Optimal design of ground source heat pump system integrated with phase change cooling storage tank in an office building

Na Zhu*, Yu Lei, Pingfang Hu, Linghong Xu, Zhangning Jiang

Department of Building Environment and Equipment Engineering, School of Environment of Science and Engineering, Huazhong University of Science and Technology, Wuhan, Hubei 430074, PR China

**Corresponding authors. Tel.: +86 027 87792164x415, E-mail address: bezhuna@hust.edu.cn (N. Zhu)*

Abstract: Ground source heat pump system integrated with phase change cooling storage technology could save energy and shift peak load. This paper studied the optimal design of a ground source heat pump system integrated with phase change thermal storage tank in an office building in Wuhan, China. The performance and economic analysis of this combined system under different thermal storage ratios were analyzed. The optimal operation mode and best storage ratio were obtained for this combined system.

Keywords: ground source heat pump; phase change cooling storage: optimal design; storage ratio

1 Introduction

Geothermal energy is increasingly used through the ground source heat pump (GSHP) in many countries. GSHP provides an efficient and environment friendly way of heating and cooling for buildings. Latent heat storage is particularly attractive since it provides a high energy storage density and has the capacity to store energy at a constant temperature or over a limited range of temperature variation, which is the temperature that corresponds to the phase transition temperature of the material. Phase change material as suitable latent heat storage material used for thermal storage attracts more and more researchers' attention. Thermal storage is an effective way to shift peak load and reduce operation cost.

Zhang et al. [1], Wang et al. [2], Sun et al. [3] and other researchers studied on ground source heat pump system integrated with ice cooling storage technology. He et al. [4] investigated numerically on ground source heat pump system integrated with ice storage technology, and the results showed that the operation cost of the combined system could be reduced by 50% compared with conventional air conditioning system .Han et al. [5] studied ground source heat pump system integrated with solar heating storage technology, and it is concluded that the system save energy obviously at early and late stages during operation. The energy performance of the combined system could be improved significantly during the medium-term operating compared with conventional heating systems. Kern et al. [6], Hyun-Kap et al. [7] and Kurklu et al. [8] studied on phase change energy storage system. Eduard et al. [9] compared and validated two different mathematical models of packed bed storage with PCM, the results show that the Brinkman equation will be the most useful when free convection play an important role. Huseyin et al. [10] studied energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating. Experimental results showed that univalent central heating operation (independent of any other heating system) cannot be met overall heat loss of greenhouse if ambient temperature is very low. There is very few research combined ground source heat pump with phase change thermal storage system in the building.

2 System Design and Modeling

2.1 Load Calculation

A numerical study on a GSHP system integrated with phase change cooling storage tank was carried in an office building located in Wuhan (30.52°N, 114.32°E), China. The total area this office building is 5175 m^2. The heating period is from 1st Dec. to 28th Feb. in winter, and the cooling period is from 1st Jun. to 30th Sep. in summer. The hourly load on architecture standard meteorological year was simulated based on DEST software. Annual dynamic building load is shown in Fig.1. The results are shown in Table 1.

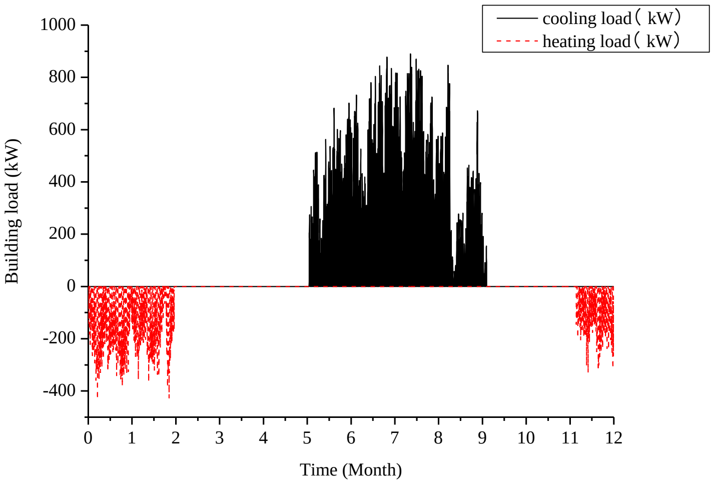

Fig.1. Annual building dynamic load

Table 1. The annual statistical results of dynamic building load

Load type	Value	Ratio of cooling load to heating load
Design cooling load（kW）	1045.46	2.42
Design heating load（kW）	432	
Cumulative cooling load（kWh）	682695	3.6
Cumulative heating load（kWh）	189132	

Fig.1 shows that the cumulative cooling load is 3.6 times the heating load. It is because Wuhan is very hot in summer and cold in winter and is a cooling-dominated area. A single ground source heat pump system can't made the underground soil cold and heat balance. Supplementary cooling technology needs to be used in summer. For the aim of lowering operating cost and shifting peak load, a phase change cooling storage tank integrated into ground source heat pump system is performed without changing conveying system and terminal Forms of the conventional air conditioning system.

