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Feasibility study on a novel freeze protection strategy for solar heating systems in severely cold areas

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Abstract

In severely cold areas, the freezing of outdoor pipes and collectors is one of the most serious problems, which, to a certain degree, limits the utilization of solar energy and decreases the system economic performance. To solve this issue, a novel anti-freezing strategy using the remnant thermal energy in solar collector as the heat source was proposed to prevent the freezing of the solar collecting system in winter nights and overcast days. The strategy was investigated and analyzed experimentally under different weather conditions to verify its anti-freezing effectiveness. The results indicated that the concentration of antifreeze fluid could be reduced from 50% to 20% or even lower due to the anti-freezing strategy. The economic feasibility of the strategy was also analyzed and compared with two conventional anti-freezing measures, which indicated that the proposed strategy was the most economical. The strategy presented in this paper can successfully resolve the issue that the initial cost of antifreeze fluid was high when all-glass evacuated tube collectors are used in solar heating systems in severely cold areas. It also can provide a key reference for the design of solar heating systems, especially for the selection of the concentration of antifreeze fluid required in severely cold areas.

Keywords: Anti-freezing strategy; Freeze protection; Solar thermal system; Severely cold areas

1. Introduction

As a sustainable and promising energy source, solar energy is attracting increasing attention due to its cleanliness and renewable nature. Nowadays, solar thermal heating systems have been widely used all over the world. It is significant to use solar energy to replace fossil fuels for heating on both energy saving and environmental conservation (Haller et al., 2012). However, the utilization of solar thermal heating systems is mostly limited by the intensity of solar radiation, the variation of weather conditions, large investment and the discrepancy between heat supply and heating demand (Muneer et al., 2008; Du et al., 2013).

Freezing is also one of the serious problems for solar collecting systems in severely cold areas, and some anti-freezing measures must be taken in such systems (Cartland, 1979; James, 1989; Saitoh et al., 2003). The conventional measures include the use of antifreeze fluid, electric tracing tapes, draining water from the collectors and using the hot water in a thermal storage tank to heat the outdoor pipes by circulation. The method of hot water circulation in the pipes and collectors requires extra power consumption of the pump and the thermal energy of hot water in the storage tank. This method can be considered in climates where freezes are infrequent. In emergencies, when pump power is lost, the collector and piping subject

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to freezing temperatures may get frozen. Electric tracing tapes is convenient and easy to maintain, which has been used in many industries, such as the piping systems, solar water heating systems and some other fields. However, it consumes more electricity, and more importantly it is not safe enough in actual projects. Drain-out and drain-back measures are widely applied in solar heating systems. The water in the system can drain back into a storage tank or drain out to waste. However, it may not be drain-out completely sometimes (Duffie and Beckman, 2013).

Antifreeze solution can be used in the collector loop with a heat exchanger between the collector and the storage tank, which is quite popular in solar heating systems (Ozgener and Hepbasli, 2005; Trillat-Berdal et al., 2007). However, the concentration of antifreeze fluid is generally selected according to the local ambient air temperature (CEN, 2006; China Academy of Building Research, 2009). The freezing point of the antifreeze fluid should be lower than the lowest ambient air temperature. Taking the city of Harbin (in severely cold areas) as an example, the suitable concentration of antifreeze fluid is 50% (its freezing point is −33.8 °C) to keep it nonfreezing because the local outdoor design temperature for heating is −26 °C. In China, evacuated tube collectors comprise 95% of the market, which are more popular than the flat-plat collector in severely cold areas because of its higher thermal efficiency and better insulation property. Additionally, they are more economical than other types of evacuated collectors (Han et al., 2010). However, the required volume of antifreeze fluid is larger and correspondingly the initial cost would be increased. Therefore, investigations on the measures to reduce the concentration of antifreeze fluid and to improve the economic performance of the solar heating system are of high significance when all-glass evacuated tube collectors are used in severely cold areas.

The applications of anti-freezing measures and its advantageous or disadvantageous in actual projects are relatively few. Zhao et al. analyzed the performance of five familiar anti-freezing methods used in solar water pipes during winter (Zhao and Wang, 2007). All of these anti-freezing strategies and measures can only be used in small buildings and are suitable for small domestic hot water systems. In solar heating systems, anti-freezing measures merely involved but little detail information was presented (Liu et al., 2014; Xi et al., 2012). To the author's knowledge, freezing problem still exists in the project occasionally if the anti-freezing measure disabled (Liu et al., 2014). In this study, a novel strategy involving the use of remnant thermal energy in solar collectors as the heat source was proposed to prevent the freezing of outdoor pipes in winter nights and overcast days. The objective of this study was to experimentally analyze the feasibility of a proposed freeze protection strategy that can decrease the concentration of antifreeze fluid and thus improve the economic performance in all-glass evacuated tube collector systems. A series of experiments were carried out to analyze the change of fluid temperature in the solar collecting loop (also called the anti-freezing loop) and to research the feasibility and economic performance of the proposed anti-freezing strategy. The suitable concentration of antifreeze fluid was also discussed, which could provide a key reference for the design of similar solar heating systems and the selection of the freeze protection measure.

2. Description of the system

2.1. Introduction of the experimental system

According to the *Technical code for solar heating system* (GB 50495-2009), the suitable type of solar heating system in severely cold areas is indirect cycle system filled with antifreeze fluid or hot air in the solar collectors, and the terminal heating mode is floor radiation or hot air heating. Thus, a typical solar system was built in Harbin in terms of the national standard criterion introduced above, as illustrated in Fig. 1. The system parameters and equipment types were selected to achieve maximum thermal efficiency under winter conditions.

The experimental system consisted of a solar collecting loop (anti-freezing loop), a heat exchanging loop and a terminal heating loop, as well as data acquisition and controlling subsystems. In this system, ethylene glycol solution was used as the antifreeze fluid. The main structural parameters and thermal performances of the system components are given in Table 1. In addition, a fan coil was set in the terminal loop to dissipate heat from the thermal storage tank. The physical pictures of the system are illustrated in Fig. 2.

2.2. The proposed anti-freezing strategy

The proposed anti-freezing strategy could be easily realized on the basis of the experimental system by adding a by-pass loop beside the heat exchanger. The purpose of the by-pass loop was to avoid the freezing of the heat exchanger when the fluid temperature in the anti-freezing loop was lower than 0 °C. The anti-freezing loop is marked with dash lines and arrows, as shown in Fig. 3.

Two operation modes could be realized in this solar collecting loop: solar collecting mode and anti-freezing mode. On sunny days, solar energy could be absorbed by the selective coating and transformed into the thermal energy of the fluid in the solar collector. Thus, the temperature of the fluid increased and the system operated in solar collecting mode. During nights and overcast days, the outdoor pipes were easy to freeze because of heat losses from the fluid to the ambient gradually. However, the fluid temperature in the solar collector could keep much higher because of its larger fluid capacity and better insulation. Therefore, it is theoretically possible to use the remnant thermal energy in the solar collector to prevent freezing of the outdoor pipes via circulation. The hot fluid from the solar collector was circulated by a pump to the outdoor pipes,