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Thermal charging of boreholes

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ABSTRACT

This paper presents experimental study of thermal charging the boreholes that are used for inter-seasonal thermal storage of heat and coolth integrated with ground-coupled heat pump and unglazed solar collectors. After 180 days of thermal charging, it was observed that the temperature of the ground at 21 m depth and 1 m distance from the borehole had increased by 2.5 °C. The unglazed collectors are able to collect heat for charging the heat storage borehole at an average of 43.9 MJ day^{-1}. The system is able to charge borehole at an average heat transfer rate of 57 W m^{-1}. A comparison of the experimental results with the simulated results of a TRNSYS model of the system showed a good agreement. The mean efficiency of the unglazed solar collector during 180 days charging operation was found to be 30% and the mean efficiency of the system was found to be 38%.

1. Introduction

Globally 40% of the total energy consumption is by buildings [1]. In Australia, household energy consumption accounted for 12% of the total energy end use during the year 2010–2011 [2], out of which more than 35% was used for space heating [3]. The demand for the space heating and cooling energy is increasing due to increasing number of buildings associated with increase in population. This demand is expected to increase over the years. Therefore there is a need to look for alternative technologies which have lower energy consumption for space heating and cooling. While renewable energy is an alternative technology which is environmentally friendly, the problem is its intermittent availability. Most of the renewable energy sources are not available continuously. Building heating and cooling loads vary continuously. Moreover the peak loads and the availability of the renewable energy sources may not match. Therefore storage of energy is necessary to enable the system to match the demand. Inter-seasonal thermal storage integrated with a heat pump and solar collector has been gaining attention in the past [4–10]. Inter-seasonal thermal storage is defined as the storing of heat/coolth from one season to another season. The accumulated heat/coolth is extracted by the heat pump for space heating in winter and cooling in summer respectively. The heat/coolth charging is expected to enhance the performance of the heat pump. Several experimental and theoretical studies have been conducted in the past regarding the performance of thermal storage with heat pump and solar collectors.

Nordell and Hellstrom [11] found that 60% of the total heat demand (both for space heating and domestic hot water) of 9000 m^2 building floor area can be supplied by 3000 m^2 glazed flat plate solar collectors mounted on roof and 60 000 m^3 of borehole storage system. The mean temperature of the borehole storage varied from 30 to 45 °C and a heat pump is not required to upgrade the heat delivered. The storage loss was estimated to be about 40% of the total energy charged by the solar collectors. Chiasson and Yavuzturk [12] studied the performance of hybrid geothermal heat pump systems with solar thermal collectors in six cities in USA. They applied the same school building parameters for all locations but different climatic data sets. From their findings the borehole length could be reduced from 16% to 33% when a fixed solar collector was used compared to a system without solar thermal collectors. Trillat-Berdal et al. [13] performed simulation using a validated model to study the performance of a glazed solar assisted ground-coupled heat pump (SAGCHP) consisting of two boreholes of 90 m deep and 12 m^2 roof top glazed solar thermal collectors for space heating and domestic hot water production for a residential house (180 m^2 floor area). They concluded that the proposed system could help to reduce the borehole length and initial cost of the system. Wang and Qi [14] studied the performance of borehole thermal storage and GCHP system for the heating and cooling of residential building. The system comprised of four boreholes of 50 m deep and 220 mm diameter and 25 m^2 glazed flat plate collector for a 120 m^2 floor area residential house. They reported that out of 42 GJ of useful energy delivered at the collector outlet, only 30 GJ (71%) could be charged to the boreholes and the rest was lost.

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Xi et al. [15] simulated a SAGCHP system for space heating and hot water supply over 20 years for Beijing climatic conditions. The system consisted of 270 m borehole, 45 m^2 glazed flat plate collector and 1.8 m^3 water storage tank. They concluded that the SAGCHP system coefficient of performance (SCOP) is 26% higher than the SCOP of conventional GCHP without solar collector and electricity consumption for heating could be reduced by 1.6 MWh annually. Moreover, SAGCHP could save borehole length up to 3.6 m per m^2 of solar collector area compared to the conventional GCHP system. Wang et al. [16] investigated the relative performance of a conventional GCHP and a SAGCHP. The conventional GCHP comprised of 66 boreholes of 120 m deep and 4 m apart while the SAGCHP comprised of 25 boreholes of 50 deep and 2.5 m apart and 280 m^2 flat plate collector. The load for the system was a four storey building having a floor area of 4953.4 m^2. The study was based on a multi-year simulation using TRNSYS. They found the simulated system SCOP varied from 3.42 to 3.17 and 2.99 to 2.95 for SAGCHP and conventional GCHP respectively at the end of 25 years of operation.

