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Review of heat/energy recovery exchangers for use in ZEBs in cold climate countries

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ABSTRACT

Realisation of Zero Energy Buildings (ZEB) for residential use cannot succeed without: minimising leakages, increasing thermal insulation and using reliable and energy efficient system solutions. However, very airtight houses may have a negative impact on thermal comfort and indoor air quality. Focussing on ventilation systems then becomes a requirement.

In cold climates, temperature differences between indoor and outdoor air often exceed 40 °C during winter. State-of-the-art heat recovery systems may not be able to handle these differences while providing proper air quality and preventing excessively dry indoor air.

The present study of energy recovery systems focuses on apartment buildings located in cold climates countries using central air handling units. Heat exchangers recovering sensible heat are compared with energy exchangers with recovery of both sensible and latent heat. For the latter, both adjacent and non-adjacent solutions are considered.

A specific net energy savings factor is developed taking into account the energy recovered, but also the pressure drops and the variation on the effectiveness of the fan given the installation of the heat/energy recovery.

Heat exchangers are efficient and reliable. Recuperative heat exchangers normally imply no air quality problems, but have severe freezing problems. Regenerative heat exchangers encounter small freezing problems, but do not prevent transfer of odours from extract air to supply air. Regenerative energy exchangers provide an efficient heat and moisture exchange between exhaust and supply air flows, diminishing ice formation and the humidification requirement for indoor air.

1. Introduction

Reduced energy consumption in buildings is one of the most cost-effective ways of reducing CO_2 emissions. Worldwide, the building sector accounts for 40% of mainland energy use [1]. Airtight and well-insulated houses are needed in order to reduce uncontrolled air infiltration and transmission heat losses [2]. Ventilation is required for removing or diluting airborne pollutants that, even in low concentrations, may become irritating or hazardous to humans.

The main function of ventilation systems is to supply fresh air and remove stale air from a room. For relatively cold climates mechanical ventilation systems are the state-of-the-art solution in many countries, even in residential buildings, for ensuring air quality, thermal comfort and reduced energy use [3]. Heat losses in ventilation systems without heat/energy recovery are very significant in cold climates. In order to achieve a further reduction in energy use, the focus must be set on high energy efficient ventilation and heat/energy recovery [4]. Estimates show that 70% of the energy lost through mechanical ventilation systems can be recovered by using heat/energy recovery systems [5]. Estimates show heat recovery systems typically recover about 60–95% of the heat in exhaust air [6]. In cold climate winters, the indoor relative humidity [7] might drop to levels far below 20%, which are lower than common comfort values.

There are other review papers addressing heat and energy recovery ventilators such as the one from Mardiana et al. [6] but this one does not address the especial conditions of cold climates. Others such as the reviews from Abdel-Salam et al. [8,9] Ge et al. [10], Zhang [11] or Chaudhry et al. [12] review the developments related to liquid-to-air membrane energy exchangers (LAMEEs),

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Nomenclature

SNES	specific net energy saving per cubic meter of supplied outdoor air (W s/m^3)
ρ	density of air (kg/m^3)
ΔP	pressure drop (Pa, N/m2)
η_G	global effectiveness or heat recovery system
Φ_L	building ventilation heat loss without heat recovery (W)
$\dot{W}_{max}$	specific fan power of the air distribution system
$\dot{V}_{max}$	largest supply or exhaust airflow rate (m^3/s)
u	throttling of the fan
NTU	number of transfer unitsNTU $= U^*A/C_{min}$,
U	overall heat transfer coefficient,
A	heat transfer area,
C_{min}	smallest of the two values for heat capacity times mass flow rate,
Cr	solution flow rate,
NTU_0	overall number of transfer units,
Cr_0	overall matrix heat (or moisture) capacity ratio,
η_{motor}	electrical effectiveness of the motor,
η_{fan}	electrical effectiveness of the fan,
EE	energy exchanger
HE	heat exchanger,
MEE	membrane energy exchanger,
ERE	energy recovery exchanger,
LAMEE	Liquid-to-air membrane energy exchangers
RAMEE	Run-around membrane energy exchangers
h	specific enthalpy of the air (J/kgK)
$\dot{m}$	mass airflow rate (kg/s)
f_p	heat production factor based on the position of the fan

Subscripts

e	exhaust
inf	infiltration
o	outdoor
x	extract (since in Norway recirculation is not allowed this value is equals to the exhaust)
exf	exfiltration
re	recovery unit exhaust side
rs	recovery unit, supply side
i	indoor
t	value measured each hour

membrane energy exchangers or heat pipes exclusively. A recent review by Rafati Nasr et al. [13] focuses on frosting in air-to-air energy exchangers and concludes that few studies have considered the energy impact of frosting in air-to-air energy exchangers. The current paper provides a method for assessing the specific energy savings with or without frosting for residential blocks in cold climates.

1.1. ZEB buildings

Zero Energy Buildings (ZEBs) lack a unified definition or common understanding. However, the guidelines to be followed in the definitions of suitable heat recovery exchangers in ventilation systems for ZEBs, will consider that:

1. ZEBs aim at reducing the energy demand through efficient technology measures,
2. ZEBs aim at reducing the energy demand through a better use and operation,
3. ZEBs aim at substituting non environmental-friendly energy sources in favour of renewable energies.

The present study relies on the first two conditions and is focused on zero energy apartment buildings located in cold countries, whose ventilation system is common and shared by all the apartments within a given building. The ideal air-to-air energy exchanger for use in ZEBs in cold climate countries has the requirements of high energy recovery effectiveness, inducing proper indoor air quality (IAQ) and avoiding odours spreading. These are major evaluation parameters since the first one affects the CO_2 emissions, while the second and third ones alter the habitability of the apartments.

Studies like the one from Blom [11] prove that heat recovery in ventilation reduce the environmental impact related to space heating. This effect proves to be even more important when dealing with high insulated buildings [12] as heat/energy exchanger will reduce the heating demands for heating and cooling.

