Simulation of operation performance of a solar assisted ground heat pump system with phase change thermal storage for heating in a rural building in Xi'an

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Abstract. Energy consumption for house heating in winter accounts for a large proportion of building energy consumption in rural buildings in western China. It is an alternative method to make full use of renewable energy for heating houses to save energy and cost. A solar assisted geothermal heat pump with phase change material heat storage tank (SAGHP-PCM) demo heating system in a rural building in Xi'an China was built up and the dynamic performance of the SAGHP-PCM heating system was simulated in different control strategies. The results show that PCM module can improve the heating effects, moreover, optimized control strategy selected by comparison can bring a better operation way and save electric energy by using solar energy as whole energy source for heating in 753 hours, and the heating performance is acceptable meanwhile. The simulated average temperature of the optimized system is 17.62℃ and the guarantee hours is 3379 h when taking 16℃ as qualified indoor temperature.

Keywords. solar energy; geothermal heat pump; phase change thermal storage; rural building; simulation

1. Introduction

Energy consumption for house heating in winter accounts for large proportion of building energy consumption in China and 45% of the total building energy consumption is used for warming 6.5 billion m^2 existing building in North China[1]. The extensive energy consumption for heating houses make it crucial to seek more energy-saving heating methods[2].Therefore, application of some sustainable technologies are applied for heating houses such as heat pump, air source heat pump, geothermal heat pump and some integrations of them [3,4].At the same time, many researchers have confirmed that the performance of heating system in single alternative energy resource is easily affected by external factors and combined system is useful to avoid the shortcomings of the single system[5,6,7,8]. Solar assisted geothermal heat pump system (SAGHP) was attempted for house heating because it can solve the problems that the soil thermal depletion would decrease after the long-term operation of geothermal heat pump system and the performance of solar heat pump system is so easily affected by weather that the system can't work at night and overcast [9]. In this study, a solar

assisted geothermal heat pump with phase change material thermal storage tank (SAGHP-PCM) heating system was equipped in a rural building located in Xi'an China. The PCM heat storage tank is added because the application of PCMs have the potential to promote the COP of the system and make the operation more stable[10,11,12].For evaluating and optimizing its performance, Transient System Simulation Tool (TRNSYS) was employed to simulate the operation of system and get the dynamic performance of the house while the heating system is running in this study.
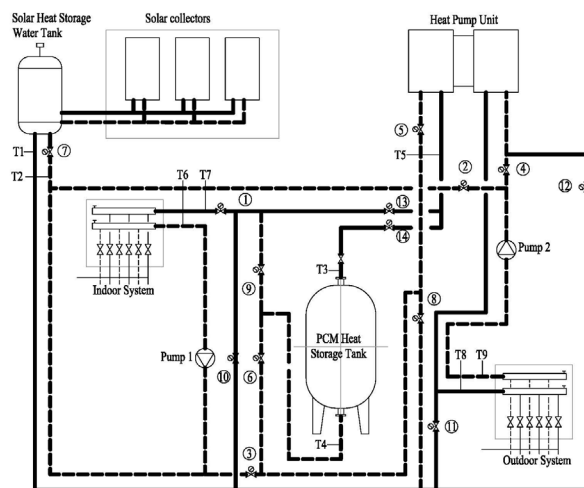
2. Description of the project
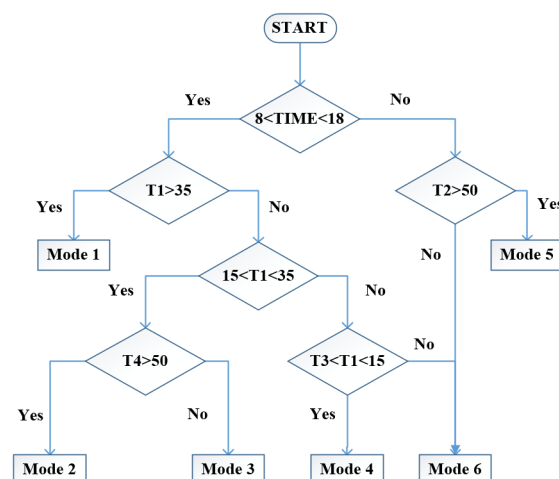
2.1. Components of the system

The solar assisted geothermal heat pump with PCM heat storage tank (SAGHP-PCM) heating system locates in a typical rural residential house in Xi'an city of China, with total areas of 138 m^2, which is shown schematically in Figure 1.The system will only bear the heat load of three rooms: the master bedroom, the second bedroom and the living room, with total areas of 56 m^2.

