A Technical Introduction of Water Pit for Long-term Seasonal Solar Thermal Energy Storage

Mingfei He[1,2,3,4], Zhifeng Wang[1,2,3,4*], Guofeng Yuan[1,2,3,4], Yakai Bai[1,2,3,4] and Xiaoxia Li[1,2,3,4]

[1] Key Laboratory of Solar Thermal Energy and Photovoltaic Systems, Beijing (China)

[2] Institute of Electrical Engineering, Beijing (China)

[3] University of Chinese Academy of Sciences, Beijing (China)

[4] Beijing Engineering Research Center of Solar Thermal Power, Beijing (China)

Abstract

The total amount of solar energy resources is abundant, clean and widely distributed, but there are also problems such as low energy density, discontinuity and large seasonal difference of radiation amount. Water pit for seasonal solar thermal energy storage is one of the important technical routes to realize "winter uses stored solar heat from summer" and "zero carbon heating." It can effectively solve the mismatch of solar energy supply and demand in time and space, and it is a crucial technology to solve the problem that solar energy cannot be continuously utilized. The key idea of this technology is to store the solar energy collected in non-heating seasons in the water pit for spacing heating in winter. On the one hand, this technology solves the idle problem of solar collector in non-heating season; on the other hand, it can realize all-weather heating under complicated weather conditions, thus achieving a high guarantee rate of solar energy. This paper introduces the basic principle, application cases and cost analysis of water pit for seasonal heat storage, and analyzes the main problems and future research directions. This paper mainly introduces the related technologies of the 3000 m^3 water pit long-term seasonal solar thermal energy storage system in Huangdicheng town, China.

Keywords: Solar energy, Seasonal thermal storage, Water pit of heat storage

1. Introduction

The total amount of solar energy resources is abundant, clean and widely distributed, but there are also problems such as low energy density, discontinuity and large seasonal difference of radiation amount. Allegrini J. et al. (2015) pointed out that the most significant mismatch is between the solar heat availability in summer and the high space heating demand in districts during the winter season. The variation trend of solar radiation, demand for heat, demand for cold and demand for domestic hot water in many typical heating areas over time is shown in Fig.1. The total amount of solar radiation changes in a single peak pattern throughout the year. In summer, solar energy resources are abundant but often cannot be utilized effectively, while in winter, solar energy resources are scarce and in great demand. In daily life, the demand for domestic hot water is generally stable, and the demand for domestic hot water in winter and spring is slightly higher than that in summer and autumn. The main contradiction between the distribution of solar energy resources and the demand for heat is that residents have a strong demand for heat in winter, but the solar radiation in winter is at the trough of the whole year, the demand for cold is mainly concentrated in summer, and the solar radiation in summer is at the peak of the whole year.

In this background, SPEYER E. (1959) and Buscheck T. A. et al. (1983) have put forward the concept of seasonal thermal energy storage (STES) that can bridge the gap of intermittency in solar energy. When the "source" side (solar heat source side) and the "load" side (energy using side) have the significant seasonal characteristic, STES can effectively solve the mismatching characteristic of the solar energy heating system in time, space and strength. Therefore STES can transfer the solar heat from the summer or transition seasons to the winter, and expand the depth and breadth of solar heat utilization. While this concept, seasonal thermal energy storage, a long-term storage system, is well known for its long storage periods that last up to several months (Guo F et al., 2017). Sweden took the lead in the research of large-scale STES in the 1980s (Ochs F. et al, 2009), and now many countries have built relevant application systems with STES (Bauer D. et al. 2010; Dahash A. et al. 2019; Fong M. et al. 2019; Rad F. M. et al. 2017; Zhou X et al. 2020). In addition, STES can provide 50%-100% solar

doi:10.18086/swc.2021.35.01 Available at http://proceedings.ises.org

guarantee rate (Hennessy J. et al. 2019; Xu J et al. 2019).

Thermal energy storage(TES) technology can be divided into sensible TES, latent TES and chemical TES according to different types and mechanisms of thermal storage (Xu J et al. 2019). Whether it is latent TES technology or chemical TES technology still in the stage of laboratory research, its application in cross STES is not mature (Li X et al. 2014). At present, sensible TES is most widely used in STES (Pinel P. et al. 2011). Sensible TES technology mainly includes borehole thermal energy storage(BTES) technology, aquifer thermal energy storage(ATES) technology, tank thermal energy storage(TTES) technology and pit thermal energy storage(PTES) technology, as shown in Fig.2. TTES technology is relatively simple and mature, which uses a large layered water tank to store hot water. PTES technology also uses a large container to store heat. The difference is that PTES technology generally stores hot water in underground containers, as shown in Fig. 2 (d). In a sense, the TTES technology is similar to the PTES technology. It should be noted that the TTES technology described in this paper specifically refers to the free stand water tank thermal energy storage technology above the ground, and the underground buried water tank thermal energy storage technology belongs to the PTES technology. The construction of water pit is generally divided into two types: one is the concrete water tank buried underground or semi underground built by reinforced concrete, also named as underground water tank thermal energy storage technology. And the other is a storage container formed by directly excavating a water pit on the ground and special treatment of the side wall and bottom, which often adopts a floating roof. The cost of the latter TES technology is significantly lower than that of the first underground water tank (Dahash A. et al. 2019), because in essence, the first underground buried water tank TES technology still belongs to TTES. There are two kinds of water pit thermal energy storage media: one is hot water, the other is the mixture of gravel (or sand) and water, which is called gravel-water TES technology (Marx R. et al. 2009; Ochs F. et al. 2008). Since the heat capacity of the gravel-water is lower than that of the single hot water, the volume required for heat storage of gravel-water is about 50% higher than that of the single hot water in order to achieve the same thermal storage (Bai Y et al. 2019; Hesaraki A. et al. 2015; Novo A. V. et al. 2010;).