2.2 Design calculation of ground heat exchanger and storage tank

This paper uses a ground-coupled heat pump system, the ground heat exchangers as heat source in winter, the cooling tower as cold source in cold storage time, the ground heat exchangers and phase change cooling storage tank were cold source in summer release cold time, Buried pipe adopts vertical single u-shape PE pipe, drilling depth is 100 m, hole spacing is 5 m, the drilling diameter 0.2 m, tube inside diameter 0.032 m, tube external diameter 0.025 m,. According to simulation building annual dynamic load calculation of buried pipe length, the ground heat exchangers as heat source in winter, the ground heat exchangers and cooling tower were cold source in summer. Choose a smaller pipe length as a design value, calculated the number of borehole is 46. However, the ground source heat pump system integrated with phase change cooling storage, without cooling tower provide cold source, because of the ratio of cooling load to heating load is relatively large, under the premise to meet the large load value, so take a summer design pipe length prevail. The number of borehole is 145,126,108,90,72,54 under ration 20%, 30%, 40%, 50%, 60% and 70%

The phase change material is type 47 ($Na_2SO_4 \cdot 10H_2O$ and other salt additives), the phase transition temperature of 8.3℃, phase change latent heat is 95.4 KJ/Kg, cool storage density is 0.0406 m3 / (kW • h).

2.3 Modeling

A numerical model of the ground source heat pump with phase change cooling storage tank have been developed bade on TRNSYS. The ground heat exchangers as heat source in winter. The ground heat exchangers and phase change cooling storage tank were cold source in summer. For cooling storage period at night, heat is dissipated by cooling tower, then the chilled water is transported by cold storage pump to heat pump units, and then the water is cooled to 4-6℃, and finally charge in the storage tank. For cooling release period at daytime, the water from user side goes through cooling storage tank to be cooled to middle temperature, and then to be cooled to set point by chillers. The schematic of composite system is shown in figure 2. The simulation platform of composite system base on TRNSYS is shown in figure 3.

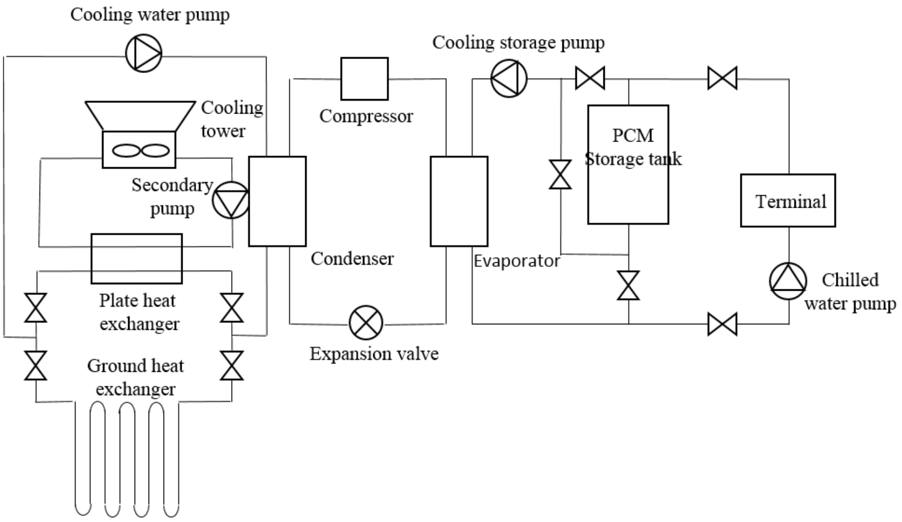

Fig.2. Schematic of composite system

3 Optimization and simulation analysis

3.1 System operation strategy

Operation cost depends on combined system operation strategy. The operation strategy refers to make optimal cooling operation arrangements based on the building load and system characteristics in the life cycle, including system cooling storage ratio and operation modes in different seasons. Cooling storage includes whole cooling storage and partial cooling storage.