It is of common knowledge that the energy/heat exchangers are an efficient technology in every type of buildings but in ZEB buildings where efficiency is compulsory for achieving the balance they became even more important. Therefore the present paper summarises an extensive literature review addressing the key technologies suiting in ZEB buildings located in the cold climate countries.

1.2. Ventilation demand in cold climate countries

The ventilation demand in the studied countries gives an idea of the available heat to be recovered, see Table 1. If the standard/code/guideline requires 0.5 air changes per hour (ach), this means that every second hour the air available in the room must be exchanged with outdoor air and, therefore, one can calculate the available heat to be recovered with other designated parameters. Table 1 also indicates that ventilation through leakages are negligible due to the requirements of leakages below 0, 5–0, 6 ACH at a pressure difference across outside walls of 50 Pa.

2. Heat and energy recovery key technologies

The exhaust air heat loss is a considerable part of the total heat loss in cold climates. If outdoor air is directly introduced into the building through openings or diffusers without any kind of heating, the occupants may feel a draft due to low outside temperatures [22]. Furthermore, heat exchangers, if used, may suffer from freezing when outdoor air remains below freezing temperatures. Freezing will happen when moisture in the extract air condenses on an exchanger surface below freezing temperature [23,24].

Energy and heat recovery systems are air-to-air or air-to-liquid exchangers that exchange energy (heat and moisture) or only heat from the exhaust air to the supply stream. In super insulated buildings, such as ZEBs, where all the makeup air is provided and exhaust air is removed by means of a ventilation system, the required recovery effectiveness of energy recovery exchangers (EREs) are higher than in previous building classifications. Standards, such as the Norwegian, will require 80% of sensible heat recovery [13], see Table 1. Fig. 1 shows the schematic of an energy recovery ventilator (ERV) used in a residential building.

Table 1
Legislation, guidelines and requirements regarding ventilation demand (when possible NZEB requirements are stated even if they are not standardised yet).

	Norway [13]	Denmark [14]	Sweden [15]	Canada & USA [16–18]	China [19–21]
Kitchen	10 (30) l/s[a]	20 l/s	10 l/s	5 ach or (50 L/s) intermittent or 12 L/s continuous or openable windows	3 ach
Bath/shower room with opening possibilities	15 l/s		10 l/s	10 l/s (≥2 ach)	1 ach
Bath/shower room without opening possibilities	30 l/s[b]	15 l/s	10 l/s Balanced ventilation (BV)30 l/s or 15 l/s	25 l/s for intermittent flow rate	
Toilet	10 l/s	10 l/s	10 l/s	10 l/s	3 ach
Room	7 l/(s·person)0.1 l/sm[b] if unoccupied		0.35 l/(sm[b])0.1 l/(sm[b])	3.5 l/s per person or 0.15 L/s m[b]	30m[c]/(h.person)
Minimum sensible heat recovery	80%. Mechanical ventilation compulsory	75-85 %[c)] [7]	70%	70%	60% (public building)
Minimum latent heat recovery	N/A	N/A	N/A	70%	N/A
Minimum total heat recovery	N/A	N/A	N/A	50%	60% (public building)
Average air changer per hour in the whole building (ACH)	0.6[d]	0.3	0.5(mixing of air 50%)	0.35	0.7–0.45 depending on area per person
Ventilation specific fan power[kW/(m3/s)]	1.5	1.5/0.8[c], [7]	2.0 BV with Heat exchanger(HX)1.5 BV without HX		1.152
Air tightness in NZEB. Tested at 50 Pa[l/s per m^2] pressure difference	0.6	0.5 [7]	0.6	0.5	N/A

[a] Forced extraction through the kitchen extract hood [13].
[b] Forced ventilation for bathrooms without allowing the opening of windows. Bathroom with enclosed showers, shower cabinets or bath tubes, having ventilation effectiveness comparable to complete mixing, should not need forced ventilation [13].
[c] For ventilation systems for a single dwelling.
[d] Average value for all the rooms of the house.

Several classifications of heat/energy exchangers can be found. Some are based on operation (moving vs. static) and others (e.g., Larson [25]) deal with heat exchangers when the only recovered heat is the sensible and energy exchangers when sensible and latent heat exchange takes place.

Table 2 shows Larson's classification of heat/energy exchangers [25]. It defines energy and heat exchangers with adjacent ducts and non-adjacent ducts that are widely used in cold climate countries.

2.1. Heat recovery systems (adjacent duct)

The only goal of heat recovery exchangers is to recover the sensible heat. Those to be studied are flat plate heat exchangers and heat wheels. Both are commercially available and common in air handling units [25].

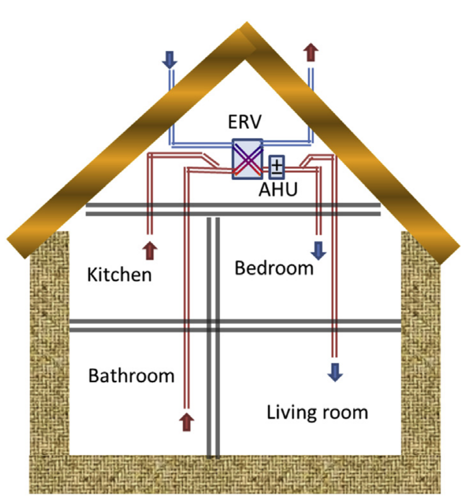

Fig. 1. Schematic of an energy recovery ventilator in a residential building.

2.1.1. Flat plate heat exchanger

Due to the desire of reducing heating costs, and more recently, legislation, different types of air-to-air heat exchangers have been developed. Flat plate heat exchangers were the first exchangers to be widely used. They only recover sensible heat from the exhaust air. Flat plate heat exchangers are available in two basic configurations: counter-flow with effectiveness 50–80 % [2] and cross-flow with effectiveness about 10% less [26]. Cross-flow has been the predominant flow arrangement due to its simple construction and sealing simplicity. These exchangers have low pressure drop and are easily cleaned [27].

