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A central solar-industrial waste heat heating system with large scale borehole thermal storage

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Abstract

In this paper, a new research of seasonal thermal storage is introduced. This study aims to maximize the utilization of renewable energy source and industrial waste heat (IWH) for urban district heating systems in both heating and non-heating seasons through the use of large-scale seasonal thermal storage. Based on this research, a demonstration project of a central solar-IWH heating system with 500,000 m^3 borehole thermal energy storage (BTES) is implemented in Chifeng, China. The detailed design, control strategies and optimization methods of the project is presented and discussed in this paper. The study showed that a smooth system operation with stable energy output and supplying temperature of seasonal storage could be achieved by adopting the developed control strategy.

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Keywords: Seasonal thermal storage; District heating; Solar water heating; Industrial waste heat;

1. Introduction

For district heating systems integrated with renewable energy sources (RES), the seasonal mismatch between energy generation and heating demand could be rather huge. Against this background, the conception of Seasonal Thermal Energy Storage (STES) is proposed. STES represents storing thermal energy for periods of up to several months and utilizing the heat recovered from the heat storage for building or district heating in heating seasons.

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At present, although all the different types of STES technologies, such as large-scale water tank storage, Aquifer Thermal Energy Storage (ATES), Borehole Thermal Energy Storage (BTES), have a range of applications, covering from single small buildings to community district heating [1-5], clear conclusions and design principles of these technologies still doesn’t form at some certain aspects. In addition, there are various problems and imperfections revealed in the existing STES applications. For instance, a large number of systems have reported a low storage efficiency due to the high heat loss ratio of the thermal storage. Moreover, most of the heating plants with BTES utilize electrical driven heat pumps for heat extraction, which causes a degeneration of energy grade.

In this study, a new demonstration project of central solar-IWH (industrial waste heat) heating system is introduced. The project aims to develop a technique route of RES district heating that avoid using fossil fuels and electrical driven heat pump by integrating a variety of heat sources with large scale BTES. The detailed design, control strategies and optimization methods of the project will be discussed.

2. Demonstration project

2.1. Project information

The project locates in Chifeng, Inner Mongolia autonomous region, China. The central heating station of the demonstration project is settled near a local copper plant, inside which a 20MW IWH recovery system is built, providing the city central heating network with 500,000GJ heat annually, serving about 1million building area.

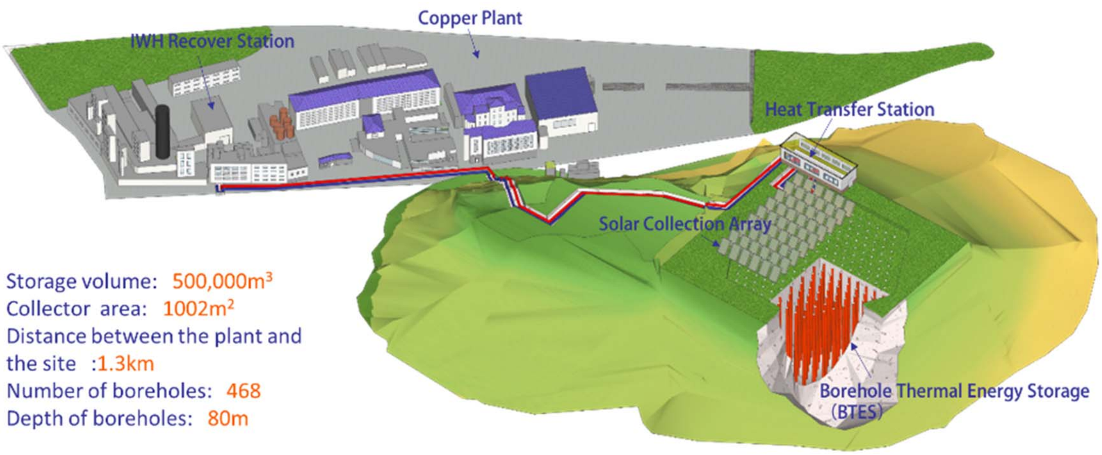

Fig. 1. Site plan of the demonstration project

The site plan of the demonstration project is shown in Fig. 1. The demonstration project is built on a hill about 1300 meters away from the heat source in the copper plant. A BTES, including 468 boreholes with 80-meters depth, is installed underground. Single U tubes are mounted in boreholes, serving as ground heat exchangers. The volume of the BTES in this project reaches 500,000m^3. Solar collector array is installed above the BETS, the total aperture area of which is 1002m^2.

