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Numerical evaluation on energy saving potential of a solar photovoltaic thermoelectric radiant wall system in cooling dominant climates

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A B S T R A C T

The energy used for mechanical cooling systems in buildings in hot climate is about 70%–80% of the total energy consumption. It is important to curtail this part of energy consumption by exploring new technologies. The proposed system is a building integrated photovoltaic thermoelectric (BIPVTE) wall system which combines the concept of active PV façade and solar cooling. We present a complex model of BIPVTE consisting of a PV system and thermoelectric radiant wall system. The thermal and electrical performance of BIPVTE under cooling dominant climates was numerically investigated using experimentally validated system model. The performance of BIPVTE is embodied by comparative analysis with a conventional concrete wall. A steady state analysis was designed to explain and explore the system working mechanism. A sensitivity analysis was conducted for model parameters optimization. With the optimized results, the energy saving potential of BIPVTE in Hong Kong and other 6 cities in Hot Summer and Warm Winter zone of China was implemented. The results indicated that in Hong Kong, the energy saving ratio of BIPVTE is nearly 480%, and the installation of BIPVTE in other 6 cities can save energy ranging from 29.19 kWh/m^2 to 62.94 kWh/m^2 annually.

1. Introduction

Buildings provide comfortable spaces for us to live and work at the cost of the huge energy consumption for indoor cooling/heating, artificial lighting etc. According to a study on building energy, heating energy demand will be decreased by 34% worldwide by 2100 as a result of climate change, and air-conditioning cooling energy demand is projected to be increased by 72% [1]. This projected drastically soaring demand for cooling energy in the building sector implies the faster depletion of fossil fuel if renewable clean energy cannot follow pace of world energy consumption. The building cooling for regions in hot climates becomes even more important. Multiple elements of high ambient temperature, intense solar radiation, internal heat input and latent heat loads collectively contribute to the building cooling load, which usually can be removed by air conditioning systems. Mechanically driven air conditioning devices are dominating the world market by the highest penetration ratio [2]. In China, the penetration of air conditioning in the newly built urban residential house has reached to almost 100% in 2010 [3]. The conventional air conditioning system is operated by electricity from the utility grid, which is the major building energy consumer. In order to curtail building energy demand, lowering heat gain by building envelope and improving system efficiency of air conditioner are two effective channels.

As for enhancing thermal performance of building envelope, adaptation of insulation is one common fashion which has been widely used in lots of newly built buildings as well as for building retrofits [4]. Some researchers have showcased that up to 50% of yearly energy saving potential can be achieved by insulation under temperate climate [5]. However, the use of insulation has not been found to be enough to reduce annual cooling loads of buildings in hot climates like Guangzhou city in China [6]. Besides insulation wall, there are many other passive technologies for higher performance of building façade. Sadineni et al. [7] conducted a thorough review study on passive building envelope systems. Systems such as passive solar wall and ventilated or double skin walls are summarized. The previous results showed 40% summer cooling energy saving by a well-designed ventilation wall and 56% higher energy

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efficiency of revised Trombe wall [7].

Besides passive building envelopes, PV envelope is a prototype of a highly efficient envelope receiving increasing attention from engineers and scientists. Building integrated photovoltaic (BIPV) [8] or building integrated photovoltaic-thermal system (BIPV-T) [9] could largely alleviate building energy problem with further advancement in materials and system design. Extensive researches have implemented and the attractive BIPV walls are PV Trombe wall [10–12], semi-transparent PV façade system [13–16], PV blinds embedded double skin façade [17,18], or PV-blind incorporated Trombe wall [19] and PV roofs [20–22]. Actually, working principle of the PV envelope is to transform solar radiation into useful electrical power and using designed air duct for extra heat dissipation or water pipes for domestic hot water production.

As for improving energy efficiency of air conditioning system (especially for cooling dominant climates), solar cooling technology could be one of the top choices because the renewable energy source is adopted for lowering the indoor temperature. Solar radiation is the major reason for excessive heat gain in summer especially for regions in hot climates. From another angle of view, solar radiation is the biggest source of energy powering the earth because the fossil fuel energy, wind energy, etc are directly or indirectly related to solar energy. The development of photovoltaic/thermal technology can take advantage of solar energy for certain purposes. Solar cooling is made possible by the principle that the irradiation level of solar energy is high during summer season, when cooling is mostly needed [23].

