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A portable solar-powered air-cooling system based on phase-change materials for a vehicle cabin

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ABSTRACT

In summer, the temperature is very high inside vehicles parked under the hot sun. This causes consuming more fossil energy to power the air conditioner and generation of harmful gases. There is currently no effective method to address this problem in an energy-saving and environmentally friendly manner. In this paper, a novel solar-powered air-cooling system for vehicle cabins is proposed based on Phase-change Materials (PCMs); the system prevents the temperature inside a vehicle cabin from rising too high when the vehicle is parked outdoor exposure to the sun. The proposed system consists of three main parts: a solar-energy collection module, power-storage module and phase-change cooling module. The solar panel converts solar energy into electricity, and the power-storage module stores the electric energy in a supercapacitor that provides power for the phase-change cooling module. Heat exchange between cabin ambient air and the PCMs is conducted in the cooling module to generate cold air. The proposed system is demonstrated through thermal simulations, which show the long-duration cooling effect of the system. Temperature drops of 30 °C were obtained in field tests, predicting that the proposed cooling system is beneficial and practical for cooling vehicle cabins.

1. Introduction

The global energy crisis and environmental pollution have become two major concerns in recent years. In particular, excessive consumption of non-renewable energy and greenhouse gas emissions by traditional vehicles (TVs) are very serious. Electric vehicles (EVs) are becoming ever more popular and are considered to be the suitable alternative for traditional fuel vehicles because of their energy-savings and emissions reduction [1,2]. However, both TVs and EVs have a common problem: high temperature inside a vehicle during exposure to the sun when parked outdoor. High temperatures not only accelerate aging of plastic materials and release harmful gases but also cause consumption of additional fuel or electricity to power the air conditioner [3]. For TVs, it is widely known that an air conditioner cannot operate when the vehicle is in the flameout state. Although the air conditioner can operate in EVs in the same situation, it will consume excessive electric energy, which leads to a reduced vehicle range. These conditions require energy-saving self-powered cooling with reduced emissions.

In recent years, application of renewable energy such as mechanical energy [4–6], phase-change latent heat energy [7–12], solar energy [13–17], magnetic energy [18–20] and acoustic energy [21–23] have been widely developed. In particular, some cooling technologies using these renewable energy sources have emerged in many studies, such as phase-change cooling, magnetic cooling, thermoacoustic cooling and geothermally heated cooling technology. Though these cooling technologies have been widely discussed for various applications, there is little research in applying these technologies to cool vehicle cabins effectively. Due to the higher availability, the solar energy and phase-change latent heat are considered to use for cooling vehicle cabin in this paper.

Phase-change cooling technology (PCCT) is an active research area and has been widely investigated recently. The thermophysical performances of various PCMs have been studied in previous literature. Zakir Khan et al. [24] found that paraffins have wide ranges of phase transition temperatures and no tendency toward supercooling and that salt hydrates have a high latent heat of fusion and higher thermal conductivity. Research on what types of PCMs are suitable for thermal energy storage at low and medium temperatures was conducted by Jose et al. [25]. They concluded that salt hydrates and organic compounds possess better energy storage performance below 100 °C, and eutectic mixtures are more promising 100–250 °C. These investigations provide

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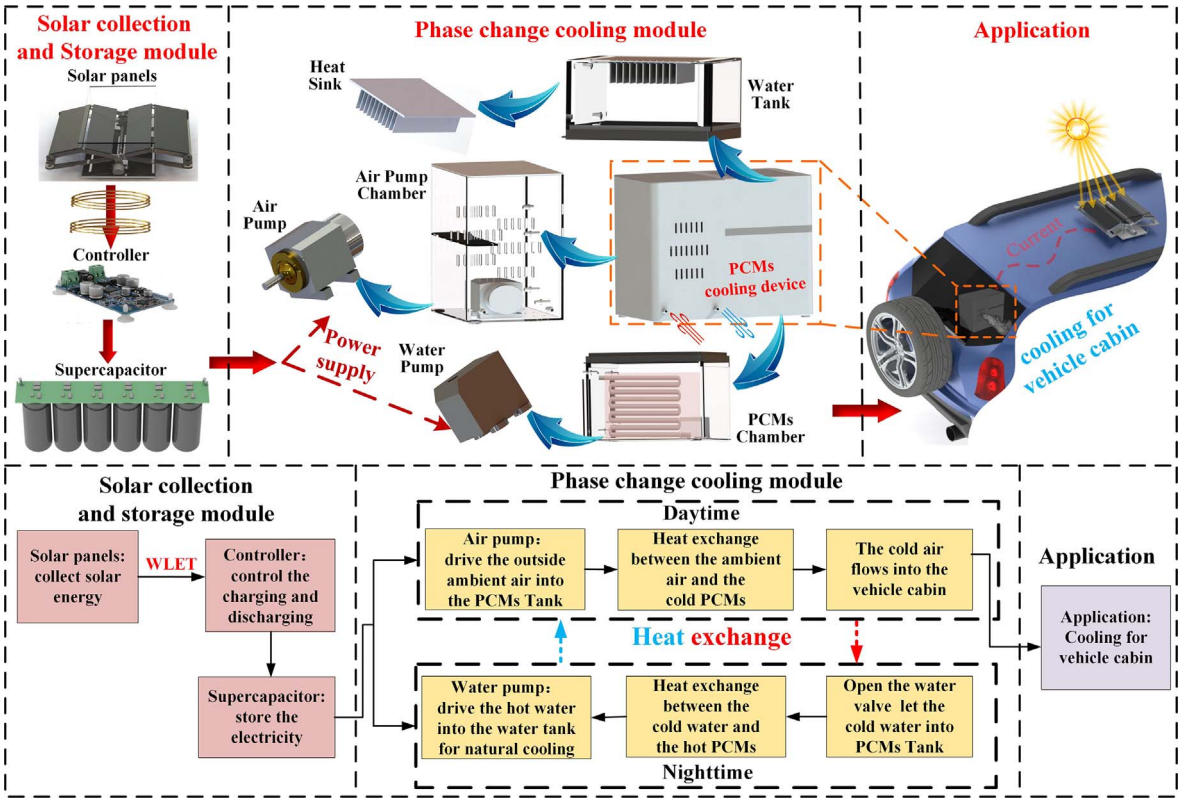