2.2. System scheme

A one-year operation cycle of the system is divided into two periods, which are: the heat storage period (from April 16th to October 14th) and the heat extraction period (from October 15th to April 15th), overlaps with local non-heating and heating seasons separately.

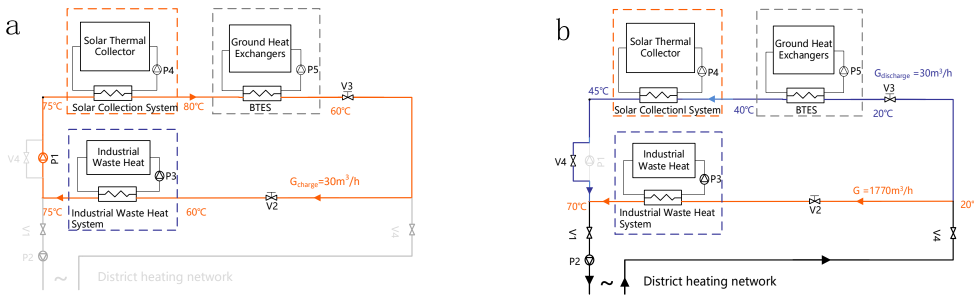

Fig. 2. (a) heat storage process; (b) heat extraction process.

In the energy storage period, the system scheme is shown as Fig. 2 (a). The heat-injection circulating pump P1 is activated, heat carrier fluid is heated by the IWH system to 75 ºC first through a steam-water heat exchanger. Then it flows through the solar collection system to further improve its temperature to about 80 ºC, and then to the BTES to charge the soil around the ground heat exchangers, with its temperature reduced to about 60 ºC at the outlet of the BTES. After that, the heat carrier fluid returns to the IWH system to recover heat.

While in the heat extraction period, as illustrated in Fig. 2 (b), the heat supplying circulating pump P2 is activated and the flow direction between the solar collection system and the BTES is reversed. A portion ($30m^3$/h) of the returning water from the district heating networks (20 ºC) passes through the BTES first to extract the heat stored underground and then further heated by the solar collectors to about 45 ºC (illustrated by the blue line). The other fraction of heat carrier fluid flows to the IWH system for heat recovering, with temperature improved to about 75 ºC (illustrated by the red line). These two flows then mix and enter the district heating network. The low temperature returning water of the district heating network is obtained by integrating AHPs (Absorption Heat Pump) in district heating stations.

2.3. Challenge for seasonal storage of IWH through BTES

As shown in Fig.2. (a), in the heat storage period, the BTES serves as a cold source for the IWH system. The heat carrier fluid returns to the IWH system after discharged at the BTES. Therefore, the returning water temperature of the IWH system is determined by the supplying water temperature of the BTES. Due to the seasonal heat injection/extraction of BTES is a typical long-term variation process with large thermal inertia, the outlet water temperature of BTES tends to change continuously in the entire operation cycle. Therefore, the maintaining of a stable supplying water temperature of BTES, which is important for the industrial waste heat system, becomes a key question for the seasonal thermal storage of IWH.

Aiming to this question, Fang et al. [6] proposed a conceptual approach named "block by block" control strategy. In this study, the design model and concept is improved and applied in the design of the demonstration system in Chifeng. Detailed system model and control method will be introduced in the next section.

