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LITERATURE REVIEW ON AIR-TO-AIR ENERGY RECOVERY EQUIPMENT APPLIED IN AIR CONDITIONING SYSTEMS

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ABSTRACT

Air-to-air energy recovery is the process of recovering heat or/and moisture in different conditions. This process is important for maintaining acceptable indoor air quality (IAQ), reducing costs associated with energy consumption in existing systems and avoiding oversizing in new projects. This paper presents a review of the literature regarding energy recovery equipment applied in air conditioning systems, showing the current state-of-the-art in this technology, encompassing the most used types of such equipment. This review covers experimental field projects, computer simulations and applications of different approaches for each type of equipment. Also, this paper presents the relationship between energy efficiency codes and technologies for energy recovery and variable air flow, aiming to show that such technologies have considerable effects not only on energy savings, but also on the scoring system for the Leadership in Energy and Environmental Design (LEED) certification. This equipment is promising for buildings to achieve the Net Zero Energy Building (NZEB) rating. Finally, the application of energy recovery systems is addressed from the perspective of pandemic scenarios, showing the main recommendations for the implementation and operation of this equipment.

Keywords: Energy recovery. IAQ. HVAC-R. Certification. Energy efficiency.

RESUMO

A recuperação de energia entre fluxos de ar é o processo de recuperação de calor e/ou umidade em diferentes condições. Esse processo é importante para manter a qualidade do ar interno (QAI) aceitável, reduzindo os custos associados ao consumo de energia em sistemas já existentes e evitar superdimensionamento em novos projetos. Este trabalho apresenta uma revisão bibliográfica sobre os principais equipamentos de recuperação de energia aplicados em sistemas de ar condicionado, mostrando o que há de mais moderno nessa tecnologia, englobando os tipos de equipamentos mais utilizados. Esta revisão abrange projetos experimentais de campo, simulações computacionais e aplicações de diferentes abordagens para cada tipo de equipamento. Ainda, este trabalho apresenta a relação entre códigos de eficiência energética e tecnologias de recuperação de energia e fluxo de ar variável, visando mostrar que tais tecnologias têm efeitos consideráveis não só na economia de energia, mas também no sistema de pontuação para a certificação *Leadership in Energy and Environmental Design* (LEED). Esses equipamentos se mostram promissores para as edificações alcançarem a classificação de Net Zero Energy Building (NZEB). Por fim, a aplicação dos sistemas de recuperação de energia é abordada sob a ótica de cenários pandêmicos, mostrando as principais recomendações para a implementação e operação desses equipamentos.

Palavras-chave: Recuperação de energia. QAI. AVAC-R. Certificação. Eficiência energética.

1 INTRODUCTION

In the present scenario, the need for energy conservation has increased attention in the field of scientific and technological research. Associated with this fact, discussions about the environmental impacts caused by uncontrolled growth of populations became more constant. Thus, several studies in various areas of science have been developed with the aim of seeking technologies that increase the efficiency of current systems and reduce the environmental impacts caused.

One of the main concerns of a country is the energy issue. According to data from the International Energy Agency (OECD/IEA, 2018), the energy demand for space cooling in buildings was around 32 TWh, representing 7.7% of total building final energy use in 2016. Thus, more efficient solutions are also required in many engineering systems to maintain the same functions and exceeds the efficiency demanded by previous systems. This is the case in Heating, Ventilation, Air Conditioning (HVAC) systems that are required to provide thermal comfort and indoor air quality in buildings or offices, with reasonable costs of installation, maintenance and operation.

The current HVAC projects must consider several criteria aimed at efficiency and reduced environmental impact. Among those, the criteria for partial operation of the system in thermal loads, requiring systems capable of modulating their operation, may efficiently be cited. Systems that do not operate at partial loads generate a high energy consumption, since they only operate at full load, even if the environment does not demand this thermal load. In addition to the concern of the operation at partial loads, another important requirement is the use of means to ensure the regeneration of heat that would initially be rejected to the environment. In this requirement, it's possible to find the energy recovery equipment allocated between the exhaust air and outside air that enters the environment.

