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Energetic, economic and environmental analysis of a health-care facility HVAC system equipped with a run-around membrane energy exchanger

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ABSTRACT

Run-Around Membrane Energy Exchanger (RAMEE) is a novel heat and moisture recovery system that consists of two separate supply and exhaust exchangers coupled with an aqueous salt solution flow. The salt solution transfers energy (heat and moisture) in a closed loop between outdoor ventilation air and the exhaust air from buildings. The system performance is a function of the flow rate of the salt solution and ventilation air and the outdoor air conditions. The dependency of system performance on the solution flow rate and the outdoor conditions requires adjustment of the appropriate flow rate which gives the optimal system performance at any specific outdoor condition. In this paper, the RAMEE is simulated for a hospital building in four different climates using TRNSYS and MATLAB computer programs. The steady-state RAMEE can reduce the annual heating energy by 60% in cold climates and annual cooling energy by 15–20% in hot climates. The RAMEE has an immediate payback in cold climates and a 1 to 3-year payback in hot climates depending on the pressure drop across the exchangers. Finally, the RAMEE reduces greenhouse gas emission (CO_2-equivalent) by 25% and 10% in cold climates and hot climates, respectively.

1. Introduction

Energy Recovery Ventilators (ERVs) have been widely used to reduce the energy required to condition the ventilation air. ERVs transfer heat (heat recovery systems) or heat and moisture (energy recovery systems) between conditioned exhaust air and outdoor ventilation air. Heat pipes, fixed-plate heat exchangers and heat wheels are examples of the heat recovery systems, and energy wheels coated with desiccant [1] and flat-plate exchangers made of water permeable membranes [2] are examples of energy recovery systems. The main disadvantage of present ERVs is that some are unable to transfer moisture. Also, they all require a side-by-side installation of the supply and exhaust ducts. This may impose higher ducting costs to install the supply and the exhaust adjacent. Adjacent air inlet and exhaust increases the probability of contaminant transfer from exhaust air to the supply air, especially for polluted spaces (e.g., some laboratories) and highly sensitive areas (e.g., surgery room).

A novel Run-Around Membrane Energy Exchanger (RAMEE) that consists of two separate supply and exhaust exchangers was presented by [3]. For this system, each exchanger is a flat-plate energy exchanger constructed with water vapor permeable membranes that allow the transfer of heat and water vapor. Such a system is suitable for retrofitting buildings even where the supply and exhaust ducts are not adjacent. Research has been done on (a) developing numerical models of the RAMEE [4–7], (b) predicting the system performance at different conditions using an artificial neural network [8], (c) investigating the crystallization risk of the salt solution [9] and (d) obtaining experimental data on RAMEE performance for two prototypes [10,11].

ASHRAE Standard 170-2008 [12], ventilation of health-care facilities, has recommended much higher rates of outdoor air flow compared to ASHRAE 62-2010 [13] for ventilation rates of other types of buildings. For example, a typical office building may require about 0.5 ACH ventilation air [14], while a minimum outdoor air change of 2–6 ACH is recommended for health-care facilities. The energy consumption due to conditioning of ventilation air increases as the ventilation rate increases [15–17]. For instance [15], showed that, without energy recovery, increasing the ventilation rate of a building in Washington DC from 0 to 10 (l/s person) (corresponding to about 0.37 ACH) increases the annual energy consumption of the HVAC system by 14%. This result is in a good agreement with Commercial Building Energy Consumption Survey (CBECS) in 2003 [18] that reported the health-care facilities as the second highest energy-intense commercial buildings with 1472 MJ/m^2 year HVAC system energy consumption. This is 2.8 times higher than

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Nomenclature

A	membrane surface area in the exchanger (m^2)
C_p	heat capacity (J/kg K)
Cr^*	ratio of salt solution heat capacity to that of the air (dimensionless group)
H^*	operating condition factor (dimensionless group)
h	enthalpy (J/kg)
h_{fg}	enthalpy of phase change (J/kg)
NTU	number of transfer units (dimensionless group)
NTU_m	number of mass transfer units (dimensionless group)
TMY	Typical Meteorological Year
U	overall convective heat transfer coefficient (W/m^2 K)
U'	overall convective mass transfer coefficient (kg/m^2 s)
ε	effectiveness (%)

Subscripts

in	refers to indoor condition (temperature, humidity ratio or enthalpy)
l	latent
out	refers to outdoor condition (temperature, humidity ratio or enthalpy)
s	sensible
t	total

the average HVAC energy consumption in US office buildings (i.e., 533 MJ/m^2 year) [18]. Although the ventilation energy is very significant in hospitals, most of the recent research has focused on energy-saving technologies in office spaces, residential buildings and educational facilities. Rasouli et al. studied [19] the application of a RAMEE in an office building HVAC system. The TRNSYS simulation of the RAMEE showed savings of about 30–40% for heating energy in cold climates (Saskatoon and Chicago) and 8–15% for cooling energy in hot climates (Miami and Phoenix). This paper presents the energy saving with a RAMEE for a hospital building (as the second case study of the RAMEE). An overview of the RAMEE is presented and the findings of [19] regarding the control and operation of the RAMEE are implemented when it operates in a hospital building. This paper presents the energy savings, Life-Cycle Cost (LCC) analysis and Life Cycle Assessment (LCA) of the RAMEE in the hospital over a 15-year life-cycle for four different climates.