During off-peak hours at night, the chiller will be used for charging cooling when the cooling storage period and operation period of air conditioning systems completely stagger, and stop the chiller while cooling storage meet the requirement of air conditioning. When cooling during the day, cooling storage tank discharges cooling to user side. Refrigerator does not run during this period. All the cooling load of user side is supplied by cooling storage equipment under the whole cooling storage mode. Cooling is stored in a storage tank under partial cooling storage mode during off-peak period at night. During the day, cooling is supplied by cooling storage tank and refrigerator. In general, the refrigerator utilization rate under partial cooling storage mode is higher than whole cooling storage mode, and cooling storage capacity is lower. Considering the system performance and economic factor, partial cooling storage is more appropriate.

Partial cooling storage operation mode includes series and parallel of chiller and cooling storage tank. When chiller and cooling storage tank in parallel, it could take account of the capacity and efficiency of the compressor and cooling storage tank, but the chilled water outlet temperature and water flow control is quite complicated and difficult to maintain at a constant value, and also waste energy. Chiller and cooling storage tank in series includes chiller priority mode and cooling storage tank priority mode. Chiller priority mode is operating chiller firstly when the air conditioning load is greater than the chiller capacity. The rest cooling load is supplemented by cooling storage, while only operating chiller when the air conditioning load is less than the chiller capacity. Cooling storage tank priority is operating cooling storage tank firstly when the air conditioning load is lower than cooling storage capacity, then operating the chiller as complement when the air conditioning load is greater than the storage capacity. This strategy can provide stable and reliable control, and improve the energy efficiency of cooling storage system. Compared with the parallel system, series system is more stable no matter full or partial load operation. Chiller efficiency is higher since higher outlet temperature. It is easier to achieve automatic control of the system.

System operating mode:

1. Summer: Charging cooling in cooling storage tank during night, and opens cooling towers. Discharging cooling during the day, and closes cooling towers, so cooling is provide by ground source heat pump and cooling storage tank.

2. Winter: Heating load is supplied by ground source heat pump systems totally.

3. Remaining season: System stops operating from Mar. 1st to May 31st and Oct. 1st to Nov. 30th.

Base on this project, the operating mode is ground heat pump system integrated with phase change cooling storage tank as partial cooling storage technology. Cooling storage tank operate priority in summer. The optimization ratio of combined system on economy and reliability will be studied in this paper.

3.2 System Optimization

The chillers stop operating or operating less under partial cooling storage mode in peak load, and it could balance the electricity utilization load and improve the power grid load. The air-conditioning electricity consumption is transferred to off-peak period, and it could improve efficiency of electricity utilization and energy efficiency significantly. It could also use cheap electricity at night and save operation cost.

For different cooling storage ratio (the ratio of cool storage tank capacity to total cooling capacity), six different ratios are analyzed in the study, including 20%, 30%, 40%, 50%, 60%, 70%. The calculation time is 20 years and the simulation time step is 1h. The initial soil temperature is 17.3℃. The return water temperature from user side is 10℃ in summer and 40℃ in winter.

The average temperature of soil area during buried pipes showed the similar increasing trend under different cooling storage ratio. Soil temperature increased significantly during the previous 10 years, and tended to stabilized after 10 years. Ground pipe inlet and outlet temperature difference also had the similar trend as above. Choose 30% as an example for analysis within the similar graphics.

The average temperature of soil area during buried pipes and the temperature difference of the inlet and outlet fluid under 30% cooling storage ratio are shown in Fig.3.