The SAGHP-PCM heating system comprises following components: (1) the solar collectors, (2) the solar heat storage water tank, (3) the heat pump, (4) the U-type ground heat exchangers, (5) the PCM heat storage tank, (6) the circulating water pumps, (7) the water distributors, (8) the valves and the thermometers. The connection of components is shown in Figure 1 too, and the indoor system here means that hot water will passes through the water distributor to the floor radiant heating system in the house; outdoor system is also mentioned lightly that cold water will passes through the water distributor to the U-type ground heat exchangers pipes, valves are marked by number 1-13, and the location of thermometers is marked symbolically by T1-T9.

In practical project, the solar collectors are put on residential roofs in groups. The other components are located in the equipment room neighbor to the residential house. And the geothermal heat pipes outdoor are buried in the courtyard of the residential buildings.

Figure 1. Schematic diagram of the structure of SAGHP-PCM heating system

Figure 2. The control strategy of SAGHP-PCM heating system

2.2. System control strategy and specifics of heating modes

Several heating modes can be operated by this composite system, and the switch between different modes is based on specific control strategy shown in Figure 2. The variables used for judgment in Figure 2 include (1) TIME, the hours in the simulation day; (2) T1 and T3, the outlet and inlet water temperature respectively of the solar heat storage water tank; (3) T2, the outlet water temperature of the PCM heat storage tank, and (4) T4, the outlet water temperature of the load side in heat pump. The 6 heating modes in Figure 2 and some corresponding explanations are listed in Table 1.
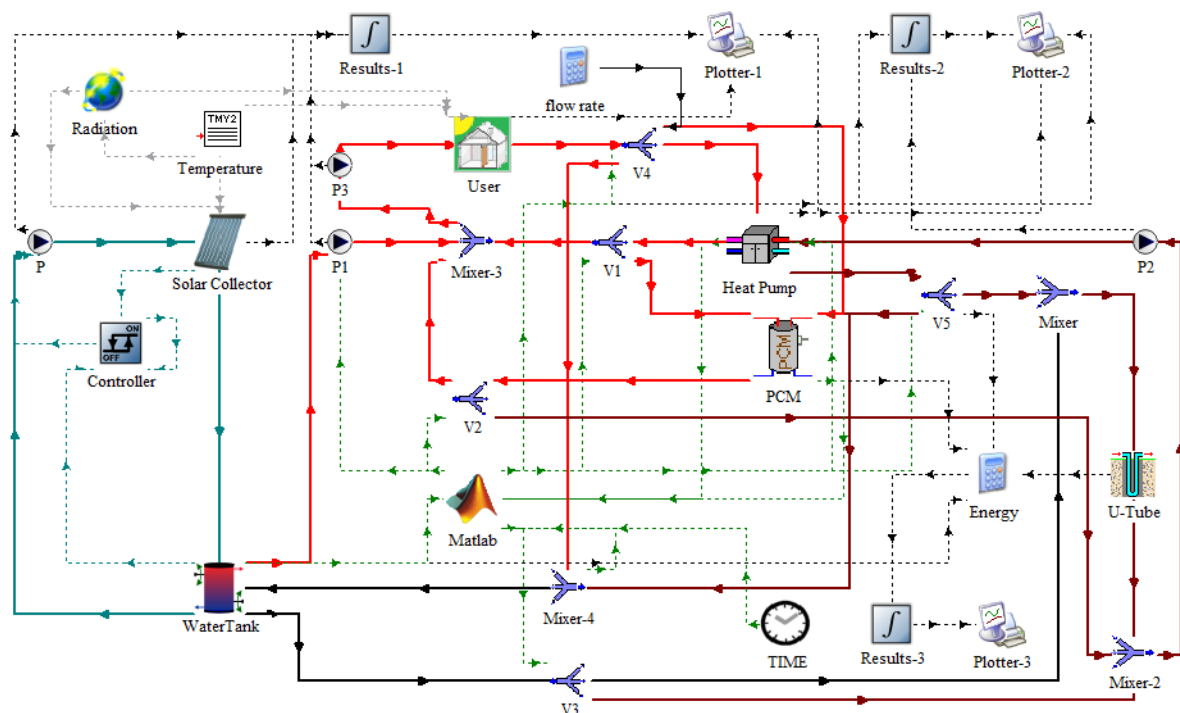
Table 1. Six operating modes

Mode	Description
1	Solar energy heating mode: Solar energy is the only heating source for the house.
2	Heat supply and storage mode by solar energy assisted heat pump: Water from the solar heat storage water tank is used to heat outdoor side of heat pump and hot water generated by heat pump flows through the PCM storage tank and then into the indoor system.
3	Solar energy assisted heat pump heating mode: Water from the solar heat storage water tank is used to heat outdoor side of heat pump and hot water generated by heat pump flows directly into the indoor system.
4	Solar energy assisted geothermal heat pump heating mode: Water from the solar heat storage water tank is used to preheat the water circulating in the U-type ground heat pipes.
5	PCM thermal storage tank heating mode: Water from the PCM thermal storage tank is the only heating source for the house.
6	Geothermal heat pump heating mode. Geothermal Heat pump is the only heating source for the house.

