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Performance investigation of a solar heating system with underground seasonal energy storage for greenhouse application

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ABSTRACT

This study reports the performance of a demonstrated 2304 m^2 solar-heated greenhouse equipped with a seasonal thermal energy storage system in Shanghai, east China. This energy storage system utilises 4970 m^3 of underground soil to store the heat captured by a 500 m^2 solar collector in non-heating seasons through U-tube heat exchangers. During heating seasons, thermal energy is delivered by the heat exchange tubes placed on the plants shelves and the bare soil. The system can operate without a heat pump, which can save electricity consumption and further enhance the solar fraction. It was found that in the first operation year, 331.9 GJ was charged, and 208.9 GJ was later extracted for greenhouse space heating. No auxiliary heating equipment was installed so that solar energy covered all the heating loads directly or indirectly. It was demonstrated that this system was capable of maintaining an interior air temperature that was 13 °C higher than the ambient value when the latter temperature was −2 °C at night. The ECOP (electrical coefficient of performance) of the first operation year was approximately 8.7, indicating a better performance than the common heat pump heating system.

1. Introduction

The main objective of a greenhouse is to provide a suitable micro-climate for various crops, and protect them from severe and variable outdoor weather conditions. However, in cold climate, the greenhouse structure is usually not sufficient to keep the inside air temperature at an appropriate level, so auxiliary heating systems are required concurrently. According to the different heating methods, these greenhouses are classified into active and passive ones [1,2]. In addition to the conventional gas boiler, several important existing heating systems with alternative energy sources, mostly solar energy, are documented by Refs. [3,4], including water storage, rock bed storage and phase change material storage. Energy storage can make it possible to use the solar heat collected in the daytime for space heating when is required. Yet, most of the agricultural applications are short-term/diurnal thermal storage by which only small part of heating loads can be satisfied [5–11]. In consecutive overcast and rainy days, such short-term storage systems are not sufficient.

STES (seasonal thermal energy storage) is an attractive option that may solve the afore-mentioned problems. The time-discrepancy between the energy supply and consumption in solar energy utilisation can be eliminated. Excess heat collected in summer compensating for the heat supply insufficiency during the wintertime can make the utmost use of solar energy, thus significantly enhancing the solar fraction and reducing the world's carbon footprint. A previous study [12] compared the cost-benefit-ratio of existing large-scale projects and concluded that long-term (seasonal) storage is more capable of conserving energy and reducing fossil fuel consumption than short-term (diurnal) storage. The STES concept has been implemented in a large number of large-scale residential projects and is being analysed by setting up models, especially using the mechanism of sensible heat storage [13–18] whereas for agriculture applications, only one project with latent heat storage has been reported to the author's knowledge [19]. Other studies [20,21] have indicated that the long-term stability of a phase-change material was one of the main barriers for the latent heat storage technique to be further employed in a large-scale. As a result, sensible heat storage which includes using water tanks, aquifers, rock beds or underground soil, is more competitive due to the reliability and technical maturity of this technology.

Among the sensible heat storage technologies, UTES (underground thermal energy storage) in aquifers or in unsaturated ground is regarded as more favourable than the other technologies

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Nomenclature

A	area, m^2
BTES	borehole thermal energy storage
c_p	specific heat, J/(kg K)
CNY	ChiNa Yuan
ECOP	electrical coefficient of performance
h	heat transfer coefficient, W/m^2 K
I	solar radiation intensity, W/m^2
$\dot{m}$	mass flow rate, kg/s
Q	heat, J
STES	seasonal thermal energy storage
STTES	short term thermal energy storage
T	temperature, °C
U	total heat transfer coefficient, W/m^2 K
UHX	U-tube heat exchanger
UTES	underground thermal energy storage
W	electricity consumption, kWh
λ	thermal conductivity, W/m K

Subscripts

amb	ambient
c	convection
charge	charged to the BTES
co	solar collector
discharge	discharge from the BTES
g	ground
gr	greenhouse
grf	greenhouse with film
h0	before heating
hac	active heating
he	end of heating
hpa	passive heating
hst	highest value
r	radiation
rin	inlet of radiant loop
rout	outlet of radiant loop
s	soil
s0	before storage
sin	inlet of the BTES loop
sout	outlet of the BTES loop
ta	water tank
w	water

from both technical and economic perspectives [22]. Although BTES (borehole thermal energy storage) is more complicated in excavating and drilling the ground to insert vertical or horizontal tubes as heat exchangers, this technology still has the advantage that the pipe network and fittings are much less exposed to scaling and clogging compared with ATES (aquifer thermal energy storage) [23].

It is well known that in China, which is a large agricultural country, a significant amount of energy consumption and the subsequent environmental pollution issues are caused by the use of conventional fossil fuel resources and have brought heavy burdens on the sustainable development. Furthermore, in east China, the climate is humid and features chilly, damp winters that are caused by the cold north-westerly winds from Siberia. Temperatures at night may drop below freezing which plants cannot endure. Under these circumstances, the BTES was introduced into the greenhouse space heating inspired by the previous documented seasonal BTES projects for residential applications [24–29].

In this project, approximately 4970 m^3 of soil directly under the greenhouse, which is embedded with 130 vertical U-type heat exchangers at a depth of 10 m are used to store the excess solar heat captured in non-heating periods. In a greenhouse application, the underground soil usually acts as an important heat source during the night [30]. In present project, the underground soil is utilised not only as the heat storage unit but also as the heat distribution unit (together with the radiant pipes) during the wintertime. The heat released from the soil can be significantly increased, thus enhancing the overall heating efficiency. Moreover, it is noteworthy that there is no auxiliary heating equipment installed in the greenhouse, which means that all the heating loads are intended to be covered by solar energy, either directly or indirectly. The electricity is only consumed by the circulating pumps and the control system.

The objective of the present work is to demonstrate the potential and evaluate the performance of the solar heating system with BTES for greenhouse applications. Experiments were initiated on April 10th, 2012 and the long-term performance has been monitored afterwards. The heat-charging process of the first-year operation is evaluated and the heating performance in the wintertime is presented according to the different weather conditions. The operation strategy of the solar-heated greenhouse is also analysed. The results of this work will be useful for the optimisation of the management of greenhouses as well as of the design and control of the seasonal storage system.

2. System description

2.1. Working principle

As schematically illustrated in Fig. 1, the entire solar heating system for the greenhouse is divided into three subsystems: a solar collection subsystem, a thermal heat storage subsystem and a heating subsystem. In non-heating seasons (Mar.–Nov. in east China), solar energy captured in the solar collection arrays is charged into the underground soil by circulating hot water through the U-tube heat exchangers embedded in the storage media. In winter, the stored heat is retrieved by the reverse process to meet the heating loads; this reverse process is also called the discharging process. Therefore, solar energy in the summer compensates the insufficient heating capacity in the low-temperature seasons.

2.2. Main components of the system

Fig. 2 shows the main components of this solar heating system with seasonal thermal energy storage which contains: solar collectors, water tank, borehole thermal energy storage (BTES) unit, heat distribution pipe. Table 1 gives the main design parameters of the system.

With respect to the system design, steady-state calculation was made compliant with the building code. Solar radiation condition of the location, heating load and heat loss of the greenhouse was taken into consideration. Despite of the received passive heat due to the transparent envelope of the glass greenhouse, the rest of the heating loads need to be met by the active heating system, which is aimed to be supplied by the underground stored heat in our project. Based on the required amount of thermal energy to keep the greenhouse temperature over 10 °C, the design parameters of the solar energy system (such as solar collector area, underground storage volume) were determined.