Nielsen et al. concluded in Ref. [28] that a family of four members produces 10 kg of water vapour per day. For a heat exchanger with high effectiveness, the temperature of exhaust air will be considerably reduced through the exchanger. Consequently, condensation of water vapour occurs and frost formation increases at low outdoor temperatures. Frost formation would reduce the effectiveness of the exchanger and total heat transfer rate, and the pressure drop at the exhaust air side of the exchanger would increase. Unless defrosting measures are taken into consideration, these heat exchangers will end up being blocked by ice and may even get damaged in cold climate.

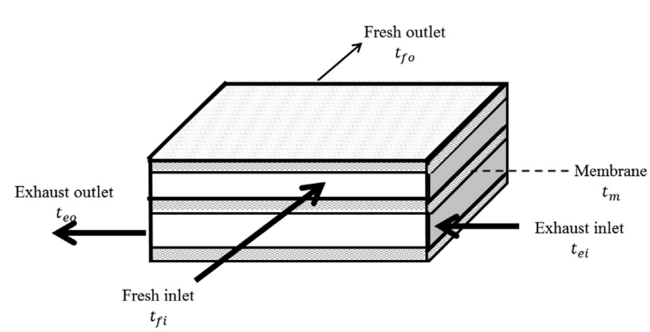

Fig. 2. Schematic of a MEE with cross-flow arrangement. Reprinted from [51].

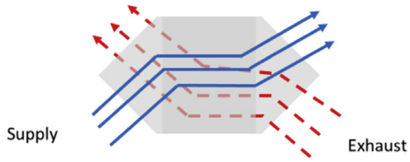

Fig. 3. Schematic of a quasi-counter-flow MEE.

Several further developments focused on the use of new materials, such as plastic or membranes instead of aluminium in order to reduce the frosting issue. Membrane exchangers will be detailed below as they recover both latent and sensible heat.

2.1.2. *Heat wheel*

Heat wheels have been extensively used in cold climates. In Europe, their use has been more focused on the recovery of sensible heat, while in the USA, Asia and Canada, moisture transfer is more important because of more humid climates. For example, in ASHRAE 84.1 [29], both latent and sensible effectiveness are included in the definition of effectiveness, or in ASRAE 90.1, total effectiveness (i.e. 50%) is a requirement [30].

The wheels' efficiencies are related to the air flow rates and the heat transfer surface area. Usually, wheels are formed by corrugated matrices that maximize surfaces relative to the volumes [31].

Wheels have the limitation of having moving parts, leading to maintenance issues [32]. Furthermore, for the ZEB case and where ventilation system supplies a whole block of apartments with one solely air handling unit, the main drawback is the transmission of odours. According to Finke [33], the largest sources of odours are filters, heat/energy wheels and humidifiers. Another concern with this technology are the so-called carryover leakages, produced when a small fraction of exhaust/inlet air is trapped in a passage and is switched from exhaust to inlet or vice versa [34]. Since carryover from exhaust to supply is undesirable, a purge section can be installed to reduce the cross contamination [10]. These leakages are difficult to avoid completely and they are a source of odour transfer. Several studies have demonstrated that VOCs can be transferred as well [35,36]. When wheels are correctly pressure-balanced and properly installed, the value of this carryover leakage is about 4%, while, when construction rules are not fully followed, values as high as 40% have been measured [37]. Therefore, for some toxic or hazardous applications, wheels may not be an appropriate choice [31] for the heat recovery. The pressure loss typically ranges from 50 to 200 Pa in each air stream and these values are lower than most of other air-to-air heat exchangers [31].

Frosting in the cold climate countries is a matter of primary concern [38]. Frosting will occur [39] when excess water is formed in the rotor or at least part of this water is formed in a cross-sectional zone in which the mean temperature of the rotor during one revolution is lower than 0 °C. Bilodeau [23] has studied the two different kinds of frost layers that are formed on the surface of rotary heat wheels. Glazed layers are normally formed in cold climate conditions. They have a higher density and larger thermal conductivity than rough frost. According to [11], due to the link between frosting conditions and effectiveness, traditional control strategies based on the freezing point or fixed time period are inadequate. In Refs. [39], practical limits when excess water is drained out of the rotor were lab-tested concluding that: “Calculations and laboratory tests show that the supply air limiting temperature […] can be assumed to be approximately −10 °C”. According to practical experience in Norway, frosting is not a frequent problem. This is probably due to the fact that the frosting process is very slow [23] and indoor humidity conditions usually change before severe frost becomes a problem. Fig. 5 shows that only during a few hours frost will start growing. However this will not cause problems due to few successive hours with growth. Frost formation if happening, is most likely to occur near the outlet of exhaust air flow, as Simonson and Besant found in Ref. [24].

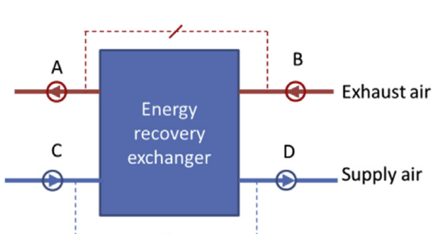

Fig. 4. Schematic of energy balance with regard the energy exchanger.

Table 2
Schematic classification of exchanger technologies based on Larson [25].

