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# Phase change materials for solar thermal energy storage in residential buildings in cold climate

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## ABSTRACT

Heating accounts for a large proportion of energy consumption in residential buildings located in cold climate. Solar energy plays an important role in responding to the growing demand of energy as well as dealing with pressing climate change and air pollution issues. Solar energy is featured with low-density and intermittency, therefore an appropriate storage method is required. This paper reports a critical review of existing studies on thermal storage systems that employ various methods. Latent heat storage using phase change materials (PCMs) is one of the most effective methods to store thermal energy, and it can significantly reduce area for solar collector. During the application of PCM, the solid–liquid phase change can be used to store a large quantity of energy where the selection of the PCM is most critical. A numerical study is presented in this study to explore the effectiveness of $NH_4Al(SO_4)_2 \cdot 12H_2O$ as a new inorganic phase change material (PCM). Its characteristics and heat transfer patterns were studied by means of both experiment and simulation. The results show that heat absorption and storage are more efficient when temperature of heat source is 26.5 °C greater than the phase transition temperature. According to heat transfer characteristics at both radial and axial directions, it is suggested to set up some small exchangers so that solar energy can be stored unit by unit in practice. Such system is more effective in low density residential buildings.



**Contents**



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## 1. Introduction

There are significant environmental impacts associated with construction activities. Globally, the building stock is responsible for a high proportion of the total primary energy use [1,2]. In many countries, this proportion is as high as 40% [3]. The energy consumption in the residential sector accounted for more than 70% of the total amount of energy consumed by buildings worldwide [4]. This is compounded by the rapid urbanization associated with massive demands of resources including energy in order to satisfy needs of human beings' activities [5,6]. It was projected that building energy use will account for more than 35% of the national energy consumption in 2020 in China of which 65% are consumed by heating, ventilation and air-conditioning systems (HVAC) [7–9]. Furthermore, it is well recognized that space heating and water heating consume a large quantity of the energy in residential buildings [10–12]. This is particularly the case in those regions located in cold climate such as North China with a prolonged period of extreme cold weather. District heating has been introduced to China as one of building energy efficiency measures to satisfy the heating demands during the winter season [13,14].

As a result, significant efforts have been made to investigate the deployment of renewable energies in buildings, either large scale or community scale [15–17]. The integration of renewable energies with buildings helps not only satisfy growing energy demand but also deal with pressing environmental pollution issues. As an inexhaustible clean energy resource, solar energy plays a crucial role in dealing with pressing climate change and global warming issues [18]. Indeed, the direct solar radiation has become one of the most effective ways of utilizing renewable energies [19,20]. A large amount of radiation energy is released by sun to its surroundings [21,22]. However, due to its nature of low-density and intermittency, solar energy needs to be collected and stored efficiently [23,24]. There are necessary conditions for utilizing solar energy, i.e. sufficient amount of solar energy resources and adequate area for solar collector [25,26]. In addition, there should be substantial amount of demand for using solar energy such as water heating, space heating and refrigeration and air-conditioning [27–30]. These external factors significantly affect the utilizing of solar energy in buildings.

China has five climate zones according to the climatic conditions of each geographic area, i.e. Cold; Very cold; Hot summer and cold winter; Hot summer and warm winter; and Moderate [16]. Regions located in cold climate zone (mainly North China) have significant amount of heating demands with sufficient solar energy resources. Therefore, these regions are very suitable for utilizing solar thermal energy storage.

This paper presents a critical review of literature related to solar thermal energy storage particularly the selection of phase change materials. This is followed by a numerical study to test the new application of this way of utilizing solar energy. The focus is placed on the solar thermal energy storage and heating in North China. PCM $NH_4Al(SO_4)_2 \cdot 12H_2O$, a new inorganic material is tested in experiments. The melting temperature of this material can satisfy the corresponding heating requirements. Consequently its phase change mechanism and heat transfer in the heat reservoir are analyzed. The findings provide useful references for future development of PCMs for thermal energy storage in those regions located in cold regions.

## 2. Solar energy storage

Solar energy is an attractive substitute for conventional fossil fuels for heating applications [38]. There are many ways of utilizing solar energy such as solar photovoltaic, solar hot water and solar lighting [39–41]. The solar water heating technologies are comparatively mature. By contrast, solar space heating has comparatively limited application due to the instable thermal energy storage and the significant demand of the collector area.

There are two mechanisms for solar thermal energy storage, i.e. sensible heat storage and latent heat storage. Sensible storage has disadvantages such as small thermal storage density and large heating loss [31]. On contrary, by using PCMs, latent heat storage is one of the most effective methods to store thermal energy due to higher heat storage capacity as well as more isothermal behavior during charging and discharging [32–34]. As a result, phase change materials have been widely applied in practice with an aim to enhance the storage capacity of various thermal energy systems [35–37].

As an important technology to deal with the time-discrepancy issue associated with the solar energy utilization, latent heat storage is a challenging key technology for space heating and can significantly increase the solar fraction [42–44]. Therefore, solar storage has attracted considerable attention from both industry and academics for its various applications especially for solar heating systems. A typical system of solar thermal energy system is shown in Fig. 1.

North China is very suitable for utilizing solar thermal energy because: (1) there are massive heating demands due to its cold climatic condition; and (2) there are abundant solar resources available in the local region. For example, in Tianjin, a typical city of North China, district heat supply will be provided 135 days every year. Many regions of North China have 3200 annual sunshine hours and annual solar radiation of 160 $kJ/cm^2$ on average [45]. According to the thermal storage temperature, solar energy storage can be classified into two methods, i.e. low temperature and high temperature. It is very common that low temperature thermal storage system is integrated with ground source heat pump in order to increase the temperature for space heating purpose [46–49]. When the storage temperature reaches 60 °C, it is suitable to utilize the direct heating. Recently, latent heat storage technology has mainly been applied in space heating and domestic hot water (DHW) supply for which the required temperature ranges from 40 to 80 °C [50]. Such storage systems must have on the one hand the lower heat losses during storing, and on the other hand, the smaller volume i.e. the highest energy density [51–53].

Materials to be used for phase change thermal energy storage must have a large latent heat and high thermal conductivity [54,55]. They should have a melting temperature lying in the practical range of operation, melt congruently with minimum subcooling and be chemically stable, low in cost, nontoxic and non-corrosive [56–58].

There are many types of materials that could be utilized for solar thermal energy storage. There materials can be broadly classified into organic and inorganic substances. Organic PCMs include Lauric acid [59–62] (melting temperature of 41–43 °C with a latent heat of