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Dynamical simulation of building integrated photovoltaic thermoelectric wall system: Balancing calculation speed and accuracy

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HIGHLIGHTS

- A non-uniform time step model was proposed for system simulation.
- The non-uniform time step solution was validated with experiment data.
- The influence of time step and superposition number parameter were discussed.
- Two linear deviation coefficients in non-uniform time step solution were analyzed.

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ABSTRACT

Building integrated photovoltaic thermoelectric (BIPVTE) wall system is highly energy efficient and self-adaptive to the environment. This sophisticated system is supported by the co-work of PV module for solar radiation transformation, air gap for thermal dissipation and thermoelectric radiant panel system (TERP) for active radiant cooling/heating. The purpose of this study is to develop an accurate and fast simulation method of this complex system which could be beneficial for system design, control and optimization for application. The present study upgraded the PV model by considering the variable resistance due to Peltier Effect in thermoelectric module. A new non-uniform time step model was proposed which can provide an improved and more efficient system simulation. The non-uniform time step solution of BIPVTE system was validated by comparing with both uniform time step solution and experimental data. The parametric studies on time step h and superposition number N under uniform time step solution, as well as two linear deviation coefficients d_T and d_G under non-uniform time step solution, were respectively analyzed. In uniform time step solution, the simulation time step h and parameter N should be properly chosen to balance simulation speed and accuracy. However, in non-uniform time step, numerical investigations demonstrated that simulation accuracy can be kept within an acceptable range even when linear deviation coefficients were large enough. The algorithm can be further accelerated by adopting Gauss-Berntsen-Espelid or Gauess-Kronrod rule in numerical integral calculation. The comparative and case study in this research has shown the validity and robustness of the proposed non-uniform time step model, which could be a useful tool for further work on BIPVTE as well as other building systems.

1. Introduction

Solar energy is regarded as one of the most important and promising energy sources powering human society. The integration of photovoltaic and solar thermal technologies with buildings is indispensable for the realization of zero energy buildings. Lots of researches on the building integrated photovoltaic/thermal (BIPV/T) were reported [1–3]. After analyzing the limitation and drawbacks of conventional system structure, a new prototype active wall system was proposed by combining the basic form of PV Trombe wall and thermoelectric radiant panel system, which was named as building integrated photovoltaic thermoelectric wall system (BIPVTE) [4]. A preliminary experimental evaluation in summer and winter conditions as well as simple economic analysis [5,6] on this system has fully demonstrated the high energy efficiency and economic feasibility of BIPVTE wall. Previous research on BIPVTE further indicated that about 70% of energy could be saved comparing with conventional brick wall system [4].

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The fundamental reason that BIPVTE outpace traditional PV wall system is the introduction of thermoelectric system. The join of thermoelectric module not only can use the power output from the PV panel more efficiently, but also can transform passive PV wall structure into active cooling or heating system. The thermoelectric module (TEM) array can be used as a tiny and compact heat pump to cool indoor space in summer proactively after connecting with PV module. More importantly, the cooling capacity of TEMs is dynamically varied with the outdoor environment, because the output voltage and current from PV cells is linked with ambient temperature and solar radiation intensity. This feature enables BIPVTE wall system as a highly self-adaptive system to ambient conditions [4]. Besides experimental investigations, simulation study for the energy system is a critical step towards deeper understanding, system optimization [7], system control [8], design decision making [9] and building system retrofit evaluation [10]. The central philosophy of conducting system simulation is to establish an equivalent physical model for the counterpart in real world and solved by analytical expressions, equations or numerical methods, which can inversely accurately reflect the status, dynamics or other characteristics of researched objectives in real world. It should be noted that based on this definition of system simulation, both system modeling and model solution are the direct influence factors on model performance. We will briefly discuss the system modeling strategy and algorithm in terms of balancing simulation speed and accuracy of BIPVTE system.

Despite of discussing specific energy system, simulation speed and accuracy are always two top concerns for any simulation program. A simulation program that can precisely predict or describe target energy system may result in longer simulation time and larger computation memory requirement, and this situation may be deteriorated for a more complex and sophisticated system. If the system model is simplified to accelerate calculation speed, the simulation accuracy may be partially damaged. Those two simulation goals are standing on the two end sides of seesaw and system model selection is a foremost step towards this end. The basic simulation strategy of BIPVTE is the modeling of the PV panel, air gap and thermoelectric radiant panel system (TERP) separately, and then to couple each sub-system to complete the work. The following part is going to discuss the model selection for each sub-system for balancing simulation speed and accuracy.