Recently, Prieto et al. [24] reviewed and summarized the latest advances in solar cooling technologies. According to this study, there are basically two sources of energy inputs for solar cooling system. One is solar-electric by PV cells and another is solar-thermal by the solar collector. Those two energy inputs use electricity or thermal energy powering cooling devices in different ways, which result in different choices for cooling generation systems. For the solar-electric type, vapor compression cooling and thermoelectric cooling (TEC) are two feasible systems. For the solar-thermal type, the sorption cooling, desiccant cooling, and thermo-mechanical cooling are suitable systems for consideration. Among all those different systems, solar powered absorption cooling system receives extensive attention, which uses solar collector for thermal energy gathering and lithium bromide -water (LiBr−H2O) absorption chiller system for indoor cooling [23,25]. Some researchers also intended to borrow merits of other systems for better performance of solar cooling system. Palomba et al. [26] incorporated lab-scale latent heat storage with solar cooling devices which lead to about 50% performance improvement compared with a system using sensible water storages. Bahria et al. [27] conducted dynamical simulation on parametric study of solar cooling using a solar storage tank. The results indicated that under hot climates of Algiers, Djelfa and Tamanrasset, building cooling loads can be significantly reduced by 12%, 44% and 22% respectively. In addition, higher performance is reported when solar cooling integrated with evaporative cooling of PV chimney [28], and Geothermal Heat Exchanger [29].

According to literature survey, upgrading building façade by using solar cooling concept or devices is attracting more and more attentions [30], because obviously it is a higher form of both the building envelope and solar cooling system. If this hybrid solar cooling envelope can be properly designed and controlled, a new solution to building energy problem can be offered. After comparing different systems adopting solar cooling envelope concept, Prieto et al. [24] suggested TEC seems to be more suitable for façade integration after comparing different types of solar cooling façade systems. Features of tiny and compact sizing, as well as easier control are the major advantages of thermoelectric module.

In terms of the delivery system of solar cooling façade using TEC, there are TE surface cooling (radiant cooling) [31–34] and TE air cooling (diffuser) [35,36] basically. If the surface radiant cooling is adopted, an aluminum panel cooled by an array of TE modules should be fabricated. While in an envelope system with TE air cooler, an internal side air duct should be designed to circulate indoor air to be cooled by TEC. The heat transfer process and indoor thermal comfort level are different for those two kinds of terminates. The TE module is powered by direct current or voltage which is just the output power of a PV panel. This important characteristic makes the combination and co-operation of TEC and PV cells possible.

Because of the favorable thermal comfort and higher energy efficiency of TE radiant system, the PV-TE radiant wall received attention recently. The related experimental investigation and economic analysis implied the application potential of such façade system. Previously the single-typical-day numerical simulation [37] and experimental investigation [34] discussed the system performance in Changsha. The result proved nearly 70% of daily heat gain reduction comparing 240 mm brick wall can be reached. Liu et al. [34] proved this PV-TE wall system can achieve 3–8 °C lower than the indoor temperature of the test room in experiments. However, the previous research conclusions can hardly help to discuss the application potential in hot climates in a comprehensive angle when the seasonal and annual energy saving ratio of PV-TE wall are still unknown under such climate. Because the study by Pons et al. [38] showed that the performances evaluated on one single day can be over-estimated (+30%) compared to the seasonal average. The previous initiative single-day numerical and experimental study results can hardly be instructive for estimation of the system year-round performance.

Therefore, the purpose of current research is to investigate the energy saving potential of PV-TE radiant wall system in cooling dominant climates by seasonal and annual simulation approach. In total, 6 big cities (mainland China) from Guangdong Province, Fujian Province, Guangxi Zhuang Autonomous Region, and Hong Kong are chosen in the present study. All those cities are fast growing cities located in Hot Summer and Warm Winter Zone of China. According to the official released GDP data of top 10 China cities in 2015 [39], 3 of them are in cooling dominant region of China. Their annual growth rate is going to be kept between 7% and 8%. The high-speed development should be maintained and supported by sustainable energy strategy generally. This can be narrowed down to the field of building energy efficiency. The typical meteorological year (TMY) data shows that, the cooling period of this region is as long as 6 months but heating period is about or less than 1 month. The top mission for the building energy saving of this region is to reduce cooling energy consumption. Based on this fact and current situation, technology advancement in building energy efficiency can better service the healthy, sustainable, and green development of the cities in cooling dominant regions. Specifically, the simulation-based steady and dynamic analysis tools can provide reference for building energy saving in other cities and can generate guideline for application of the PV-TE wall system by rating energy saving ratio.

2. Models and methods

2.1. System description

First of all, a short name for the researched photovoltaic thermoelectric wall is defined for convenient description and specification in the following context. Borrowing the conventionally used term BIPV for building integrated photovoltaics, the PV-TE wall