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A seasonal cold storage system based on separate type heat pipe for sustainable building cooling

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ABSTRACT

Seasonal cold storage is a high-efficient and environmental-friendly technique that uses the stored natural cold energy in winter (e.g., snow, ice or cold ambient air) for free-cooling in summer. This paper presents a seasonal cold storage system that uses separate type heat pipes to charge the cold energy from ambient air in winter automatically, without consuming any energy. The charged cold energy is stored in the form of ice in an insulated tank and is extracted as chilled water for cooling supply in summer, which help to reduce the chiller running time and reduce the associated electricity consumption and greenhouse gas emission significantly. A quasi-steady two-dimensional mathematical model of the system is developed for characterizing the dynamic performance of ice growth (i.e., cold charging). The model is validated using the field measurement data from an ice charging experiment conducted in Beijing. The impacts of various affecting factors, including the weather data and the key parameters of heat pipes, on the charging performance of the cold storage system are analyzed. The effectiveness and sustainability of the proposed system for cooling are demonstrated through a case study of a kindergarten building in Beijing.

1. Introduction

The worlds' cooling demand has increased significantly in the past decades due to the rapidly increased population, urbanization, comfort requirements and electronic equipment usage [1]. Conventional cooling is usually produced by electrically or thermally driven devices that consume a large amount of fossil energy. By contrast, seasonal cold storage using the stored winter cold energy for cooling in summer is a less fossil energy-consuming alternative. This ancient technique date from two thousand years ago and it was widely used worldwide before the emergence of modern refrigerating technique. Seasonal cold storage is feasible in large parts of the world, particularly in cold regions such as northern Europe, Siberia, North America, Northeast and Northwest of China.

Due to the high energy efficiency and environmental benefits, modern applications of seasonal cold storage have attracted increasing attentions since the energy crisis from 1970s. Numerous seasonal cold storage techniques for cooling applications have been found. In Japan, about 100 projects have been implemented during the past 30 years and about 50–100 seasonal cold storage systems are found in China [2]. The first modem seasonal cold storage project for comfort air-conditioning was established by Princeton University in the late 1970s. The cold energy was stored in a big ice pond (with 10,000 m^3 capacity) and used to supply cooling for a 12,000 m^2 office building [3]. In Ottawa, Canada, the performance of using an abandoned rock quarry for the storage of 90,000 m^3 snow was studied [4]. Näslund investigated a district cooling system using stored snow in Sundsvall, Sweden. About 122,500 m^3 of snow, including the natural snow from streets and squares and the artificial snow made from snow guns or water spraying, was stored for providing the cooling energy that accounting for 43.6%~66.8% of the total cooling demand [5]. Hamada Y et al. investigated the effectiveness of a hybrid system for snow storage/melting and air conditioning on energy conservation and environmental protection through field measurements and numerical analyses [6]. Ground source heat pumps with earth heat exchangers or ground water offer a favorable cooling potential. In addition to the use of reversible ground source by heat pumps, the cold produced in wintertime can also be directly used for cooling in summertime, without running a refrigerant cycle [7]. The performance data of 50 seasonal cold storage projects in four countries (Canada, Germany,

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The Netherlands and Sweden) were collected and analyzed by IEA (the International Energy Agency) in an annex entitled "Innovative and Cost-effective Seasonal Cold Storage Applications" [8]. Results shown that most seasonal cold storage projects have good cost-effectiveness with paybacks of five years or less.

The cooling sources of seasonal cold storage can be natural snow and ice, or artificial snow and ice produced from the cold ambient air, or the frozen soil and rocks in winter. Collecting natural snow or ice is the oldest and simplest way to obtain cold energy. It requires the least initial cost and consumes almost no auxiliary energy. The limitation is that collecting snow or ice exclusively is very labor-intensity and expensive [9]. In addition, the collected snow or ice usually contains many impurity substances that may corrode the chilled water pipes. In modern applications, the seasonal cold energy is usually charged from ambient cold air using snow guns, heat exchangers or heat pipes. Snow guns are the commonly used tools for producing snow. Two types of snow guns were used to produce snow for cooling supply in the Sundsvall Regional Hospital in Sweden. The pressurized water and air are sprayed separately and mixed in the air and the energy usage is 1–3 kWh per ton snow [10]. A seasonal cold storage project named "Icebox" was carried out in Canada [11]. The outdoor cold air was directly blown by fans into an indoor box to freeze the thinly sprayed water into ice layer by layer. The coefficient of performance (COP, i.e., the ratio between cooling energy to electricity consumption) in this Icebox project was about 90–100. The feasibility and performance of using the underground gravel mixed with ice for seasonal cold storage was studied by Illinois State University in the Gravel-Ice Storage Mass project [12]. The circulated antifreeze was firstly chilled-down by outdoor heat exchangers and then used to charge the cold energy into the mixture of gravel-ice by underground heat exchangers. Yang etc. proposed a similar seasonal soil cold storage system [13]. In winter, the system collects natural cold energy by outdoor air heat exchanger and stores it in soil by the U-tube using water-glycol mixture as refrigerant. Results show that the COP of the system ranges from 7.90 to 13.32. Although they are more energy efficient than conventional mechanical cooling, using aforementioned methods for cold charging still consume a certain amount of energy due to the usage of fans or pumps.

