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A review on borehole seasonal solar thermal energy storage

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Abstract

Because of the intermittence and unreliability of solar radiation, a seasonal thermal energy storage system is needed to maximize the potential utilization of solar energy. Borehole seasonal solar thermal energy storage is one of the most common energy storage methods and some applications have been conducted. This paper reviews the studies on borehole seasonal solar thermal energy storage. Analytical and numerical models of underground regenerator and system simulations are summarized here. Large application projects used for center solar heating in European counties and some small scale experimental studies are included. Problems and barriers of the development of borehole heat storage in China are also given.

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Keywords: Solar energy, seasonal thermal energy storage, borehole heat storage

1. Introduction

The development and utilization of renewable energy is a current hot topic in energy field. And solar energy seems to be the most promising one. But unfortunately solar radiation is intermittent and unreliable while energy supply demand is continuous and stable, and the period of time when solar radiation is strongest is always not in accord with that when thermal energy demand is highest. To solve this contradiction, a seasonal solar thermal energy storage system is needed. During the 1960s seasonal storage of thermal energy was first proposed in the US [1]. Since then, seasonal solar thermal energy storage has been the subject of many researches and some energy storage systems were proposed. Among the four kinds of thermal energy stores (hot-water thermal energy store, borehole thermal energy store, aquifer thermal energy store, gravel-water thermal energy store), aquifer heat storage and borehole heat storage are the most common ones [2]. Nowadays, borehole heat storage is preferred, for the reason that aquifer heat storage may affect the important water resources -aquifer and cause undesirable influence on hydro-geologic and engineering-geologic condition.

Borehole heat storage stores heat in soil/rock through borehole heat exchanger embedded in the drilled holes with a depth of 30-200m [3], and the stored heat is extracted whenever needed. The borehole seasonal solar thermal

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storage system is always equipped with heat pumps due to the relative small temperature difference between the soil and the working fluid. A simplified schematic of borehole seasonal solar thermal storage system is shown in Fig. 1. It can be seen from the figure that the system is composed of solar collectors, short-term thermal storage device, heat pump, borehole heat exchanger and end-user device. In non-heating season, surplus solar thermal energy is stored underground, while in heating season the stored heat is extracted and heat pump is used to raise temperature for the end user.

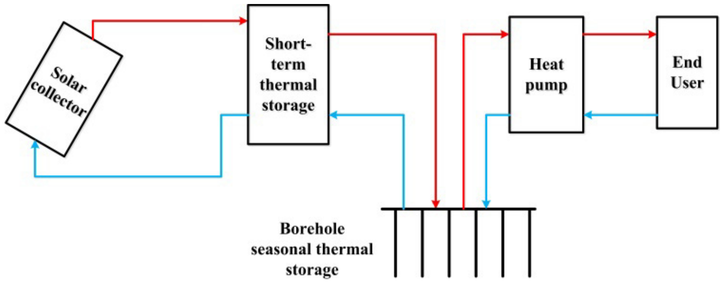

Fig. 1. A schematic of borehole seasonal solar thermal storage system.

Penrod first proposed the idea that combines solar collector and borehole heat exchanger in1956, and then he extended this idea into storing solar thermal energy underground [4-6]. Because of energy crisis and the temperature imbalance caused by the utilization of ground source heat pump in place where heating load is greater than cooling load, borehole seasonal solar thermal energy receives extensive attention. Many researches have been published and some demonstration projects have been conducted. This paper presents a detailed review on various investigations done so far on borehole heat storage, for fully understanding the development of borehole seasonal solar thermal storage. Analytical and numerical models of underground regenerator and system simulations are summarized here. Large application projects used for central solar heating in European counties and some small scale experimental studies are included. Problems and barriers of the development of borehole heat storage in China are also given.

2. Analytical and simulation study

2.1. Underground heat transfer

Heat transfer of underground regenerator is of essential importance for system performance. Three basic analytical models (seeing Table 1) for borehole heat exchanger in ground heat pump system can also be applied to the borehole heat storage. In the beginning, to simplify the model, the heat transfer in the soil/rock is taken as pure heat conduction. But then, researchers found that subsurface seepage flow, water content, soil layers, soil constituent and so on has great impact on the heat transfer, and underground temperature differs great in time and space. So the basic models are modified and extended to be suited to different situation, and new models are proposed.

Table 1. The characteristics of three basic models for borehole heat exchanger [7-9].