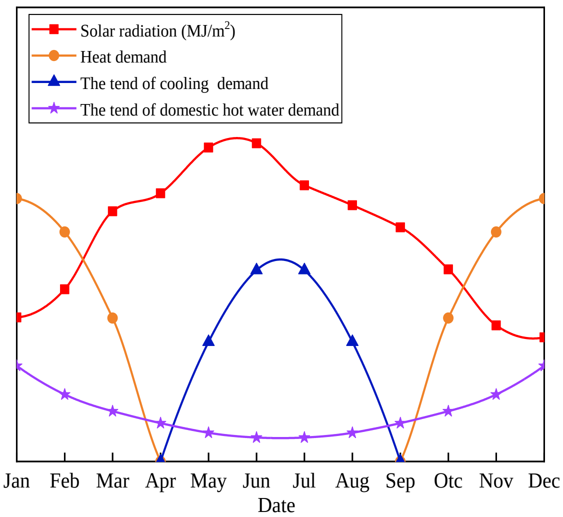


Fig. 1: Annual variation trend of solar radiation and demand for heat (cold) in typical heating areas

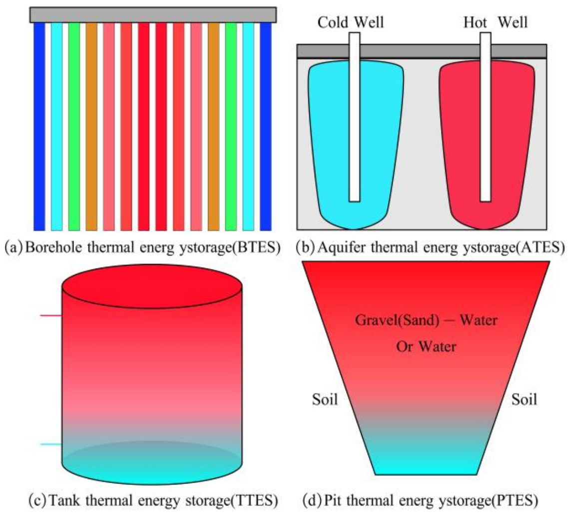


Fig. 2: Four types of seasonal sensible thermal energy storage

Whereas Table 1 compares the four types of STES in terms of TES medium, TES density, the equivalent TES volume, performance parameters, characteristic requirements and system cost (Argiriou A. A. 1997; Dahash A. et al. 2019; Novo A. V. et al. 2010; Sibbitt, B. et al. 2015; Pinel P. et al. 2011; Xu J et al. 2014; Zhao X et al. 2017). Then, the TES density of TTES is the highest, followed by PTES, and the BTES is the lowest. BTES and PTES have high requirements for local geology. The cost of TTES is the highest, and BTES is the lowest. In general, water pit thermal energy storage system is currently the most reliable and widely used system for STES at present (Novo A. V. et al. 2010; Pinel P. et al. 2011).

Many countries in the world have carried out research on the water pit for long-term STES and built some application projects. For example, Chemnitz District Heating project of Germany, Denmark's Marstal PTES, and so on (Fan J et al. 2017; Mangold D. et al. 2004). Asia is rich in solar energy resources, but there are relatively few projects of STES. And the STES technology is in the development stage in Asia at present. China has established some demonstration small-scale STES projects, and is actively developing large-scale, long-term, low heat loss and low-cost STES technologies (Huang J et al. 2019; Tao T et al. 2019; Xu L et al. 2018; Xiao W et al. 2010). This paper mainly introduces the related technologies of the 3000 m^3 water pit long-term seasonal solar thermal energy storage system in Fanshan Town, Zhuolu County, Zhangjiakou City, Hebei Province, China(40° 13′ 18″ N,115° 26′ 6″ E).