Heat Exchanger – Adjacent duct	Heat Exchanger- Non adjacent duct
• Flat plate	• Glycol Run around
• Heat wheel	• Thermosiphon
• Heat pipe	
Energy Exchanger – Adjacent duct	Energy Exchanger- Non adjacent duct
• Membrane energy exchanger	• Run around Membrane Energy Exchanger
• Enthalpy wheel	• Twin tower enthalpy recovery loop
• VENTIREG Exchangers	

2.1.3. *Heat pipe and thermosiphon*

Heat pipes are normally cooper tubes sealed where a fluid is evaporating and condensing passively. This fluid is the heat transfer fluid. The latent heat of vaporization is utilized to transfer heat over a long distance with a corresponding small temperature difference [10]. The exhaust air heats the fluid that evaporates changing its density moving towards the supply air that gets heated up while cooling down the refrigerant and returns to the warmer side. They have no moving parts and therefore no external power is required for them to work making them very reliable. As the flows are not touching there is not risk of cross contamination, finally they are

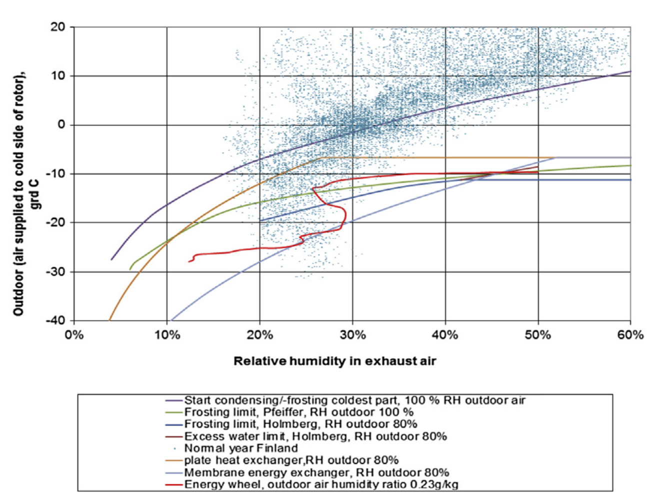

Fig. 5. Frost threshold Pfeiffer [87], Holmberg [88] limits against RH for a heat wheel, frost threshold for plate heat exchanger (75% sensible effectiveness), frost threshold for energy wheel after 2 h operation [23] and plate membrane energy exchanger (75% sensible effectiveness) given average conditions in Finland [39].

suitable for all temperature application in HVAC. Their use is also very interesting in naturally ventilated houses [40]. Their biggest drawback is their low effectiveness measured between 0.35 and 0.6 [41].

Thermosiphon tubes operate in a similar way to heat pipes but they differ from them as they rely on gravity to return the refrigerant whereas heat pipes rely on capillarity and secondly because thermosiphon needs nucleate boiling (heat pipes vaporize the refrigerant from a liquid vapour interface) requiring higher temperature differences to initiate the process [42].

Run around membrane exchangers are a specific type of this used when the airflows are separated by long distances.

2.2. Energy recovery systems (adjacent duct)

These systems recover both latent and sensible heat. Energy wheels, flat plate membrane energy exchangers and VENTIREG exchangers will be studied. They are newer technologies, even though energy wheels are an established technology.

2.2.1. Flat plate membrane energy exchangers

In recent years, the energy recovery exchangers with both heat and mass transfer significantly attract researchers' attention due to their potential of energy conservation and indoor environmental quality improvement. Membrane based energy exchangers are a new class of flat plate heat exchanger [43,44].

Membrane energy exchangers (MEEs) were proposed as a novel alternative for energy exchangers by Zhang [45]. A schematic of a MEE with cross-flow arrangement is shown in Fig. 2. Its structure is the same as a flat plate heat exchanger with the difference that the MEE uses semi-permeable membrane plates instead of metal sheets. Membrane composition, shape and dimensions play important roles in the effectiveness, temperature and humidity distribution. By using polymer membranes, they efficiently recover sensible and latent heat by moisture transfer. Additional energy required for dehumidification or humidification of fresh air is then reduced [46]. Paper membrane solutions such as used in Ref. [47] may not be appropriate for cold climates due to the ice formation on the membranes. The improvement of these efficiencies has been the main point of several studies, with focus on the air side improvements [43], on the structural distribution [48,49], and on the membrane itself [50], for instance. The heat and moisture gradients between the fresh and exhaust air streams drive the heat and mass transfer through the penetrative membrane. It is a static and continuous manner to recover both sensible and latent heat given no moving parts and no regeneration of desiccant being involved [44].

The conjugate heat and mass transfer mechanisms for MEE were widely studied to discuss the influencing factors of performance. Niu and Zhang derived and validated the fundamental dimensionless groups for coupled heat and mass transfer in cross-flow MEEs [52]. They concluded that MEE's moisture diffusive resistance is not a constant since it is co-determined by the slopes of sorption curves and the operation conditions. The analysis for moisture resistance provided theoretical support to the operation and preparation of high performance membrane. They proposed that for MEEs, sensible effectiveness is determined by number of transfer units for heat (NTU), while latent effectiveness is determined by the number of transfer units for moisture (NTU_L) [52]. NTU_L is a factor to summarize the influence of membrane material and operation conditions. The relationship between NTU and NTU_L is derived with proper separation of moisture resistance. Zhang compared the performances of heat and moisture transfer in cross-flow MEEs with three different cores: common paper, cellulose acetate membrane and modified cellulose acetate membrane. Both numerical and experimental results showed that the sensible effectiveness of three exchangers was insensitive to membrane materials and operation conditions, while their influence in moisture transfer was tremendously. For the same core, the membrane thickness is the determining factor [53]. Min built a mathematical model to investigate the effect of the membrane spacing (channel height) and membrane thickness on cross-flow MEE performance [54]. It showed that the enthalpy transfer had a maximum rate at certain membrane spacing for a fixed fan power. Further on, the thinner the membrane, the higher the enthalpy effectiveness. For a MEE with a fixed fan, it is important to utilize a thin membrane and a proper channel height to achieve a satisfactory performance.