3. Model description

3.1. The SAGHP-PCM heating system

The operating performance of the system was simulated by TRNSYS16.1. The logic diagram of simulation system is shown in Figure 3, and the main components are listed in Table 2.

Figure 3. Schematic diagram of the TANSYS simulation model

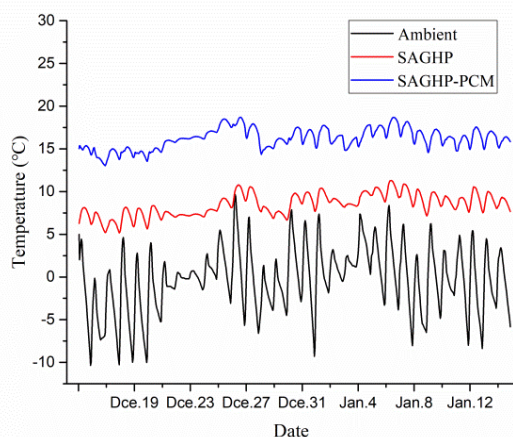**Table** 2. Main components of TRNSYS simulation model

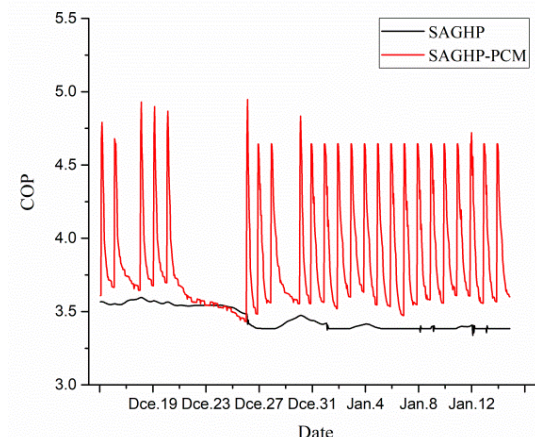| Name	Types	Parameter	Description
Solar Collector	Type 71	Collector area: 36 m^2; slope of collector: 48°; intercept efficiency: 0.7.	Simulates the Evacuated Tube Collector, turns radiation to energy and gives out the hot water to others.
User	Type 56	Zone volume: 157.92 m^3; capacitance:189.5 kJ/K.	Active layer added in the floor is used to simulate the radiant floor heating system.
Heat Pump	Type 668	Source flow rate: 2260 kg/h; load flow rate: 1840 kg/h.	The catalog data for the capacity and power draw based on the entering temperatures make the calculation possible.
PCM	Type 840	The fluid in tank: water; the PCM in tank: paraffin wax; volume: 0.77 m^3.	Stores and releases energy through the phase change process in daytime and nighttime respectively.
Water tank	Type 4a	tank loss coefficient: 2.5 kJ/h·m2·K；Volume: 0.3 m^3.	Stores the energy from solar collector and releases it when the temperature is proper.
U-Tube	Type 557	Storage volume: 2200 m^3; number of boreholes: 3; borehole depth: 110 m.	A heat carrier fluid is circulated through the U-tube ground heat exchanger and either rejects heat to or absorbs heat from the ground.
Matlab	Type 155	Mode: 0; calling mode: 10.	Links the Matlab engine, which is launched as a separate process.

4. Results and discussion

4.1. Comparison with the SAGHP with and without PCM storage tank

Figure 4 and Figure 5 shows the simulated results under SAGHP system with and without PCM storage tank during the coldest month in Xi'an from Dec 15th to Jan 15th.

It can be seen from Figure 4 that indoor temperature of the SAGHP without PCM is lower and the number of the qualified temperature only accounts for 12.18% of the total hours (taking 15 °C as standard), and the average temperature is 10.96 °C, so the heating effect of the SAGHP heating system is disable to guarantee the comfort effectively.

Figure 4. The instantaneous indoor and outdoor temperature

Figure 5. COP distribution of two systems

Contrastively, the heating performance of the SAGHP-PCM heating system is much better, it is qualified in almost whole simulation time, the highest and average temperature are 28.34 and 18.84 °C respectively, and the amount of the temperature lower than 15 °C only accounts for 8.5%.