Tab. 1: Comparison of characteristic of four types of sensible thermal energy storage (Argiriou A. A. 1997; Dahash A. et al. 2019; Novo A. V. et al. 2010; Sibbitt, B. et al. 2015; Pinel P. et al. 2011; Xu J et al. 2014; Zhao X et al. 2017)

TES type	TES medium	TES density /（kW•h/m^3）	Equivalent TES volume(Relative to 1 m^3 water)/m^3	Burial depth（m）	Characteristic requirements	Overall cost
TTES	Water	60~80	1	(a). Can be built on the ground [24]. (b). Underground 5~15	(a). High requirements for thermal insulation technology when on the ground [24]; (b). Relatively stable ground conditions are required when buried underground.	Highest
PTES	Gravel (Sand)-water/Water	30~50	2~3	5~15	(a). stable ground condition. (b). No ground water flow is preferred.	Higher
ATES	Gravel (Sand)/Water	30~40	2~3	20~50	(a). Stable ground condition. (b). Natural aquifers with high permeability. (c). There is a clear boundary between the top and bottom of the aquifer. (d).No or low natural ground water flow.	Minimum
BTES	Water/Soil	15~30	3~5	30~100	(a). Stable ground condition. (b). Easy drilling construction (c). The heat capacity and thermal conductivity of soil are large. (d). No or low natural ground water flow.	Low

2. Profile of the long-term PTES demonstration Project in Huangdicheng town

The long-term PTES demonstration project in Huangdicheng town was designed by the Institute of Electrical Engineering, Chinese Academy of Sciences, and Dahua Group was responsibled for the auxiliary design of buildings and system pipelines, providing 3000 ~ 5000m^2 building heating for Dahua Jianguo Hotel. The construction of the project began in April 2017 and has been put into operation since April 2018. The design objective of the system is realize the efficient thermal collection and storage of solar energy in the heat storage season. In the heating season, it realizes the efficient collection of solar energy and the efficient heat extraction of water pit for thermal storage, completes the central heating of energy-saving buildings of 3000 m^2, and solves the problems of low solar energy utilization rate and the imbalance of heat supply and demand between summer and winter in the traditional solar central heating system. The system can collect and store solar energy throughout the whole year to meet the heating needs of the hotel during the heating season (Bai Y et al. 2019).

The system consists of three subsystems: solar tower thermal collection system, seasonal thermal storage system and heating system, as shown in Fig. 3. Basic operating principle of the system: in the non-heating season, the circulating pump of the solar tower thermal collection system pumps water from the bottom of the cylindrical thermal storage water pit, and after passing through the solar tower thermal collection system, the abundant solar energy in the non-heating season is converted into thermal energy, which is returned from the upper part of the thermal storage water pit, and the cycle repeats until the water temperature reaches the design temperature. During the heating season, the control system pumps hot water from the upper outlet of the thermal storage water pit to provide heat to the heating user. The density of water is relevant to temperature. In the long-term heat storage process, water will have temperature stratification due to the action of buoyancy, resulting in the phenomenon of high upper temperature and low lower temperature. A good temperature gradient is not only conducive to improve the operation efficiency of the heat collection system, but also an important measure to improve the heat storage efficiency, because the destruction of temperature stratification will enhance the mixing of cold and hot fluids in the water pit and reduce the heat storage effect of the thermal storage water pit.

Fig. 3: The long-term water pit thermal storage/heating system in Huangdicheng town

2.1. Solar tower thermal collection system

The system is mainly composed of heliostat field, tower heat receiver, pipe network and other components, reflecting the advantages of high thermal collection temperature, high light concentration ratio, large capacity and so on.

The heliostat field of the system has a total daylighting area of 739m^2 which is composed of 66 small heliostats with a single daylighting area of 11.2m^2. Each heliostat is assembled by four unit mirrors with a size of 1700mm × 1640 mm, the heliostat surface is a 4 mm ultra white float glass silver plated mirror with reflectivity $\geqslant$ 93%. The tubular receiver is composed of 88 vertical Q235 steel pipes, which are welded on the upper and lower headers, and the surface is coated with Pyromark1200 high temperature coating. The heliostat field focuses the sunlight reflection on the surface of the tubular receiver, and the water is heated from the inlet header at the lower end of the heat collector to the outlet header at the top. The tubular receiver is the core component that converts radiant energy into thermal energy, and its relevant structural parameters are shown in Table 2.

Tab. 2: The structural parameters of tubular receiver

Parameters	Numerical value
Number of receiver tubes N_t	88
Outer diameter of receiver tubes D_o	25mm
Inner diameter of receiver tubes D_i	20mm
Surface coating emissivity of receiver tubes ε	0.87
Surface coating absorption of receiver tubes α	0.9
Height of daylighting opening of receiver H	1.7m
Width of daylighting opening of receiver W	2.8m
Thermal conductivity of receiver tubes λ	50W/(m•K)

2.2. The system of seasonal thermal storage

The system of seasonal thermal storage includes 3000m^3 water pit thermal storage, supporting equipment and relevant sensors, as shown in Fig. 4 and Fig. 5. The cylindrical water pit is poured by concrete, the concrete wall is 0.3m thick, the underground burial depth is 1m, and the top cover of the water pit is covered with 0.2m thick polystyrene extruded insulation board. Relevant physical parameters are shown in Table 3.

