Energy 113 (2016) 9–24

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

A study on thermoelectric technology application in net zero energy buildings

Limei Shen [a], Xiwang Pu [a], Yongjun Sun [b,*], Jiongde Chen [a]

[a] Department of Refrigeration and Cryogenics, Huazhong University of Science and Technology, Wuhan, China
[b] Division of Building Science and Technology, City University of Hong Kong, Hong Kong

A R T I C L E I N F O

Article history:
Received 12 October 2015
Received in revised form
7 July 2016
Accepted 7 July 2016

Keywords:
Net zero energy building
Thermoelectric cooling
Thermoelectric generation
Application feasibility
Annual energy balance

A B S T R A C T

Net Zero Energy Building (NZEB) has gained increasingly wide attentions over last few years and net zero energy starts to become a new design target of future buildings. This paper presents the first study on thermoelectric technology applications in NZEBs in which both thermoelectric cooling and thermoelectric generation are adopted. Substituting conventional air-conditioning system, the thermoelectric radiant ceiling and the thermoelectric primary air handling unit are adopted to provide thermal comfort and fresh air in NZEBs. Meanwhile, the thermoelectric generation is employed to improve the solar energy generation. Case studies have been performed to investigate the application feasibility of the proposed thermoelectric systems by evaluating the annual energy balance. The study results show that the thermoelectric cooling is able to supply sufficient cooling and heating to ensure thermal comfort. Moreover, the thermoelectric generation significantly improves the annual solar energy generation by 767 kWh (34%) in comparison with conventional photovoltaic system, which eventually turns the targeted office building from a non-zero energy building to a plus energy building. This study provides a new way to apply thermoelectric technology in NZEBs which directly lead to benefits including zero Freon, simple piping, and quiet and reliable operations.

1. Introduction

U.S. and China stroke a deal on carbon cuts in pushing for global climate change pact in 2014. In the deal, U.S. aims for carbon reduction of a quarter or more by 2025; while China sets a goal for carbon emission to fall after 2030 or earlier. With renewable energy used, net zero energy buildings (NZEBs) are gaining increasingly wide attentions and interests for cutting carbon emission. Net zero energy also starts to become a new design target of future buildings. Many countries have set up clear targets through legislations for promoting NZEB applications in future. For instance, the Europe has planned to transfer all its new buildings to be "nearly net zero energy buildings" after 2020 [1].

Meanwhile, Freon refrigerants in conventional HVAC (heating, ventilation and air-conditioning) systems are a main source of greenhouse gases. Using no refrigerant, thermoelectric cooling technology has been considered as one green cooling method which may replace conventional HVAC systems for effective Freon reduction. In addition, directly using direct current (DC) power, thermoelectric cooling systems can be easily integrated with renewable systems which also provide DC power.

Many studies have been conducted on thermoelectric cooling/heating [2–4] and thermoelectric generation [5–7]. Thermoelectric cooling/heating are based on the Peltier effect to convert electrical energy into a temperature gradient, and cooling and heating modes can be easily switched by reversing the input current direction. In contrast, thermoelectric generation relies on the Seebeck effect to convert a temperature gradient into electrical energy [8].

With regard to thermoelectric cooling/heating, existing studies mainly focused on solar driven thermoelectric air-conditioning systems [9–12]. For instance, Cheng et al. proposed a solar-driven thermoelectric cooler module which was employed to absorb heat from the indoor space of a green building [13]. The application feasibility of the proposed thermoelectric cooler module was also tested in a constructed model house. It was found that the room temperature in the house can be most dropped by 16.2 °C in comparison with the ambient temperature. Similarly, Miranda et al. experimentally studied the application feasibility of a solar driven thermoelectric air-conditioner for an electric vehicle [14]. It was

* Corresponding author.
E-mail address: yongjsun@cityu.edu.hk (Y. Sun).

http://dx.doi.org/10.1016/j.energy.2016.07.038
0360-5442/© 2016 Published by Elsevier Ltd.