Researchers	Method	Proposed time	Basic characteristic
Ingersoll	Line source model	1948	The underground heat exchanger is taken as infinite line source; The heat flux is constant.
Carslaw and Jaeger	Cylindrical heat source model	1954	The underground heat exchanger is taken as infinite cylindrical source ; The fluid in the pipe is considered.
V.C.MEI	Model	1986	Based on system energy balance and heat conduction equation.

In 1983, Brookhaven National Laboratory modified the line source model. The heat transfer region around the buried pipes was divided into two parts – the strict part and the free part. The IGSHPA [10] also recommended a commonly used borehole heat exchanger model. The model is based on the line source model but adopted the developed formulae that approximate the exponential integral appearing in the line source solution [10]. Kavanaugh [11] conducted a theory approximate treatment for cylindrical source model in 1985. In his model, the two legs of the U-pipe is equivalent to one pipe, and the equivalent diameter is $\sqrt{2}$ times of that of the U-pipe. Deennan and Kavanaugh [12] extended the model to be used in the variable heating condition, and the modified model can make a more accurate simulation for the long term operation of the borehole heat exchanger. Lamarche and Beauchamp proposed a modified analytical model based on g-function that yields results very similar to those obtained by Eskilson and can be used to medium and longtime analyses of any kind of configuration [13]. Yang et al [14] proposed an updated two-region analytical model for vertical U-tube ground heat exchanger. The model divided the heat transfer region into two parts at the boundary of borehole wall. Transient heat transfer in soil region outside borehole is calculated by a variable heat flux cylindrical source model, while a quasi-three dimensional steady-state heat transfer analytical model for the borehole is developed based on the element energy conservation. Using a matched asymptotic expansion technique, Li et al. [15] developed an analytical full-scale model which is of composite solution (G-function) for heat transfer by borehole ground heat exchangers with U-shaped tubes. This composite solution consists of the composite-medium line source solution (inner solution) for short time, the conventional finite line source solution (outer solution) for long time, and the conventional infinite line-source model for intermediate time. Meanwhile, the model is rewritten as a multi-stage model based on Duhamel's theorem to reduce the computational cost.

The underground heat storage designs are often developed on the basis of the results of numerical simulations. So numerical models of the borehole are of great importance, and quite a lot of numerical models and simulation tools are proposed [16]. Eskilson [17] presented a method based on dimensionless parameters which were called ''G-functions'' to give the performance of a borehole for various bore field configurations. And the borehole wall temperature was calculated by transient finite difference method. The model was implemented into the simulation tools EED [18] and GLHEPRO [19, 20]. Carli et al. [21] proposed the computational CaRM (CApacity Resistance Model) for three different types of vertical heat exchangers (single U-tube, double U-tube and coaxial) based on electrical analogy. And the model is validated by HEAT2, a detailed two dimensions finite differences calculation method. Zarrella et al. [22] improved the model CaRM by taking into account the thermal capacitance of the filling material and the heat carrier fluid for short time step analysis. This time the model is validated by the COMSOL and ground response test for double U-tube ground heat exchanger. Ozudogru et al. [23] developed a 3D numerical model for the vertical ground heat exchangers which can calculate 3D transient heat and mass transport processes with minimal computational effort by the COMSOL. The model uses 1D element for simulating the flow and heat transfer inside the pipes and 3D element for heat transfer in the surround mediums. The comparison of the proposed model and the finite line source model conducted on a borehole with a single U-tube and an energy pile with double U- tubes shows that the two models are coincident. Lanini et al. [16] proposed and validated a 3D multilayer numerical model which was developed with the COMSOL from the experimental data of the SOLARGEOTHERM project, and used it for simulating different configurations over many years. The modelling results shows that, for the investigated heat range, the BTES (borehole thermal energy store) configuration with three 180 m-deep boreholes will not be efficient for seasonal storage. Therefore, a theoretical approach to optimizing BTES design was proposed. Luo, et al. [24] modelled the heat transfer of three groups of borehole heat exchangers in Nuremberg, Germany in a layered subsurface by a numerical model developed using FEFLOW. The result for considering the ground to be homogenous is similar with that when the ground is taken to be with five bedded sedimentary layers. Zheng et al. [25] established transient physical and mathematical models of a vertical U-pipe and the temperature field around the soil and used MATLAB to conduct finite element numerical simulation. Bouhacina et al. [26] conducted simulations on the dynamic and thermal behavior of geothermal vertical U-tube heat exchanger intended for solar energy storage by FLUENT. Results are in good agreement with work from the literature. A numerical model in MODFLOW/MT3DMS of a single U-pipe in a sandy aquifer considering the groundwater flow effects was proposed by Angelotti et al [27]. And a rigorous validation of the model under a broad range of groundwater velocities is also provided. Lazzarotto [28] proposed a numerical network-based methodology which can be used to analyze borehole field configuration arrangement and optimize strategies to operate borehole thermal energy storage systems. This method divided the storage system into two parts: a local problem (a region inside the borehole) and a global problem (a region outside the borehole).