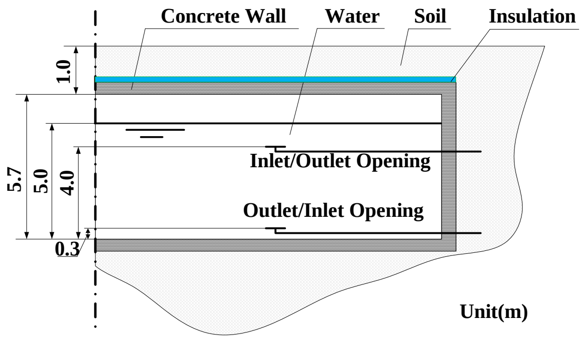


Fig. 4: 3000m^3 water pit of seasonal thermal storage

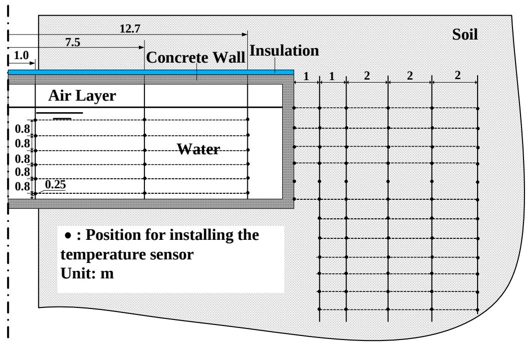


Fig. 5: The temperature sensor layout diagram of water pit thermal storage

Tab. 3: Material physical parameters

Material	**Density (kg • m^{-3})**	**Thermal conductivity (W • m^{-1} • K^{-1})**	**Thermal capacity (J • kg^{-1} • K^{-1})**
Soil	900	1.3	2500
Concrete	2500	1.28	970
Polystyrene extruded insulation board	28	0.042	1500
Water	1000	0.642	4200

2.3. Pipe network and other components

Pipe network, water pump, heat exchanger and other equipment are not highlighted. And there is a buffer tank in the system. The buffer tank is a vertical stainless steel tank with a structural size of 4 m × 4 m × 3 m (length × wide × High), with a volume of 48 m^3. The buffer water tank can not only achieve short-term thermal storage, but also play the role of heat buffer and stable working conditions between the heat collection system and the heat load. Therefore, it plays an important role in the whole seasonal storage/heating system.

It should be noted that the first phase of the seasonal thermal storage/heating system is designed to provide heat for the building with a heating area of 3000 m^2, and then to increase to the hotel with a construction area of 18044.4 m^2 and the hotel apartment with a construction area of 19379.8 m^2. It is also equipped with 2t gas-fired boiler and 1080 kWh electric boiler.

3. System operation mode and control strategy

The system sets up four operation modes and three control strategies considering the actual needs and system design characteristics.

3.1. System operation mode

The operation of the seasonal thermal storage system is designed into two stages: thermal storage season and heating season from the perspective of energy source and transfer according to different functional objectives due to the inevitable unstable and discontinuous characteristics of solar radiation and the time-varying energy demand of heat users. The operation mode of each phase is described as follows:

Mode 1: Thermal storage season - thermal storage mode of water pit

The softened water at the bottom of water pit is heated by circulating pump and solar tower thermal collection system, and then filled into the upper part of the water pit in the thermal storage season. The temperature stratification is gradually formed inside the water pit. At the same time, the soil around the water pit is gradually heated, and the temperature of the upper layer of the water pit finally reaches 80 ~ 95 ℃, as shown in Fig. 6(a). According to the actual heat demand of users and scientific research demand, two common operation control modes are designed for the heat collection system: temperature control operation control and continuous operation control.

Mode 2: Thermal storage season - thermal storage mode of buffer water tank

The system operates in the thermal storage mode of buffer water tank considering the demand of users for domestic hot water and the over-temperature protection of the water pit in the thermal storage season, as shown in Fig. 6(b). That is, the thermal collection system heats up the water at the bottom of the buffer water tank and fills it into the upper part of the buffer water tank. The thermal storage control modes can be divided into two types: temperature controlled thermal storage mode and continuous thermal storage mode according to the different control modes of thermal collection system.

Mode 3: Heating season - direct heating mode

In the heating season, the solar tower thermal collection system charges heat to the buffer water tank, and the buffer water tank supplies heat to the heating network, as shown in Fig. 6(c). The control mode of thermal collection system is continuous operation or temperature control mode, and the control mode of buffer water tank heating is constant temperature and constant flow heating mode.

Mode 4: Heating season - combined heating mode

In the heating season, the solar tower thermal collection system charges heat to the buffer water tank, and the buffer water tank supplies heat to the heating network. When the source (low solar radiation) charge (large heating load) mismatch leads to the buffer tank heating temperature is lower than the set value, and the temperature of the water pit is high, the combined heating of the water pit and the concentrating heat absorption system is adopted. The heating control mode of buffer tank is constant temperature and constant flow heat supply mode. As shown in Fig. 6(d).

The system operation is divided into two stages: thermal storage season and heating season during the system design. In order to meet the different energy needs of users, the system can provide domestic hot water or adjust the heating time according to the outdoor ambient temperature to ensure the thermal comfort of users.