Another important requirement in HVAC systems is the indoor air quality. Although not recent, with the standardization of parameters of comfort and air quality by Brazilian and international institutes, this subject has come increasingly under discussion, present in almost all projects to thermal comfort. Accordingly, in view that the introduction of external air in the system causes an increase in the thermal load due to the parameters of dry bulb temperature and absolute humidity, studies regarding the flowrates of air required are very important about energy efficiency aspects. This situation leads to the use of systems with variable flow of outdoor air.

Thus, the use of traditional HVAC systems that require high rates of outdoor air will also require greater ventilation power to meet the demands of the building. Along with this fact, larger air handlers, with larger coils and fans will be required. This leads to an oversized system that does not press the requirements of energy conservation. Therefore, studies addressing the analysis of optimum outdoor air flow, still associated with energy recovery, have great potential for significant cost savings in the design, operation and maintenance phases of the system.

2 ENERGY CODES AND ERVs

The energy consumption of an office or commercial building during its operational lifetime is significantly greater than the energy built in materials and construction (Claridge et al 1994). Thus, several efforts have been used to give the building and its facilities a higher level of efficiency, meeting national and international standards, defined by laws, rules, codes, strategies, policies or certification systems. Among the various existing facilities, HVAC systems are the largest energy consumers of nonresidential buildings, accounting for about 10-20% of the final energy consumption in developed countries (Perez-Lombard et al, 2008).

Perez-Lombard et al (2011) analyzed the development of energy efficiency codes of HVAC systems for buildings in relation to its scope and compliance. Twelve major energy efficiency codes for buildings around the world were analyzed. Also, six categories of prescriptive requirements that would serve as the basis for an efficient selection of several components of HVAC systems were classified: a) minimum equipment efficiency, b) fluid distribution systems, c) control systems; d) outside air ventilation e) energy recovery f) economizer cycle.

The outside air ventilation is a requirement for obtaining an acceptable IAQ. The rules generally define a minimum flow of outside air and filtering level to reduce the concentration of air contaminants to acceptable levels. Ventilation systems generally use thermal energy to treat the outside air and electricity for filtration and air distribution in the conditioned spaces, hence the IAQ requirements are directly related to energy efficiency in HVAC systems. Thus, the higher the rate of air exchange, higher energy consumption and operating costs of HVAC systems. Thus, given that the flow of outside air is usually sized based on the conditioned space area and number of occupants, the minimum rates are estimated considering the maximum number of occupants. For this reason, it is recommended that HVAC systems are adjustable, so that ventilation rates can be reduced according to demand, avoiding excessive ventilation (Perez-Lombard et al, 2011).

In general, the thermal cooling or heating loads of outside air ventilation are from 20% to 40% of the total thermal load for commercial buildings (ASHRAE, 1997). Fortunately, a large fraction of the energy required to condition outside air can be recovered if energy recovery ventilation (ERV) solutions are used (Dorer and Breer, 1998).

Technologies for energy recovery, another category addressed normative prescription, are well known and widely used as a measure of energy efficiency both in construction and industry. The main process for energy recovery in HVAC installations is the heat recovery from the exhaust air. Outside air enters the building at external climatic conditions and is exhausted at internal conditions. This process thus requires the addition or extraction of thermal load. The thermal energy of the exhaust air can be recovered to preheat or cool the outside air ventilation, resulting in a reduction in the thermal load due to ventilation.

3 LEED CREDITS TO SYSTEMS WITH ERVs AND NZEB PROJECTS

The specification and use of recovery energy and variable outdoor air flow systems can contribute significantly to obtaining LEED, credits on projects for New Construction, Existing Buildings, Commercial Interiors Buildings and others. These systems can contribute up to three categories: i) Indoor Environmental Quality, ii) Energy & Atmosphere, iii) Innovation Priority Credits (USGBC, 20--).