A comparative study on performance of SAGCHP in three cities in Canada (Edmonton, Montreal and Vancouver) by Eslami-Nejad and Bernier [17] found that by charging solar energy collected into the boreholes using double U-tubes, the design borehole length could be reduced in the respective locations by 13%, 12% and 18% with a corresponding reduction of annual heat pump electricity consumption by 6%, 5.3% and 6.3%. Mempouo [8] also found that borehole length could be reduced up to 60% by using a SAGCHP system compared to system without solar collectors. A recent study by Rad et al. [4] found that by charging heat from 6.81 m^2 solar collector into four boreholes of 55 m deep each, the borehole length could be reduced by 15% compared to the system without thermal charging. The system was used for heating a two-storey detached residential house having 498 m^2 floor area with design heating and cooling demand of 11.5 kW and 9.5 kW respectively.

The presented past studies indicated that the solar thermal charging of the boreholes provides two potential benefits, improvement of COP of the system or reduction in design borehole length compared to the system without solar collectors with same or slight increase in COP. The above studies are limited to heating application only, whereas in most parts of Australia, there is demand for both heating and cooling. Therefore an inter-seasonal heat and coolth storage system is being investigated at the University of Melbourne. The system consists of a separate heat and coolth storage boreholes integrated with a GCHP and unglazed solar collectors. The unglazed solar collectors allow charging of both heat and coolth. The heat collected during the day is charged into the heat storage borehole (HSB). During the night the heat extracted from the coolth storage borehole (CSB) is dissipated from the unglazed solar collector surface to the ambient. The aim of this paper is to present the potential of heat charging using unglazed solar collector conducted experimentally on a small scale set up in Melbourne. The coolth charging experiment was presented in Lhendup et al. [18].

2. Experimental set up

The experimental set up consists of two 40 m deep boreholes, two 3.84 m^2 unglazed solar collectors connected in parallel, two circulating pumps, piping networks and six 21 m deep monitoring boreholes. One 40 m deep borehole is used as HSB and another 40 m deep borehole as a CSB. Each borehole has two U-tubes which enable independent charging and discharging operations. For detailed descriptions of the experimental set up, refer to Lhendup et al. [18]. The design parameters used in this study are summarised in Table 1. Fig. 1 shows the schematic diagram of the experimental set up. Water pump PP1 is switched ON when ($T_{co}-T_{gd\_HSB} > 1$) and switched OFF otherwise. T_{co} is the collector outlet temperature (°C) and T_{gd_HSB} is the ground temperature of HSB at 21 m deep (°C). When pump PP1 is ON, valves V1, V4, V5, V17, V18, V20 are open and all other valves are close. The uncertainties of the measurements are summarised in Table 2.

Table 1
Design parameters used in the study.

Parameter	Value
Borehole depth (m)	40
Distance between the boreholes (m)	8
Diameter of borehole (mm)	115
No of U-tube (HDPE pipe)	2
U-tube pipe inside diameter (mm)	21.32
U-tube pipe outside diameter (mm)	25
Total solar collector area (m^2)	7.68
Fluid flow rate ($kg\ h^{-1}$)	840
Ground thermal conductivity ($W\ m^{-1}\ K^{-1}$)	2.23
Grout thermal conductivity ($W\ m^{-1}\ K^{-1}$)	1.2
Thermal conductivity of pipe ($W\ m^{-1}\ K^{-1}$)	0.4

3. TRNSYS model

The experimental set up for heat charging was modelled in TRNSYS-17 [19]. Fig. 2 shows the components used in graphical user interface of the TRNSYS model. HSB is represented by Type 257, a modified version of thermal energy system specialists (TESS) Type 557 [20]. The unglazed solar collector is represented by a modified version of TESS Type 559. The other components such as circulating pump, buffer tank and pipes were used from the standard TRNSYS library. The heat charging experiment was conducted from October 2012 to March 2013. During the experiment, temperatures of the water at the inlets and outlets of the heat storage borehole, solar collectors and the buffer tank were measured (Fig. 1). These measurements enabled validation of the TRNSYS Types for HSB, solar collectors and buffer tank. Although the experiment was conducted and TRNSYS types applied were validated for a period of 180 days, only a week data (17–23 December 2012) was presented in this paper. The validated model will later be used to simulate the performance of the entire system which is not discussed in this paper.

4. Results and discussion

Fig. 3 shows the measured short wave- solar radiation on the collector plane and ambient air temperature on site during the period 17–23 December 2012.

The undisturbed ground temperature of the HSB was measured to be 17.3 °C [18]. The ground temperature near to the surface fluctuates depending on the thermal properties of the ground and the conditions at the surface. This fluctuation disappears below a certain depth and becomes stable. Fig. 4 shows the monthly average ground temperature at 2, 21 and 40 m along with the monthly average ambient air temperature. As evident from the measurements the temperature at 2 m below the ground surface fluctuates with the monthly average ambient air temperature whereas the temperature at 21 m and 40 m depths are nearly constant throughout the year. Below 21 m deep, the ground temperature is higher than the ambient in winter and lower than ambient in summer. This feature of the ground temperature is the reason behind the use of GCHP systems.

4.1. Temperature

Each section of the model has input and outlet temperature measured which enable to compare with the simulated values. The