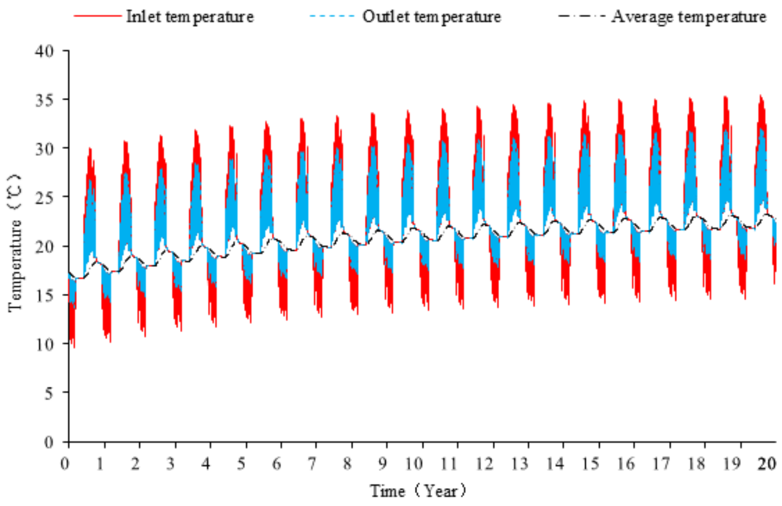

Fig.3. The average temperature of soil and inlet and outlet fluid temperature

Results show that the average soil temperature increased yearly in this region. Soil temperature increases significantly during the previous 10 years, and tends to stabilized after 10 years. After 20 years operation, the average soil temperature increases from the initial 17.3℃ to 23.26℃, and the average annual increases 0.3℃. Ground pipe temperature difference between inlet and outlet changes significantly during the previous 10 years, and tends to stabilized after 10 years. The system operates under different ratio of 20 years, and the maximum soil temperature is shown in Fig.4.

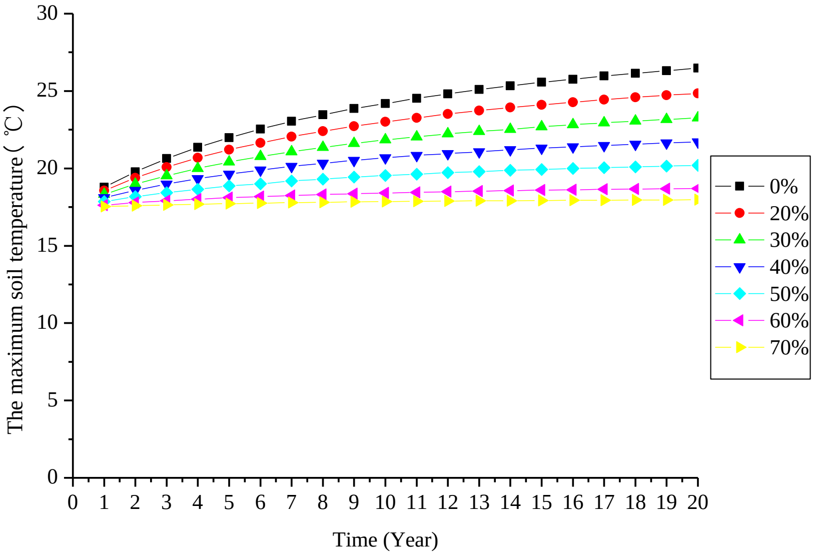

Fig.4. Maximum soil temperature in each storage ratio

Fig.4 shows that with the increase of cool storage rate, maximum average soil temperature decreases with the increase of cooling storage ratio. The initial soil temperature Increased increases from 17.3℃ to 26.48℃、24.85℃、23.26℃、21.71℃、20.19℃、18.7℃ and 17.97℃ under ration 0%,20%, 30%, 40%, 50%, 60% and 70%, respectively. Storage ratio increased by 0.1 per, The annual average temperature of soil Increased increases 0.46℃、0.38℃、0.3℃、0.22℃、0.14℃、0.07℃ and0.03℃ under ration 0%,20%, 30%, 40%, 50%, 60% and 70%, respectively. The system operates under different ratio of 20 years, and the maximum heat pump units outlet temperature is shown in Fig.5 and the maximum ground pipe outlet temperature is shown in Fig.6