Each category has its own requirements for obtaining LEED score, which range from 1 to 3 points depending on the requirement met. The requirements range from adopting management strategies such as having certified professionals and an indoor air quality plan, to using natural ventilation design methods, monitoring carbon dioxide and air filtration, to reducing noise and optimizing the system itself.

The highest point attainment, which can reach up to 18 points, is in the compliance requirement, where there are 3 options: 1) Energy Performance Compliance; 2) Prescriptive Compliance: ASHRAE Advanced Energy Design Guide and 3) Systems

Optimization.

ERV systems have gained significant attention in recent years as a valuable strategy to attain Net Zero Energy Buildings (NZEB). An ERV system helps reduce a building's energy consumption by recovering heat or coolness from the exhaust air and using it to pre-condition the incoming fresh air. This results in energy savings on heating, ventilation, and air conditioning (HVAC) systems, which account for a significant portion of a building's total energy consumption.

According to a study by Choudhary et al. (2021), ERV systems can reduce the energy consumption of HVAC systems by up to 40%. The authors also found that the use of ERV systems can improve indoor air quality and reduce the carbon footprint of buildings. Similarly, a study by Hasan et al. (2020) found that incorporating ERV systems in NZEB designs can help achieve energy efficiency, reduce operational costs, and improve indoor air quality.

Another study by Cho and Kim (2020) analyzed the potential energy savings of an ERV system in a multi-family residential building in South Korea. The authors found that the use of an ERV system resulted in a 25% reduction in energy consumption and a 22% reduction in carbon dioxide emissions.

Overall, the use of ERV systems is a promising strategy for achieving NZEBs. They can significantly reduce a building's energy consumption and improve indoor air quality. However, the success of ERV systems largely depends on proper design, installation, and maintenance. It is important to consult with experts and follow guidelines to ensure optimal performance and energy savings.

4 AIR-TO-AIR ENERGY RECOVERY EQUIPMENT

ERV systems are an energy-efficient and sustainable solution for improving indoor air quality while reducing a building's energy consumption. These systems work by exchanging heat and moisture between the incoming and outgoing air streams, thereby reducing the load on heating and cooling systems. ERV systems are becoming increasingly popular in commercial and residential buildings due to their many benefits, including improved IAQ, reduced energy consumption, and low cost.

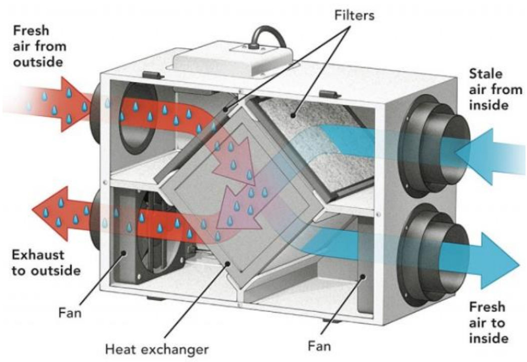
There are several types of ERV systems available, each with its own set of features and benefits. The most common types include (as shown in Fig 1):

- Plate Heat Exchanger: Uses a flat plate to transfer heat between the incoming and outgoing air streams. The plates are stacked together in a compact design, making them ideal for small spaces. Plate heat exchangers are highly efficient, easy to maintain, and are suitable for a wide range of applications. Some equipment use permeable membranes, which also allow the moisture transference between the air streams.
- Rotary Heat Exchanger: This type of ERV system uses a rotating wheel or drum to transfer heat and moisture between the incoming and outgoing air streams. They are highly efficient, durable, and require minimal maintenance.
- Run-Around Coil: This type of ERV system uses two separate coils to transfer heat between the incoming and outgoing air streams. The two coils are connected by a set of pipes, allowing for the transfer of heat and moisture between them.

Run-around coil systems are highly efficient and are suitable for a wide range of applications.

- Heat Pipe: A heat pipe ERV system uses a sealed tube filled with a refrigerant to transfer heat between the incoming and outgoing air streams. Heat pipe systems are highly efficient and are suitable for a wide range of applications.