2. Methods

In this paper, the building and its HVAC system will be simulated using the TRNSYS building energy simulation tool [20] equipped with the Second version of TESS libraries [21]. The RAMEE will be simulated using the Artificial Neural Network (ANN) developed by Akbari et al. (2012) The RAMEE performance (effectiveness values) for each hour of the year will be calculated using MATLAB [22] and used as input data for TRNSYS. Fig. 1 contains a schematic of the building, its HVAC system and the RAMEE. The methods used to model these components will be presented in the following sections.

2.1. Building description

A 3-storey hospital with total floor area of 3150 m^2 is chosen for this study. The thermal resistance of walls, roof and the floor are 2.72, 3.64 and 3.45 (m^2 K/W), respectively. The building has double-glazed windows, about 31 (W/m^2) of internal heat gains (includes lighting, cooking and equipment loads based on CBECS data [18]) and an occupant density of 5 People/100 m^2. The building is simulated in Saskatoon (Saskatchewan, Canada), Chicago (Illinois), Miami (Florida) and Phoenix (Arizona) as the four North American cities which represent different climatic conditions. Chicago, Miami and Phoenix are chosen as representatives of cool-humid, hot-humid and hot-dry climates, respectively, based on [23] climatic classifications for building energy analysis. Saskatoon is chosen to represent a cold climate because heating is required for a large fraction of a year [19].

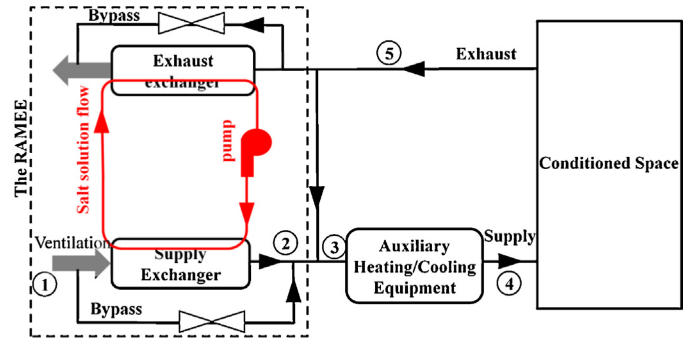

Fig. 1. Schematic view of the HVAC system equipped with RAMEE.

2.2. HVAC system description

A variable air volume HVAC system is used to maintain the indoor temperature of the building within ASHRAE comfort zone (i.e., 24 °C in summer and 22 °C in winter [24]), and the indoor humidity below 60% RH. The day–time (6:00–22:00) ventilation rate is set at 2 ACH as an average rate recommended by ASHRAE ventilation standard for different spaces in health-care facilities [12] and is reduced to 1.3 ACH during the night (22:00–6:00) when a lower occupancy is expected. A total air change rate of 3 times the ventilation rate is always maintained for the space (as recommended by ASHRAE for most of health-care spaces [12]).

2.3. Run-Around Membrane Energy Exchanger (RAMEE)

The RAMEE consists of two separate exchangers – one in the supply duct and one in the exhaust duct, as shown in Fig. 1. Each exchanger is a flat-plate, liquid-to-air membrane energy exchanger (LAMEE) that is made using water vapor permeable membranes. The LAMEEs are coupled with an aqueous salt solution that is pumped in a closed loop and transfers both heat and moisture between the exhaust and ventilation airstreams. Such a design has the capability of transferring both heat and moisture in new and retrofit applications where the ducts are not adjacent.

During the winter, the mixture of outdoor ventilation air and the return air is heated by the heating system up to the desired supply temperature. In the absence of the RAMEE, the ventilation air temperature is equal to the outdoor temperature. But, the RAMEE transfers energy (heat and moisture) from the exhaust air to the supply air. Such an energy transfer increases the ventilation air temperature and consequently lowers the heating energy consumption of the heating system. During the summer, the mixture of outdoor ventilation air and the return is cooled and also dehumidified when the humidity of the mixture (state 3) is unable to maintain the indoor humidity within comfort zone (i.e., below 60% RH; [24]). In the summer, RAMEE transfers heat and moisture from warm–humid outdoor air to the cool–dry exhaust air. This reduces the enthalpy of the ventilation air and consequently decreases the cooling energy for the auxiliary cooling system. The air and salt solution can flow in counter flow, cross flow or counter/cross flow