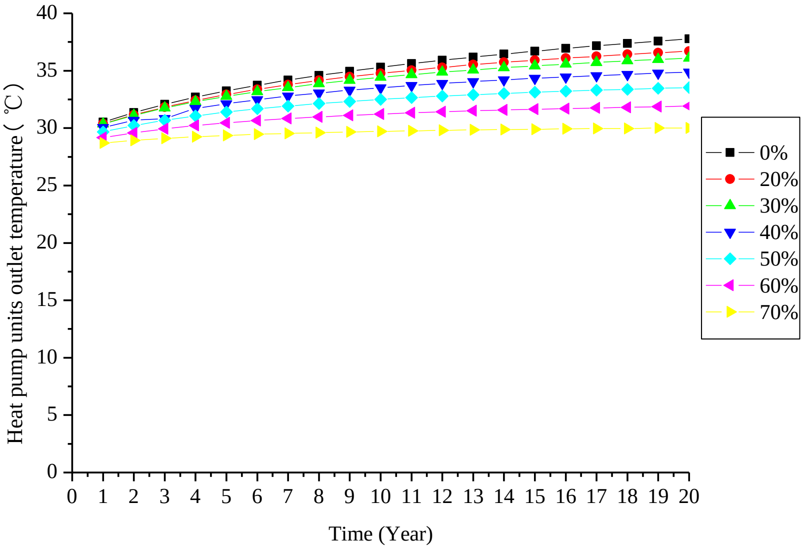

Fig.5. Maximum heat pump units outlet temperature in each storage ratio

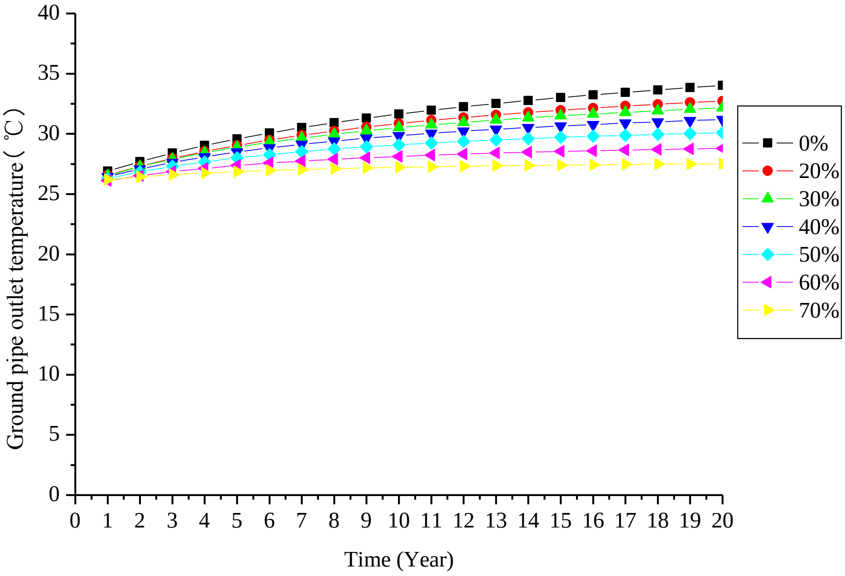

Fig.6. Maximum ground pipe outlet temperature in each storage ratio

Fig.5 and Fig.6 shows that with the increase of cool storage rate, maximum heat pump units outlet and ground pipe outlet temperature decreases with the increase of cooling storage ratio. The temperature increases significantly during the previous 10 years, and tends to stabilized after 10 years. After 20 years operation, the heat pump units outlet temperature increases 7.26℃、6.32℃、5.74℃、4.83℃、3.86℃、2.73℃、1.31℃under ration 0%,20%, 30%, 40%, 50%, 60%,70%. The ground pipe outlet temperature increases 7.12℃、6.17℃、5.63℃、4.74℃、3.79℃、2.69℃、1.31℃ under ration 0%, 20%, 30%, 40%, 50%, 60%，70%.