When choosing an ERV system, it is important to consider factors such as the building's size, the number of occupants, and climate. Additionally, it is important to choose a system that is easy to maintain and repair, as this will help to ensure the longevity and efficiency of the system.



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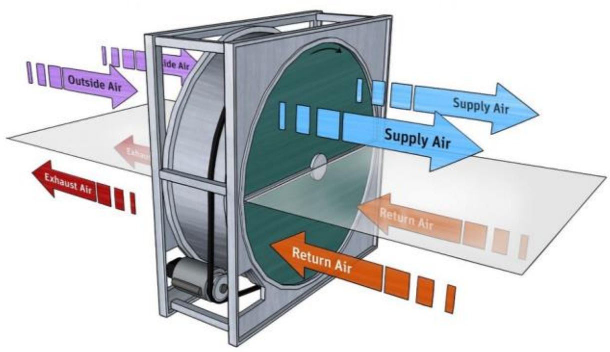

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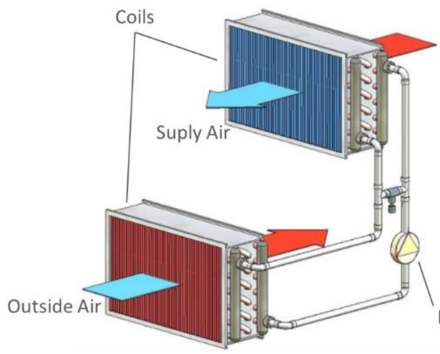

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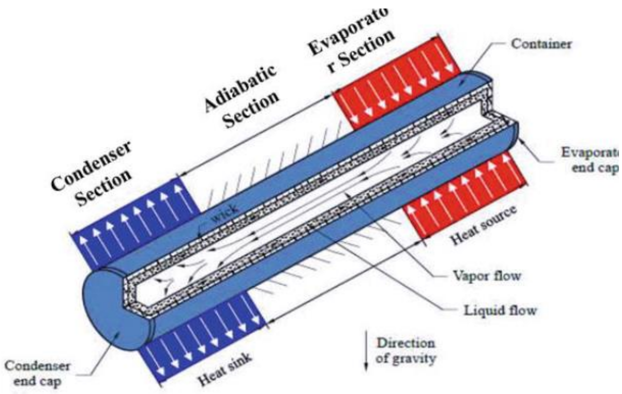

(d)

Fig 1. Main ERVs types: a) Plate Heat Exchanger (EP Sales Inc., 2023), b) Rotary Heat Exchanger, (Soundman2020, 2023) c) Run-Around Coil (The Renewable Energy Hub, 2023) and d) Heat Pipe (IntechOpen, 2023).

4.1 Heat Recovery

In the past, studies were focused only on the recovery of sensible energy, which gave rise to the first HRVs. With the study and development of new techniques and materials, ERVs were created, equipment capable of recovering both sensible energy and energy in latent form, present in air humidity. Although ERVs are more efficient depending on the application and climate of the place where they are installed, HRVs show very satisfactory results.

Dhital et al (1995) investigated the effects of run-around heat exchangers in energy consumption and cost analysis of energy life cycle of a typical office building. The simulations were made in four American cities and the results showed annual energy savings of up to 4.8%, associated with a reduction of up to 8% in capacity chillers.

Kim et al (2012) determined schedules of operation of an HRV in order to maximize energy savings in large residential buildings. The measured results showed that the energy consumption of each building was reduced when the HRV was operated in accordance with the recommended ventilation rates and in certain comfort temperature ranges. The simulations showed an annual contribution to energy savings of 9.45% for heating loads and 8.8% for cooling loads, when the HRV operated intermittently.