Cross-flow distribution has been widely used due to the simplicity of duct sealing; however, its effectiveness is lower than counter-flow. On the other hand, counter-flow systems are likely to get contamination of fluids due to sealing problems. Consequently, quasi-counter flow combining both feeding techniques appears as the best solution as tested by Refs. [22,46,55–57]. Zhang and Niu compared the energy consumption for conditioning fresh air between MEE and traditional sensible-only exchangers. About 58% of the energy consumed to condition fresh air could be saved with MEE in Hong Kong, for sensible only exchangers this value drops to 10%. They also indicated that the more humid the weather, the better are MEEs compared to traditional sensible-only exchangers [58]. The MEE as novel air dehumidification system was compared to the mechanical dehumidification systems combined with a heat pump, MEE, sensible-only heat exchanger and desiccant wheel by an hour-by-hour simulation [59] and it resulted in the least energy consuming. Liang et al. [60] further analysed this system with numerical and experimental investigations. It is addressed that the air dehumidification rate and COP in dehumidification systems with MEE is 3.5 and 2.2 times higher respectively compared to a conventional mechanical dehumidification system.

Thereafter, Zhang constructed a new quasi-counter-flow MEE. A schematic of its structure is present in Fig. 3. Conjugate heat and mass transfer in the quasi-counter-flow MEE was investigated by means of numerical analysis and experimental validation. Sensible and latent effectiveness of the quasi-counter flow MEE were generally improved by 5% compared to pure cross-flow MEE [46].

With continuous moisture recovery in MEE, one could theoretically avoid frosting; the primary concern when utilizing heat exchanger in cold climates [61]. It involves neither preheat part or complicated control strategies. However, the application of MEE for cold climates is rarely discussed. To estimate the feasibility of MEEs in cold climates, Justo Alonso tested different membranes' performances, among the tested, the one which has the best overall characteristics is a porous substrate coated with a hydrophilic polymer layer [62]. Aarnes conducted experiments to compare the frost formation in both quasi-counter-flow MEE (with the same membrane as described in Ref. [62]) and non-permeable membrane MHE (membrane heat exchanger). She proved that for conditions where frost appeared with plastic layer, she could not detect any frost layer when using the porous [63].

The mechanism and limit of frosting in MEE needs to be further explored with theory and experiments. The performances of quasi-counter-flow MEE should be investigated in cold climates. So far with the few research examples in cold climates, one can refer to: flat plate polycarbonate membrane heat exchangers were tested in cold climates giving promising values [22]. Tested units provided about 85% total effectiveness and 82% temperature effectiveness in a system. According to the authors, the system can be further developed, and the volume of the unit remains to be optimized. Theoretical calculations show an increase of the effectiveness (latent and sensible) for increasing NTU, as shown by Niu in [52].

2.2.2. Energy wheel

Energy wheels have the same working principle as heat wheels with the advantage of recovering latent heat. General advantages and drawbacks of heat wheels apply to both.

Frosting threshold in energy wheels is very dependent on air properties, design and materials, though from the studies in Refs. [64,65], it can be concluded that its value lies between 5 and 15 degrees lower than in plate heat exchangers.

Energy wheels are regenerative exchangers used to transfer heat and moisture between supply and exhaust air streams in HVAC systems. During cold and dry weather, air flows through the desiccant coated wheel in the supply section and gets heat and moisture taken from the exhaust air and stored (adsorbed) in the wheel. As the wheel turns, the sensible and latent energies accumulate in the wheel and are released to the supply air, warming it up to a higher temperature and increasing humidity content. Regarding frost, energy wheels are therefore less likely and exposed to condensation and frosting due to the simultaneous heat and moisture exchange [31]. As a result of the rotation, the conditions experienced by the wheel are steady periodic [66]. The rotational speed of the wheels and thermal capacity of the matrix are very important parameters that affect the capability of the wheels to adsorb moisture and therefore their effectiveness that remains around 50–85 % for both latent and sensible heat recovery [2]. Increasing NTU_o and C_{ro} increases the effectiveness of a sensible rotary heat exchanger as it is shown in Refs. [67], the same trend is assumed for energy exchangers.

The use of the proper desiccant for the wheels will also have a positive effect as physical barrier for VOC [68]. Some materials will increase the adsorption and de-adsorption properties on the surface of the wheel [37]. The majority of energy exchangers which are in the form of cycling packed beds and rotary wheels are developed and implemented based on alternate sorption and regeneration of desiccant [69]. However, the regeneration of desiccants is very slow and energy consuming. In addition, cycling beds are bulky and the maintenance of rotating wheels is problematic [44].

2.2.3. VENTIREG exchangers

VENTIREG exchangers are developed for regenerating heat and moisture in ventilation systems in cold climates. It can be classified as desiccant wheel for their similar principle. Aristov et al. [70] investigated how the moisture was exchanged if a stationary adsorbent layer was considered. From their studies, it arises that commercially produced desiccants can be effectively used as a buffer for humidity. The adsorption degree increases with the decrease in sizes of adsorbent granules.

Based on the knowledge achieved by this study, Aristov et al. [5] created the regenerating heat and moisture exchanger VENTIREG. VENTIREG exchangers are formed by a layer of heat storing material and a layer of water absorbent that operate intermittently [4]. The warm humid air first passes the desiccant and then the heat absorption media. Outdoor air flows in the opposite direction.

The use of efficient heat exchange between exhaust and supply reduces heat losses and avoids ice formation at the same time as the supplied air is humidified. The system works intermittently and achieves energy recovery up to 95%, while 70–90 % of moisture is recovered preventing ice formation. It achieves around 85% sensible effectiveness and 60% latent effectiveness, as tested in Russia [4].

However, even when no bacteria formation was found on the adsorbent, the odours problem is still to be considered.

2.3. Heat and energy exchangers (non-adjacent duct)

Non-adjacent ducts heat exchangers are systems composed of supply and exhaust air streams, two separate air-to-water/glycol heat exchangers and a coupling liquid (antifreeze solution or water, for example). The solution/water is pumped into a closed loop between the heat exchangers, gains heat from the exhaust stream and releases it to the supply stream (heating mode) [56].