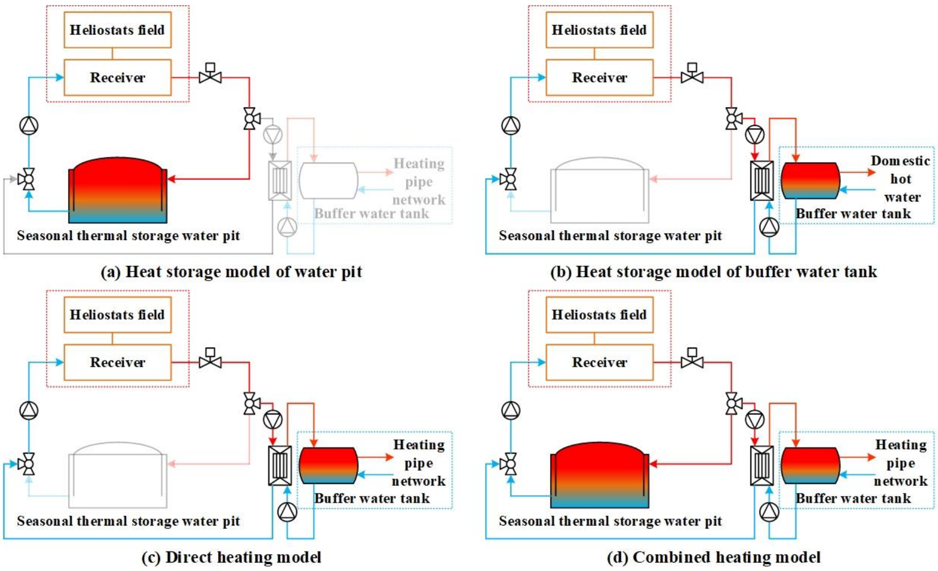


Fig. 6: System operation mode

3.2. System control strategy

The control strategy is divided into the following situations during the seasonal solar thermal storage/heating system operation, which according to the different operation stages and operation modes of heat storage season and heating season, combined with the operational performance of main components of the system. The logic diagram of the control strategy is shown in Fig. 7.

1) Operation control of solar energy collector subsystem

The solar collector subsystem in the system often operates in two modes: temperature-controlled operation mode and continuous operation mode according to different weather conditions or energy demand. Start or stop the thermal collecting circulating pump according to the set temperature, which taking the outlet temperature of the receiver as the monitoring object in the temperature-controlled operation mode. The thermal collection circulating pump will be closed at first when the temperature-controlled mode is selected for the thermal collection subsystem. The continuous operation control mode is mainly used to reduce the frequent start-up of the thermal collector circulation pump when the solar irradiation conditions are good. The two operation modes of the thermal collection subsystem can be selected according to the different heat demands in the thermal storage season and heating season in the actual operation of the system.

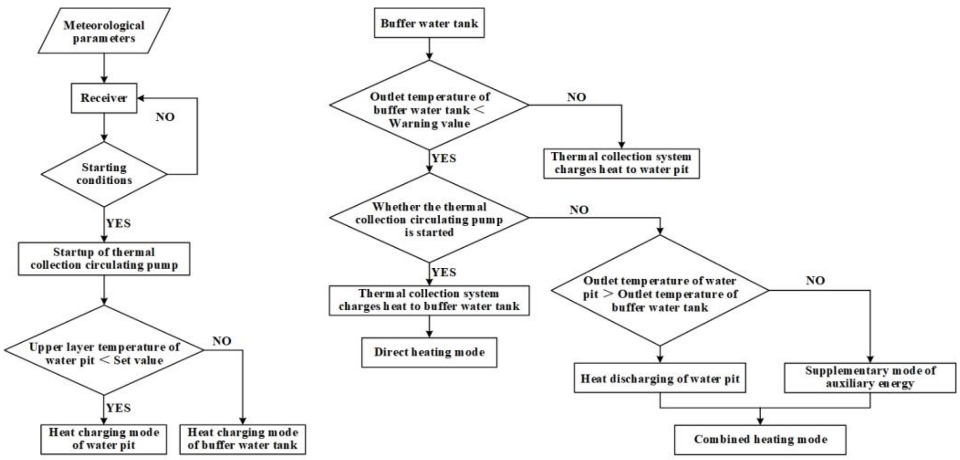
2) Thermal storage season, the operation control strategy of water pit or buffer water tank

The thermal collection subsystem selects the temperature control operation mode or continuous operation mode to preferentially charge heat to the water pit in thermal storage season. The thermal collection subsystem stops charging heat to the water pit and instead charges heat to the buffer water tank when the upper temperature of the water pit is higher than 90℃ considering the temperature resistance and service life of the water pit structure. The thermal collection subsystem pumps water from the bottom of the water pit, and then charges heat to the top of the water pit after heating by the thermal receiver during heat charging of the thermal collection subsystem to the water pit. It is essentially to control the start and stop of the thermal collection circulating pump by comparing the outlet temperature of the thermal receiver with the top temperature of the water pit when the system operating in the temperature control mode. And in order to prevent damage to the internal temperature stratification of the water pit, the outlet temperature of the thermal receiver is generally higher than the top temperature of the water pit.

3) Heating season, the operation control strategy of heating subsystem

The thermal collection subsystem preferentially charges heat to the buffer tank and controls the system by monitoring the temperature at the top of the buffer tank in the heating season. And the thermal collection subsystem charges heat to the water pit when the temperature at the top of the buffer tank is higher than 90 ℃.