2.2. System simulation and optimization

For economical and reliable design and operation of the solar system with borehole seasonal thermal storage, simulation and optimization should be conducted. Though such system is with a highly dynamic behavior and the calculation is quite complex, there still have been several simulation on the borehole seasonal thermal storage system. Some software such as TRNSYS, MINSUN, SOLCHIPS and commercial numerical calculation codes has been used for system simulating [29, 30]. Among them, SOLCHIPS is a predesign tool and cannot be used to analysis existing system [31], while the most widely used one is TRNSYS. So the following meanly reviews the system simulation using TRNSYS. In the following, several simulation researches for different kinds of system with different emphasis are summarized.

Detailed design studies of central solar heating plants with a ground duct seasonal store have been performed with TRNSYS [32]. Pahud [33] conducted a dynamic system simulation of a central solar heating plant with seasonal duct storage under typical Swiss conditions and several types of heat load over several years by TRNSYS. He also established a methodology for the optimization of main system parameters including buffer volume, duct storage volume and collector area based on a solar fraction of 70%. The optimal ratios for buffer volume, duct storage volume and collector area are 110 to 130 l per m^2 of collector area, 4 to 13 m^3 per m^2 of collector area and 2 to 4 m^2 per MWh of annual heat demand, respectively.

Argiriou [29] compared the design data of an interseasonal storage system in Greece with the results of MINSUN and SOLCHIPS. And the comparison showed good agreement. Nordell and Hellström [34] performed a preliminary study of a high-temperature solar-heated borehole seasonal storage system for low-temperature space-heating. The TRNSYS and MINSUN together with the ground storage module DST were used. The system was studied for utilization in a new residential area, Anneberg. The simulation indicated that 3000 m of roof-mounted solar collectors and a borehole storage system of 60000m^3 (99 boreholes, borehole depth 65 m) for the area with 90 building units of 100 m each would provide 60% of the total heat demand (space heating and domestic hot water).

Sibbitt et al. [35] presented the simulated performance in the design phase of Drake Landing system in Canada (see Fig. 2 (Left)) from a detailed TRNSYS with ESP-r system simulation. The results showed that collector efficiency would drop from 32% to 25%, the BTES efficiency would increase from 9% to 41%, and the solar fraction would increase from 66% to 89% over 5-years. The five years operation monitoring of the system showed that the design simulations had proven to be accurate.

Fig. 2. (Left) Drake Landing solar community [35]; (Right) Scheme of Solar-Ground Coupled Heat Pump with Seasonal Storage [65].

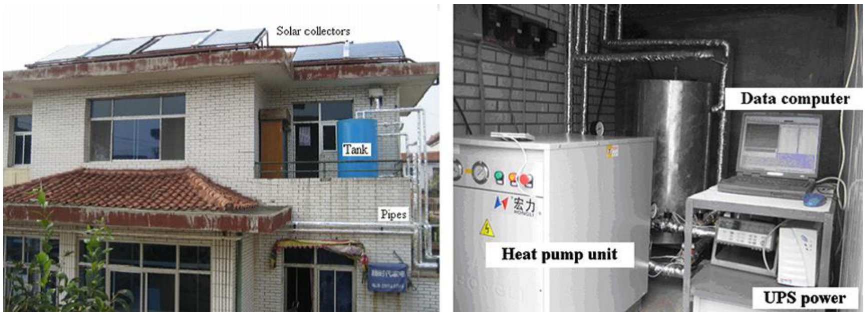

Fig. 3. (Left) View of residential buildings.Scheme; (Right) View of the experimental system [36].