Given that the exchanger is a membrane heat exchanger (e.g., run around membrane energy exchanger with the liquid running in a close loop), or any other exchanger which allows the transfer of both sensible and latent heat (e.g., twin tower loops when there is a sorbent and the liquid runs in an open loop) these exchangers will be called energy exchangers.

Unlike other air-to-air heat or energy recovery devices, non-adjacent ducts heat or energy exchangers do not require both air ducts to be adjacent. This gives them an advantage over systems where cross contamination is a concern (e.g.,. operation theatre) or in retrofitting applications where the exhaust and supply air ducts are already installed [71]. A limitation of these systems is that air may be polluted in the heat/energy exchanger by entraining desiccant in aerosol form and corrode ducts, fans or coils, enhancing the possibility of bacteria and lowering the IAQ.

2.3.1. Run-around membrane energy exchanger (RAMEE)

Run-around membrane energy exchangers (RAMEEs) are energy recovery systems using flat-plate liquid-to-air membrane energy exchangers [72] to recover energy from exhaust air and precondition the outdoor ventilation air. The semi-permeable membranes are used in the LAMEEs to separate the liquid desiccant flow from the air streams and prevent the entrainment of liquid desiccant aerosol into the air streams. Adachi and Alberti in Refs. [73,74] respectively show the construction of a counter-flow LAMEE and a schematic of a typical counter-cross-flow RAMEE system. RAMEEs can transfer both heat and moisture by circulating liquid desiccant between LAMEEs in the supply and exhaust airstreams. The supply and exhaust air streams can be located adjacent to each other or far apart from each other. This flexibility of non-adjacent ducting means that the RAMEE is more suited for retrofit applications than currently available energy recovery systems.

The RAMEE effectiveness is significantly dependent on outdoor air conditions (temperature and humidity) [75], air and solution flow rates [76,77], and semi-permeable membrane properties [78]. Generally, the sensible effectiveness of a RAMEE increases as humidity ratio of outdoor air increases when the outdoor temperature is greater than the indoor temperature (i.e. 24 °C) and as outdoor humidity ratio decreases when the outdoor temperature is lower than indoor. The latent effectiveness increases with increasing temperature of outdoor air when the outdoor humidity ratio is greater than the indoor humidity ratio (i.e. 9.3 g/kg) and with decreasing temperature when the outdoor humidity ratio is lower than indoor [75]. The effects of outdoor air temperature and humidity ratio on the RAMEE effectiveness are opposite to that of a single LAMEE [79].

Experimental measurements and numerical simulations found that an increase in NTU (or a decrease in airflow rate) resulted in an increase in the total (sensible and latent) RAMEE effectiveness. The RAMEE effectiveness increased as Cr^* (or solution flow rate) increased at lower Cr^* values until the effectiveness reached a peak value. After the peak value, the effectiveness decreased slightly as Cr^* increased [76,77]. The effects of NTU and Cr^* on the RAMEE effectiveness are shown in [77].

The vapour diffusion resistance (VDR) of a membrane used in a RAMEE is critical to the effectiveness of the energy recovery exchanger. The lower VDR, the greater moisture flux for a given moisture content difference. For a given test condition, the latent effectiveness of the RAMEE improves if a membrane with lower VDR is used. The effectiveness of the RAMEE is sensitive to membrane VDR when it is higher than 20 s/m, as shown in Ref. [78].

Early experimental tests showed that a 55% total effectiveness could be achieved by the counter-cross-flow RAMEE system [74], which was higher than the minimum total effectiveness (50%) required by ASHRAE Standard 90.1 [80]. Using hourly simulations for office and hospital buildings in four different North American cities, Rasouli et al. [76,81,82] found that a RAMEE provided up to 40%–60% annual heating energy saving and up to 20% annual cooling energy saving in the office and hospital buildings, depending on the climate and RAMEE effectiveness. The payback period of the RAMEE was within 2 years in cold climates and 1–5 years in hot climates [82].

Patel et al. [83] have experimentally measured VOCs transfer between the exhaust and supply airstreams by a RAMEE. The results showed that only a small fraction of contaminants from the exhaust air stream were passed to the supply air stream. VOCs with highest solubility in water had the highest possibilities to be transferred even though the transferred ratio of VOCs was not significant for the case of a nearly saturated liquid desiccant.

2.3.2. Twin tower enthalpy recovery loops

Twin towers are a case of RAMEE where instead of using membrane exchangers one is using exhaust and supply air towers. In twin towers enthalpy recovers a sorbent liquid is circulated between the supply air tower to the exhaust air towers and vice versa so that water vapour and energy are recovered. Due to this contact cross contamination may happen. Their main drawback in cold climates is the over dilution of the sorbent as a result of moisture losses in the exhaust stream. For these climates, heating of the sorbent liquid coupled to an automatic makeup water addition may be needed in order to maintain the sorbent solution concentration. This implies a loss in effectiveness [89].

3. Analitic comparison of energy exchangers

This section addresses two methodologies proposed by the authors for the analytical comparison of energy exchangers. The first Specific net energy saving compares exchangers based on the possibilities to recover and the increased energy use due to pressure drops related to the exchanger and it probable freezing and the cost attached from installing the recovery system. The second compared methodology addresses the frost limits.

3.1. Specific net energy saving

Among the energy recovery solutions, the concept to be chosen depends on the possibilities to recover energy and the costs attached from installing the recovery system (investment in the unit and increased pressure drop, i.e. higher fan consumption) for the building in consideration. The recovery effectiveness is often used in the energy saving calculation [84]. A crucial issue of air handling units is that, while they recover energy, they induce a pressure drop and an increase on the use of energy in the fans. In addition, during non-recovering periods, the heat recovery unit and extra fans represent only a pressure drop. For some cases, a bypass of the exchanger is possible, but this also causes a pressure drop that has to be considered.