There are two modes for the system to supply heat to users through the buffer tank when the temperature at the top of the buffer tank is lower than the set heating temperature. One is the direct heating mode: Charging the buffer tank with heat if the thermal collection subsystem (temperature control mode or continuous mode) reaches the operating condition. And the other one is the combined heating mode: The water pit releases heat to the buffer tank when the thermal collection subsystem does not operate and the temperature of the water pit is higher than the top temperature of the buffer tank.



(a) Operation mode of thermal storage season (b) Operation mode of heating season

Fig. 7: The control logic of system

4. Summary of system operation

The first natural year of system operation is from April 11, 2018 to April 10, 2019. The operation period covers four operation modes and three control strategies in Section 3. And the relevant performance of the system is analyzed as follows according to the actual monitoring data of system operation.

4.1. Evaluation parameters of system

The solar energy calculation formula of heliostat field input solar tower thermal collection subsystem:

$$Q_{solar} = \int N_h \cdot A_h \cdot I_{DNI} d\tau \quad \text{(eq. 1)}$$

Where N_h is the number of heliostats working normally at the current time. A_h is the daylighting area of a single heliostat, m^2; I_{DNI} is normal direct irradiance, W/m^2.

The effective heat gain formula of the solar tower thermal collection subsystem:

$$Q_{col} = \int c_{p,w} \cdot m \cdot \left(T_{rec,out} - T_{rec,in}\right) d\tau \quad \text{(eq. 2)}$$

Where Q_{col} is the effective heat gain of the receiver, J; $c_{p,w}$ is the thermal capacity of water J/(kg • ℃); $T_{rec,out}$ is the outlet water temperature of the receiver, ℃.

The calculation formula for thermal collection per unit lighting area of the solar tower thermal collection subsystem:

$$Q_a = \frac{Q_{col}}{N_h \cdot A_h} \quad \text{(eq. 3)}$$

The calculation formula of the water pit heat loss:

$$Q_{loss} = Q_{CH} - Q_{DC} - \Delta Q \quad \text{(eq. 4)}$$

Where Q_{CH} is the heat charge of the water pit, and its calculation formula is:

$$Q_{CH} = c_{p,w} \int m_{CH}\left(T_{in,CH} - T_{out,CH}\right) d\tau \quad \text{(eq. 5)}$$

Q_{DC} is the heat supplied from the water pit in the heating season, and its calculation formula is:

$$Q_{DC} = c_{p,w} \int m_{DC}\left(T_{in,DC} - T_{out,DC}\right) d\tau \quad \text{(eq. 6)}$$

ΔQ is a variation of internal energy in water pit, and its calculation formula is:

$$\Delta Q = \rho_w c_{p,w} \int T_w - T_{w,0}\, dV \quad \text{(eq. 7)}$$

The calculation formula of thermal storage efficiency of seasonal thermal storage water pit:

$$\eta = \frac{Q_{DC} + \Delta Q}{Q_{CH}} \quad \text{(eq. 8)}$$

The calculation formula of solar fraction:

$$SF = \frac{Q_{sol}}{Q_{load}} \quad \text{(eq. 9)}$$

Where Q_{sol} is the amount of heat supplied by solar energy for heating in the system, Q_{load} is the total heat load of the system.

4.2. Performance analysis of the solar tower thermal collection subsystem

Fig. 8 shows the statistics of annual monthly average environment temperature and cumulative normal direct radiation. In December, the monthly average outdoor environment temperature reached the lowest minus 7.5 ℃, the highest monthly average environment temperature was 24.1 ℃, and the annual cumulative normal direct radiation was 5580.2 MJ/m^2. Fig. 9 shows the annual operation data of the solar tower thermal collection subsystem. The highest monthly thermal collection was 50.9 MWh in October. It should be noted that only 20 days were counted in April 2018 and only 10 days were counted in April 2019 according to the actual operation of the system, so the monthly cumulative normal direct radiation and heat collection are low. It basically shows that the higher the cumulative normal direct radiation throughout the year, the more thermal collection of the solar tower thermal collection subsystem, and the greater thermal collection per unit daylighting heat collection area. The annual thermal collection is 325.0 MWh, and the annual thermal collection per unit daylighting area of the thermal collection field is 439.6 kWh/m^2.

The thermal collection subsystem has operated for 276 days since the system has been in operation for the first year and is still in the debugging and maintenance period. Therefore the efficiency of the collector is relatively low, and it can reach more than 50.8% under typical working conditions.