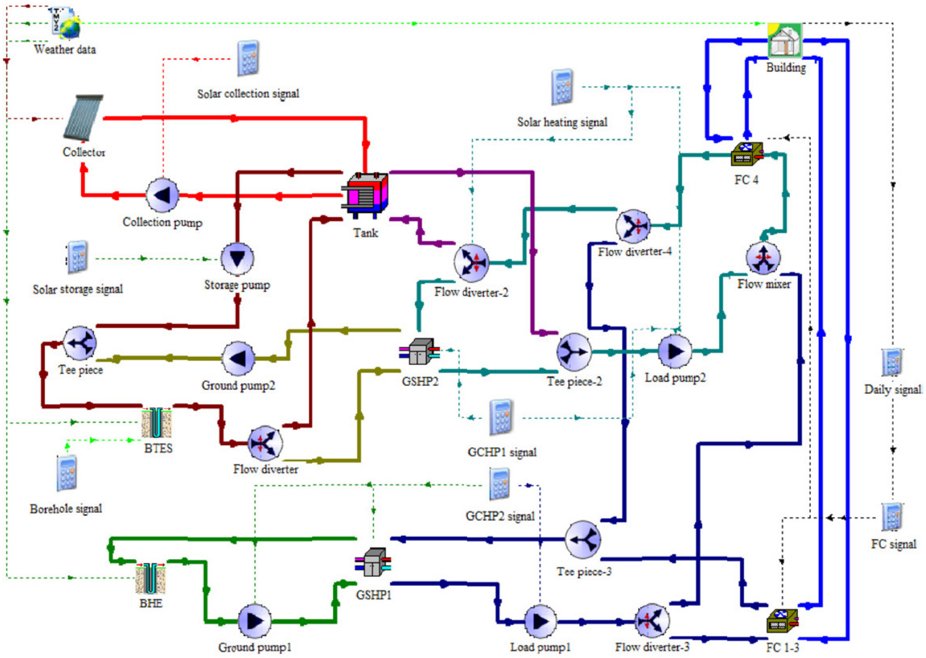

Fig. 4. Simplified hydraulic scheme of a hybrid solar ground-source heat pump system in TRNSYS [38].

Based on experimental results, the Visual Basic was used by Wang and Qi [36] to analyze performance and parametric effects of a solar-ground coupled heat pump system with underground thermal storage for residential building (see Fig. 3). The modelling system is installed in a 120m^2 family house in Jinghai county, Tianjin, and the boreholes is 50m depth. The simulation results during the operation period of 180 days (from 1 May to 27 October) suggest that the efficiency of underground thermal storage based on the total solar radiation can reach 40%, while the reasonable ratio between the tank volume and the area of solar collectors should be in the range of 20-40 L/m^2.

The experimental set up of interseasonal heat and coolth storage system with two 40m deep boreholes (one for heat storage and one for coolth storage) and two 3.84m^2 unglazed solar collector at the University of Melbourne for heat charging was also modelled in TRNSYS-17 by Lhendup et al. [37]. The simulation was validated by the experiment for a period of 180 days. And the mean efficiency of the system was found to be 38%. Wang et al. [38] used TRNSYS 17 to predict the multi-year performance of a novel hybrid solar ground source heat pump system (HSGSHPS) composed of a GSHPS and a solar assisted GSHPS used in an office building with a total floor area of

4953.4 m^2 for heating and cooling, suitable control strategy for the solar collection and storage was found, and the effect of first-time operation time is simulated (see Fig. 4).

Energy analysis for a closed greenhouse which had a borehole seasonal thermal energy storage system and a daily storage system for peak load management was also carried out by Vadiee and Martin [39]. And the results are used for a thermoeconomical feasibility study. The analysis showed that the payback time was 7 years for the system that only had seasonal thermal energy storage while the time reduced to 5 years for that had both short-term and seasonal thermal energy storage.

3. Experiment and application

For the reason that construction always needn't permit, there is no official statistics on the number of borehole thermal energy storage plants [40]. However, based on very rough estimates, it is estimated that there are approx. 400 borehole thermal energy storage systems in operation in Swedish at the end of 2011 [41]. The number of borehole thermal energy storage boreholes is estimated to have grown from 24 in 1996 to approximately 18,000 in 2006 in Dutch. The boreholes in the Netherlands are almost 22500 in 2007 [42]. Similar strong growth rates are reported in other European countries [43]. While in China, the borehole thermal energy storage only develops a little [44].

Table 2. The characteristics of some large application projects in Europe.