Therefore based on [84], the authors have defined a specific net energy saving (SNES) parameter for balanced exchanger (the mass flow rates and pressure drops equal in both sides of exchanger). This is depending on the sensible and latent heat recovery, pressure drop through the exchanger and bypass channel, extra electricity demand related to the exchanger. In that way, the SNES is defined in specific energy savings per cubic meter of supplied outdoor air [Ws/m^3] as:

$$\mathrm{SNES}=\sum_{\substack{\forall\,\mathrm{hour}\\ \mathrm{year}}}\rho V\frac{\left|\Phi_{\mathrm{L}}\eta_{\mathrm{G}}+\sum_{\mathrm{fan}}\left(\frac{\Delta p_{t}\nu}{\eta_{\mathrm{motor}}\eta_{\mathrm{fan}}}-\Delta p_{\mathrm{min}}\nu\right)f_{\mathrm{p}}-\left(\frac{\Delta p_{t}^{'}\nu}{\eta_{\mathrm{motor}}\eta_{\mathrm{fan}}}-\Delta p_{\mathrm{min}}^{'}\nu\right)f_{p}^{'}\right|}{\dot{m}}-W-\sum_{\substack{\forall\,\mathrm{hour}\\ \mathrm{year}}}\frac{\left(\Delta p_{t}\nu-\Delta p_{\mathrm{min}}^{'}\nu\right)}{\dot{V}}-\frac{\sum_{\forall\,\mathrm{hour}/\mathrm{year}}\left(2\Delta p_{\mathrm{bypass}}\right)\nu}{\dot{V}} \tag{1}$$

where

$$\Phi_{\mathrm{L}}=(h_{\mathrm{x}}-h_{\mathrm{o}}) \tag{2}$$

$$\eta_{\mathrm{G}}=\frac{\dot{m}_{\mathrm{re}}(h_{\mathrm{x}}-h_{\mathrm{re}})}{\left(\dot{m}_{\mathrm{x}}+\dot{m}_{\mathrm{exf}}\right)(h_{\mathrm{x}}-h_{\mathrm{o}})} \tag{3}$$

Equation (3) is the global energy recovery effectiveness of the system (in case of heat recovery only, the latent term has to be withdrawn in this equation).

The term $\sum_{\mathrm{fan}}\left(\frac{\Delta p_{t}\nu}{\eta_{\mathrm{motor}}\eta_{\mathrm{fan}}}-\Delta p_{\mathrm{min}}\nu\right)f_{\mathrm{p}}$ takes into consideration the heat from the fans that it is recovered in the case of having the heat recovery unit. The term $(\Delta p_{t}^{'}\nu/\eta_{motor}\eta_{fan}-\Delta p_{\mathrm{min}}^{'}\nu)f_{\mathrm{p}}^{'}$ stands for the same as the previous in the case of not having any recovery unit. These terms depend on the pressure drop that the fans have to overcome and the position of the fans regarding the exchanger. The factor f_{p} represents the effect of the fan's position on the amount of the energy recovered from the fan. The factor f_{p} is close to one for supply fans (position D in Fig. 4) and zero for exhaust fans (position A Fig. 4), for positions C and B, f_{p} equals η_{G}. The factor f'_{p} is close to one for supply fans (position D in Fig. 4) and zero for exhaust fans (position A Fig. 4) the other positions in Fig. 4 will not be possible in the case of not having the recovery unit. W stands for the electricity needed for running the energy recovery. For a rotary wheel, this value will be equivalent to the energy to rotate the wheel, while for a run around exchanger; the value will correspond to the electricity to run the pumps.

$\sum_{\substack{\forall\,\mathrm{hour}\\ \mathrm{year}}}\frac{((\Delta p_{t}\nu-\Delta p_{\mathrm{min}}^{'}\nu))}{\dot{V}}$ is the extra energy required from the fans for having to compensate the pressure drop of the energy recovery. $\Delta p_{\mathrm{min}}^{'}\nu$ stands for the minimum pressure drop, considered to be the air handling unit without energy/heat recovery exchanger installed and $\Delta p_{t}\nu$ stands for the pressure drop when the system is running due to different types of energy exchanger, different rotation velocity, clogging or fouling due to condensation or frost. Therefore, this value varies with time and hourly calculations have to be done. As for the calculation of pressure drop due to clogging as a result of frost or condensation, many references are available [85], however the real value will be very dependent on the type of heat exchanger, the width of the channels and the type of growth of the ice [23]. The values of the pressure drop due to existence of the exchanger must be obtained from the manufacturer for each case.

Finally, $\frac{\sum_{\forall \text{hour}}^{\text{year}} (2\Delta p_{\text{bypass}})\, v}{\dot{V}}$ takes into consideration the energy consumption changes due to changed pressure drop for the cases when bypassing the energy exchanger is a possibility and then, given the position of the dampers, the values of the pressure drop will vary.

Fan losses due to leakages will not be considered in this calculation since their value will be negligible in comparison with the other factors. For a balanced flow situation these losses may be accounted as a 0.4% of the whole airflow. In case of known unbalance this loss can be calculated as

$$P_{\text{loss fan}} = \left(\frac{q_{\text{v,leak}}}{q_{\text{v,ea}}}\right) P_{\text{el}} \tag{4}$$

where $q_{\text{v,leak}}$ is the leakage flow in rotor from supply air side to exhaust air side in m^3/s, $q_{\text{v,ea}}$ is the exhaust air flow in m^3/s and P_{el} is the fan power to exhaust fan without rotor leakage in kW.

Given all these losses, one can calculate the real energy savings coming from the use of an air handling unit taking into account the whole system and making the value more representative of the real energy saving effect of having this type of recovery.

