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Applicability of rotary thermal wheels to hot and humid climates

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Abstract

Buildings in hot and humid climates spend more than 60% of the total energy cost for Air Conditioning and Mechanical Ventilation Systems (ACMV) to maintain the required thermal comfort for occupants. The required air conditioning load drastically increases with the fresh air demand of the conditioned space which leads to excessive energy bills for central air conditioning systems of buildings, particularly in hot and humid climates. Therefore, this study mainly focuses to investigate and evaluate the applicability of rotary thermal wheel to recover the energy available on the return air of the air handling unit (AHU) of the central air conditioning systems in hot and humid climates. The results reveal that, the percentage energy saving due to the rotary thermal wheel increases when the temperature and the relative humidity of outdoor fresh air increases, and also when Coefficient of Performance (COP) of the central chiller decreases. Moreover, case studies show that the simple payback period of a building which is supplied with 20% fresh air varies from 1.1 years to 4 years depending on the fresh air mass flow rate. Results reveal that the use of rotary thermals in the hot and humid climates is highly recommended. © 2019 Published by Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

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Keywords: Rotary thermal wheel; Energy recovery; Air Handling Unit (AHU); Hot and humid climates; Air conditioning

1. Introduction

Installation of an air conditioning system is essential to maintain the required thermal comfort and the indoor air quality of the occupants in a given conditioned space. Generally, the buildings in developed countries consume around 20%–40% of the total energy consumption of those countries. Perez-Lombard et al. [1] highlighted that more than 45% of the total energy of an office building is usually consumed by the Heating, Ventilation and Air Conditioning (HVAC) system in the developed countries. Hegana and Kulkarni [2] emphasized that the buildings in the tropical region spend more than 60% of the total energy bill for the Air Conditioning and Mechanical Ventilation System (ACMV).

Buildings in the hot and humid climates spend even more amount of energy for the ACMV system. Therefore, it is encouraged to implement an energy recovery system to recover the heat that would otherwise be wasted reduce

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Nomenclature	
Q	Heat transferred
$\dot{m}_{R.A.}$	Return air mass flow rate
$\dot{m}_{F.A.}$	Fresh air mass flow rate
hout	Enthalpy of outlet flow
h _{in} -	Enthalpy of inlet flow
$\varepsilon_{R.T.W.}$	Effectiveness of the rotary thermal wheel

the energy consumption. 'Rotary thermal wheels' have been identified as the best, among the available heat recovery techniques i.e. heat pipes, run-around coils, thermosiphon, twin-towers, to be used in ACMV systems [3]. Rotary thermal wheel is a cylindrical device which contains deep packed small air passages parallel to the axial direction of the cylinder. Normally the shape of these air passages are sinusoidal or triangular. This cylindrical device has a length usually about 10–25 cm.

Rotary wheels can be classified as sensible wheels (heat wheel) and the enthalpy wheels (energy wheel). Sensible wheels only exchange the sensible heat between the two air streams while changing the dry bulb temperatures, whereas, enthalpy wheel exchange both the sensible and latent heat between the two air streams while changing both the dry bulb temperatures and the moisture ratios [4]. Among rotary wheels, enthalpy wheels are capable of transferring both latent and sensible heat which could be much applicable for hot and humid climates. Enthalpy wheels consists of desiccant material layer which attracts the water vapor includes in the fresh air stream [5]. Rotary wheels rotates between two air flows and exchanges heat among them. The surface area exposed to airflow in rotary thermal wheels is in between $300-3300 \text{ m}^2/\text{m}^3$ [5].

Rotary thermal wheel consists of a wheel matrix made of smooth Aluminum channels serves as a storage medium and a motor to drive the wheel [6]. The wheel rotates slowly at about 8–15 RPM (revolution per minute). As it rotates, the matrix material in the warm air stream absorbs heat from the warm air (outside air in Fig. 1) and releases the absorbed heat to the cooler air stream (extract air stream in Fig. 1a) which flows through the wheel in the opposite direction [7]. Using this device, the hot and humid atmospheric air can be cooled and dehumidified compared to the atmospheric temperature and moisture ratio by applying a desiccant coating on the matrix material.



Fig. 1. a. Rotary thermal wheel and b. Central Air conditioning system including — AHU, chiller, conditioned space and the proposed rotary thermal wheel.