By contrast, seasonal cold storage using heat pipe might be a more attractive option in terms of energy efficiency since no additional energy is needed for cold charging. A heat pipe is a highly efficient heat-transfer device that can charge the cold energy from outdoor air into the cold storage medium automatically. Such technology has been successfully applied in frozen soil reinforcement and fruit and vegetable refrigeration projects. For example, a simple type of heat pipes, i.e., thermosyphons are commonly used as the seasonal cooling devices in permafrost areas for maintaining frozen conditions in the soil bases of buildings and structures [14]. In fact, the seasonal cold storage using heat pipes can be also used for comfort or process cooling in buildings. However, such investigations or studies are still very limited and only few studies can be found in the existing literature. For example, Singh etc. proposed a heat pipe based cold storage system for the thermal control system of a datacenter. Two types of cold energy storage, namely cold water storage and ice storage, can be realized in this system as daily based (night to day) or seasonal based (winter to summer) storage [15].

This paper therefore presents a novel seasonal cold storage system based on separate-type heat pipes for sustainable building cooling. It can store a large amount of cold energy without consuming any energy in winter and help to reduce the chiller running time in summer. Consequently, a massive amount of the electricity related cost and greenhouse gas emissions resulting from the electricity generation from non-renewable sources can be reduced. A quasi-steady two-dimensional mathematical model is developed for characterizing the dynamic process of ice growth (i.e., cold charging). The model is validated using the field measurement data from an ice charging experiment in Beijing. The impacts of key affecting factors, including weather data and heat pipes parameters, on the charging performance of the cold storage system are analyzed. A case study on the application of the proposed system for free cooling of a kindergarten building in Beijing is presented as well, which demonstrate the sustainability and effectiveness of the proposed system on energy conservation and environmental protection.

2. System configuration and operation principle

The schematic of the proposed seasonal ice storage system is presented in Fig. 1. The system consists of two parts or two subsystems, i.e., the cold charging subsystem and the cold discharging subsystem. In winter, the cold charging subsystem collects natural cold energy from the outdoor low-temperature air through separate type heat pipes to cools down the water in the underground tank until all water is frozen to be ice. In summer, the cold discharging subsystem extracts the stored cold energy by pumping chilled water through the discharging coilers, which are submerged into the mixture of ice and melting water, to AHUs (air handling units) or FCUs (fan coil units) for air conditioning.

The working principle of separate heat pipes for cold charging can be illustrated using Fig. 2. The cold charging device consists of a separate-type heat pipe and an ice storage tank. In a separate-type heat pipe, the evaporator segment and the condenser segment are separated in diffident locations. In this system, the evaporator is located in the ice storage tank (as heat source) and the condenser is located in the outdoor air (as heat sink). The altitude of the condenser should be higher than that of the evaporator so that the liquid working fluid (i.e., refrigerant) can return to evaporator by gravity. The heat pipe works as follows: In winter, when the outside air temperature is below the water temperature, the liquid refrigerant within the evaporator is heated into vapor. The vapor then travels along the vapor ascending pipe to condenser segment and condenses back into a liquid-releasing the latent heat to the outdoor air. The liquid then returns to the evaporator segment through the liquid descending pipe by gravity, and the cycle repeats. During this process, the water around the evaporator is frozen into ice gradually. Once the outdoor temperature is higher than the ice temperature, the heat pipe stops working automatically which ensures that only the one-way heat transfer (i.e., heat release from the water tank to outdoor air) is allowed. The cold storage tank is typically located in underground and well-insulated to minimize the cold loss.

3. Mathematical model for cold charging

In order to effectively analyze the dynamic cold charging performance of the seasonal cold storage system, a simplified physical configuration and a quasi-steady two-dimensional mathematical model are developed. The simplified configuration is used to describe the physical dimensions and key parameters of the cold charging device while the mathematical model is used to calculate the cold charging performance of the system by combining a series of heat transfer equations.

3.1. Simplifications on the physical configuration

A simplified physical configuration is used to highlight the dynamic process of the ice growth around the evaporator of the heat pipe. As shown in Fig. 3, these parallel pipes in both the evaporator