews, 2015. **51**

[7] Omer, A.M., *Renewable building energy systems and passive human comfort solutions.* Renewable and sustainable energy reviews, 2008. **12**(6): p. 1562-1587.

[8] Vangtook, P. and S. Chirarattananon, *Application of radiant cooling as a passive cooling option in hot humid climate.* Building and Env., 2007. **42**(2): p. 543-556.

[9] O'Connor, D., J.K.S. Calautit, and B.R. Hughes, *A review of heat recovery technology for passive ventilation applications.* Renewable and Sustainable Energy Reviews, 2016. **54**: p. 1481-1493.

[10] Zender–Świercz, E., *A Review of Heat Recovery in Ventilation.* Energies, 2021.

[11] Mumovic, D., et al., *Winter indoor air quality, thermal comfort and acoustic performance of newly built secondary schools in England.* Building and environment, 2009. **44**(7): p. 1466-1477.

[12] Bakó-Biró, Z., et al., *Ventilation rates in schools and pupils' performance.* Building and environment, 2012. **48**: p. 215-223.

[13] Mikola, A., T. Kalamees, and T.-A. Kõiv, *Performance of ventilation in Estonian apartment buildings.* Energy Proc., 2017.

[14] Son, G., *Ventilation Systems for removing fine dust, The Society of Air-Conditioning and Refrigerating Engineers of Korea.* Mag. Sarek, 2018. **47**: p. 16-23.

[15] Lechtenböhmer, S. and A. Schüring, *The potential for large-scale savings from insulating residential buildings in the EU.* Energy efficiency, 2011. **4**(2): p. 257-270.
[16] Merzkirch, A., et al., *Field tests of centralized and decentralized ventilation units in residential buildings–Specific fan power, heat recovery efficiency, shortcuts and volume flow unbalances.* Energy and buildings, 2016. **116**: p. 376-383.
[17] Hurnik, M., A. Specjal, and Z. Popiolek, *On-site diagnosis of hybrid ventilation system in a renovated single-family house.* Energy and Buildings, 2017. **149**: p. 123-132.
[18] Fehrm, M., W. Reiners, and M. Ungemach, *Exhaust air heat recovery in buildings.* International Journal of Refrigeration, 2002. **25**(4): p. 439-449.
[19] Besant, R. and C. Simonson, *Air-to-air exchangers.* ASHRAE, 2003. **45**(4): p. 42.
[20] Dieckmann, J., K.W. Roth, and J. Brodrick, *Air-to-air energy recovery heat exchangers.* ASHRAE Journal, 2003. **45**(8): p. 57.
[21] Carlsson, M., M. Touchie, and R. Richman, *Investigating the potential impact of a compartmentalization and ventilation system retrofit strategy on energy use in high-rise residential buildings.* Energy and Buildings, 2019. **199**: p. 20-28.
[22] Chenari, B., J.D. Carrilho, and M.G. da Silva, *Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review.* Renewable and Sustainable Energy Reviews, 2016. **59**: p. 1426-1447.
[23] Gao, J., P. Wargocki, and Y. Wang, *Ventilation system type, classroom environmental quality and pupils' perceptions and symptoms.* Building and Environment, 2014. **75**: p. 46-57.
[24] Cao, G., et al., *A review of the performance of different ventilation and airflow distribution systems in buildings.* Building and environment, 2014. **73**: p. 171-186.
[25] Liddament, M.W., *A review of ventilation and the quality of ventilation air.* Indoor air, 2000. **10**(3): p. 193-199.
[26] Li, Y., et al., *Role of ventilation in airborne transmission of infectious agents in the built environment-a multidisciplinary systematic review.* Indoor air, 2007. **17**(1): p. 2-18.
[27] Sundell, J., et al., *Ventilation rates and health: multidisciplinary review of the scientific literature.* Indoor air, 2011. **21**(3): p. 191-204.
[28] Corgnati, S.P., et al., *Indoor Climate Quality Assessment-: Evaluation of indoor thermal and indoor air quality.* 2011.
[29] Cuce, P.M. and S. Riffat, *A comprehensive review of heat recovery systems for building applications.* Renewable and Sustainable Energy Reviews, 2015. **47**: p. 665-682.
[30] Mardiana-Idayu, A. and S. Riffat, *Review on heat recovery technologies for building applications.* Renewable and Sustainable Energy Reviews, 2012. **16**(2): p. 1241-1255.
[31] Yilmaz, M., O. Sara, and S. Karsli, *Performance evaluation criteria for heat exchangers based on second law analysis.* Exergy, an International Journal, 2001. **1**(4): p. 278-294.
[32] Guo, J., M. Xu, and L. Cheng, *Principle of equipartition of entransy dissipation for heat exchanger design.* Science China Tech. Sciences, 2010. **53**(5): p. 1309-1314.
[33] Çakmak, G., et al., *Experimental investigation of thermal performance in a concentric-tube heat exchanger with wavy inner pipe.* International Journal of Thermophysics, 2012. **33**(6): p. 1055-1067.
[34] Shah, R.K. and D.P. Sekulic, *Fundamentals of heat exchanger design*. 2003: John Wiley & Sons.