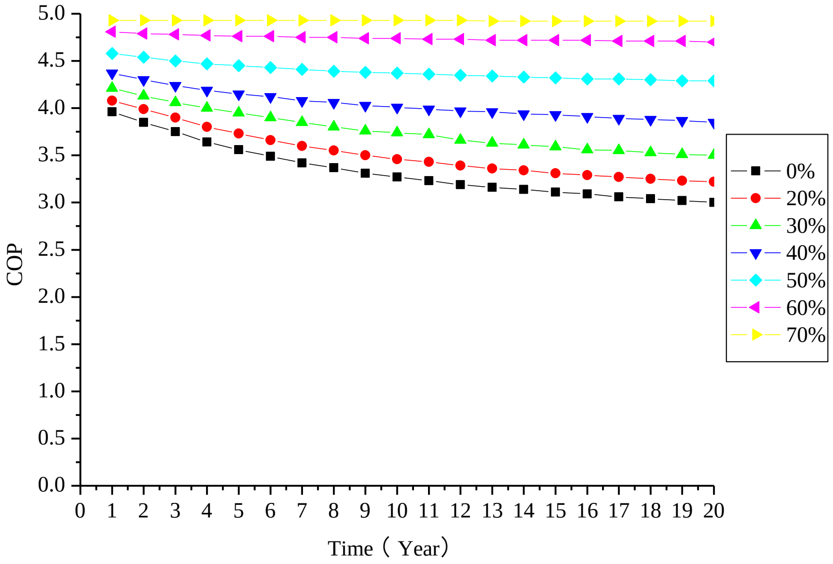

Fig.7. Minimum COP

The minimum COP is shown in Fig.7. Fig.7 shows that with the increase of cool storage rate, The COP decreases with the increase of cooling storage ratio. The COP decline 0.96、0.86、0.71、0.52、0.29、0.11、0.01 under ration 0%,20%, 30%, 40%, 50%, 60%, 70%. After 20 years operation, the COP reduce to 3.5 under ration 0%,20%, 30%，this is not energy-saving. Other cases remained at a high value.

3.3 Energy consumption in life-cycle under different ratios

The calculation time is 20 years and the simulation time step is 1h. The electricity profile of Wuhan is as follow：electricity price is 0.83 RMB/kWh during 7:00-8:00 and 11:00-18:00; it is 0.332 RMB/kWh during 23:00-7:00; it is 1.16 RMB/kWh during remaining time. The system energy consumption in life-cycle under different ratio is shown in table 2. Annual operation cost under different cooling storage ratio is shown in Fig.8. The system energy consumption and annual operation cost in 20 years operation under optimal ratio compared with the system without cooling storage is shown in Fig.9.

Table 2. The system energy consumption in 20 years operation under different ratio

Cooling storage ratio	Total energy consumption（kWh）	Annual energy consumption（kWh）	Annual operating costs（RMB）	Total operating costs（RMB）	The initial investment（RMB）	Annual cost（RMB）
0%	5187256	259362.8	215271.1	4305422	1212780	275910
20%	4036898	201845	117324	2346478	1530075	193828
30%	3920841	196042	112296	2245918	1387415	181667
40%	3923352	196167	110330	2206598	1293947	175027
50%	4411028	220551	121724	2434483	1617451	202596
60%	4797924	239896	131502	2630039	1940931	228548
70%	5015936	250796	136978	2739568	2102684	242112