Fig. 1. Architecture of the solar-powered PCMs-based cooling system.

the reference basis for selecting the appropriate PCMs for energy storage systems (ESS) in various conditions. In general, PCMs have the common characteristics of high latent heat and thermal inertia which are crucial for ESS.

Based on their excellent thermal performance, PCMs used for cooling system have been extensively discussed in many literature works recently. Roberto et al. [8] described a novel method to enhance the thermal performance of a refrigerated container by using PCMs. The high reliability of the proposed solution was validated numerically and experimentally. Sun et al. [11] developed a novel free-air cooling system based on PCMs for cooling telecommunications base stations; it proved to achieve lower space-cooling energy consumption through in-situ tests in five different climatic regions. Anisur et al. [12] proposed a tube latent-heat storage system for cooling air, and experimental results showed that this system has a good cooling effect. Little research on using PCMs for vehicle cabin cooling has been published [26–28]. Lan and Sadrameli presented a PCMs-based vehicle roofing structure to improve thermal resistance and keep the vehicle interior comfortable [27,28]. It is well-known that phase-change cooling is passive cooling which the cooling effect no better than active cooling. For enhancing the cooling effect, active driven heat transfer fluid (HTF) should be integrated to the PCCT. However it will consume extra energy to drive the HTF if the traditional energy is employed. Renewable energy is considered to power the HTF instead of traditional energy aiming to energy-saving.

Compared to other renewable energy sources, solar energy is more abundant, easier to acquire and cheaper. Solar is regarded as the best potential alternative to traditional primary energy resources [29]. Solar-powered cooling technology (SPCT) has been widely developed to reduce non-renewable energy consumption and greenhouse gas emissions [13–17]. Annamaria et al. [13] conducted an experimental analysis and dynamic simulation for a high-temperature solar-driven cooling system. From the aspects of technology and economy, the author demonstrated that prototypal solar cooling systems have promising application prospects. To enhance energy efficiency, investigations of the utilization of combined multiple energy sources have been made. Jiangjiang Wang and Ying Yang analysed the energy and exergy efficiency and environmental benefit of utilizing biomass and solar energy for a hybrid combined cooling, heating and power system [14]. The study of solar refrigeration technology based on the adsorption principle is very timely at present. Ibrahim et al. [15] researched the performance of a solar-powered cooling system theoretically, based on the principle of adsorption. The maximum cooling capacity of this system approximated 14.8 kW and 15.8 kW in two different climate conditions in the Middle East. To improve the coefficient of performance, a PCMs-based heat-transfer-enhancement system integrated into a solar-powered absorption cooling system was investigated in [16]. Recent studies of solar-powered cooling systems for vehicles are rare. Zhang et al. [17] proposed a solar photovoltaic collector for a vehicle-mounted air conditioner, however there is no experimental data to validate the cooling effect of this system. In general, SPCT is of great importance in various cooling fields.

Despite the successful applications of the SPCT and PCCT in various areas particular to building space cooling, there has been hardly any published work on integrating these two technologies and applying them into vehicle cabins. In this paper, a novel solar-powered air-cooling system based on PCMs for vehicle cabins is presented. A foldable mechanism for solar energy collection enables this system to achieve portability and ease of installation. PCMs were considered as the cooling medium because of their high latent heat and cleanliness. The proposed cooling system can prevent the temperature inside a vehicle cabin from rising too high when the vehicle is parked with exposure to the sun. Therefore, energy consumption to power the air conditioning and the production of harmful gases inside vehicle cabin will be significantly reduced. Additionally, this cooling system can assist the standard vehicle air conditioner when the vehicle is running to achieve even greater energy savings and emissions reduction.

The remainder of this paper is structured as follows. In Section 2,