It was identified that the performance of the rotary thermal wheels have been analyzed in various methods i.e. mathematical modeling, CFD modeling and testing. Performance of the rotary wheels measures in terms of the effectiveness. O'Connor et al. [8] predicted the efficiencies of the rotary thermal wheels and showed that they are varied from 50%–85% depending on the matrix configuration, matrix materials and the rotational speed of the device. Heat storage matrix should be designed to obtain a trade-off between the pressure drop and the effectiveness, as the narrowed flow channels in the matrix would enhance the pressure drop and hence, the requirement of powerful blowers increase the electricity consumption. Leakage or the carryover of exhaust air into supply air stream should

be limited to less than 5% to ensure that the toxic or hazardous exhaust gases would not mix with the supply fresh air.

Several mathematical models are developed for the heat and moisture transfer in thermal wheels [9–11] and some of them have been partially validated using experimental setups [12–14]. Besant and Simonson [15] have performed an economic analysis considering the US winter and summer climatic conditions to calculate the energy saving and cost saving from rotary thermal wheels.

There are some drawbacks integrated with the rotary thermal wheels. Among them fresh air and exhaust air mixing is a significant factor that could be a problem when the air supply should be highly hygienic such as for hospitals. Another issue might be the additional pressure drop occurs due to the additional component in the system. According to ASHRAE handbook [16] the pressure drop lies in the range 100–300 Pa. Due to this additional fan power may be required.

Air mixing of rotary heat exchangers are named as Cross-Leakage [16]. This could occur in two mechanisms and are 'carryover' and 'seal leakage'. Carryover is the air mixing occurred due to trapped air volume inside the porous structure in the rotation motion. Seal leakage the air flow occurred from the exhaust side to fresh air side due to pressure difference in two air streams via the separation interface near the thermal wheel. This can be avoided by proper arrangement of fans and introducing purge sector to the device. Purge sector is a small conical region that connects exhaust and inlet air regions. Carryover can be reduced to less than 0.1% of the air flow by introducing of a purge section in the device. Normally purge sections are having an angle about 15 degrees [17]. In many applications recirculating small amount of air not concerned such as in office buildings but it is critical in laboratories, theaters, clean rooms and hospitals. The theoretical carryover is proportional to the wheel rotation speed and the wheel matrix structure (void volume 75%–95%) and it is below 5% of air flowrate in a section [16].

In this work the performance of thermal wheels are studied to obtain the overall performance of a thermal wheel integrated HVAC system. Also several case studies are done and simple payback periods have been calculated. In literature, it has been found that there exists a gap for analyzing the economic feasibility for hot and humid climates. This work would be a significant reference for HVAC designers in hot and humid climates to integrate thermal wheels to their designs.

2. Analytical study of rotary thermal wheels

It is essential to understand the energy saving potential and the simple payback period (SPP) of rotary thermal wheels for different environmental conditions and for a given application respectively. As shown in Fig. 2, the rotary thermal wheel should be placed before the Air Handling Unit (AHU) of the central air conditioning system. According to the ASHRAE standards, minimum of 20% fresh air should be provided for commercial office buildings to ensure the required indoor air quality is maintained. The amount of fresh air percentage varies depending on the application i.e., operation theaters of the hospitals require 100% fresh air. In the case of hot and humid climates, the cooling coil capacity of the AHU significantly increases with the increased fresh air requirement due to high outdoor temperatures and the moisture contents. As a result, the electricity consumption by the chiller also increases.

This works has been conducted for a thermal wheel without a purge section, while neglecting the carryover of the air flow. When calculating the payback period, the fan power increment due to introduction of thermal wheel has also been neglected.

Heat exchange between the two air streams in the rotary thermal wheel (for Steady State (S.S.) conditions) is,

$$Q_{rejected}$$
 by F.A. = $\varepsilon_{R.T.W.}.Q_{max}$ h/e between two streams (1)

$$\dot{m}_{F.A.}\left(h_{F.A.in} - h_{F.A.out}\right) = \varepsilon_{R.T.W.}.\dot{m}_{R.A.}\left(h_{F.A.in} - h_{R.A.in}\right) \tag{2}$$

All the enthalpy values should be obtained from the psychrometric charts.

$$Q_{reduction at the cooling coil} = Q_{rejected by F.A.}$$
 (3)

 $Q_{reduction at the c.c.} = \varepsilon_{c.c.} Q_{reduction of the cooling water}$ (4)

 $Q_{reduction of the c.water} = \varepsilon_{evap,h/e}. Q_{reduction at the evap.}$ (5)