Nomenclature

A	ceiling area of the room [m^2]
$A_{SHW-TEG}$	area of flat plate solar thermal collector [m^2]
$C_{p,w}$	specific heat capacity at constant pressure of water [$kJ\ kg^{-1}{}^{\circ}C^{-1}$]
COP	coefficient of performance
E	energy [kWh]
E_b	annual energy balance value [kWh]
f	the solar assurance
G	solar radiation intensity [Wm^{-2}]
G_d	annual-average daily solar radiation intensity [$kJm^{-2}\ d^{-1}$]
h	enthalpy of the air [Jkg^{-1}]
H	free convection heat transfer coefficient [$W\ K^{-1}\ m^{-2}$]
$HVAC$	heating, ventilation and air-conditioning
I	input electric current of thermoelectric cooler module [A]
I_g	output electric current of thermoelectric generation module [A]
K_c	thermal conductance of thermoelectric cooler module [$W\ K^{-1}$]
K_g	thermal conductance of thermoelectric generation module [$W\ K^{-1}$]
m_a	mass flow rate of dry air [$kg\ s^{-1}$]
N	number
$NZEB$	net zero energy building
P	electrical power [W]
PV	photovoltaic
Q_c	cooling capacity of thermoelectric cooler module [W]
Q_h	heating capacity of thermoelectric cooler module [W]
$Q_{h,TEG}$	heat absorption rate of thermoelectric generation module [W]
R_c	electrical resistance of thermoelectric cooler module [Ω]
R_g	electrical resistance of thermoelectric generation module [Ω]
R_L	electrical load [Ω]
R_w	thermal resistance of water radiator [K/W]
R	thermal resistance of heat sink in TE-PAU system [K/W]
R_{cg}	thermal resistance of heat sink in SPV-TEG system [K/W]
$SPV\text{-}TEG$	solar photovoltaic-thermoelectric generation hybrid system
SPV	solar photovoltaic panel of SPV-TEG system
$SHW\text{-}TEG$	solar hot-water thermoelectric generation hybrid system
T	temperature [K]
$T_{ai,ave}$	the average temperature of fresh air [K]
$T_{ao,ave}$	the average temperature of exhaust air [K]
T_c	cold side temperature of thermoelectric cooler/generation module [K]
T_h	hot side temperature of thermoelectric cooler/generation module [K]
$\triangle T$	temperature difference [K]
TEG	thermoelectric generation
$TE\text{-}RC$	thermoelectric radiant ceiling
$TE\text{-}PAU$	thermoelectric primary air handing unit
V_d	annual-average daily water-demand [Ld^{-1}]

Greek letters

α_c	seebeck coefficient of thermoelectric cooler module [$V\ K^{-1}$]
α_g	seebeck coefficient of thermoelectric generation module [$V\ K^{-1}$]
π	Peltier coefficient [V]
η	power generation efficiency
η_0	the criterion efficiency of solar photovoltaic panel
η_{loss}	heat loss efficiency of solar thermal collector
η_{ee}	the ratio of excessive solar heat to solar heat
$\eta_{PV,con}$	power generation efficiency of conventional solar photovoltaic panel
τ	transmissivity of the glass cover
ρ_w	density of water

Subscripts

ai	indoor air
ao	outdoor air
c	cooling mode
con	conventional
h	heating mode
rh	reheating process in the cooling mode of TE-PAU
w	domestic water

found that the coefficient of performance (COP) in the cooling mode was about 0.5 as the temperature difference was about 13 °C between the cold-side and the hot-side of the thermoelectric air-conditioner. In contrast, the COP in the heating mode was much larger (i.e. 1.72) as the temperature difference between the two sides was 15 °C. He et al. experimentally studied the solar driven thermoelectric cooling and heating system. The experiments were firstly conducted in a model room, and they found the average COP of thermoelectric cooing system was 0.6 in summer. Then, for a practical room, the COP was found to be 0.45 in summer and 1.7 in winter [15,16].

With regard to thermoelectric generation, the first solar thermoelectric generator was proposed in the patent by Weston in 1888 [15], which was a solid state heat engine that generated electricity from concentrated sunlight. Recently, researchers performed both theoretical [16–18] and experimental studies [19–21] to improve the electricity generation efficiency through increasing temperature difference between the two sides and using better thermoelectric materials. To date, the energy generation efficiency of the solar thermoelectric generators can be as high as 4.6% [19]. Considering the complementary feature of solar panel and thermoelectric generators, Sark proposed a photovoltaic-thermoelectric hybrid system which used thermoelectric generator to cool the back of photovoltaic (PV) panel for improving the efficiency of PV panel. It was found that the hybrid system effectively increased the annual renewable energy yield [22]. Zhu et al. experimentally studied the photovoltaic-thermoelectric hybrid power generation system, and a water block radiator was used to cool the cold side of thermoelectric generator. They found that the developed hybrid system achieved a peak efficiency of 23% which was increased by 25% compared with that of the PV cells (i.e. 19%) when the temperature gradient of thermoelectric generator remained about 52 °C [23]. Hence, the thermoelectric generation technology has the potential to be used in NZEBs for improved renewable energy generation.

However, very few studies have been conducted on application feasibility study of thermoelectric technology in NZEBs. This study,