Yaici et al (2013) numerically analyzed the energy recovery in ERVs and HRVs with membranes using CFD software. The proposed model includes mechanisms for heat and mass transfer for laminar flow in order to investigate the thermal performance of such systems. Equipment with parallel flows in the same direction and counter current, in summer and winter seasons in Canada were analyzed. The numerical results confirm the superiority in efficiency of the counter current flow device. The season also showed significant effect on the performance of HRV and power consumed ventilation, whose value was approximately 18% higher in summer compared to winter.

4.2 Energy Recovery

In recent years, increasing attention has been given to energy recovery, also called enthalpy recovery, in which both the sensible and latent heat are recovered. The enthalpy recovery technique is mainly based on alternating sorption processes (adsorption and absorption) and regeneration, from the use of desiccant material, or in the form of closed cyclic beds (beds packed cycling) (San, 1993) or rotary enthalpy wheels.

Klein et al (1990) developed a computer model of an air-to-air enthalpy exchanger with a solid desiccant. Correlations for which the enthalpy exchanger efficiency would be maximum were established, and defined the function based only on the number of transfer units (NTU). The correlations presented are efficient for certain operating conditions where there is enthalpy exchange.

Li et al (2005) have proposed a new type of outside air unit that is basically composed by a desiccant liquid enthalpy recovery and a refrigeration cycle of small capacity. Experimental tests of this unit installed in a hospital had an energy efficiency ratio (EER) ranging between 6.3-7.3 in summer and 4.7-5.0 in winter. The equipment proved reliable in eliminating wet surfaces in air conditioning systems, providing better air quality inside.

Fauchoux et al (2007) showed the undesirable impacts of an ERV (enthalpy wheel) without running operation control cooling loads in cold and mild climates (Vancouver and Saskatoon, Canada). The results showed that cooling energy consumption can be reduced by applying a temperature-based control strategy. Still, it was verified that the use of ERV in these cities gave improvements in indoor air quality and reducing humidity.

Yanming et al (2009) studied the applicability of ERV systems in China. Because of differences in local climates between southern and northern China, the fractions of sensible and latent heat per unit flow of outside air are different between regions, as well as the overall efficiency of energy recovery devices. The analysis verified the applicability of ERV systems in China in different operating conditions. The results showed that the efficiency of ERVs is significantly higher than the efficiency of heat recovery only in applications in controlled ventilation systems in buildings with small emission of moisture throughout the year. Furthermore, the relationship between the consumption of sensible and latent energy is the key factor for the use of an ERV or an HRV, since these consumptions depend on the climate, the design conditions of the internal air and approaches used for the characterization of outside air. Thus, it was shown that for hot and humid climates the use of ERV is better than the HRV.

Rasouli et al (2010) studied the applicability and defining a strategy for optimal ERV devices in different climatic conditions control. The impacts of the use of ERV in annual energy consumption for cooling and heating were investigated using a model of a ten floors commercial building in four American cities. The results showed that the recovery of heat and moisture can lead to significant reductions in annual energy consumption for heating, over 40 % savings. Still, one ERV operating under a great control strategy was able to save over 20% in annual energy consumption for cooling loads.

Liu et al (2010) analyzed the efficiency of an ERV in different climatic conditions and its performance in energy savings in residential apartments. Nowadays. Based on the relationships between the sensible, latent and total efficiencies, the equations with weighted coefficients that describe the performance of the ERV in different climate zones in China were analyzed. According to climate information, the total efficiency of the device depends mainly on the sensible efficiency in winter and on the latent efficiency in summer. Thus, the performance in energy savings were studied in five different climatic conditions, also the overall efficiency, the ventilation power consumed and certain variations in the flow of outside air. The results showed that fan power and also the percentage of energy saved increases with the increase in external air ventilation.

4.2.1 Systems that use Enthalpy Wheels

Stiesch et al (1995) studied the rotary enthalpy wheels applied in buildings, with the aim of analyzing their annual efficiency. Office buildings were analyzed in three U.S. cities, with ventilation rate according to ASHRAE standard at the time (20 cfm / person). The energy savings were analyzed, both for heating and for cooling, for 15 years, for enthalpy exchangers and sensible heat exchangers only. The accumulated savings were approximately $ 28,000 to $ 38,000 for the enthalpy exchanger and from $ 7,000 to $ 24,000 for the sensible heat exchanger.