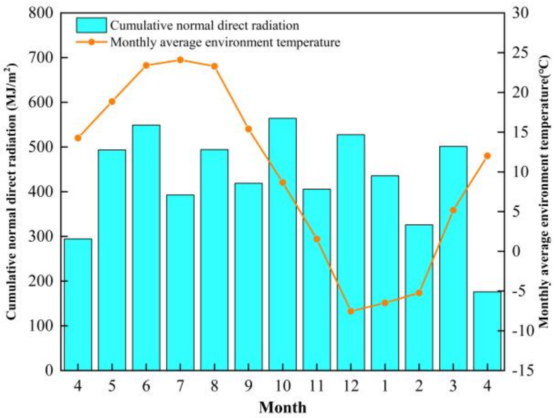


Fig. 8: System operation data Annual meteorological data

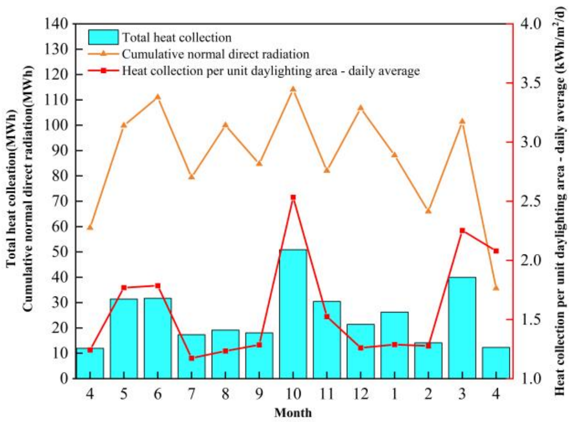
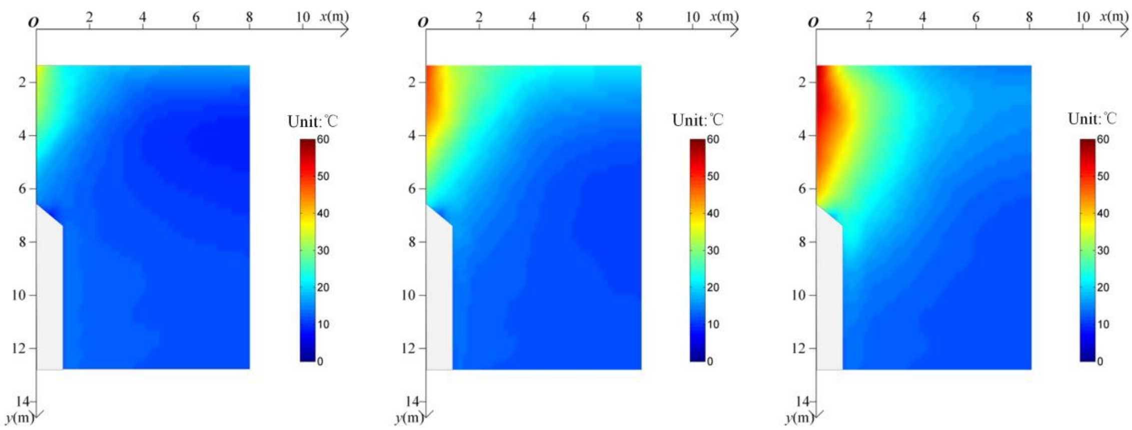


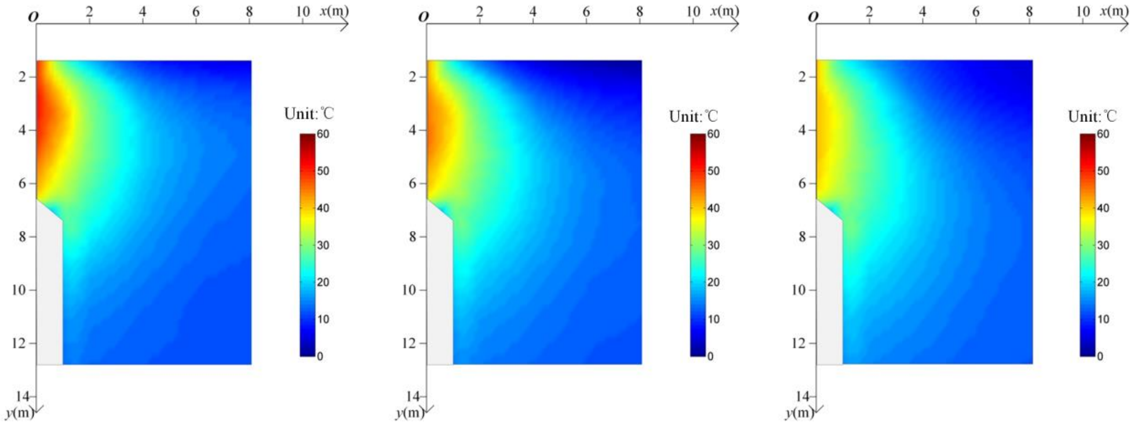
Fig. 9: Comparison of annual heat collection

4.3. The variation of soil temperature

Fig. 10 shows the cloud map of the soil temperature field every two months throughout the year. The x-axis in the figure represents the size from the wall of the water pit, and the y-axis direction is the depth direction of the underground soil. It is replaced by blank since no temperature measuring points are arranged in the soil under the water pit. The water pit goes through three stages: thermal charging, thermal storage and thermal release during the year of operation of the system, and the wall temperature of the water pit first gradually increases and then decreases. Due to the thermal conduction of soil and water pit wall, the heat conducts along the surface of the water pit wall in the radial and depth direction of the soil, and the soil temperature increases gradually. However, the soil itself is an infinite unsteady thermal transfer process, with many influencing factors and randomness, and its thermal analysis is extremely complex, which needs to be further explored.