Electricity saving at the compressor of the chiller,

$$W_{saving at the comp.inlet} = \frac{1}{COP} \left(\frac{Q_{reduction at the evap.}}{\varepsilon_{evap.h/e}} \right)$$
(6)



Fig. 2. a. Energy Saving – (%) and Energy Saving – (kW/kg of fresh air) vs. Temperature of Atmospheric Fresh Air Temperature (°C) and b. Energy Saving – (%) and Energy Saving – (kW/kg of fresh air) vs. Temperature of Atmospheric Fresh Air Temperature (°C)

Eqs. (1) to (6) show that the electricity consumed by the compressor of the chiller can be significantly reduced by implementing a rotary thermal wheel prior to the AHU of the central air conditioning system. Following section summarizes the results of the energy analysis and economic analysis of rotary thermal wheels.

3. Results

As explained above, energy saving potential from a rotary thermal wheel has been calculated for different operating conditions. Fig. 2a shows the findings of the energy saving % and energy saving in kW per kg of fresh air, for different outdoor fresh air temperatures for steady state conditions. Calculations were performed assuming the relative humidity (%RH) of fresh air as 80%, effectiveness of the heat recovery wheel as 0.55, return air conditions are as 25 °C and 50%RH and the COP of the chiller as 4.0. It can be seen that the energy saving potential increases when increasing the fresh air temperatures.

Fig. 2b shows the energy saving potential from the rotary thermal wheels for different relative humidity's assuming the outdoor dry bulb temperature of fresh air as 30 °C, effectiveness of the heat recovery wheel as 0.55, return air conditions are as 25 °C and 50%RH and the COP of the chiller as 4.0. According to the findings, it can be seen that the energy recovery potential increases when increasing the relative humidity. Combination of Figs. 2 and 3 show that the energy utilization by the chiller of a central air conditioning system can be significantly reduces by implementing a rotary thermal wheel prior to the AHU.

Fig. 3 shows the energy saving potential by rotary thermal wheels for different chiller performances. It is taken for the fresh air conditions 30 °C and 80%Rh and conditioned air temperatures 25 °C and 50%Rh. Implementation of energy recovery wheels is always encouraged regardless of the chiller performance. However, the results show that the more energy recovery benefits and then the less payback period can be obtained by implementing the energy recovery wheel for low efficient chillers. As explained above, central air conditioning system operates on low efficient chillers in hot and humid climates are highly encouraged to operate with the assistance of energy recovery wheels.



Fig. 3. Energy Saving - (kW/kg of fresh air) vs. COP (Coefficient of Performance) of the Chiller.

4. Discussions

It was identified that effectiveness of a thermal wheel is in the range 50%–85% and, air mixing inside the wheel is less than 5%. An additional backpressure is imposed in the overall system due to the pressure drop in the matrix material of the wheel. This backpressure will enhance the required intake fan size and the respective electricity consumption of the fan.

It was calculated that the thermal wheels are able to recover 20%–40% of energy wasted in the system compared with a system not having thermal wheels in the system configuration. Moreover, it was shown that when the fresh air percentage to a particular facility increases, the energy recovery capability in that system also increases. Further, it has shown that when the fresh air temperature and relative humidity increases, the opportunity to recover the heat using a thermal wheel also increases. When considering the COP of the chillers in central air conditioning systems, the energy that could be recovered increases when the COP of the chiller reduces. Above case studies show that the simple payback period for a thermal wheel (enthalpy wheel) is in the range of 1–5 years. So the use of thermal wheel for hot and humid climates is highly recommended.

5. Conclusion

This work has analyzed the energy savings that could be obtained with the installation of thermal wheels to central air conditioning systems. Thermal wheels can be used to recover about 20%–40% of total energy consumption comparing with a configuration without having thermal wheels in operations. The amount of energy recovery

increases with the increment of fresh air temperature and the moisture content. Chillers with low COP values can recover more energy with the introduction of thermal wheels. The simple payback periods of 1–5 years can be possible by using the thermal wheels according to the above economic analysis.

6. Future works

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An energy wheel will be modeled using an available computational fluid dynamics (CFD) software to investigate the opportunities to enhance heat exchange rate. Modeling work will be further extended to identify the critical parameters of the rotary thermal wheels and then efficient energy will be designed, fabricated and tested. Finally, designers' guideline will be prepared to select the proper energy recovery wheel depending on the required fresh air mass flow rates and climatic conditions. A user friendly software will be prepared and make it freely available to provide the specifications of the required energy wheel and to provide the required economic figures of this energy recovery device.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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