Country	Plant	Year of initial operation	Service building	Solar collector	Borehole storage	Load size (MWh/a)	Solar fraction (%)	Ref
Italy	Treviglio	1985	Existing residential area	2727m^2, roof-mounted, flat plate.	43000m^3		70	45
Sweden	Lidköping		New residential area, 40 two family houses	2500m^2, roof module.	15 000 m^3 clay	980	70	45,46
Sweden	Anneberg	2002.	50 residential units with about 120m^2 floor area each	2400m^2, roof-mounted.	60,000m^3 crystalline rock; 100 65-m-deep boreholes that filled with double U-pipes	550	70 (calculated)	47,63
Germany	Neckarsulm	1999	20000 m^2	5470 m^2	63360m^3, doubled in U-shape duct of 30-m-deep	1700	50	48-50
Germany	Attenkirchen	2002	6200m^2, 30 low energy homes	836 m^2	9350m^3, 90 borehole double-U-loops heat exchangers with 30 m depth	487	55	46, 50-52
Germany	Crailsheim (see Fig. 5(Right))	2007	260 houses, school and gymnasium	7300 m^2 vacuum tubes collector	37500 m^3, double U-pipes, 80 boreholes with a depth of 55 m	4100	50a	53, 54
Netherlands	Groningen	1984	New residential area	2400 m^2 roof-mounted evacuated	23000		65	45, 53
Canada	Drake Landing Solar Community (DLCS)	2007	52 detached energy-efficient homes	2293 m^2 flat-plate, roof- mounted	33657 m^3; 144 boreholes with a depth of 35 m	530	97	35, 55-57

The first project of borehole thermal energy storage in Netherlands is commissioned in 1983 [62]. Anneberg plant (Germany) at the planning period was expected to be one of the 10 largest in Europe and the very first project to use borehole storage with crystalline rock. After 2 years of operation, the high temperature solar heated seasonal storage system for low temperature heating of buildings showed that, although problems have occurred and several parts seem to work less efficient than expected, the overall system idea works as intended. The project needs however a careful supervision and evaluation in order to minimize the risk of further problems [34, 63]. The Drake Landing Solar Community in Okotoks, Canada is the first major implementation for using borehole seasonal thermal energy storage in district heating in North America, the first system of this type designed to supply more than 90% space heating with solar energy and the first operating in such a cold climate. The operation monitoring since it initial operation in June 2007 showed its solar fraction had risen to beyond the original goal. And the solar fraction in the fifth year is 0.91 [35, 64]. Attenkirchen project [51] was carried out to study the feasibility of the system that combined an underground water storage thermally coupled to borehole storage (see Fig. 5(Left)).

Table 3. Some experiment set-up for borehole seasonal solar thermal energy storage system.

Location	Building type	Service area	Borehole storage	Solar collector	Load size	Ref
University of Melbourne, Australia			Two 40m deep boreholes (one for heat storage and one for coolth storage)	7.68m^2 unglazed		37
Eastern Pyrenees, French			Three subvertical boreholes with a depth of 180 m, double-U pipe	42 m^2		16
Tianjin	3 floors multi-function hall	5700m^2	8 double U boreholes with 120m depth	600 m^2 flat plate	design heat load: 310kW; hot water load :180kW; cooling load: 460kW	65
Hebei University of Technology, China	Energy Conservation Laboratory Centre	4953.4 m^2; Four stories	U-pipes, vertical boreholes; 25 vertical boreholes with depth of 50 m			38
Tianjin, China		Family house	120m^2	Rooftop, with 25m^2 effective collection area		36
Shanghai, China	Greenhouse	2304 m^2	4970 m^3, 130 vertical U-type heat exchangers at a depth of 10m	500 m^2 vacuum tube		67
Harbin, China	Adetached house	496m^2	Two sets of total 12 vertical single U-tubes installed 50 m deep below the house	50 m^2 flat plate	Maximum design heat load: 15.9kW; heat consumption indexes: 19.9W/m	66