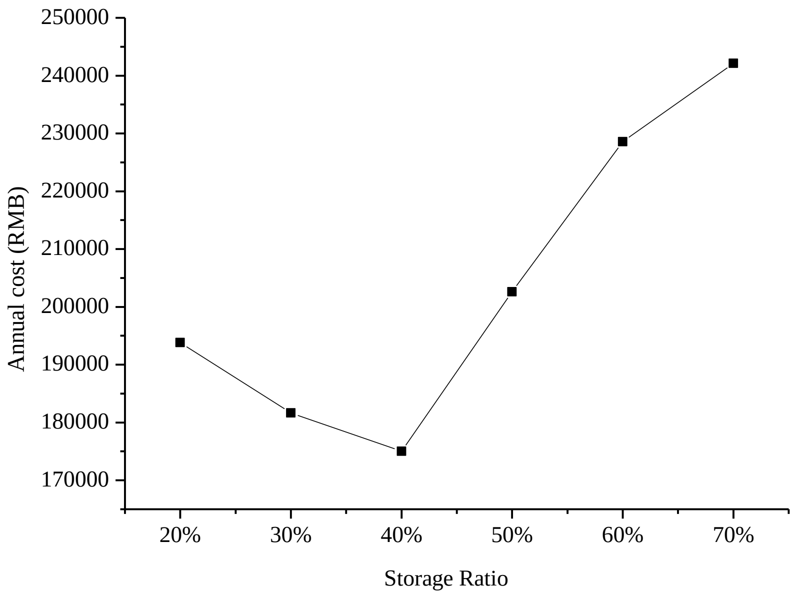

Fig.8. Annual cost under different cooling storage ratio

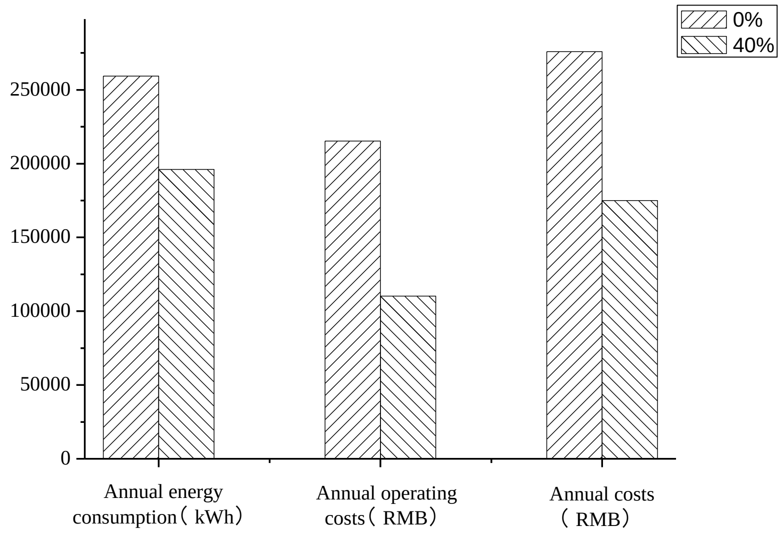

Fig.9. The optimal ratio system compared with the system without cooling storage

Simulation results show that the total energy consumption of the system decreases with the cooling storage ratio and achieves the lowest valuations under cooling storage ratio 30%, and then energy consumption gradually increases. The annual cost reaches minimum value under cool storage ratio 40%. It decreases with the increasing of cooling storage ratio, and then increases with the increasing of cooling storage ratio. Compared with the cooling storage system, the annual operation costs is the largest when there is no cooling storage, while its minimum initial investment. Considering the initial investment and operation costs, it also has the same trend and reached minimum under cooling storage fraction 40%, so the composite system is optimal designed under this ratio.

4 Conclusions

This paper study the performance of ground source heat pump system integrated with phase change cooling storage tank for an office building in Wuhan. Numerical simulation and analysis the composite system have been carried out. A few specific conclusions, which may be useful for optimal design of the combined system, are listed below:

(a) Wuhan is a cooling-dominated area with abundant geothermal energy. Ground source heat pump technology could use renewable energy and the phase change cooling storage technology could shifted peak load and reduce electricity costs. Ground source heat pump system integrated with phase change cooling storage tank is an efficient and environment friendly way of cooling and heating for buildings. The combined system improves the economy and reliability of the operation performance.

(b) Cooling storage system uses the partial cooling storage and prior cooling mode. The operation mode can make the storage cooling energy release fully and improve the utilization efficiency of cooling storage system. This mode could provide stable and reliable control for the combined system.

(c) With the operation of the system, the average soil temperature increases yearly in this region. Soil temperature increases significantly during the previous 10 years, and tends stabilized after 10 years. The maximum soil temperature decreases with the increasing of cooling storage ratio.

(d) In the system 20 years operation, the energy consumption and operating cost increases with the increasing of cool storage ratio, and then decreases with the increases of cooling storage ratio. Considering initial investment and operation cost, the optimal cooling storage ratio is 40%.

References

[1] X. Zhang. Heat pump technology. Beijing, Chemical Industry Press, 2007.

[2] Y. Wang. Design research of ground source heat pump system integrated with energy storage tank in an office building. Building Science 2010, 26(10): 266-273.

[3] X.F. Sun, Z.H. Zhou. The application of phase change materials in HVAC. Gas & Heat 2006, 26(4): 67-69.

[4] C.F. He, J. Zhu, H.D. Xu. Superiority and application of a combined water-source heat pump and ice storage air conditioning system. HV&AC 2009, 39(10): 116-119.

[5] Z.W. Han, M.Y. Zheng, F.H. Kong, W. Liu. Operation model of solar-assisted ground source heat pump heating system with phase change storage. Renewable Energy Resources 2007, 25(4): 10-14.

[6] M. Kern, R.A. Aldrich. Phase change energy storage in a greenhouse solar heating system. Paper presented at the summer meeting of ASAE and CSAE, pp24-27, University of Manitoba Winnipeg, 1979, 06.

[7] K.S. Hyun. Development of heat pump – PCM latent heat storage system for the greenhouse heating, (I). J Korean Soc Agric Mach 1997, 19(3).

[8] A. Kurklu. Energy storage applications in greenhouse by means of phase change materials (PCM): a review. Renew Energy 1998, 26（1）: 391–399.

[9] O.A. Eduard. Comparative study of different numerical models of packed bed thermal energy storage systems. Applied Thermal Engineering 2013, 50 (1): 384-392.

[10] B. Huseyin. Energetic performance analysis of a ground-source heat pump system with latent heat storage for a greenhouse heating. Energy Conversion and Management 2011, 52(1): 581-589.