11 June, 2018 **11 August, 2018** **11October, 2018**



11 December, 2018 **11 February, 2019** **11 April, 2019**

Fig. 10: The cloud map of soil temperature field

4.4. System energy balance analysis

The thermal balance data of the system in this natural year is shown in fig. 11. The thermal collection system collects 450.8 MWh throughout the year, including 325.0 MWh from the solar tower thermal collection subsystem and 125.8 MWh from other thermal collection systems in the site. The internal energy of water pit increased by 94.5 MWh, and the average temperature of water increased from 13℃ to 54.2℃(the maximum temperature). The average temperature of water at the end of the heating season was 42.7℃. The system provides domestic hot water and heating for the heating terminal with a total of 183.1MWh. Based on the calculation that 1 kg of standard coal can produce 0.0293 GJ heat(without considering boiler efficiency, pipe loss, etc.), the system can save at least 22.5T standard coal every year. And based on 2.662 t carbon dioxide produced by 1 t standard coal combustion, 59.9 t carbon dioxide can be reduced by the system. The thermal storage efficiency of the system can reach 62%. Based on the average annual heat load of buildings of 40 W/m^2, the annual building heat load of the system is 436.7 MWh, and the system provides total heat energy of 183.1 MWh to the heating terminal, so the solar energy guarantee rate is 49.4%.

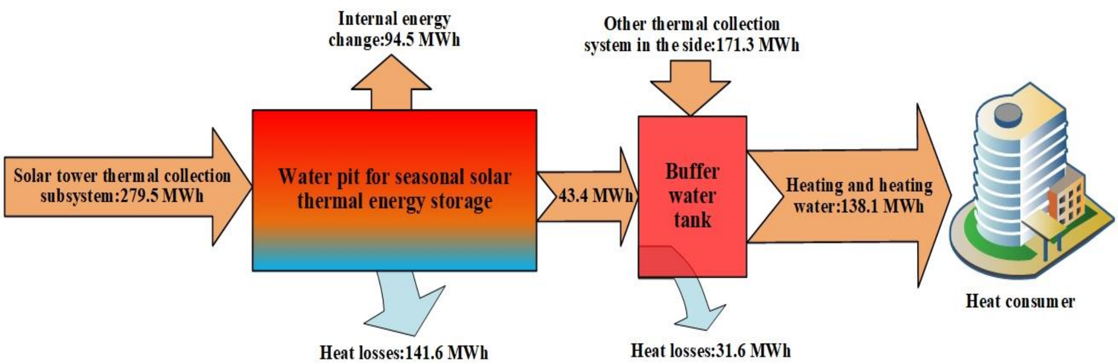


Fig. 11: System heat balance diagram

As mentioned above, in the first natural year when the system was put into operation, it was still in the debugging and maintenance period, and the soil temperature was low, so the heat loss of water was large. And on the other hand, the heat in the water pit cannot be fully utilized, resulting in low utilization rate of water pit when the water temperature is below 40℃ because the heat pump and other facilities are not added in the system. Moreover, the water pit is in the thermal storage state above 40℃ for a long time, resulting in large heat loss. There is room for optimization of performance parameters in all aspects of the system with the continuous adaptation of the system.

5. Conclusion

Water pit for seasonal solar thermal energy storage is one of the important technical routes to realize "winter uses stored solar heat from summer" and "zero carbon heating." At present, water pit for seasonal solar thermal energy storage is the most mature, reliable and widely used technology of large-scale clean heating technology.

This paper mainly introduces the related technologies of the 3000 m^3 water pit long-term seasonal solar thermal energy storage system in Huangdicheng town, China. The operation in the first natural year is analyzed, and the feasibility of clean heating in north China is verified. The key research findings are as follows:

- The four operation modes of the system can not only deal with the unstable and discontinuous characteristics of solar irradiation, but also actively deal with the time-varying characteristic of users heat demand and heliostat field efficiency. The three control strategies can meet the different operation stages and modes of thermal storage season and heating season, and give full play to the design performance of the main components of the system.
- The annual thermal collection of the solar tower thermal collection subsystem is 325.0 MWh, and the annual thermal collection per unit daylighting area of the thermal collection field is 439.6 kwh/m^2. The efficiency of the heat collection field can reach more than 50.8% under typical working conditions. This project proved that the solar tower thermal collection subsystem could operate efficiently in the water pit for long-term seasonal solar thermal energy storage, and expanded the application idea for the existing concentrating solar thermal application technology.
- The system collected 450.8MWh of solar thermal energy in the whole year, the internal energy of water pit increased 94.5MWh, the average temperature of water pit increased from 13℃ to 54.2℃, the average temperature of water pit at the end of heating season was 42.7℃, the thermal storage efficiency reached 62%, and the solar energy guarantee rate reached 49.4%.
- The thermal dissipation process of water pit is a very complicated unsteady process. Moreover, the thermal transfer and coupling process among water pit, insulation layer, soil and environment is a very challenging work. And the future research can be carried out from the water separator layout of water pit, economy of insulation layer, optimization of energy transfer and thermal exchange control theory etc.

6. Acknowledgments

The authors thank the Strategic Priority Research Program of the Chinese Academy of Sciences (No. XDA21050200) for funding this project.

7. References

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