[35] Liu, X., et al., *Membrane-based liquid desiccant air dehumidification: A comprehensive review on materials, components, systems and performances.* Renewable and Sustainable Energy Reviews, 2019. **110**: p. 444-466.
[36] Alonso, M.J., et al., *Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries.* Building and Environment, 2015. **84**: p. 228-237.
[37] Alkhudhiri, A., N. Darwish, and N. Hilal, *Membrane distillation: A comprehensive review.* Desalination, 2012. **287**: p. 2-18.
[38] Liu, P., et al., *Performance of a quasi-counter-flow air-to-air membrane energy exchanger in cold climates.* Energy and buildings, 2016. **119**: p. 129-142.
[39] Al-Turki, Y.A., et al., *Flat sheet direct contact membrane distillation desalination system using temperature-dependent correlations: thermal efficiency via a multi-parameter sensitivity analysis based on Monte Carlo method.* Journal of Thermal Analysis and Calorimetry, 2021. **144**(6): p. 2641-2652.
[40] Min, J. and M. Su, *Performance analysis of a membrane-based energy recovery ventilator: Effects of membrane spacing and thickness on the ventilator performance.* Applied Thermal Eng., 2010. **30**(8-9): p. 991-997.
[41] Ge, G., et al., *Material properties and measurements for semi-permeable membranes used in energy exchangers.* Journal of membrane science, 2014. **453**: p. 328-336.
[42] Asasian-Kolur, N., et al., *Membrane-based enthalpy exchangers for coincident sensible and latent heat recovery.* Energy Conversion and Management, 2022. **253**: p. 115144.
[43] Albdoor, A.K., Z. Ma, and P. Cooper, *Experimental investigation and performance evaluation of a mixed-flow air to air membrane enthalpy exchanger with different configurations.* Applied Thermal Engineering, 2020. **166**: p. 114682.
[44] Nasif, M.S. and R. Al-Waked, *Seasonal weather conditions effect on energy consumption and CO2 emission for air conditioning systems coupled with enthalpy energy recovery heat exchanger.* APCBEE procedia, 2014. **10**: p. 42-48.
[45] Nasif, M., *Effect of utilizing different permeable material in air-to-air fixed plate energy recovery heat exchangeron energy saving.* ARPN Journal of Engineering and Applied Sci. 2015. **10**(21): p. 10153-10158.
[46] Woods, J., *Membrane processes for heating, ventilation, and air conditioning.* Renewable and Sustainable Energy Reviews, 2014. **33**: p. 290-304.
[47] Scott, N., *An area modulus of elasticity: definition and properties.* Journal of elasticity and the physical science of solids, 2000. **58**: p. 269-275.
[48] Alonso, M.J., et al., *Performance of a lab-scale membrane-based energy exchanger.* Applied Thermal Engineering, 2017. **111**: p. 1244-1254.
[49] Larson, M., R. Besant, and C. Simonson, *The effect of membrane deflections on flow rate in crossflow air-to-air exchangers.* HVAC&R Research, 2008. **14**(2): p. 275-288.
[50] Bui, T., et al., *Effect of hygroscopic materials on water vapor permeation and dehumidification performance of poly (vinyl alcohol) membranes.* Journal of Applied Polymer Science, 2017. **134**(17).
[51] Bolto, B., M. Hoang, and Z. Xie, *A review of water recovery by vapour permeation through membranes.* Water research, 2012. **46**(2): p. 259-266.
[52] Zhang, L.-Z., *Fabrication of a lithium chloride solution based composite supported liquid membrane and its moisture permeation analysis.* Journal of Membrane Science, 2006. **276**(1-2): p. 91-100.

[53] Zhang, L.-Z., *Heat and mass transfer in plate-fin enthalpy exchangers with different plate and fin materials.* Int. Jou. of Heat and Mass Tra., 2009. **52**(11-12): p. 2704-2713.
[54] Al-Waked, R., D. Bani Mostafa, and M.S. Nasif, *Performance of energy recovery ventilators under different climatic regions.* Energy Efficiency, 2021. **14**: p. 1-21.
[55] El-Bourawi, M., et al., *A framework for better understanding membrane distillation separation process.* Journal of membrane science, 2006. **285**(1-2): p. 4-29.
[56] Khayet, M., K. Khulbe, and T. Matsuura, *Characterization of membranes for membrane distillation by atomic force microscopy and estimation of their water vapor transfer coefficients in vacuum membrane distillation process.* Jour. of memb. sci., 2004. **238**(1-2): p. 199-211.
[57] Liu, S., et al., *Comparative study of hydrophilic materials for air-to-air heat/mass exchanger.* International Journal of Low-Carbon Technologies, 2009. **4**(2)

Qu, M., et al., *Isothermal membrane-based air dehumidification: A comprehensive review*. Renewable and Sustainable Energy Reviews, 2018. **82**: p. 4060-406