3. System modelling and control strategy

3.1. System model

The production of the solar collectors could be calculated by Equation. 1, thus the outlet temperature of solar collector could be calculated accordingly.

$$\dot{Q}_{collection} = A_C\left[I_T F_R\left(\tau\alpha\right) - F_R U_L\left(t_{in} - t_{amb}\right)\right]^+ \tag{1}$$

Where A_C is the total collector area, m^2; I_T represents the solar radiation intensity on the surface plane of the solar collector, W/m2; F_R is the collector heat removal factor, $(\tau\alpha)$ is the average transmittance absorptance product; U_L is the collector overall heat loss coefficient, W/m2·K; t_{in} represents the inlet temperature of fluid to collector and t_{amb} represents the ambient temperature, K; The total radiation intensity I_T need to be calculated according to the local radiation profile and tilt angle of the solar collectors. In this method, isotropic sky diffuse model is used for the calculation of I_T. The tilt angle adopted in the project is 55°.

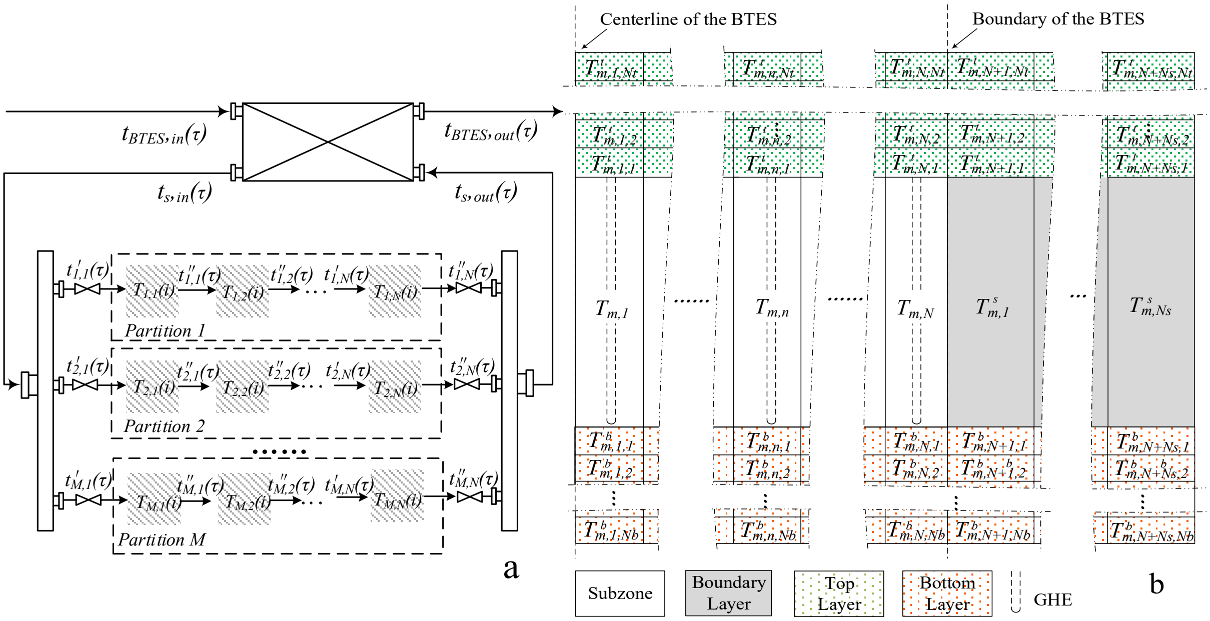

Fig. 3. Partition-by-partition model of the BTES

The concept of the control strategy for the demonstration project is illustrated in Fig. 3. The BTES is divided into several partitions, and each partition contains an equal number of GHEs. Partitions are connected in parallel through a pair of water distributor and collector. Partitions could be opened or closed independently. Thus the supplying water temperature of the BTES, $t_{BTES,out}$, could be controlled to a stable range by selecting feasible combinations of partitions from all the possible combinations. At any given time, the controller compares $t_{BTES,out}$ with its set point t_{set}, if the difference is within the allowable deviation range ($|t_{BTES,out} - t_{set}| \leqslant \Delta t_d$), the in-use combination will be hold, otherwise a switch of combination will be executed according to a certain calling sequence. In each partition, the GHEs are divided into several subzones that connect in serial. Each subzone has an equal number of GHEs. To reduce the global heat loss of the storage, subzones are partitioned from the center to the boundary of BTES.