As for China, there are no practical soil/rock borehole seasonal solar thermal storage systems in place [44]. Only a few experiment and demonstration projects installed for one building are conducted, and the main focus is to solve the imbalance of the underground temperature caused by ground heat pump. Harbin Institute of Technology and Tianjin University plays the leading role. Li et al. [65] took part in the set-up of demonstration project of solar-ground coupled heat pump with borehole seasonal storage and phase change heat storage for a 3 floors building with a total area of 5700m^2 in Tianjin (see Fig. 2(Right)). The experiments shown that the solar collection power reached maximum 78kW in early September and that the average heat storage power was 22.9 kW, which lasted 3~5hours per day. Wang et al. [66] presented the experimental study from April 2008 to April 2009 of a solar-assisted ground-coupled heat pump system with borehole seasonal solar thermal storage installed in a detached house of 500m^2 in Harbin. The system had two sets of total 12 high-density polyethylene vertical single U-tubes installed 50 m deep below the house and 50 m^2 flat plate solar collectors. The experimental results showed that the system can meet the heating-cooling energy needs of the building, and that after a year of operation, the heat extracted from the soil by the heat pump accounted for 75.5% of the heat stored by solar seasonal thermal storage. Xu et al. [67] evaluated the performance of a demonstrated 2304 m^2 solar heating system with borehole seasonal energy storage in Shanghai, China. The system had a 4970 m^3 underground storage with 130 vertical U-type heat exchangers at a depth of 10m, and 500 m^2 vacuum tube solar collectors. The system can operate without a heat pump. In the first operation year, 331.9 GJ was charged, and 208.9 GJ was later extracted for greenhouse space heating.

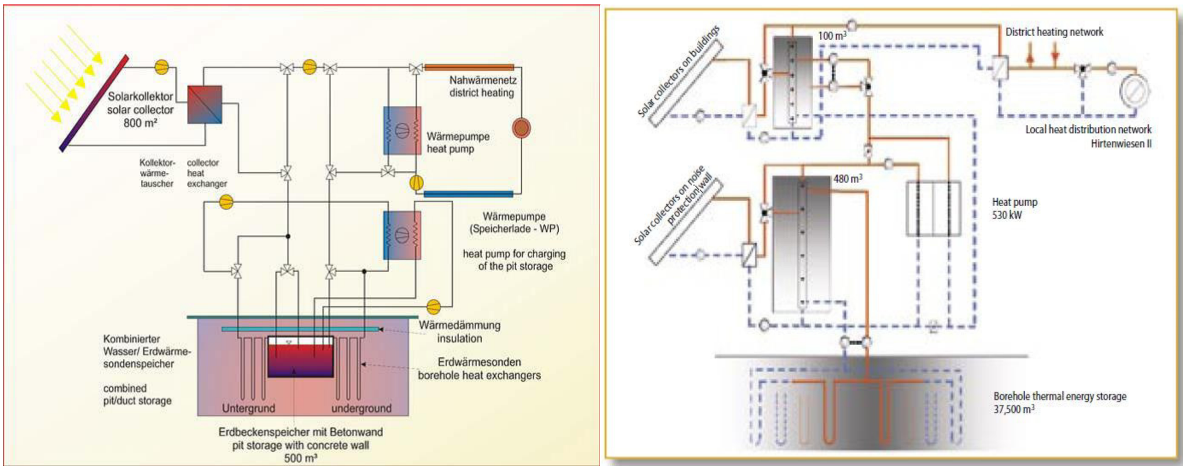

Fig. 5. (Left) Scheme of the system with an underground water storage and an borehole storage in Attenkirchen [51]; (Right) System concept of the solar assisted district heating system in Crailsheim, Germany [54].

4. Problems and barriers for development in China

Even though borehole seasonal solar thermal storage is usual and preferred to aquifer storage today, there are still some common barriers for its development in the world. These includes special geological conditions for underground water flow, soil construct and so on, unclear heat transfer mechanism underground, small heat capacity leading to large storage volume, not fully understanding system operating characteristic, and worries of disturbing underground environment. There are still some special problems for the development of borehole seasonal solar thermal storage in China. The key problems are the lack of land and quit slow development of building integrated solar collector. Still, no design specifications, poor thermal insulation of building and low degree public acceptance also hold back the development of such systems. So, to speed up the development of the system, the heat transfer model for underground regenerator should be modified to use under China condition; system operating characteristic should be fully studied through both simulation and experiment; building integrated solar collector must be developed; design specifications should be proposed; awareness should be first promoted in rural area where heating is needed.

5. Conclusion

This paper presents analytical and numerical studies on underground heat transfer. The simulation researches on borehole seasonal solar thermal storage systems are summarized. Large application projects used for central solar heating in European counties and some small scale experimental studies are included. The barriers for the borehole storage development in China are reviewed. The review shows that the original models for underground regenerator are all proposed by foreign researchers; the most common used software for system simulation is TRNSYS; large application projects are always used for central solar heating in European counties; in China only a few experiment and demonstration projects installed for single building are conducted, and Harbin Institute of Technology and Tianjin University plays the leading role; the key problems are the lack of land and quite slow development of building integrated solar collector.

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