Accurate simulation of air movement and air temperature distribution is frequently asked by a large number of buildings simulations. In BIPVTE wall system, there is an air duct sandwiched between the PV module and thermoelectric radiant system. The air duct is designed to dissipate the heat from PV cells and hot side of TEMs to ensure system efficiency. Currently, computational fluid dynamics (CFD) method was widely adopted for the simulation of air gap in similar systems like PV Trombe wall structure [11]. Steady-state CFD simulation can provide detailed spatial distribution of air velocity and temperature but long computation time is needed for irritation convergence. In addition to unsteady state CFD simulation of air flow, time step should be set as small as 0.0002 s [12], which inevitably will consume longer simulation time in order to maintain simulation accuracy. Considering the slow simulation by conventional CFD, fast fluid dynamics (FFD) was introduced by Stam [13] and further developed by Wangda Zuo and Qingyan Chen [14] on GPU calculation. It was proved by a case study that FFD can be over 30 times faster than conventional CFD [14]. This calculation speed is largely improved but still not fast enough for some engineering applications. At the same time, other simulation methods, such as Multi-zone approach [15] and Zonal approach [16] for ventilation are more suitable for long time dynamic simulation. However, the simulation results by those two methods are more likely a presentation of average values of air temperature and mass flow.

The power source of BIPVTE system is PV module mounted onto the external wall transforming solar energy to electric energy for the operation of TEMs cooling/heating. According to different equivalent electrical circuits, the commonly used PV model comprises ideal single diode model, single diode R_S-model, single diode R_P-model, and two-diode model [17]. The manufacturer of silicon-based PV module only provides the parameters of the short circuit current, open circuit voltage, maximum working current and voltage under standard testing condition. Important parameters have to be extracted by some algorithm [18], and then various numerical and theoretical models [19,20] were proposed to calculate dynamic power output under real ambient radiation and temperature conditions. During this process, a non-linear transcendental equation set should be solved and the stable and accurate equation solution is a big challenge. Even if the equation solution is obtained and internal parameters are extracted, the output current-voltage equation is still expressed as an implicit form which should be further solved so as to get the actual power output of the PV panel. Some studies even chose to use the optimization methods (Differential Evolution [21] and Genetic Algorithm [22]) or black-box modeling (Artificial Neural Network algorithm [23]) to avoid complex white-box modeling work.

The core component of BIPVTE system is the thermoelectric radiant panel system (TERP), which serves as cooling/heating terminal using TEMs as heat sources. The thermoelectric module array is attached on the surface of radiant panel. The non-uniform surface temperature field of the radiant panel exchanges heat flux with indoor air and other surfaces through convective and radiative heat transfer. Conventional hydraulic radiant panel system using water pipes as a heat source is usually modeled and simulated with CFD method [24], the finite difference method [25], or simplified calculation method [26]. If the CFD or finite difference method is used for TERP, the refined grid should be adopted to ensure simulation accuracy but calculation speed is a big concern, especially when dynamic simulation is coupled with other parts of BIVTE system. Luo et al. [27] reconstructed the governing differential equation for TERP and solved in an analytical expression which can accurately predict the dynamic and steady-state thermal behavior in both cooling and heating mode [28]. This simulation method can provide a solid foundation for modeling of BIPVTE system.

Luo et al. [4] comprehensively considered the modeling methods of air gap, PV module and TERP system for BIPVTE system simulation. The zonal approach for air duct, five-parameter model for PV module and an analytical model of TERP were coupled and solved in state-space method [29,30] for accurate simulation. This system solution can largely avoid the small time step selection in finite difference method or finite volume method which was previously adopted by the study of PV Trombe wall system [31]. The previous simulation study on BIPVTE can describe the system dynamically, but it was not prepared for simulation on large time scale such as annual analysis under a standard PC platform.

The purpose of this study is to develop a more efficient numerical simulation method for BIPVTE system, which can ensure an accurate and fast simulation even on a large time scale. Specifically, a new non-uniform time step model was developed which can utilize the least input data to realize a complete and accurate description of BIPVTE system. Therefore, the simulation speed and accuracy can be balanced. The methods and results of this study can be applied for further research on this system or other relevant engineering problems.

The major aspects of this work are: (1) to upgrade PV model by considering resistance in electrical circuit due to Peltier Effect in TEMs; (2) to upgrade and propose a new analytical model of TERP and state-space method with non-uniform time step solution; (3) to analyze and optimize two important model parameters (time

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