The calculation of the heat exchange of BTES could be expressed as follows:

The sequence number of each partition and subzone is denoted as m and n separately (with the total number of partitions and subzones denoted as M and N separately), thus a subzone of the BTES could be represented by the combination of (m, n). The mean soil temperature of each subzone is denoted by the uppercase letter T, the water temperature is denoted by the lowercase letter t. Superscripts $'$ indicates the inlet water temperature, while $''$ indicates the outlet water temperature of each subzone. At any given time τ, the heat transfer between the soil and the circulating fluid in subzone (m, n) could be calculated by Equation. 2.

$$\dot{m}C_w\left[t_{m,n}''(\tau)-t_{m,n}'(\tau)\right]=\frac{t_{m,n}(\tau)-T_{m,n}(\tau)}{R}\cdot N_b\cdot l \qquad (2)$$

Where R is the total thermal resistance between the water and the mean soil temperature of each subzone. R involves the thermal resistance between the circulating fluid and the outside wall of the borehole (denoted as R_b) and the thermal resistance between the outside wall of the borehole and the mean soil temperature of the subzone (denoted as R_h). The mean circulating water temperature of subzone (m, n) could be calculated as follows:

$$t_{m,n}(\tau)=\frac{1}{2}\left(t_{m,n}''(\tau)+t_{m,n}'(\tau)\right) \tag{3}$$

R_b could be calculated by Equation. 4 [7].

$$R_b=\frac{1}{2}\left\{\frac{1}{2\pi\lambda_g}\left[\ln\left(\frac{d_b}{d_o}\right)+\ln\left(\frac{d_b}{D}\right)+\frac{\lambda_g-\lambda_s}{\lambda_g+\lambda_s}\ln\left(\frac{d_b^4}{d_b^4-D^4}\right)\right]+\frac{1}{2\pi\lambda_t}\ln\left(\frac{d_b}{d_o}\right)+\frac{1}{\pi d_i h_w}\right\} \tag{4}$$

Where d_b, d_i and d_o represent the diameter of borehole, inside diameter and outside diameter of the U-tube respectively, m; D is the distance between the two branches of the U-tube, m; h_w denotes the convective heat transfer coefficient between the circulating fluid and the inner wall of the tube, W/m^2·k; λ_s, λ_g, and λ_t are the thermal conductivities of the soil, grout, and the pipe wall respectively, W/m·k. h_w could be generated through the Dittus-Boelter equation:

$$\mathrm{Nu}=\frac{h_w d_i}{\lambda_w}=0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^n, n=0.4(\text{extract})/0.3(\text{storage}) \tag{5}$$

R_h could be calculated as following [8]:

$$R_h=\frac{1}{2\pi\lambda_s}\left[\ln\left(\frac{B}{\pi d_b}\right)+\frac{\pi}{6}\right] \tag{6}$$

The heat conduction between the adjacent subzones, as well as the global heat transfer between the BTES and the surrounding soil, is introduced into the model. The discretization of the computing region of one partition is illustrated in Fig. 3 (b). The ground within a certain distance to the boundary of BTES is divided into a certain number (denoted as N_S) of vertical layers, the temperature of each boundary layer is denoted by the subscript S. The top/bottom soil beyond/under the BTES and the boundary layers is divided into a certain number (denoted as N_t and N_b separately) of layers at vertical direction, and N+N_S layers at horizontal direction.

The heat injection/extraction gives a distribution of heat sources and sinks for the global heat transfer solution of the BTES, which could be expressed as:

$$\left(C_s\cdot V_{sub}\right)\frac{\partial T}{\partial \tau}=\nabla\cdot\left(\lambda_s\nabla T\right)+\dot{q}_{borehole} \tag{6}$$

At each time step, the outlet water temperature for subzone (m, n) could be generated through solving Equation.2 and Equation.3 simultaneously, thereby $\dot{q}_{borehole}$ for each subzone could be calculated.

