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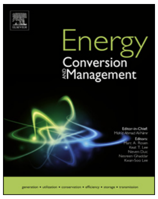

Energy analysis and multi-objective optimization of a novel exhaust air heat recovery system consisting of an air-based building integrated photovoltaic/thermal system and a thermal wheel

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ABSTRACT

This paper presents a feasibility investigation of integrating an air-based photovoltaic/thermal (PV/T) system with a thermal wheel (TW) system for residential applications. The innovative system is capable of pre-heating/pre-cooling the ambient fresh air in winter/summer as well as producing electricity. The performance of the system is numerically evaluated and compared with the conventional building integrated PV/T (BIPV/T) and TW systems. Then, a multi-objective optimization approach is utilized to find the optimum values of geometric and operating parameters in order to maximize the annual average effectiveness of the TW and the first-law efficiency of the BIPV/T collector. The performances of the optimized and un-optimized BIPV/T-TW systems are compared for a complete year. The results demonstrated that the BIPV/T-TW system has a better thermal performance compared with the BIPV/T and TW systems, while it has a slightly lower electrical performance compared with the BIPV/T system. Furthermore, it was found that the annual average first-law efficiency and TW effectiveness of the optimized BIPV/T-TW system is 118.3% and 59.7% higher than that of the un-optimized system.

A	heat transfer surface area of TW (m^2)
a_c	height of wheel channel (m)
$a_c^{'}$	height of wheel inner channel (m)
A_c	cross section area of wheel channel (m^2)
A_M	cross section area of matrix layer (m^2)
b_c	base of wheel channel (m)
$b_c^{'}$	base of wheel inner channel (m)
C^*	ratio of minimum to maximum heat capacity rate
C_c	heat capacity rate of cold stream (W K^{-1})
C_h	heat capacity rate of hot stream (W K^{-1})
c_m	specific heat capacity of matrix layer (J kg^{-1} K^{-1})
C_{max}	maximum heat capacity rate (W K^{-1})
C_{min}	minimum heat capacity rate (W K^{-1})
c_p	specific heat capacity of air (J kg^{-1} K^{-1})
$c_{p,c}$	specific heat capacity of cold stream (J kg^{-1} K^{-1})
$c_{p,h}$	specific heat capacity of hot stream (J kg^{-1} K^{-1})
C_r	total heat capacity rate of matrix layer (W K^{-1})
C_r^*	ratio of matrix to minimum heat capacity rate (W K^{-1})
D	wheel diameter (m)
$D_{H,PV/T}$	hydraulic diameter of PV channel (m)
$D_{H,TW}$	hydraulic diameter of wheel inner channel (m)

$\dot{E}$	rate of electrical energy produced by the BIPV/T-TW system (W)
$\dot{E}_{fan,c}$	rate of electrical energy consumed by fans to circulate cold stream (W)
$\dot{E}_{fan,h}$	rate of electrical energy consumed by fans to circulate hot stream (W)
$\dot{E}_{fan,PV/T}$	rate of electrical energy consumed by fans to circulate air through PV channel (W)
$\dot{E}_{PV/T,net}$	net rate of electrical energy produced by PV panels (W)
$\dot{E}_{TW}$	total rate of electrical energy consumed by thermal wheel (W)
$f_{PV/T}$	fanning friction factor for BIPV/T system
f_{TW}	fanning friction factor for TW
h	convective heat transfer coefficient of TW (W K^{-1} m^{-2})
h_c	convective heat transfer coefficient of BIPV/T system (W K^{-1} m^{-2})
$h_{r,pv-b}$	radiative heat transfer coefficient between PV panels and back wall (W $K^{-1}m^{-2}$)
$h_{r,pv-s}$	radiative heat transfer coefficient between PV panels and sky (W $K^{-1}m^{-2}$)
h_w	wind convective heat transfer coefficient (W $K^{-1}m^{-2}$)

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I_r	solar radiation intensity (W m^{-2})
k	thermal conductivity of air (W m^{-1} K^{-1})
$k_{c,PV/T}$	loss coefficients of BIPV/T system
$k_{c,TW}$	loss coefficients of TW
k_{ins}	thermal conductivity of insulation material (W m^{-1} K^{-1})
l	wheel length (m)
L	length of PV channel (m)
$\dot{m}_f$	air mass flow rate for BIPV/T system (kg s^{-1})
$\dot{m}_{f,c}$	mass flow rate of cold stream (kg s^{-1})
$\dot{m}_{f,h}$	mass flow rate of hot stream (kg s^{-1})
M_m	matrix effective mass (kg)
N	matrix rotational speed (rpm)
NTU	number of transfer units
Nu	Nusselt number
ΔP	frictional pressure drop (Pa)
$\Delta P_{PV/T}$	frictional pressure drop during air flow in BIPV/T system (Pa)
ΔP_{TW}	frictional pressure drop during air flow in TW (Pa)
Pr	Prandtl number
$\dot{Q}$	rate of thermal energy received by air from the BIPV/T-TW system (W)
$\dot{Q}_{PV/T}$	rate of thermal energy received by air from BIPV/T system (W)
$\dot{Q}_{TW}$	rate of thermal energy received by air from TW (W)
$\dot{Q}_{TW,max}$	maximum possible heat transfer rate in TW (W)
$Re_{PV/T}$	Reynolds number of airflow through BIPV/T system
Re_{TW}	Reynolds number of airflow through TW
s	wheel thickness (m)
S	depth of PV channel (m)
T_a	ambient temperature (K)
T_b	back wall temperature (K)
$T_{c,i}$	inlet temperature of cold stream (K)
$T_{c,o}$	outlet temperature of cold stream (K)
T_f	air temperature (K)
$T_{h,i}$	inlet temperature of hot stream (K)
$T_{h,o}$	outlet temperature of hot stream (K)
T_{in}	inlet temperature of air inside PV channel (K)
T_{mf}	mean air temperature inside PV channel (K)
T_{pv}	PV panel temperature (K)
T_s	sky temperature (K)
u	air velocity in wheel channel (m s^{-1})
U_b	bottom heat loss coefficient (W K^{-1}m^{-2})
v	air velocity through PV channel (m s^{-1})
v_w	wind velocity (m s^{-1})
W	width of PV channel (m)