Simonson and Besant (1999a) presented the fundamental dimensionless groups for rotary wheels air to air exchangers that transfer sensible heat and water vapor. These groups are derived from the governing equations of heat and mass transfer coupled. Simonson and Besant (1999b) have given the physical meaning for these dimensionless groups and used them to develop correlations of efficiency for energy wheels. The correlations presented in efficiency allow the designer to predict the efficiency of sensible heat, latent and total energy when operating conditions are known. The results showed that the total efficiency can be greater than 70%.

4.2.2 Systems that use Membranes

In addition to the enthalpy wheel, there is another type of enthalpy recovery technology based on membrane plates, which is a variation of the technology of recovering sensible heat named fixed plates. Membranes have been widely used in separation processes moisture/air in industrial processes over the years (Pan et al, 1978; Asaeda and Du, 1986; Wang et al, 1992; Cha et al, 1996). The membrane system is based on the use of novel hydrophilic membranes, allowing the heat and moisture to be transferred simultaneously, unlike the traditional fixed plates exchanger which exchange only sensible heat. They are easy to build and install and require little maintenance.

Zhang (2014) investigated the feasibility of an integrated HRV and ERV system, namely HERV, with a built-in economizer used in the residencial sector to reduce dependency on furnace and air conditioning systems. The potential of integrated heat and ERV was evaluated based on its calculated operating cost ratio (OCR) and its payback period. Results collected for Vancouver and Toronto, corresponding to temperate and continental climate, indicated that the OCRs of the HERV were four times smaller than the ERVs, meaning that the proposed system was cost-efficient. It was also evidenced that the high demand on the economizer resulted in higher energy saving and shorter payback period of the system. In conclusion, the integrated HERV system with a built-in economizer could be a feasible option for both temperate and continental climates.

4.3 HRVs and ERVs Benefits

One of the main goals of ERV systems is to save operational and implementation costs. Therefore, Table 1 compiles some economic studies about works quoted in the previous sections, in sensible and/or latent form, presenting the potential for operational cost reduction.

Table 1 – HRVs and ERVs benefits.

Author	Type of study	Equipment type	Benefits
Dhital et al (1995)	Simulation	Run-around heat exchanger	Up to 4,8%
Stiesch et al (1995)	Experimental	Enthalpy Wheel	\$28,000 - \$38,000 (enthalpy exchanger) \$7,000 - \$24,000 (sensible heat exchanger)
Li et al (2005)	Experimental	Liquid enthalpy recovery	4.7 - 5.0 ERR in winter 6.3 - 7.3 ERR in summer
Rasouli et al (2010)	Simulation	ERV	40% for heating 20% for cooling
Kim et al (2012)	Simulation	HRV	9.45% for heating 8.8% for cooling

5 OPERATION OF ERVs IN PANDEMIC SCENARIOS

The COVID-19 pandemic has had a significant impact on HVAC-R systems, as one of the primary modes of virus transmission is through the air. Many international institutions in the field have identified increased outdoor air ventilation in enclosed spaces to contain the spread of cases.

Although outdoor air has the necessary quality for indoor environments, it often does not have the ideal conditions to ensure occupant thermal comfort, necessitating air conditioning before it is introduced into the space, resulting in an increase in thermal load. Thus, in addition to the cost of higher energy demand, increasing the air exchange rate is accompanied by the costs of purchasing and implementing new solutions (Agopian, 2020).

It is important to note the need for filtering outdoor air to reduce contaminants and particulates that serve as vectors for virus transport. Therefore, the need arises for the use of energy recovery systems to reduce the energy demand of existing HVAC installations or even avoid oversizing in new buildings, while promoting occupant health.