3.2. Generation of the control strategy

The generation of the control strategy throughout a whole heat storage/extraction period is illustrated by computing flowchart (Fig. 4.). Where A denotes the set of all possible combinations of partitions. K denotes the total number of combinations in set A. To generate the optimal set point temperature, an initial value of t_{set}, which might be much beyond (in the heat extraction period) or below (in the heat storage period) the optimal set point temperature that could be actually achieved is given. Then, if the generation of control strategy with the given t_{set} is failed, the requirement will be lowered by improving (in the heat storage period) or reducing (in the heat extraction period) t_{set} by 1 ºC for each time of strategy generation.

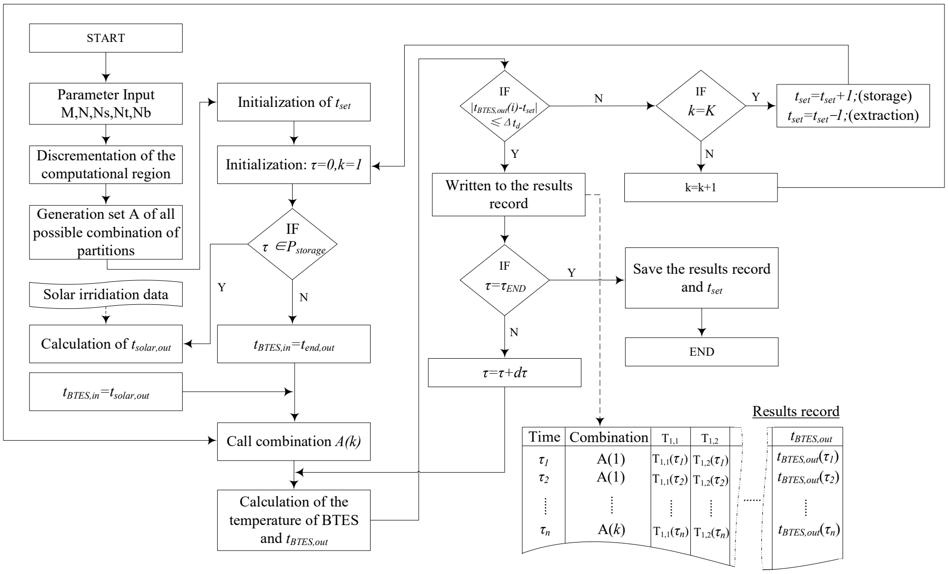

Fig. 4. Computing flowchart of control strategy generation.

4. Results

With the developed model and control strategy, the long-term thermal performance of the system is simulated. The specific parameters used in the simulation is given in Table.1

Table.1 Parameter setting

Item	Unit	Value
Collector area, A_c	m^2	1002
Flowrate at collection loop, G_c	m^3/h	30
Collector efficiency	-	η=0.497-1.483T_i^*
Heat conductivity of grout, λ_g	W/(m·K)	2.2
Heat conductivity of soil, λ_s	W/(m·K)	0.852
Heat conductivity of pipe wall, λ_s	W/(m·K)	0.544
Outer diameter of the tube	mm	32
Inner diameter of the tube	mm	23.2
Inner diameter of the borehole	m	0.15
Initial soil temperature	ºC	12
volumetric heat capacity of the soil, C_{vs}	J/m^3·k	1655000
Total flowrate in the heat exchange pipe	m^3/h	30
Total flowrate in the GHEs	m^3/h	30
Length of pre-heating duration	Hour	12000
Length of heat storage season	Hour	4320
Length of heat extraction season	Hour	4320
Supplying temperature of the IWH system, $T_{IWH,out}$	ºC	75
Returning temperature of the heating network, $T_{end,out}$	ºC	20
Feasible outlet temperature deviation，Δt_d	ºC	±6℃(pre-heating),±5℃(heat storage/extraction)
Number of boreholes	-	468
Depth of the boreholes	m	80
Number of partitions, M	-	6
Number of subzones in each partition, N	-	6

Fig. 5. shows the variation of the mean soil temperature, as well as the outlet temperature of the BTES. As shown, after 12000-hours pre-heating, the mean soil temperature of the BTES reaches around 60 ºC. Then the system is put

into regular operation of heat storage and extraction alternatively. The soil temperature reaches around 42.5 ºC after a heat extraction process and around 60 ºC after a heat storage process. By using the developed control strategy, the supplying temperature of the BTES could be controlled to a relatively stable range.