3.2. *Frost threshold for flat plate and heat/energy wheel exchangers*

Based on the calculations from Refs. [86], for a membrane heat exchanger the frost limits can be calculated as follows:

Using the definition of sensible effectiveness

$$\varepsilon_{\text{S}} = \frac{t_{\text{fo}} - t_{\text{fi}}}{t_{\text{ei}} - t_{\text{fi}}} = \frac{t_{\text{ei}} - t_{\text{eo}}}{t_{\text{ei}} - t_{\text{fi}}} \tag{5}$$

Rewriting Equation (5), then t_{eo} can be expressed as

$$t_{\text{eo}} = t_{\text{ei}} - \varepsilon_{\text{S}} t_{\text{ei}} + \varepsilon_{\text{S}} t_{\text{fi}} \tag{6}$$

Assuming exhaust outlet temperature $t_{\text{eo}} = 0°\text{C}$, Equation (6) yields the critical outdoor air temperature. Combining critical latent effectiveness (43) and ε−NTU method, we get

$$\frac{U_{\text{l}}}{\frac{1-\varepsilon_{\text{S}}}{\varepsilon_{\text{S}} c_{\text{p}}} U_{\text{S}} + U_{\text{l}}} = \frac{\frac{\phi_{\text{ei}}}{e^{5294/(t_{ei}+273)}} - \frac{\phi_{\text{eo}}}{e^{5294/\left(T_{ei}-\varepsilon_S T_{ei}+\varepsilon_S T_{fi}+273\right)}}}{\frac{\phi_{\text{ei}}}{e^{5294/(t_{\text{ei}}+273)}} - \frac{\phi_{\text{fi}}}{e^{5294/\left(t_{\text{fi}}+273\right)}}} \tag{7}$$

By means of using the equation above, the condensation limits could be addressed with respect to indoor RH, ϕ_{ei} outdoor air temperature, t_{fi}, when the remaining variables are provided as constants.

In Fig. 5 relative humidity and outdoor temperature for each hour of an average year are indicated. The humidity in the exhaust air is calculated using the outdoor air's humidity and adding humidity production from the occupants. The humidity production follows a user profile for a four member family, similar profiles each weekday and weekend.

The frosting limits model is built through combing condensation limits and critical outdoor air temperature. The limits are expressed as a function of outdoor air temperature and indoor relative humidity with this combination [86]. Under the assumption of constant surface temperature, using the clarification of moisture resistance procedure [52], the total heat and moisture transfer coefficient can be computed. When the properties of cores of heat/energy exchangers are substituted into this model, the frosting limit is plotted and the comparison of the effects of sensible effectiveness on the risk of frosting is revealed as well. One can conclude from Fig. 5 that using MEE and energy wheel enable recovery in a bigger share of the year as the hours when frost happens are much less than with other recovery systems.

4. Summary

Table 3 shows a summary of the relevant properties of different recovery exchangers in cold climate countries. In the specific case of cold climate NZEBs, the properties of odours transfer and effectiveness are the most important.

The stated values of effectiveness refer to these countries. The values for effectiveness are in some cases based on values from widely tested and commercially available systems, and in some others from referenced experimental investigations.

The stated affirmations of possible problems and limitations apply to cold climate countries conditions.

Membrane energy exchangers, energy wheels, and run-around loops do not show frost formation as major issue. Though energy wheels may transfer odours, they proved to be as efficient as membrane energy exchangers (Table 3).

Run-around membrane heat exchangers are very well suited for building rehabilitation, since no adjacent ducts are required.

Table 3
Summary of properties for different recovery systems. Values for normal cold climate conditions: temperature [-20, −25] °C and RH [10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35,36,37,38,39,40] %.

Type of exchanger	Freezing problems	Odour transference	Moving parts	Latent effectiveness	Sensible effectiveness	Use in toxicenvironments
Flat plate heat exchanger cross flow	Yes	No	No	No	60–80%	Yes
Flat plate heat exchanger counter- flow	Yes	No	No	No	70–90%	Yes if good sealing
Flat plate membrane quasi counter flow	No	No	No	46–76% [46]	80–85% [22]	Yes
Heat wheels	Moderate problems	Yes	Yes	No	50–80%	No
Energy wheels	No	Yes	Yes	50–85% [2]	50–85% [2]	No
Dessicant drying wheels	No	Yes	yes but low rotational speed	70–90% [5]	95% [5]	No
Run around heat exchangers	Yes	No	No	No	65–70%	Yes
Run around membrane energy exchangers (only preliminary experimental data [32])	No	No	No	50–65% [32]	60–80% [32]	Yes

5. Conclusions

Energy exchangers are recommended to be used in buildings in cold climates in order to recover both latent and sensible heat, and therefore increase effectiveness and reduce energy consumption of the HVAC system. The selected exchangers must provide an efficient exchange of heat between the exhaust and supply air, avoid ice formation and moisten the supplied air to provide acceptable indoor thermal comfort.

Plate heat exchangers are a well-known technology. The effectiveness of these exchangers is high and when enthalpy recovery is also utilised, they seldom have frost problems. They are not likely to transfer odours since both air streams are separated by the heat/energy exchange layer.

Membrane energy exchangers for cold climate are promising, but still remains development and tests to prove their applicability.

Heat/Energy wheels are rotating recovery systems. The first recovers solely sensible heat, while the second recovers both latent and sensible heat becoming a much more efficient system under hot and humid outdoor air conditions. In cold climate energy wheels could improve the humidity level of the indoor air. They are distinguished from other heat exchangers for their high effectiveness ranging from 50 to 90% and large internal surface areas. The biggest concern to be taken into account with this technology is a certain risk of freezing for heat wheels and the leakages in both kinds of wheel.

Run-around technology with latent heat recovery seems promising and should be further developed when considering effectiveness. In addition, their capacity of being installed in retrofit application gives more interest.

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