Although it is an important means of combating infections, ASHRAE has recommendations for the use of ERVs in epidemic scenarios (ASHRAE, 2020). In general, the institution remains favorable to the use of these equipment. It is worth noting that, if possible, 100% outdoor air flow should be used. Among the most general recommended changes are: the use of filters with higher efficiency; proper positioning of fans and use of appropriate seals and purgers to ensure system balancing; and finally, proper installation, configuration, and maintenance of ERVs.

Smith and Johnson (2020) examine the impact of the COVID-19 pandemic on the energy efficiency of commercial buildings, including the role of ERV systems. It highlights how the reduced occupancy and altered usage patterns during the pandemic have affected the design and operation of ERV systems, leading to potential energy savings but also emphasizing the need for adaptive controls to optimize ventilation rates and indoor air quality.

Brown and White (2021) explores strategies for adapting HVAC systems, particularly ERV systems, to the new normal after the COVID-19 pandemic. It emphasizes the importance of improved air filtration and the need to balance energy efficiency with enhanced indoor air quality. The authors propose the integration of high-efficiency filters and UV germicidal irradiation within ERV systems to mitigate the spread of airborne pathogens.

In a recent study from Lee and Kim (2023) investigates the impact of the COVID-19 pandemic on the design of ERV systems. It discusses the increased focus on the design of ERV systems to accommodate higher ventilation rates, improved filtration, and the integration of air disinfection technologies. The authors propose advanced modeling and simulation techniques to optimize the design and performance of ERV systems in the context of post-pandemic indoor environments.

As it can be seen the COVID-19 pandemic has prompted significant considerations and adaptations in the design, operation, and maintenance of ERV systems. Recent papers emphasize the need for enhanced air filtration, increased outdoor air supply, and improved ventilation rates to ensure optimal indoor air quality and minimize the potential transmission of respiratory diseases. Integration of advanced technologies such as UV germicidal irradiation and high-efficiency filters within ERV systems has been proposed to mitigate the spread of airborne pathogens. Further research and development are essential to optimize the design and performance of ERV systems in the context of post-pandemic indoor environments, considering both energy efficiency and health-related factors.

6 CONCLUSIONS

In the early 90s studies on the applicability of energy recovery equipment in HVAC systems focused on HRVs, whose implementation was simple. Studies showed savings in annual operating costs up to 24%.

After this period, research on ERVs started, including analysis of heat and mass transfer mechanisms in the main enthalpy recovery equipment, enthalpy wheels (using desiccant materials) and membrane plates equipment (which use permeable membranes). From these analyses, some phenomena, such as condensation and freezing, under certain weather conditions were verified during the operation. This fact required the development of appropriate materials and other processes, so that these effects were mitigated.

At the same time, sensible, latent and total efficiencies were analyzed for each type of equipment. It has been found that the efficiency varies depending on the operating conditions (temperature and humidity) of the airstream. Results presented total efficiency values above 70% for some ERVs.

More recent studies showed the influence of climatic conditions in the operation of ERVs, energy and financial effects on the operation of air conditioning systems. The performance of equipment was evaluated in several locations, seasons, and different weather conditions. Still, some control strategies were used, such as indoor temperature-based, indoors humidity and enthalpy of the exhaust airstream.

Annual energy savings results have been presented up to 40%, with payback periods less than three years, for cooling and heating loads, using ERVs under certain control strategies. Studies have indicated that under certain climatic conditions, ERVs have better performance than HRVs. In cold and dry climates, ERVs are effective in preventing the reduction of internal moisture, retaining the moisture to the outside airstream. In hot and humid climates, ERVs provide a better humidity control, and reduce the heat load of the outside air, reducing the electricity consumption of air conditioning systems. The use of HRVs is more significant when there is a large temperature difference between the exhaust airstream and the outside airstream.

The research also shows that ERVs can play a significant role in achieving NZEB goals, and their efficient use in buildings is recommended by several prominent organizations in the field. By conducting a thorough energy analysis, optimizing the building envelope, and integrating with other renewable energy systems, buildings can realize significant energy savings and contribute to a more sustainable future.

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