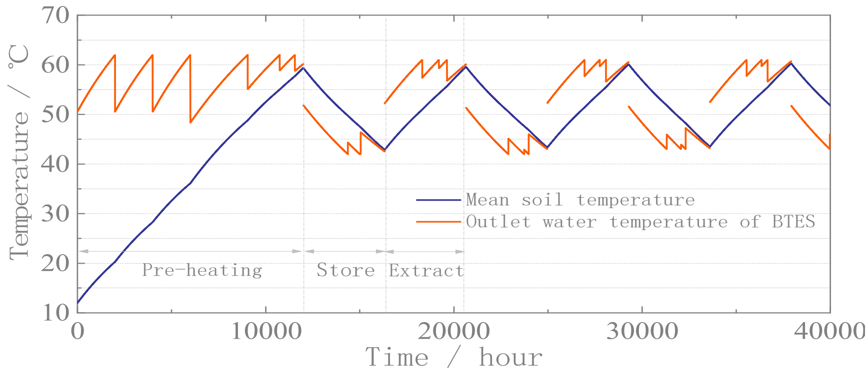

Fig. 5. Variations of mean soil temperature and outlet water temperature of the BTES

Fig. 6. shows the variation of the annual heat loss ratio of the system (the ratio between the annual heat loss of the BTES and the annual heat storage to the BTES) and the mean soil temperature of the surrounding layers. As shown, the heat loss ratio reduces continuously with the increase of the mean soil temperature of the surrounding layers. After a ten-years operation, the annual heat loss ratio of the BTES decreases to around 6.52%.

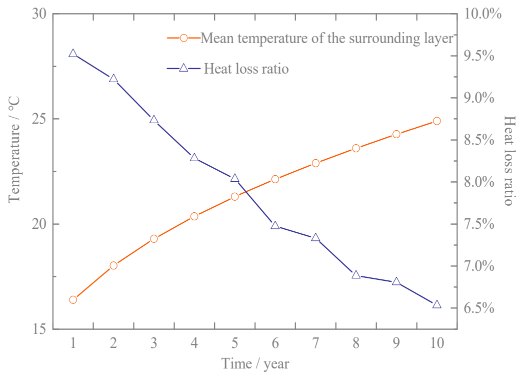

Fig. 6. Variations of heat loss ratio of the BTES

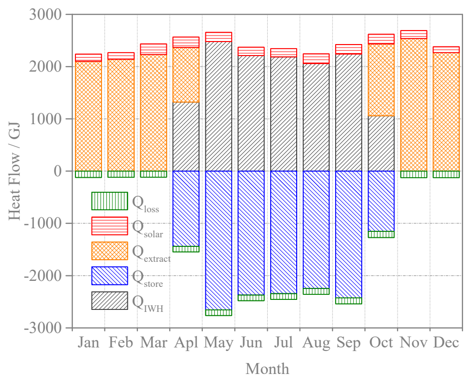

Fig. 7. Accumulative heat flow of the system on a month basis

The accumulative heat flow of the system on a monthly basis over an entire operation year (the 10th year) is shown in Fig. 7. As shown, by integrating IWH and solar energy into district heating network through the utilization of large scale BTES, a smooth energy output could be achieved. The annual heat storage of the system is 14633 GJ and the heat extraction is around 13699 GJ.

5. Conclusions

A demonstration project of seasonal thermal storage of IWH and solar energy for urban district heating is introduced in this paper. The project is a new attempt to explore utilizing renewable energy or waste heat more efficiently. Comparing with the existing STES applications, the demonstration project brings a number of new features including (1) the system does not require fossil fuel as auxiliary heating sources. (2) By reaching the ground storage volume up to 500,000m^3 and optimizing BTES configuration, heat loss ratio of the system can be lower than 90%. (3) Heat extraction by direct heat exchange, instead of using electric heat pumps is achieved in this project.

The detailed modelling and control methods of the system are presented and discussed in this study. Long term simulation shows that a smooth system operation with stable energy output and supplying temperature of BTES could be achieved by adopting the developed control strategy.

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