Figure 5 further proves that overall performance of the SAGHP with PCM is effectively improved. The distribution of system COP has been significantly improved and the average COP in whole simulation time increase from 3.4 to 3.8.
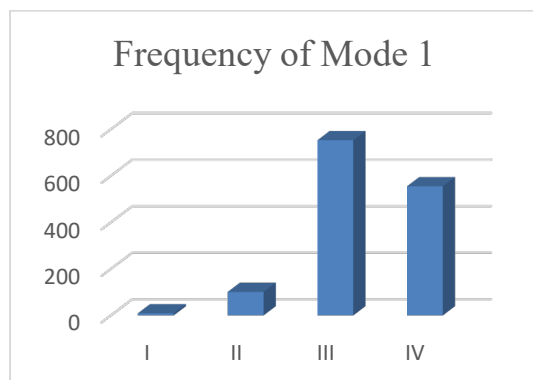
4.2. Comparison with Different Operation Strategies of the SAGHP-PCM Heating System

Besides PCM, the switch condition may also have influence on the final performance of system. To evaluate the effect of different operating strategies, the performance with four different operation strategies with different switch temperature based on T1 was simulated as listed in Table 3.
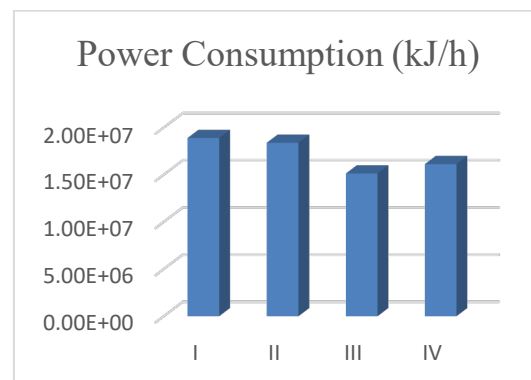
Table 3. Four switch strategies of operation modes based on different switch temperature of T1

Control strategies	Grading standard of T1			
	Mode1	Mode2,3	Mode4	Mode7
I	(+∞ , 35）	(35 , 15)	(15 , T3)	(T3 , -∞)
II	(+∞ , 30）	(30 , 15)	(15 , T3)	(T3 , -∞)
III	(+∞ , 28）	(28 , 15)	(15 , T3)	(T3 , -∞)
IV	(+∞ , 25）	(25 , 15)	(15 , T3)	(T3 , -∞)

Of the five heating modes related to T1, Mode 1 saves most electric energy by using solar energy as whole energy source, so the frequency of Mode 1 can somehow represents the energy-saving capability. As shown in Figure 6 and Figure 7, the system under Strategy III runs Mode 1 most frequently, for 753 hours, in the whole simulation period, which means components except solar collectors and water tank can all be turned off during these times, so the power consumption of Strategy III is lowest, which is the purpose we pursuit.

Figure 6. Frequency of Mode 1 of control strategies

Figure 7. Power consumption of control strategies

Compared with the control strategy in Figure 2, the control standards (T1) of the four control strategies in this section are lower, which will inevitably lead to the decline of heating effect. In order to ensure the heating effect under these conditions, the heating performances of the strategies are also simulated and summarized. The results exhibited in Table 4 show that the behavior of strategy III is indeed not good because the temperature is lower, but the hours when indoor temperature meets

indoor standard (16℃) is 3379 h and the lowest indoor temperature is 11.49℃,which is acceptable. To sum up, control strategy III is a better way for the operation of the SAGHP-PCM heating system.

Table 4. Performance of control strategies in coldest month

Performance	Control strategies			
	I	II	III	IV
highest temperature	28.34	27.58	28.21	28.03
lowest temperature	13.03	12.78	11.49	12.38
average temperature	18.84	18.63	17.62	17.98
Guarantee hours (16℃)	3417.00	3379.00	3379.00	3387.00

In the optimized operation strategy, when the temperature is qualified, the PCM heat storage tank is used to replace the U-tube heat exchanger to provide energy for the source side of heat pump unit at night. According to the simulation results, this model operated for 1963 hours during the whole heating season, which is also helpful for saving electric energy.

5. Conclusion

Compared with the traditional SAGHP heating system, by implementing the graded utilization of solar energy and adding PCM heat storage tank, the average temperature of the SAGHP-PCM heating system has improved 7.88 ℃, the proportion of unqualified temperature decreased from 87.2% to 8.5%, and the average COP increased from 3.4 to 3.8. So, the SAGHP-PCM heating system is valuable to researching and practically applicable.

Analyzing the simulation results of the four different operation strategies and the conclusion that strategy III is a better way for running the SAGHP-PCM heating system can be obtained. Because the system under control strategy III saves most electric energy by using solar energy as whole energy source for heating in 753 hours, and the heating performance is acceptable meanwhile, the Guarantee hours is 3379 h when taking 16℃ as qualified standard and the average temperature is 17.62℃.

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