Greek symbols

α_{pv}	absorptance of PV panels
μ	air viscosity (kg m^{-1} s^{-1})
δ_{ins}	thickness of insulation material (m)
ε	wheel effectiveness
ε_0	effectiveness of a cross-flow heat exchanger
ε_{pv}	emissivity of PV panel
η_{el}	electrical conversion efficiency of PV panels
η_{fan}	fan efficiency
ρ	air density (kg m^{-3})
ρ_m	Matrix material density (kg m^{-3})
σ	Stefan-Boltzmann constant (5.67 × 10^{-8} W m^{-2} K^{-4})
ω	wheel porosity

1. Introduction

Energy consumed in the buildings sector consists of residential and commercial end users and accounts for 20.1% of the total delivered energy consumed worldwide [1]. Heating, ventilation and air conditioning (HVAC) systems in buildings account for about 40% of the global energy consumption [2], which shows the necessity of HVAC efficiency improvement in buildings. This can be achieved by recovering part of the energy from the exhaust air stream to pre-condition the incoming fresh air stream. There are many different types of exhaust air energy recovery systems available for transferring energy from the exhaust air to the supply air or vice versa. Some devices transfer sensible heat only (e.g. heat pipe, sensible plate, sensible wheel and glycol run-around systems), while some transfer both heat and moisture between the air streams (e.g. enthalpy plate and enthalpy wheel).

Sensible and enthalpy wheels are rotary air-to-air heat exchangers. They have high effectiveness values, low installation and operating costs, and low pressure drops, making them both economical and environmentally friendly. The sensible wheel (also known as a TW) is positioned within the supply and exhaust air streams of an air-handling unit (AHU), in order to recover the heat energy. It is usually made of porous materials to increase the surface area of heat transfer. As the wheel rotates, the matrix material in the air stream picks up heat from the warmer air stream and transports it again to the re-entering countercurrent flow of a cooler air stream. The rotation of the wheel allows for a continuous heat transfer from one air stream to the other due to the heat storage capacity of the porous medium. The enthalpy wheel and TW have the same construction except that the enthalpy wheel contains desiccant material on the matrix.

Plenty of efforts have been devoted to the investigation of the performance of various HVAC systems with thermal/enthalpy wheels throughout the recent years by many researchers. El-Maghlany et al. [3] proposed a novel double wheels configuration as a retrofit solution to an existing HVAC system of intensive care unit (ICU) of a hospital in Egypt. The system consisted of a cooling coil, a sensible wheel and an enthalpy wheel. The building energy simulation program was utilized to evaluate the yearly performance of both existing and novel retrofit HVAC systems. They found that the new HVAC system can reduce the monthly total electrical energy usage by up to 87.15% compared with the existing system. Chen and Yu [4] studied the performance of an enthalpy wheel based hybrid HVAC system with a natural cold source in two typical outdoor meteorological conditions. The results revealed that the system under high temperature-low humidity condition can satisfy the indoor environment demand for civil buildings more than the system under high temperature-high humidity condition. Ali et al. [5] compared five configurations of balanced flow dedicated outdoor air systems. In the system, the enthalpy wheel was employed under typical office/lab ventilation loads coupled to an air-cooled outdoor unit. It was reported that using an enthalpy wheel across the evaporator is a more efficient configuration than placing the enthalpy wheel between the supply and return air streams. Shahzad et al. [6] experimentally evaluated the performance of an enthalpy wheel integrated with a cross flow Maisotsenko cycle evaporative cooler. They assessed the impact of a wide range of inlet air parameters including ambient temperature, humidity ratio, and regeneration temperature. It was demonstrated that the proposed system is around 60–65% more efficient than the conventional enthalpy wheel.

Although the rotary heat exchangers have many advantages, they need electricity to rotate the wheel and fans to overcome the pressure drop across the wheel. One method of meeting this extra electric power demand is the use of renewable resources of energy [7–13]. In this framework, a possible attractive option is the use of a PV/T collector which is a combination of PV panel and a thermal collector in one integrated system. The aim of the thermal collector is twofold, firstly, to cool the PV panel and thus improve its electrical performance and secondly, to collect the produced thermal energy, which would have otherwise been lost as heat to the environment. These systems can produce higher energy output per square meter of surface area than separate PV modules and solar thermal collectors, at a potentially lower production and installation cost [14].

Literature survey reveals that very few works have been conducted on the PV/T assisted rotary heat exchangers. Beccali et al. [15] carried out a detailed investigation on the thermo-economic performance of